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Abstract

The Indus River Basin faces severe water quality degradation because of nutrient enrichment from human activities. Excessive nutrients in tributaries are transported to the river mouth, causing coastal eutrophication. This situation may worsen in the future because of population growth, economic development, and climate change. This study aims at a better understanding of the magnitude and sources of current (2010) and future (2050) river export of total dissolved nitrogen (TDN) by the Indus River at the sub-basin scale. To do this, we implemented the MARINA 1.0 model (Model to Assess River Inputs of Nutrients to seAs). The model inputs for human activities (e.g., agriculture, land use) were mainly from the GLOBIOM (Global Biosphere Management Model) and EPIC (Environmental Policy Integrated Model) models. Model inputs for hydrology were from the Community WATer Model (CWATM). For 2050, three scenarios combining Shared Socio-economic Pathways (SSPs 1, 2 and 3) and Representative Concentration Pathways (RCPs 2.6 and 6.0) were selected. A novelty of this study is the sub-basin analysis of future N export by the Indus River for SSPs and RCPs. Result shows that river export of TDN by the Indus River will increase by a factor of 1.6 - 2 between 2010 and 2050 under the three scenarios. More than 90% of the dissolved N exported by the Indus River is from midstream sub-basins. Human waste is expected to be the major source, and contributes by 66-70% to river export of TDN in 2050 depending on the scenarios. Another important source is agriculture, which contributes by 21-29% to dissolved inorganic N export in 2050. Thus a combined reduction in both diffuse and point sources in the midstream sub-basins can be effective to reduce coastal water pollution by nutrients at the river mouth of Indus.

Key words:

river export of nitrogen (N); nitrogen sources; sub-basins; shared socio-economic pathways; representative concentration pathways; Indus River;

Highlights:

- Dissolved N export to sea by the Indus River will likely increase in the future
- More than 90% of dissolved N exported by Indus is from midstream sub-basins
- Over two-thirds of dissolved N export is from human waste in 2050
- Around one-third of dissolved inorganic N export is from agriculture in 2050
- Improved nutrient management for both diffuse and point sources is needed

1. Introduction

Rapid population and economic growth in many Asian countries such as India, Pakistan and China has resulted in increasing agricultural production and urbanization. This, in turn, has led to large and increasing nutrient inputs to rivers (Bouwman et al., 2009; Grigg et al., 2018; Morée et al., 2013; Suwarno et al., 2014; Wang et al., 2018). These nutrients are transported by rivers to seas, causing coastal water pollution and blooms of harmful algae (Amin et al., 2017; De et al., 2011; Seitzinger et al., 2014; Strokal et al., 2015). The total population in Asia is projected to increase by 14-37% between 2010 and 2050 in the Shared Socio-economic Pathways (SSPs) (Samir and Lutz, 2014). Thus, in the future, coastal water pollution may continue to increase in Asia, because of both expected population and economic growth (Crespo Cuaresma, 2017).

The Indus River is one of many Asian rivers that is enriched with nutrients from human activities. It is a transboundary river that flows through four countries: China, Afghanistan, Pakistan and India. As such, it is an important source for drinking water and irrigation (Azizullah et al., 2011). The basin covers the world's largest irrigation system: the Indus basin Irrigation system (Liaqat et al., 2015). Excessive fertilizer use in agriculture and improper disposal of wastewater (e.g., untreated sewage, open defecation) have led to high nutrient inputs to the Indus river. The resulting algae blooms pose a threat to the environment and human health (Azizullah et al., 2011; Raza et al., 2018; Tahir and Rasheed, 2008). Water stress caused by high water demand and nutrient pollution in the Indus basin may further increase in the future (Hashmi et al., 2009; WWF, 2007).

However, not many studies exist that analyze future nutrient transport from land to the Indus and to the sea as affected by human activities and climate change (Amin et al., 2017; Mayorga et al., 2010; Seitzinger et al., 2010). Moreover, these few studies that quantify future river export of nutrients from different sources (e.g., agriculture, human waste), do not account for spatial variability within the basin. A better quantification of the relative contributions of sub-basins will increase our understanding of the underlying spatial patterns of nutrient export by rivers. This is particularly important for transboundary rivers such as the Indus River to formulate effective water and nutrient management policies.

Thus, this study aims at a better understanding of the magnitude and sources of current (2010) and future (2050) river export of nitrogen (N) by the Indus River at the sub-basin scale. To achieve this, we implemented the MARINA 1.0 model (Model to Assess River Inputs of Nutrients to seAs) to quantify river export of total dissolved N (TDN) by sub-basin and source for 2010 and 2050. This model was applied with model inputs for human activities (e.g., agriculture, land use) derived from the GLOBIOM (Global Biosphere Management Model) and EPIC (Environmental Policy Integrated Model) models, and model inputs for hydrology derived from the Community WATer Model (CWATM). For 2050, three scenarios combining Shared Socio-economic Pathways (SSPs 1, 2 and 3) and Representative Concentration Pathways (RCPs 2.6 and 6.0) were selected. A novelty of this study is that we applied the sub-basin approach of MARINA 1.0 to the Indus basin to analyze future N export by rivers for SSPs and RCPs.

2. Method

2.1. Study area

The Indus River is a transboundary river that flows through four countries: China, Afghanistan, Pakistan and India (Figure 1). This basin has the largest contiguous irrigation system in the world (Liaqat et al., 2015). The basin covers 0.84 million km^2 (Döll and Lehner, 2002), with more than 60% of its drainage area in Pakistan. The basin had in total 180 million inhabitants in 2010. Around 30% of this population resided in urban areas.

The Indus basin was divided into 10 sub-basins following the MARINA 1.0 model approach (Figure 1) based on the Drainage Direction Map (DDM-30) (Döll and Lehner, 2002). The sub-basins were named according to the local streams covered by the sub-basins. The upstream sub-basins with tributaries: *Nubra* and *Zanskar* drain into the sub-basin *Upper stem* with the main channel. These upstream sub-basins cover in total 21% of the Indus basin. The dominant land use in these sub-basins are forests and other natural land (Figure 1). *Kabul*, *Middle stem 1*, *Chenab*, *Sutlej* and *Middle stem 2* are the midstream sub-basins covering 66% of the Indus basin. More than 80% of the arable land in the Indus basin is distributed in the midstream sub-basins Chenab and Sutlej (Figure 1). *Downstream* and *Delta* are the downstream sub-basins that cover in total 13% of the Indus basin.

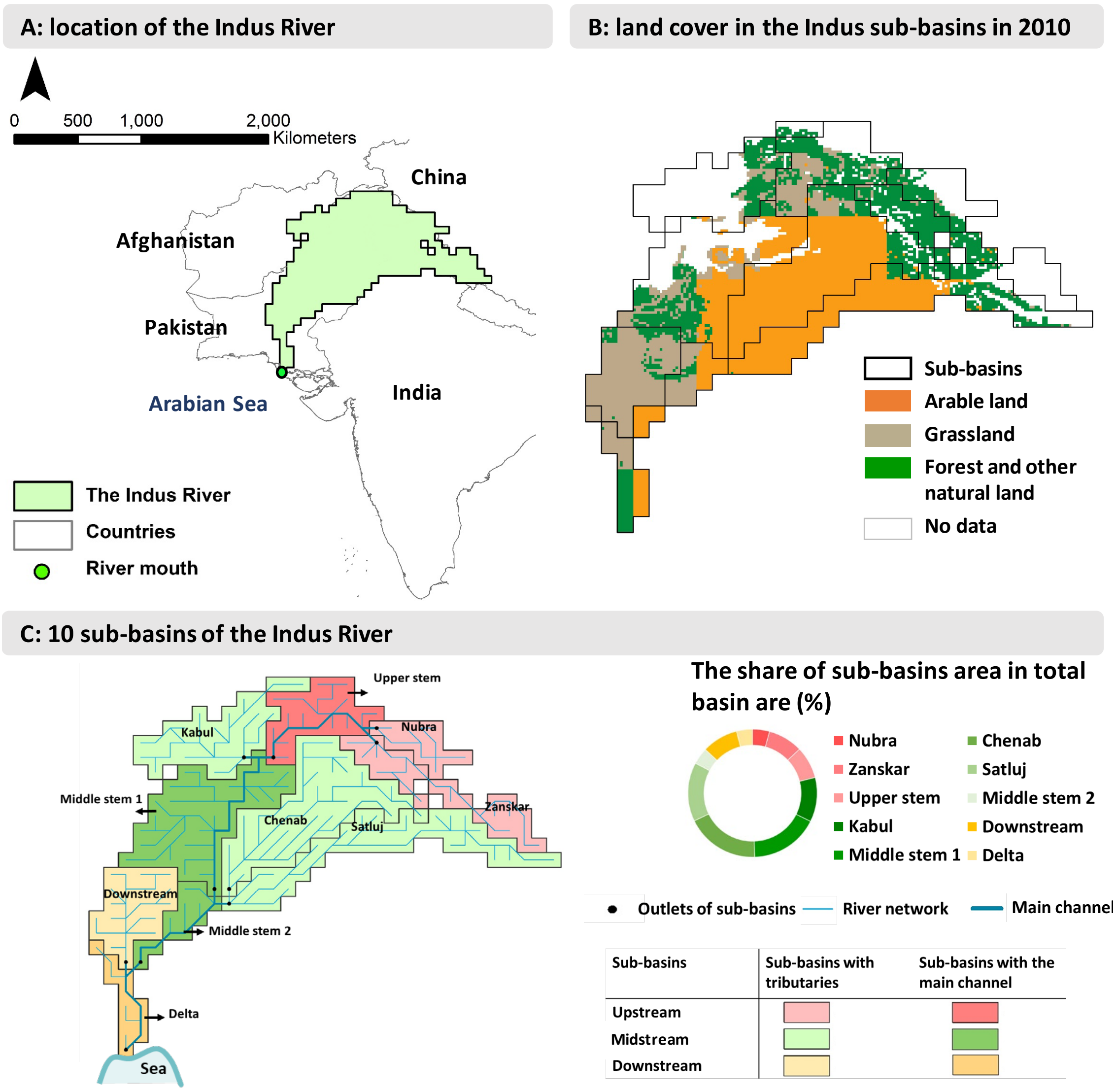

Figure 1 (A) Location of the Indus River; (B) Dominant land use in the Indus-sub-basins; (C) Sub-basins of the Indus River and the shares of the sub-basin areas in the total basin area. Drainage areas of the rivers and their sub-basins are from the Drainage Direction Map (DDM-30) at the resolution of 30 arcmin (0.5°x0.5° grids) (Döll and Lehner, 2002). The land use in 2010 is from the GLOBIOM model at the resolution of 5 arcmin (0.083°x0.0.083° grids) (Havlík et al., 2014).

2.2. Model description

We applied the MARINA 1.0 model to quantify river export of total dissolved N (TDN) by the Indus sub-basins, by source, for 2010 and 2050. TDN is the sum of dissolved inorganic (DIN) and dissolved organic (DON) N.

2.2.1. The Original MARINA 1.0 model

The original MARINA 1.0 model was developed by Strokal et al. (2016) for six large rivers in China. This model quantifies river export of different nutrient forms (dissolved inorganic N and P, and dissolved organic N and P) to the river mouth by source at the sub-basin scale on an annual basis. The MARINA 1.0 model quantifies dissolved N export by rivers as a function of *N inputs to surface waters (rivers) from diffuse and point sources* and *retention of N in rivers* based on the overall equation:

$$\mathbf{M_{F.y.j} = (RSdif_{F.y.j} + RSpnt_{F.y.j}) \cdot FE_{riv.F.outlet.j} \cdot FE_{riv.F.mouth.j}} \quad \mathbf{(1)}$$

Where $M_{F.y.j}$ (kg year^{-1}) is river export of N in form F (DIN, DON) by source y from sub-basin j. $RSdif_{F.y.j}$ (kg year^{-1}) refers to N inputs in form F to surface waters (rivers) from diffuse sources y in sub-basin j. $RSpnt_{F.y.j}$ (kg year^{-1}) refers to N inputs in form F to surface waters (rivers) from point sources y in sub-basin j. $FE_{riv.F.outlet.j}$ (0-1) is the fraction of N in form F exported to the outlet of sub-basin j. $FE_{riv.F.mouth.j}$ (0-1) refers to the fraction of N in form F exported from the outlet of sub-basin j to the river mouth. The equations to quantify $RSdif_{F.y.j,}$ $RSpnt_{F.y.j,}$ $FE_{riv.F.outlet.j}$ and $FE_{riv.F.mouth.j}$ are summarized in Box A.1 in Appendix A.

Diffuse sources of N include synthetic fertilizers, animal manure, human waste, atmospheric N deposition (for DIN) and biological N_2 fixation (for DIN) over agricultural land, and atmospheric N deposition (for DIN) and biological N_2 fixation (for DIN) over natural land. The diffuse source inputs to rivers from the above sources are quantified by correcting for N export via crop harvesting, and for N retention and losses (e.g., denitrification) calculated as a function of annual runoff from land to rivers. Leaching of organic matter is another diffuse source of DON input to rivers and is quantified as a function of annual runoff. The detailed equations to quantify diffuse sources inputs ($RSdif_{F.y.j}$) are summarized in Box A.1 in Appendix A.

Point sources of N include direct discharge of animal manure, uncollected human waste from urban and rural population that is not connected to sewage systems, and human waste from the sewage systems. The detailed equations to quantify point sources inputs ($RSpnt_{F.y.j}$) are summarized in Box A.1 in Appendix A.

River retention of N is quantified considering the retention within the sub-basins ($FE_{riv.F.outlet.j}$) and the retention during N transport through the river segments between sub-basin outlets and the river mouth ($FE_{riv.F.mouth.j}$) (Figure 2). Both the retention factors are quantified accounting for water consumption, denitrification (for DIN), and retention by dams (reservoirs) and lakes in the river systems. N retention by lakes are included in this study with lake information from the HydroLAKES database (Messager et al., 2016). Following the approach by Strokal et al. (2016), N retention in each lake was calculated based on the lake depth and water residence time. The N retention in lakes at the sub-basin scale was derived by averaging the retentions of individual lakes using actual river discharge at the sub-basin outlets. The detailed equations to quantify $FE_{riv.F.outlet.j}$ and $FE_{riv.F.mouth.j}$ are summarized in Box A.1 in Appendix A.

2.2.2. The MARINA 1.0 model for the Indus

In this study, the original MARINA 1.0 model was modified and applied to the Indus River Basin. *First*, we created the basin delineation for the Indus basin using the 30-arcminute Drainage Direction Map (DDM-30). The original MARINA 1.0 model used the 30-arcminute Simulated Topological Networks (STN-30) (Strokal et al., 2016). *Second*, we updated the approach in MARINA 1.0 to quantify human excretion according to the MARINA-Global model by Strokal et al. (2019). This was done by adjusting the method to calculate protein N intake using units of 2005 US$ instead of 1995 US$ for GDPppp (national gross domestic product at purchasing power parity). The relationship between protein N intake and GDPppp was developed by Van Drecht et al. (2009) based on dietary per capita consumption by assuming 16% of N content in protein (see the last equation in Box A.1). *Third*, MARINA 1.0 was modified to account for human waste from rural population that is connected to sewage systems. This was not considered in the original MARINA 1.0 for China assuming rural population in China did not have connection to sewage systems in 2000 (MOHURD, 2001). *Fourth*, river retention of N by lakes were added to the model in addition to the retention by reservoirs in MARINA 1.0 (Strokal et al., 2016).

To apply the modified MARINA 1.0 model to the Indus River, we also updated the model inputs for 1) hydrology (e.g., runoff and river discharge) with data from the CWATM model (Burek et al., 2017b), 2) diffuse sources (e.g., synthetic fertilizers, animal manure) with data from the GLOBIOM and EPIC models (Balkovič et al., 2014; Havlík et al., 2014) and other sources (e.g., atmospheric deposition), and 3) point sources (e.g., population, population connection to sewage systems, N removal during sewage treatment). The detailed description of model inputs and their sources are in Figure B.1 and Tables B.1 - B.8 in the Appendix B. CWATM is an open source hydrological model that was developed by the Water Program at the International Institute for Applied Systems Analysis (IIASA) (Burek et al., 2017b). Apart from modelling the water cycle as other existing hydrological models do, CWATM aims to account for the effects of socio-economic changes and climate change on future water demands, water supply and water availability. GLOBIOM was developed to analyze the competition for land use in the main land-based production sectors (e.g., agriculture, forestry and bioenergy) (Havlík et al., 2014). EPIC is used to analyze the effect of land and forest management systems on the environment, for example, water availability, nitrogen and phosphorous levels in soil, and greenhouse gas emissions (Balkovič et al., 2014).

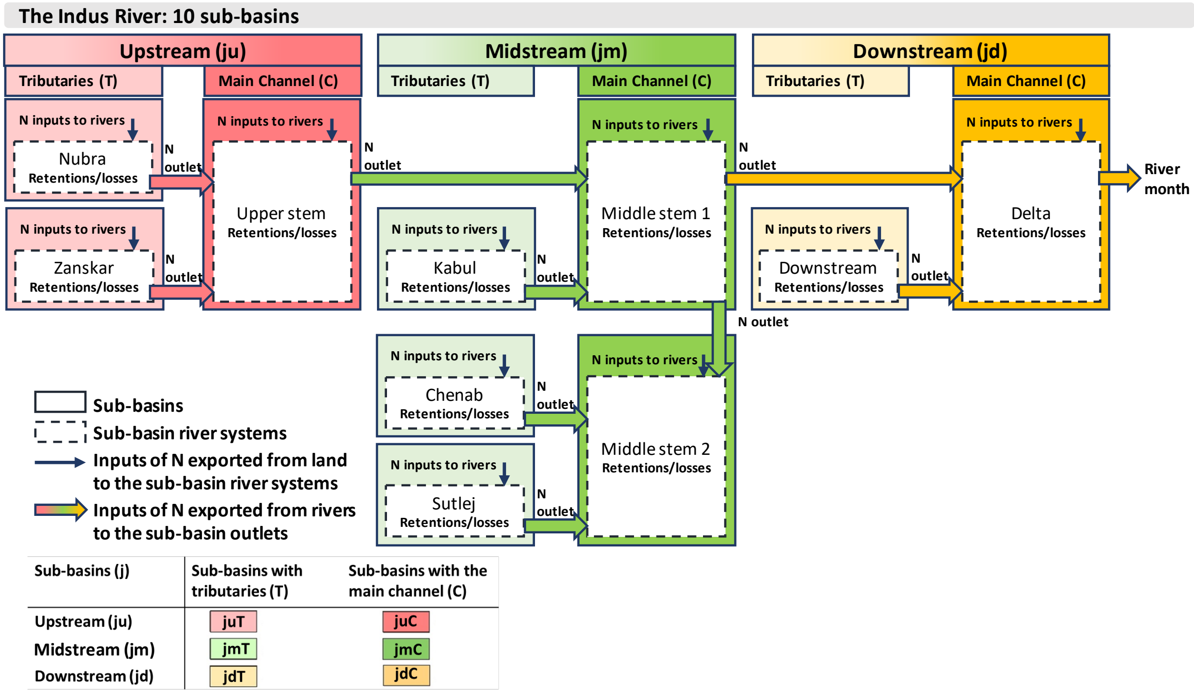

Figure 2 The schematic overview of the sub-basin scale modeling framework for the Indus River in the MARINA 1.0 model (Model to Assess River Inputs of Nutrients to seAs) based on Strokal et al. (2016). The locations of the rivers and their sub-basins are in Figure 1. This is the first time that MARINA 1.0 model approach has been implemented to the Indus River.

2.2.3. Model validation

We validated the MARINA 1.0 model for Indus by comparing our modeled results with measurements and other modelling studies. First, we compared our results on river export of DIN and DON with measurements from the GEMS/Water Data Centre (UNEP, 2017), Pakistan Council of Research in Water Resources (Imran et al., 2018) by assuming these measurements are good indicators for average annual water quality (Table 2). We did this comparison at the outlets of the Chenab and Sutlej sub-basins where measurements of N concentrations are available. Measured DIN and DON loads (kton year^{-1}) were calculated from N concentrations and river discharge. DIN is the sum of nitrite (NO_2^-), nitrate (NO_3^-), ammonium (NH_4^+), and DON refers to organic N forms (e.g., proteins, urea in human or animal excretion) in rivers. In general, the number of available measurements in literature is limited for the Indus River. Here we validated our modeled results for 2010 against measurements after 2000. Some estimates of N transport by the Indus river to Arabian Sea are available for the 1990s (Dewani et al., 2000; Singh and Ramesh, 2011). We did not use these estimates for validation because they were for the 1990s while we model 2010. This would not be an appropriate comparison, given the rapid agricultural and population expansion over the Indus basin in the last 20 years (Azizullah et al., 2011). Moreover, these estimates were mainly based on measurements in the river course rather than at the river mouth for which we modeled river export of N.

The measurements show river exports of 29 - 140 kton of DIN in 2000, and 30 - 98 kton of DON in 2003 at the outlet of Chenab. Our modeled results are within the range of these measurements (Table 2). We quantified 65 kton of DIN, and 38 kton of DON at the outlet of the Chenab sub-basin in 2010. At the outlet of Sutlej we modeled river export of DIN as 49 kton in 2010, whereas 17 kton of DIN in the form of nitrate was measured between 2015 and 2016 (Table 2). The measurements of DIN in other forms (NH_4^+, NO_2^-) were not available to us. DIN in NH_4^+ and NO_2^- forms can take a large or small share in total DIN, depending on when and where the concentrations were measured (Seitzinger and Kroeze, 1998). This may explain why we estimate higher DIN than the measurements for the Sutlej sub-basin.

We evaluated the model performance against available measurement data, however, these measurements may also have uncertainties. First of all, measurement data that reflect annual total nitrogen fluxes are rare for the Indus River. The measurements available from the GEMS/Water Data Centre are typically based on samples on one or a few more days (maximum four days) in one year. Nutrient concentrations in rivers can vary largely within a year as affected by temporal variations in river discharge, nutrient inputs from human activities and nutrient cycling and retention. In addition, measurements of river discharge were not available for all stations where NO_3^- concentrations were measured in the report by Imran et al. (2018). Thus, CWATM simulated river discharge at the outlet of Sutlej were used to derive DIN loads.

We also compared our modeled results for river export of DIN and DON with other modeling studies (see Table 1). The result shows that we modeled lower DIN, but higher DON loads at the river mouth for 2010 than the studies of Amin et al. (2017) and Mayorga et al. (2010) for 2000. These differences can be explained as a net effect of changes in water consumption and nutrient inputs to rivers from human waste between 2000 and 2010. Water consumption in the Indus basin has been increasing in the last decade because of the increasing population and agriculture (Azizullah et al., 2011), which may have led to higher river retention of nutrients through water consumption in 2010 than in 2000. Since increased river retention through water consumption would reduce both river export of DIN and DON (Figures D.1 and D.2 in appendix), the opposite changes in DIN and DON are mainly associated with their dominant sources. We modeled that human waste is the dominant source for DON, whereas both human waste and diffuse source (e.g., use of synthetic fertilizers) are important for DIN (Figure 5). Thus increases in N inputs to rivers from human waste will likely result in larger relative increases in river export of DON than of DIN (see Figures D.1 and D.2 in appendix). This may explain the lower estimates of DIN and higher estimates of DON for 2010 in our study than in Amin et al. (2017) and Mayorga et al. (2010) for 1990. Another reason for the higher DON in our study than in Mayorga et al. (2010) is the underestimation of N inputs to rivers from human excretion via open defecation in Mayorga et al. (2010). Amin et al. (2017) included this missing source and quantified higher river export of DON in 2000 than Mayorga et al. (2010) for the Indus River.

Table 1 Comparison of our modeled river export of dissolved inorganic nitrogen (DIN) and dissolved organic nitrogen (DON) at the outlets of the Chenab and Sutlej sub-basins, and at the river mouth of the Indus River with measurements and previous modeling studies. Our modeled results are in the grey shaded row. See Figure 1 for the location of the sub-basin outlets and river mouth.

Location	DIN (kton $year^{-1}$)	DON (kton $year^{-1}$)	Year	Method	Sources
Sub-basin outlet of Chenab	29 - 140*	30 - 98*	2000 for DIN, 2003 for DON	Measurements	(UNEP, 2017)
	65	38	2010	Modeled results	This study
Sub-basin	17 (Nitrate-N)**	-	August 2015-	Measurements	(Imran et al.,

outlet of Sutlej			July 2016		2018)
	49	-	2010	Modeled results	This study
River mouth	77	26	2000	Modeled results	(Mayorga et al., 2010)
	80-105	28-50	2000	Modeled results	(Amin et al., 2017)
	65	87	2010	Modeled results	This study

* The DIN and DON loads were calculated based on the measurement on river discharge, nitrate and nitrite concentrations, and ammonium concentrations at the stations: Ravi Syphon gauging station (31°34'30"N, 74°26'28"E), and Upstream Baloki Headworks (31°28'56"N, 74°17'10"E). The nitrate and nitrite concentrations were measured using Cadmium Reduction Methods. The ammonium concentrations were measured using Titrimetric methods. The DON concentrations were measured using the Macro-Kjeldahl method with Titration and Removal of NH_3 ** The annual load of DIN was calculated based on the monthly nitrate concentrations at a sampling point (29°23'35"N, 71°11'49"E) close to the outlet of the Sutlej River, and the average monthly river discharge at the outlet of the Sutlej River from the CWATM model. The nitrate concentrations from (Imran et al., 2018) were measured using Cadmium Reduction methods (Hach-8171) by Spectrophotometry.

2.3. Scenario analysis

We modeled river export of N by the Indus River for 2050. Three Shared Socio-economic Pathways (SSPs) were selected for strong, rapid (SSP1 - “Sustainability”), moderate (SSP2 - “Middle of the Road”), and slow (SSP3 - “Regional Rivalry”) socio-economic development (O’Neill et al., 2014), and two Representative Concentration Pathways (RCPs) for the lowest and medium (RCP2.6 and 6.0) greenhouse gas concentrations for climate change (Nakicenovic et al., 2014; Van Vuuren et al., 2011). Three scenarios combining SSPs and RCPs: SSP1-RCP2.6, SSP2-RCP6.0, SSP3-RCP6.0 were selected based on the SSP-RCP matrix from Kok (2016) and on data availability of the model input database (Figure B.1 in Appendix B). SSP1-RCP2.6 is a scenario that assumes big shift towards sustainability with relatively rapid economic growth, low population growth, efficient use of resources, improved environmental policies and technical solutions to pollution. SSP2-RCP6.0 assumes moderate shifts towards sustainability with moderate population growth, slightly improved resource use efficiencies and environment policies only for local pollution. SSP3-RCP6.0 assumes a fragmented world in the future with high population growth, strong environment degradation and limited environmental policies (O’Neill et al., 2017).

Model inputs for MARINA 1.0 for hydrology (e.g., river discharge) for the selected SSP-RCP scenarios were derived by running the calibrated CWATM for the Indus River for RCP2.6 and RCP6.0. Most model inputs for MARINA 1.0 for human activities for the selected scenarios were available from the models and databases we used in this study (Figure B.1 in Appendix B). For data on synthetic fertilizers, agricultural N_2 fixation and N in harvested crops we used projections for SSP1-RCP4.5, SSP2-RCP4.5 and SSP3-RCP4.5, obtained by combining the land use projections from the GLOBIOM model (Havlík et al., 2014) and the nitrogen fluxes estimations from the EPIC model (Balkovič et al., 2014) as done in Byers et al. (2018) (see Appendix C for details). We did this because the projections from the GLOBIOM and EPIC models are not available for the selected scenarios.

Model inputs for calculating river export from human waste for the selected scenarios were also not directly available from the databases we used (see Figure B.1 in Appendix B). Therefore, we estimated 1) the fraction of the population connected to sewage systems, and 2) N removal efficiencies during wastewater treatment based on the SSP-RCP storylines and existing studies (O'Neill et al., 2017; Van Drecht et al., 2009; Wada et al., 2016) (see Table 2). SSP1-RCP2.6 assumes a big shift towards sustainability with improved environmental policies and technical solutions to pollution. Therefore, we assumed in SSP1-RCP2.6 advanced sanitation system with relatively high population connection to the sewage systems and improved N removal efficiency during treatment. SSP3-RCP2.6 assumes a fragmented world in the future with limited attention on environmental issues. Thus we assumed in SSP3-RCP6.0 limited improvement in sanitation system, which is comparable to its level in 2010. SSP2-RCP6.0 is a scenario that assumes moderate shifts towards sustainability. Therefore, SSP2-RCP6.0 shows a slightly improved sanitation system compared to 2010. The main model inputs are presented in Figures C.2-C.5 in Appendix.

Table 2 Scenario assumptions for 2050 to calculate nitrogen export by the Indus River from human waste for scenarios: SSP1-RCP2.6, SSP2-RCP6.0 and SSP3-RCP6.0. SSPs are the Shared Socio-economic Pathways. RCPs are the Representative Concentration Pathways. Based on these assumptions, N inputs to the basin from human waste were quantified (see Figure C.4 in Appendix C).

Scenarios	Rural and urban population connected to sewage systems in the Indus basin	N removal during wastewater treatment in the Indus basin
SSP1-RCP2.6	Urban: as in China in 2010 Rural: as in Pakistan in 2010	50% shift from lower to higher wastewater treatment classes[1]
SSP2-RCP6.0	Average of SSP1 and SSP3	30% shift from lower to higher wastewater treatment classes[1]
SPP3-RCP6.0	As in 2010	As in 2010

[1] Following the approach of Van Drecht et al. (2009) adjusted according to Hofstra and Vermeulen (2016), we assumed four classes of wastewater treatment plants in the Indus basin: wastewater treatment plants with 1) no treatment, 2) primary treatment 3) secondary treatment and 4) tertiary treatment. The plants with tertiary treatment have the highest (88%) N removal efficiencies. The plants with no treatment have lowest (0%) N removal efficiencies. The plants with secondary and primary treatment have N removal efficiencies of 42% and 10%, respectively. For the SSP-RCP scenarios with improved sewage treatment in the future, we assumed the wastewater treatment plants shift from lower to higher classes based on the approach of Van Drecht et al. (2009).

3. Results

3.1. Nitrogen Inputs to the Indus basin

The N inputs to the Indus basin are calculated to increase by 69-74% between 2010 and 2050 in all three scenarios (Figure 3). Agriculture and human waste are important drivers of N inputs to the basin. Synthetic fertilizers and human waste together contribute by more than 65% to total N inputs in the basin in 2010, and by 69-77% in 2050 (range indicates the differences among the scenarios). The increasing contributions by synthetic fertilizers and human waste are associated with the changes in population and agricultural production between 2010 and 2050. The Indus basin had 214 inhabitants per km^{-2} in 2010. The population density in this basin is expected to increase between 2010 and 2050 by 41%, 66% and 133% in the SSP1-RCP2.6, SSP2-RCP6.0 and SSP3-RCP6.0 scenarios, respectively (Figure C.1 in Appendix C). The increasing demand for food results in increased agricultural production between 2010 and 2050 in the three scenarios (Figure C.1 in Appendix C). As a result, N inputs from synthetic fertilizers increase by 69%, 98% and 87% between 2010 and 2050 in the SSP1-RCP2.6, SSP2-RCP6.0 and SSP3-RCP6.0 scenarios, respectively (Figure C.2 in Appendix C). N inputs from animal manure will increase by 32-39% in three scenarios (Figure C.5 in Appendix C). N inputs from human waste double to triple between 2010 and 2050 (Figure C.4 in Appendix C). More than 80% of the N inputs to the Indus basin are from midstream sub-basins. This is due to the high population density (75% of the population in the Indus basin) and intensive irrigation system for crop production in the Middle stem 1, Chebab and Sutlej sub-basins, where the Indus basin irrigation system is located (see Figure 1 for location of the sub-basins) (Liaqat et al., 2015).

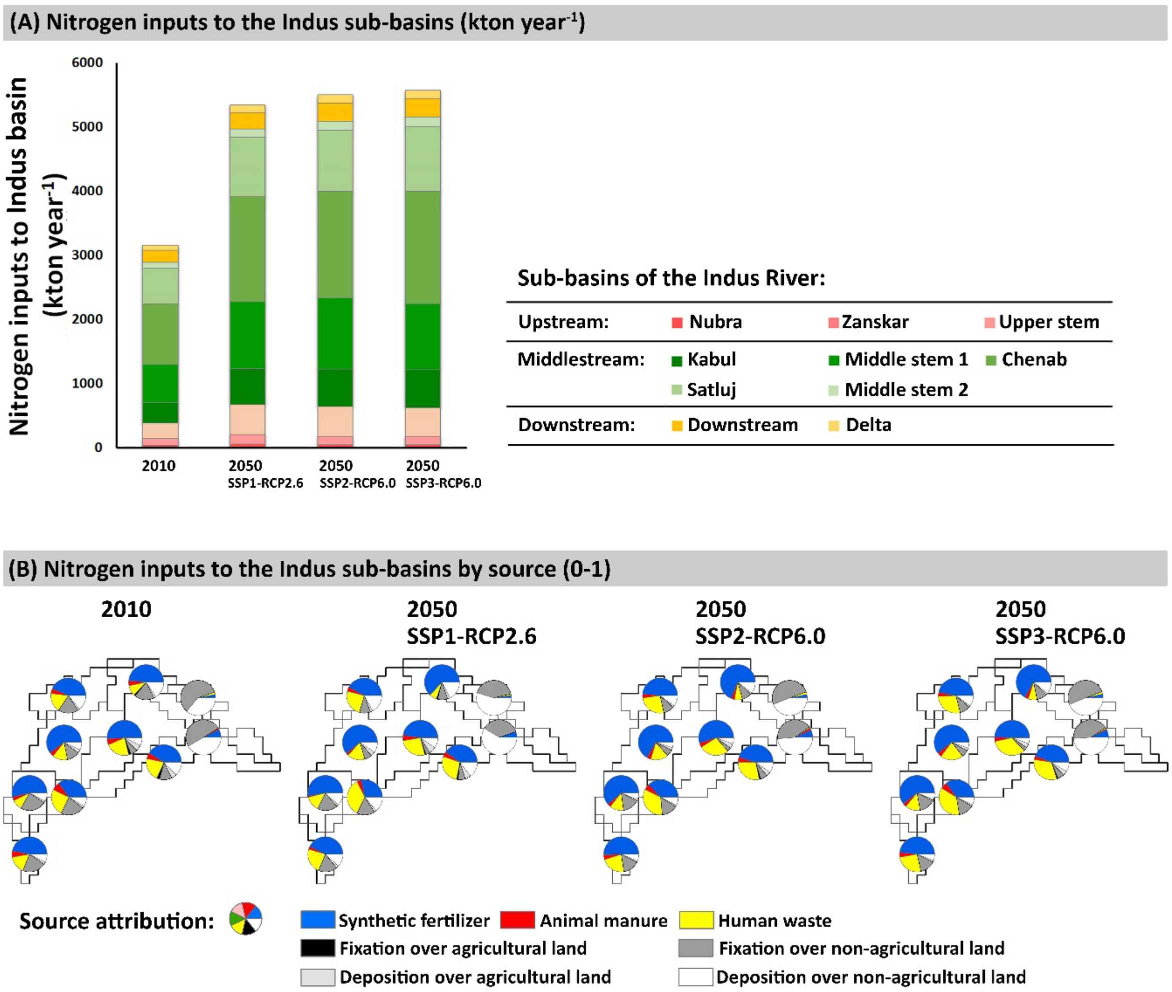

Figure 3 (A) Nitrogen (N) inputs to the Indus sub-basins (kton year^{-1}), and (B) by source (0-1) in 2010 and 2050 for three scenarios: SSP1-RCP2.6, SSP2-RCP6.0 and SSP3-RCP6.0. SSPs are the Shared Socio-economic Pathways. RCPs are the Representative Concentration Pathways. Details on the SSP-RCP scenarios are in section 2.3. For source attribution, fixation refers to biological N_2 fixation; and deposition refers to atmospheric N deposition and. For sources of data see Figure B.1 in Appendix B. The locations of the sub-basins are in Figure 1.

3.2. River export of N by Indus

In 2010, the Indus River transported 152 kton year^{-1} of TDN including 65 kton year^{-1} of DIN and 87 kton year^{-1} of DON to the river mouth (Figure 4). The N exports varied from 0.1 to 122 kg km^{-2} year^{-1} for DIN, and from 0.2 to 95 kg km^{-2} year^{-1} for DON among the 10 sub-basins of the Indus River, indicating large spatial variabilities (Figure 5). The midstream sub-basins contributed 90% to river export of TDN. This is a result of the intensive irrigation system for crop production and high population density in the midstream sub-basins as was shown in section 3.1. Discharge of treated and untreated human waste (point source) and synthetic fertilizers (diffuse source) were the main sources of DIN (Figure 5). Result shows that up to 35% of the DIN was from synthetic fertilizers, and up to 74% from human waste among the sub-basins. For DON, human waste was important and contributed by 44-81% to DON export from the midstream and downstream sub-basins. In the upstream sub-basins, particularly in *Nubra* and *Zanskar* (see Figure 1 for the sub-basin locations), atmospheric N deposition and biological N_2 fixation (for DIN) were important sources of river export of TDN, as well as leaching of organic matter (for DON). This can be explained by the low agricultural activities and low population densities in the *Nubra* and *Zanskar* sub-basins (Figure 3).

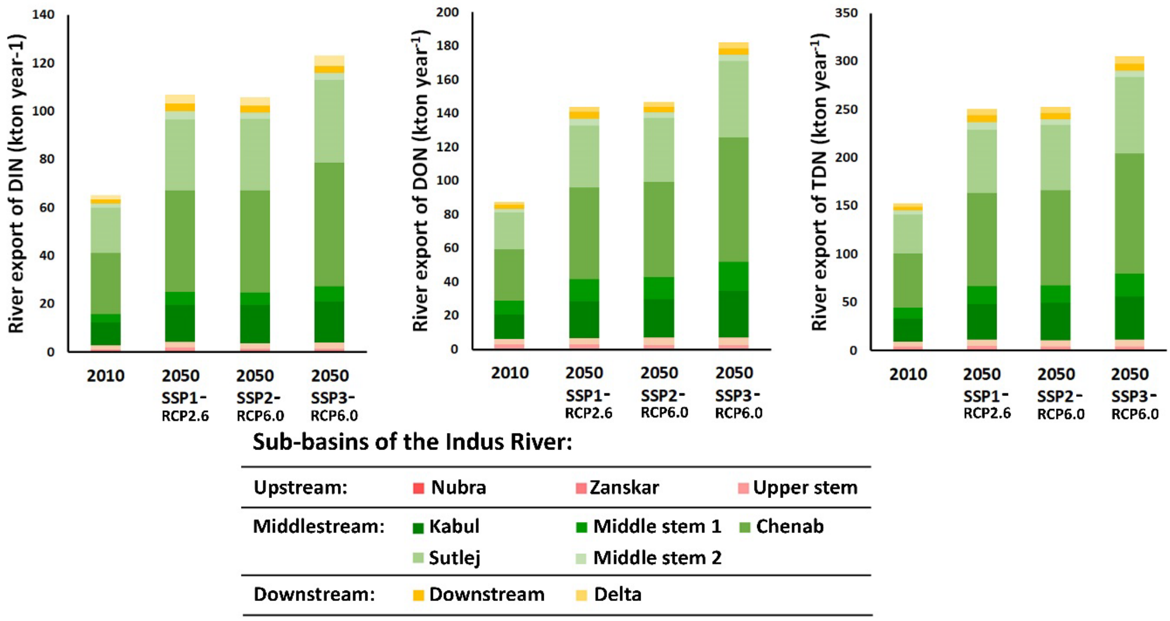

Figure 4 River export of dissolved inorganic (DIN, kton year^{-1}) and organic (DON, kton year^{-1}) nitrogen, and total dissolved nitrogen (TDN, kton year^{-1}) by the Indus sub-basins in 2010 and 2050. For 2050 the three scenarios are: SSP1-RCP2.6, SSP2-RCP6.0 and SSP3-RCP6.0. SSPs are the Shared Socio-economic Pathways. RCPs are the Representative Concentration Pathways. Details on the SSP-RCP scenarios are in section 2.3. The locations of the sub-basins are in Figure 1.

Scenarios. We modeled river export of TDN by the Indus River in 2050 for three scenarios combining the SSPs and RCPs. SSP1-RCP2.6 assumes a shift towards sustainability with relatively rapid economic growth, low population growth, efficient use of resources, improved environmental policies and technical solutions to water pollution. SSP3-RCP6.0 assumes a fragmented world in the future with high population growth, strong environment degradation and limited environmental policies. SSP2-RCP6.0 is an intermediate scenario in between SSP1-RCP2.6 and SSP3-RCP6.0, assuming moderate shifts towards sustainability. We discussed the results of the scenario analysis below.

For the SSP1-RCP2.6 scenario we calculate a relatively large increase in river export of TDN by 64% from the Indus River between 2010 and 2050 (Figure 4). This includes a 64% increase in DIN, and a 65% increase in DON exported by the river. These increases are driven by high inputs of N to the basin from agriculture and human waste (Figure 3). N export varies largely among the sub-basins, ranging from 0.2 to 190 kg km^{-2} $year^{-1}$ for DIN, and from 0.2 to 88 kg km^{-2} $year^{-1}$ for DON (Figure 5). Midstream sub-basins remain the main contributors to river export of TDN. Human waste and synthetic fertilizers contribute by 53% and 19%, respectively, to DIN (Figure 5). Our result shows increasing shares of DIN (53%) and DON (76%) from human waste. This is attribute to an increasing population, urbanization and improved sanitation with an increasing fraction of the population connected to sewage systems in this scenario (Table 1, Figures C.1, C.3 and C.4 in Appendix C).

In the SSP2-RCP6.0 scenario, river export of TDN from the Indus River increases by 66% between 2010 and 2050 (Figure 4). This include a 62% increase in DIN, and a 68% increase in DON. Again, agriculture and human waste are the main drivers (Figure 3). N export varies largely among the sub-basins, ranging from 0.1 to 193 kg km^{-2} $year^{-1}$ for DIN, and from 0.2 to 86 kg km^{-2} $year^{-1}$ for DON (Figure 5). More than 90% of TDN at the river mouth origins from midstream sub-basins. Human waste and synthetic fertilizers remain as important sources for DIN (Figure 5). We estimated that 27% of DIN is from synthetic fertilizers. The relative shares of DIN (52%) and DON (77%) from human waste are higher than in 2010 because of the increasing population and higher connection rates to sewage systems in this scenario (Table 1, Figures C.1, C.3 and C.4 in Appendix C).

SSP3-RCP6.0 is the scenario with the highest nutrient export by Indus, with a doubling for TDN by 2050 (Figure 4). This includes 123 kton year^{-1} of DIN and 182 kton year^{-1} of DON. Sub-basin export varies from 0.1 to 224 kg km^{-2} year^{-1} for DIN, and from 0.2 to 86 kg km^{-2} year^{-1} for DON (Figure 5). Up to 92% of the TDN originates from midstream sub-basins. Human waste and synthetic fertilizers remain major sources of both DIN and DON (Figure 5). Untreated human waste from people not connected to sewage systems is the most important source, and contributes by more than half to TDN exported by the Indus River. This is due to a doubling of the population, relatively slow urbanization and conventional sanitation with a low fraction of the population connected to sewage systems in this scenario (Table 1, Figures C.1, C.3 and C.4 in Appendix C).

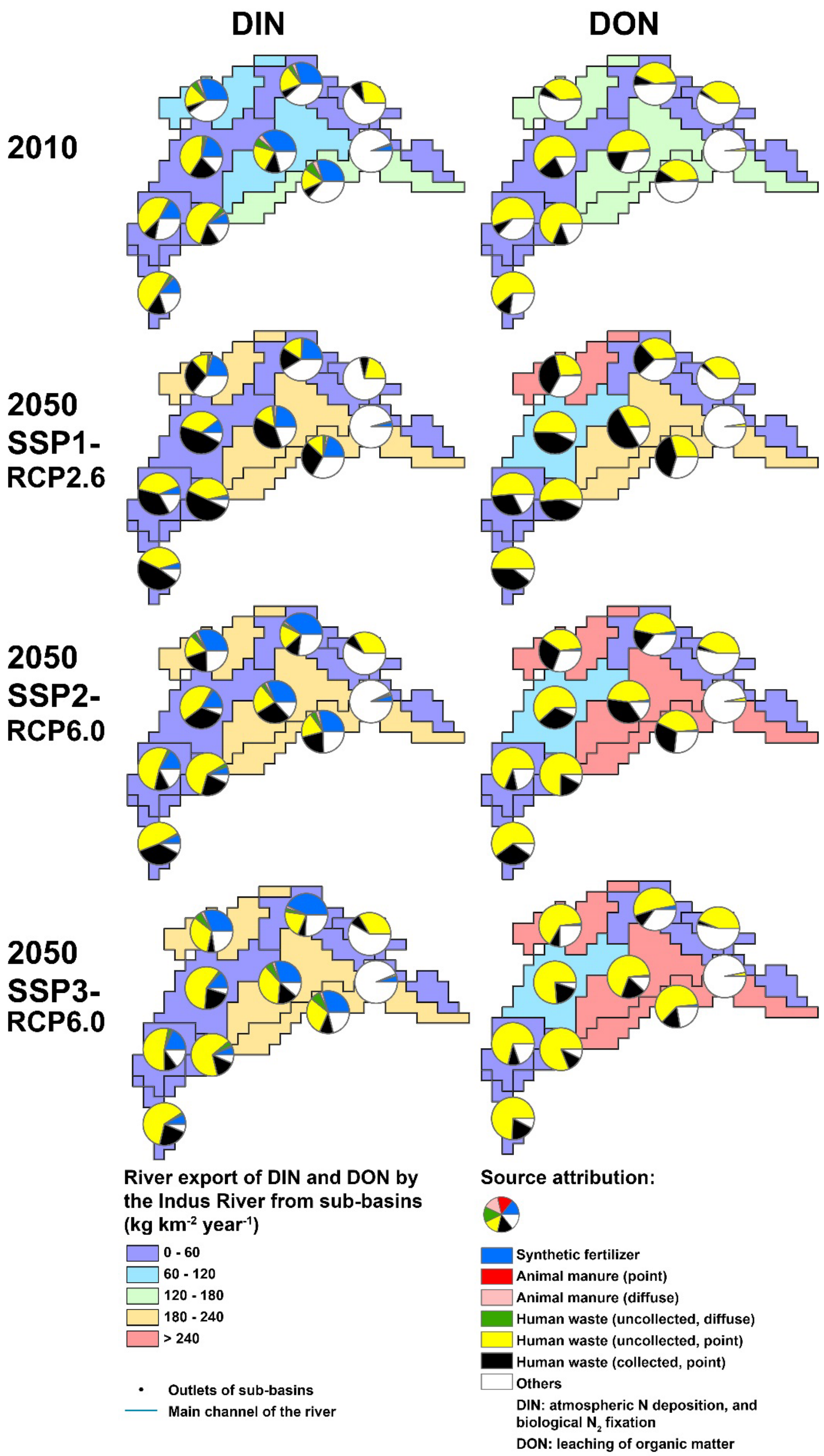

Figure 5 River export of dissolved inorganic (DIN, kg km^{-2} year^{-1}) and organic (DON, kg km^{-2} year^{-1}) nitrogen by the Indus sub-basins by source in 2010 and 2050 for the three scenarios: SSP1-RCP2.6,

SSP2-RCP6.0, and SSP3-RCP6.0. SSPs are the Shared Socio-economic Pathways. RCPs are the Representative Concentration Pathways. Details on the SSP-RCP scenarios are in section 2.3. The names and locations of the sub-basins are in Figure 1.

4. Discussion

4.1. Strengths and uncertainties

Water quality in the Indus River and at the river mouth was reported to be poor and becoming worse as affected by human activities in recent years (Azizullah et al., 2011; Daud et al., 2017; Grigg et al., 2018; Kazmi and Khan, 2005; Subramanian, 2008). Existing modelling studies for river export of nutrients from different sources by sub-basins are limited (Amin et al., 2017; Mayorga et al., 2010; Seitzinger et al., 2010). This study is the first to account for the spatial variability at the sub-basin scale for quantifying river exports of dissolved inorganic and organic N by the Indus River from different sources. Our results indicate that agriculture (diffuse source) and sewage (point source) were the main sources of dissolved N exported by the Indus River in 2010 and will remain the main sources in 2050. In 2050, human waste is expected to contribute by 66-70% to river export of TDN depending on the scenarios. Agriculture including use of synthetic fertilizers and manure application contributes by 21-29% to DIN export among the SSPs-RCPs. Midstream sub-basins were found to be the main contributors to river export of dissolved N in 2010 and 2050. Knowing the main sources of N export, and the relative contributions of sub-basins can help to formulate more spatially targeted policies and, therefore, better address the increasing nutrient pollution in the Indus basin.

This study is also the first to analyze the future trends in river export of N by the Indus River for the SSPs and RCPs scenarios. This was done by linking the nutrient model (MARINA) to the land use and crop models (GLOBIOM and EPIC) and hydrological model (CWATM). The SSPs and RCPs scenarios were applied to the GLOBIOM and EPIC models to project future human activities in agriculture as affected by socio-economic developments, and to the

CWATM model to project river discharge as affected by climate change. The results of the projections were used in the MARINA 1.0 model as inputs. Through this way we provide a basis to better understand future river export of N as affected by the socio-economic developments and climate change.

All model studies have their uncertainties. Uncertainties in our study are related to *model structure*, *model inputs and parameters*, as well as to *scenarios for the future*. Uncertainties related to model structure reflect our possible misunderstanding of nutrient flows in water systems. Uncertainties also exist in model inputs and parameters. Many model parameters (see Tables B.3-B.8) were taken from the original MARINA1.0 model that was validated for Chinese rivers (Strokal et al., 2016) and the Global *NEWS-2 (Global Nutrient Export from WaterSheds)* model. Global *NEWS-2* was calibrated and validated for rivers worldwide (Mayorga et al., 2010), and for rivers draining into the Bay of Bengal from the Indian continent (Amin et al., 2017; Pedde et al., 2017). Most of the model inputs for MARINA 1.0 in this study were from peer-reviewed papers, published projects and databases (Figure B.1 in Appendix B). Model inputs for river discharge were simulated by the calibrated CWATM model. We calibrated CWATM for the Indus River using a single objective optimization approach (Burek et al., 2017a). The calibrated model was validated against river discharge at the UIB Besham station of the Indus River. A few parameters were used to assess the model performance: KGE ($-\infty$ to 1, Kling-Gupta Efficiency), NSE ($-\infty$ to 1, Nash–Sutcliffe Efficiency), R^2 (0-1, coefficient of determination), and B (bias estimator). The validation shows that in general our modeled river discharge compares reasonably well with measurements (KGE is 0.66, NSE is 0.37, R^2 is 0.72, B is -8%; see Figure B.2 in Appendix B for the CWATM model performance). We ran the calibrated CWATM for the Indus River with climate inputs (precipitation, temperature, etc.) from four General Circulation Models (GCMs): GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC5. The averaged river discharge from these four runs was used to reduce the uncertainties that are introduced by the GCMs.

We tested the sensitivity of the MARINA 1.0 model outputs to changes in several important model inputs and parameters (Figures D.1 and D.2 in Appendix D). Our sensitivity analysis shows that for 2010 the modeled river export of DIN and DON are both sensitive to changes in river discharge, water consumption, and population. For example, increasing the river discharge by 50% results in up to 57% and 46% increases in calculated river export of DIN and DON at the sub-basin scale, respectively. The modeled river export of DIN is more sensitive to changes in use of synthetic fertilizers than DON. This is because of the differences in the source attribution of DIN and DON (Figure 5). Our result shows that model outputs are also sensitive to changes in the model parameters for sewage systems. Modeled river export of DIN is relatively sensitive to changes in sewage connection (population that is connected to sewage system) and treatment (fraction of N removed during treatment) in the rural area. Modeled river export of DON is relatively sensitive to changes in sewage connection and treatment in both rural and urban areas. This difference is associated with the source attribution of DIN and DON, and the low percentage of people connected to sewage systems (< 50% in urban area, < 5% in rural area) and waste water treatment (fraction of N removal < 2% in rural and urban area) in the Indus basin (Figure C.4 in Appendix). Thus, to reduce N pollution in rivers and coastal waters, great efforts are needed in improving the sewage systems in the Indus basin.

There are also uncertainties related to the scenarios for the future. For example, for scenario analysis the selected SSPs-RCPs (SSP1-RCP2.6, SSP2-RCP6.0, SPP3-RCP6.0) scenarios, projections were not available from the GLOBIOM and EPIC models for synthetic fertilizers, N in harvested crops, agricultural N_2 fixation. Therefore, alternative projections for scenarios SSP1-RCP4.5, SSP2-RCP4.5 and SPP3-RCP4.5 were used. This introduces some inconsistencies in model inputs for scenarios in 2050. However, this does not lead to large changes in our conclusions since the use of synthetic fertilizers, N in harvested crops and agricultural N_2 fixation are mainly affected by socio-economic drivers (e.g., food demand, nutrient management practices in agriculture). Despite the uncertainties, the MARINA 1.0

model provided acceptable results for the Indus River compared to the measurements and modelling studies, as indicated in the model validation in section 2.2.3.

4.2. Implications for management

We assessed river export of TDN by the Indus River combining the impacts of socio-economic development (SSPs) and climate change (RCPs). Our result shows increasing river export of TDN between 2010 and 2050 for all three scenarios. More than 90% of TDN export is from midstream sub-basins in 2010 and 2050. Human waste and agriculture were found to be the most important sources of TDN export. This indicates that improved nutrient management for a combined reduction in both diffuse and point sources in the midstream sub-basins may help reduce water pollution by N in rivers and coastal waters of Indus.

Improved nutrient management for the point sources implies 1) increasing population connection to the sewage systems, and 2) improving sewage treatment in the Indus basin. Our scenario analysis shows that 66-70% of river export of TDN is from human waste in 2050 depending on the scenarios. The SSP3-RCP2.6 scenario has the highest (70%) share from human waste. More than 75% of TDN from thesese human waste originates from the population that is not connected to sewage systems (e.g., open defecation). This is the result of fast population growth, low connection rate to the sewage systems and poor treatment of the sewage (e.g., sewage treatment plants with no treatment or primary treatment dominant). The SSP1-RCP2.6 scenario has the lowest (66%) share from human waste with improved sewage systems (e.g., increase sewage connection and sewage treatment). However, it is surprising that TDN export still increase by more than 60% in this scenario. This is explained by the insufficient improvement in sewage connection and treatment under the rapid urbanization in this region. The SSP2-RCP6.0 scenario assumes moderate improvements in sewage systems. Human waste, especially the untreated part still remain the dominant source for the increasing river export of TDN in this scenario. The discharge of human waste without sufficient treatment to rivers not only causes N pollution, but also may lead to other problems such as transporting pathogens to the rivers (Vermeulen et al., 2015; Vermeulen et al., 2019). Thus, we suggest that, great effort in improving sewage systems is needed. This has the potential to reduce river export of TDN by up to 70% in the future. Many policies and technologies from other countries could be adopted for this. These are, for example, updating wastewater treatment facilities (Koff and Maganda, 2016), and onsite wastewater treatment in rural and slum areas (Katukiza et al., 2012),

Improved nutrient management for the diffuse sources implies improving N use efficiencies in crop production. Our results indicate that fertilizer application in agriculture contributes by 21-29% to river export of DIN by the Indus River in 2050 among the scenarios. The river export of DIN from agriculture is higher in SSP2-RCP6.0 (31 kton year^{-1}) and SSP3-RCP6.0 (36 kton year^{-1}) than in SSP1-RCP2.6 (23 kton year^{-1}). The lower river export of DIN in SSP1 results from the relatively fast increase in both crop yield and improved N use efficiencies (Leclère et al., 2017a). However, as mentioned above, river export of DIN still increases in the SSP1-RCP2.6 between 2010 and 2050, indicating that further improvement in N use efficiencies has the potential to decrease water pollution by N. Policies and technologies could focus on fertilizing the crops regarding their needs for nutrients (Bouraoui and Grizzetti, 2014; Oenema et al., 2009; Salomon et al., 2016).

In summary, we quantified annual river export of dissolved N by the Indus River from difference sources at the sub-basin scale. This information may facilitate policy makers and stakeholders among the four countries covered by the transboundary Indus basin to formulate effective nutrient management policies. We suggest that policies targeting the Indus midstream sub-basins combining improvements in sewage systems and in nutrient use efficiencies in agriculture would be the most efficient to reduce water pollution. Our suggestions for improved nutrient management may be considered useful to achieve the sustainable development goals (SDGs) in the basin as well, in particular to achieve SDG 6 that aims for clean water and sanitation (Cf, 2015). Developing and analyzing alternative scenarios that incorporates the above suggested nutrient management options by engaging local stakeholders may help to identify further solutions for the increasing nutrient pollution in the Indus River. Further work is needed on collecting data and characterizing seasonal concentrations and fluxes of nutrients.

5. Conclusion

In this study we quantified river export of dissolved N by the Indus River from different sources at the sub-basin scale using the MARINA 1.0 approach. We also analyzed trends in dissolved N exported by the Indus River to sea between 2010 and 2050 under SSP and RCP scenarios.

River export of dissolved N will likely increase by a factor of 1.6 - 2 between 2010 and 2050 under the selected SSP-RCP scenarios. This may lead to a higher risk for coastal water pollution in the future. The increase in N export by the river illustrates the need for effective nutrient management in the Indus basin. Agriculture and human waste were the main sources of dissolved N exported by the Indus River in 2010 and will remain the main sources in 2050. For example, we projected that over two-thirds of dissolved N export by the Indus River is from human waste, and around one-third of dissolved inorganic N export from agriculture in 2050 in the SSP-RCP scenarios. This indicates that reductions in both diffuse and point sources are needed to improve water quality in the Indus River. Combining options to improve N use efficiencies in agriculture (e.g., reducing/efficient use of synthetic fertilizers, recycling of animal manure) and to improve sewage treatment (e.g., increasing connection to sanitation, improving wastewater treatment) may effectively reduce water pollution across the Indus basin.

Our analysis shows how future coastal water pollution is affected by socio-economic developments and climate change. We present the relative contributions of pollution sources and sub-basins. This can support the formulation of effective cross-sectoral cooperative policies for improving water quality in the transboundary Indus basin.

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Appendixes

Increasing Nitrogen Export by the Indus River

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The following appendices provide additional information on:

Appendix A: Model description

Box A.1 The main equations in the MARINA 1.0 model to quantify river export of nitrogen (N) forms F (DIN: dissolved inorganic N, DON: dissolved organic N) to the river mouth by source y from sub-basin j. More detailed equations are available in Strokal et al. (2016).

River export of nitrogen forms F to the river mouth (kg year^{-1}) by source y from sub-basin j

$$M_{F.y.j} = (RSdif_{F.y.j} + RSpnt_{F.y.j}) \cdot FE_{riv.F.outlet.j} \cdot FE_{riv.F.mouth.j}$$

$RSdif_{F.y.j}$: nitrogen inputs to surface waters from diffuse sources y in sub-basin j

Over agricultural area:

$$RSdif_{F.y.j} = WSdif_{N.y.j} \cdot G_{F.j} \cdot FE_{ws.F.j}$$

(Where $WSdif_{N.y.j}$ refers to $WSdif_{N.fe.j}$, $WSdif_{N.ma.j}$, $WSdif_{N.hum.uncon.j}$, $WSdif_{N.dep.ant.j}$, and $WSdif_{N.fix.ant.j}$)

$$RSdif_{F.y.j} = f_F(Rnat_j) \cdot EC_F \cdot Ag_{fr.j}$$ Leaching of organic matters

Over non-agricultural area:

$$RSdif_{F.y.j} = WSdif_{N.y.j} \cdot FE_{ws.F.j}$$

(Where $WSdif_{E.y.j}$ refers to $WSdif_{N.dep.nat.j}$ and $WSdif_{N.fix.nat.j}$)

$$RSdif_{F.y.j} = f_F(Rnat_j) \cdot EC_F \cdot (1 - Ag_{fr.j})$$ Leaching of organic matters

$RSpnt_{F.y.j}$: nitrogen inputs to surface waters from point sources y in sub-basin j

$$RSpnt_{F.y.j} = RSpnt_{N.y.j} \cdot FEpnt_{F.y}$$

(Where $RSpnt_{N.y.j}$ refers to $RSpnt_{N.ma.j}$, $RSpnt_{N.hum.uncon.j}$ and $RSpnt_{N.hum.con.j}$)

$FE_{riv.F.outlet.j}$: the fraction of nitrogen exported to the outlet of sub-basin j

$$FE_{riv.F.outlet.j} = (1 - D_{F.j}) \cdot (1 - L_{F.j}) \cdot (1 - FQrem_j)$$

$FE_{riv.F.mouth.j}$: the fraction of nitrogen exported from the outlet of sub-basin j to river mouth

Upstream sub-basins:

$$FE_{riv.F.mouth.juT} = {}^{juT}FE_{riv.F.outlet.juC} \cdot {}^{juT}FE_{riv.F.outlet.jmC} \cdot {}^{juT}FE_{riv.F.outlet.jdC}$$

$$FE_{riv.F.mouth.juC} = {}^{juC}FE_{riv.F.outlet.jmC} \cdot {}^{juC}FE_{riv.F.outlet.jdC}$$

$${}^{juT}FE_{riv.F.outlet.juC} = (1 - [D_{F.juC} \cdot {}^{juT}A_{juC}]) \cdot (1 - [L_{F.juC} \cdot {}^{juT}A_{juC}]) \cdot (1 - [FQrem_{juC} \cdot {}^{juT}A_{juC}])$$

$${}^{juT}FE_{riv.F.outlet.jmC} = (1 - [D_{F.jmC} \cdot {}^{juT}A_{jmC}]) \cdot (1 - [L_{F.jmC} \cdot {}^{juT}A_{jmC}]) \cdot (1 - [FQrem_{jmC} \cdot {}^{juT}A_{jmC}])$$

$${}^{juT}FE_{riv.F.outlet.jdC} = (1 - [D_{F.jdC} \cdot {}^{juT}A_{jdC}]) \cdot (1 - [L_{F.jdC} \cdot {}^{juT}A_{jdC}]) \cdot (1 - [FQrem_{jdC} \cdot {}^{juT}A_{jdC}])$$

$${}^{juC}FE_{riv.F.outlet.jmC} = (1 - [D_{F.jmC} \cdot {}^{juC}A_{jmC}]) \cdot (1 - [L_{F.jmC} \cdot {}^{juC}A_{jmC}]) \cdot (1 - [FQrem_{jmC} \cdot {}^{juC}A_{jmC}])$$

$${}^{juC}FE_{riv.F.outlet.jdC} = (1 - [D_{F.jdC} \cdot {}^{juC}A_{jdC}]) \cdot (1 - [L_{F.jdC} \cdot {}^{juC}A_{jdC}]) \cdot (1 - [FQrem_{jdC} \cdot {}^{juC}A_{jdC}])$$

Middle sub-basins:

$$FE_{riv.F.mouth.jmT} = {}^{jmT}FE_{riv.F.outlet.jmC} \cdot {}^{jmT}FE_{riv.F.outlet.jdC}$$

$$FE_{riv.F.mouth.jmC} = {}^{jmC}FE_{riv.F.outlet.jdC}$$

$${}^{jmT}FE_{riv.F.outlet.jmC} = (1 - [D_{F.jmC} \cdot {}^{jmT}A_{jmC}]) \cdot (1 - [L_{F.jmC} \cdot {}^{jmT}A_{jmC}]) \cdot (1 - [FQrem_{jmC} \cdot {}^{jmT}A_{jmC}])$$

$${}^{jmT}FE_{riv.F.outlet.jdC} = (1 - [D_{F.jdC} \cdot {}^{jmT}A_{jdC}]) \cdot (1 - [L_{F.jdC} \cdot {}^{jmT}A_{jdC}]) \cdot (1 - [FQrem_{jdC} \cdot {}^{jmT}A_{jdC}])$$

$${}^{jmC}FE_{riv.F.outlet.jdC} = (1 - [D_{F.jdC} \cdot {}^{jmC}A_{jdC}]) \cdot (1 - [L_{F.jdC} \cdot {}^{jmC}A_{jdC}]) \cdot (1 - [FQrem_{jdC} \cdot {}^{jmC}A_{jdC}])$$

Downstream sub-basins:

$$FE_{riv.F.mouth.jdT} = {}^{jdT}FE_{riv.F.outlet.jdC}$$

$$FE_{riv.F.mouth.jdC} = 1$$

$${}^{jdT}FE_{riv.F.outlet.jdC} = (1 - [D_{F.jdC} \cdot {}^{jdT}A_{jdC}]) \cdot (1 - [L_{F.jdC} \cdot {}^{jdT}A_{jdC}]) \cdot (1 - [FQrem_{jdC} \cdot {}^{jdT}A_{jdC}])$$

Table A.1 Abbreviations of model variables and parameters in Box A.1. The abbreviations were introduced by Strokal et al. (2016).

Variables /parameters	Description	Unit
y: source		
j: sub-basin	F: nitrogen form (DIN, DON)	
For diffuse sources		
$RSdif_{F.y.j}$	inputs of nitrogen form (F) to surface waters from agricultural and non-agricultural areas in sub-basin j from diffuse source y	kg $year^{-1}$
$WSdif_{N.y.j}$	inputs of nitrogen to agricultural and non-agricultural land in sub-basin j from source y	kg $year^{-1}$
$G_{F.j}$	the fraction of nitrogen (F) applied to agricultural land that remained in soils of sub-basin j after animal grazing and crop harvesting	0-1
$FE_{ws.F.j}$	the export fraction of nitrogen form (F) entering surface waters of sub-basin j. The fraction is calculated as a function of annual runoff from land to streams	0-1
$WSdif_{N.fe.j}$	inputs of N in synthetic fertilizers to agricultural land in sub-basin j	kg $year^{-1}$
$WSdif_{N.ma.j}$	inputs of N in animal manure to agricultural land in sub-basin j	kg $year^{-1}$
$WSdif_{N.hum.uncon.j}$	N in human excretion that are recycled in agriculture from rural and urban population (not connected to sewage systems) in sub-basin j	kg $year^{-1}$
$WSdif_{N.dep.ant.j}$, $WSdif_{N.fix.ant.j}$	atmospheric N deposition on agricultural land ($WSdif_{N.dep.ant.j}$) and biological N_2-fixation by agricultural crops (e.g., legumes) in sub-basin j	kg $year^{-1}$
$f_F(Rnat_j)$	a function of annual runoff from land to streams in sub-basin j	-
$Rnat_j$	annual runoff from land to streams in sub-basin j	m
EC_F	the coefficient for P weathering and leaching of organic matter	kg km^{-2} $year^{-1}$
$WSdif_{N.dep.nat.j}$, $WSdif_{N.fix.nat.j}$	atmospheric N deposition on non-agricultural land ($WSdif_{N.dep.nat.j}$) and biological N_2-fixation by natural vegetation in sub-basin j	kg $year^{-1}$
$Ag_{fr.j}$	the fraction of agricultural areas in sub-basin j.	0-1
For point sources		
$RSpnt_{F.y.j}$	inputs of nitrogen form (F) to surface waters of sub-basin j from point source y	kg $year^{-1}$
$RSpnt_{E.y.j}$	inputs of nitrogen to surface waters in sub-basin j from point source y	kg $year^{-1}$
$FEpnt_{F.y}$	the fraction of nitrogen form entering surface waters in sub-basin j from point source y	0-1
$RSpnt_{N.ma.j}$	direct discharges of N in animal excretion to surface waters in sub-basin j	kg $year^{-1}$
$RSpnt_{N.hum.uncon.j}$	direct discharges of N in human excretion from rural and urban population (not connected to sewage systems) to surface waters in sub-basin j	kg $year^{-1}$
$RSpnt_{N.hum.con.j}$	N in sewage effluents that enter surface waters from rural and urban sewage systems in sub-basin j	kg $year^{-1}$
For retention of nitrogen before it reaches the outlets of the sub-basins		
$FE_{riv.F.outlet.j}$	the export fraction of nitrogen reaching the outlet of sub-basin j	0-1
$D_{F.j}$	the fraction of nitrogen form (DIN) retained in reservoirs and lakes in sub-basin j	0-1
$L_{F.j}$	the fraction of nitrogen form (DIN) retained in or/and lost from water systems (e.g., denitrification for DIN) in sub-basin j	0-1
$FQrem_j$	the fraction of nitrogen (generic for DIN, DON) removed from water systems in sub-basin j via water consumption	0-1
For retention of nitrogen from outlets of the sub-basins to river mouth		
$FE_{riv.F.mouth.juT}$	the fraction of nitrogen form (F) exported from the outlet of up-stream tributary (juT) to the river mouth	0-1

$FE_{riv.F.mouth.juC}$	the fraction of nitrogen form (F) exported from the outlet of up-stream main channel (juC) to the river mouth	0-1
$FE_{riv.F.mouth.jmT}$	the fraction of nitrogen form (F) exported from the outlet of middle-stream tributary (jmT) to the river mouth	0-1
$FE_{riv.F.mouth.jmC}$	the fraction of nitrogen form (F) exported from the outlet of middle-stream main channel (jmC) to the river mouth	0-1
$FE_{riv.F.mouth.jdC}$	the fraction of nitrogen form (F) exported from the outlet of down-stream main channel (jdC) to the river mouth	0-1
${}^{juT}FE_{riv.F.outlet.juC}$ ${}^{juT}FE_{riv.F.outlet.jmC}$ ${}^{juT}FE_{riv.F.outlet.jdC}$	fractions of nitrogen form (F) exported from the outlet of up-stream tributary (upper case: juT) to the outlets of the main channel in up-stream (lower case: juC), middle-stream (lower case: jmC) and down-stream (lower case: jdC) sub-basins	0-1
${}^{juC}FE_{riv.F.outlet.jmC}$ ${}^{juC}FE_{riv.F.outlet.jdC}$	fractions of nitrogen form (F) exported from the outlet of up-stream sub-basins with the main channel (upper case: juC) to the outlets of the main channel in middle-stream (lower case: jmC) and down-stream (lower case: jdC) sub-basins	0-1
${}^{jmT}FE_{riv.F.outlet.jmC}$ ${}^{jmT}FE_{riv.F.outlet.jdC}$	fractions of nitrogen form (F) exported from the outlet of middle tributary (upper case: jmT) to the outlets of the main channel in middle-stream (lower case: jmC) and down-stream (lower case: jdC) sub-basins	0-1
${}^{jmC}FE_{riv.F.outlet.jdC}$	the fraction of nitrogen form (F) exported from the outlet of middle-stream sub-basin with the main channel (upper case: jmC) to the outlet of the main channel in down-stream (lower case: jdC) sub-basin (the outlet of the this down-stream sub-basin is the river mouth)	0-1
$D_{F.juC}$ $D_{F.jmC}$ $D_{F.jdC}$	Fractions of DIN retained in reservoirs of up-stream (juC), middle-stream (jmC) and down-stream (jdC) sub-basins with the main channel (C). These fractions were calculated for sub-basins using equations for $D_{DIN.j}$ from Box A.1.	0-1
$L_{F.juC}$ $L_{F.jmC}$ $L_{F.jdC}$	Fractions of DIN that is lost from surface waters of up-stream (juC), middle-stream (jmC) and down-stream (jdC) sub-basins with the main channel (C). These fractions were calculated using the equation for $L_{DIN.j}$ from Box A.1.	0-1
$FQrem_{juC}$ $FQrem_{jmC}$ $FQrem_{jdC}$	Fractions of nitrogen (generic for all nitrogen) that are lost from surface waters of up-stream (juC), middle-stream (jmC) and down-stream (jdC) sub-basins with the main channel (c) via water consumption. These fractions were calculated using equations for $FQrem_j$ from Box A.1	0-1
${}^{juT}A_{juC}$ ${}^{juT}A_{jmC}$ ${}^{juT}A_{jdC}$	Drainage area (A) of the main channel (C) in up-stream (lower case: juC), middle-stream (lower case: jmC) and down-stream (lower case: jdC) sub-basins that exports nitrogen from the outlet of up-stream tributary (upper case: juT). This drainage area was calculated as the fraction to the total sub-basin area.	0-1
${}^{juC}A_{jmC}$ ${}^{juC}A_{jdC}$	Drainage area (A) of the main channel (C) in middle-stream (lower case: jmC) and down-stream (lower case: jdC) sub-basins that exports nitrogen from the outlet of up-stream main channel (upper case: juC). This drainage area was calculated as the fraction to the total sub-basin area.	0-1
${}^{jmT}A_{jmC}$ ${}^{jmT}A_{jdC}$	Drainage area (A) of the main channel (C) in middle-stream (lower case: jmC) and down-stream (lower case: jdC) sub-basins that exports nitrogen from the outlet of middle-stream tributary (upper case: jmT). This drainage area was calculated as the fraction to the total sub-basin area.	0-1
${}^{jmC}A_{jdC}$	Drainage area (A) of the main channel (C) in the down-stream (lower case: jdC) sub-basin that exports nitrogen from the outlet of middle-stream main channel (upper case: jmC). This drainage area was calculated as the fraction to the total sub-basin area.	0-1

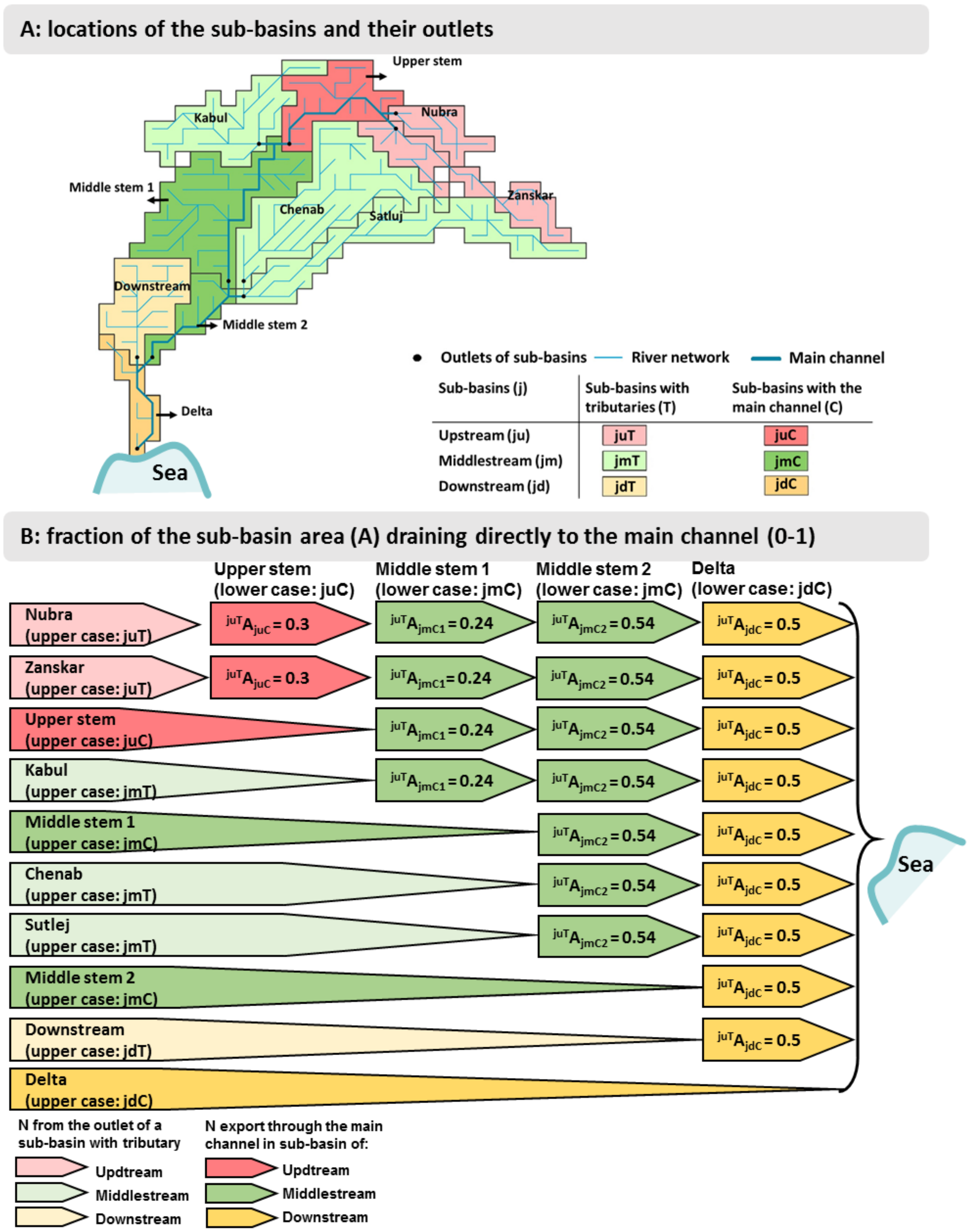

Figure A.1 (A) Sub-basins of the Indus River and (B) the drainage area of the main channel in sub-basins that export nitrogen to the river mouth. The drainage area was calculated as a fraction (0-1) of the total sub-basin area. Explanations of the variables can be found in Table A.1. The main channel is defined based on the Strahler Order from the Drainage Direction Map (DDM30) using the approach that is described in Strokal et al. (2016) and the basin boundaries from the HydroBASINS database (Lehner and Grill, 2013). The main channel of the Indus River is formed by streams with the Strahler Oder between five (small streams) and seven (large streams).

Appendix B: Model inputs

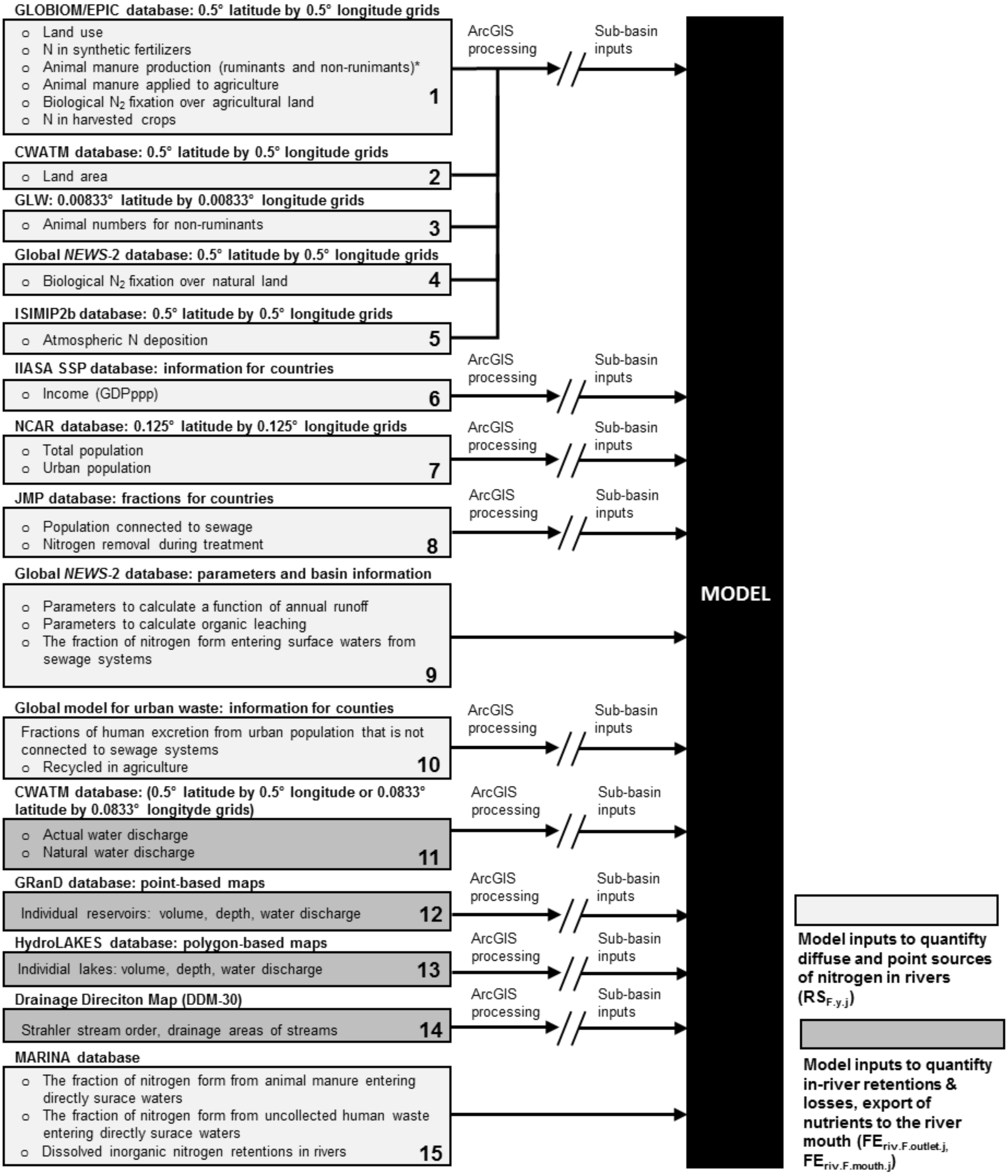

Figure B.1 Model inputs and their sources. Explanations for the abbreviations of the database or projects and their sources are in Table B.1. Explanations for the model inputs or parameters are in Table A.1 and Box A.1. Description of how we processed the model inputs and parameters are in Table B.2. *The animal manure production and manure applied to agriculture from non-ruminant animals are available only on the country level. The method we used to process these model inputs to sub-basins are described in Table B.2.

Table B.1 Abbreviations of the database or projects that are listed in Box A.1 and their sources. The model input category of the database or project can be found in Figure B.1.

Database/project	Description	Sources	Model input category
GLOBIOM/EPIC	Global Biosphere Management Model/ Environmental Policy Integrated Model system	(Byers et al., 2018)	1
CWATM	Community WATer Model	(Burek et al., 2017b)	2, 11
GLW	Gridded Livestock of the World database	(Robinson et al., 2014)	3
Global *NEWS*-2	Global Nutrient Export from WaterSheds model, version 2, Run 5	(Mayorga et al., 2010a)	4, 9
ISIMIP2b	Inter-Sectoral Impact Model Intercomparison Project	(Warszawski et al., 2014)	5
IIASA SSP	The projections of GDP for Share Socio-economic Pathways by the International Institute for Applied Systems Analysis	(Crespo Cuaresma, 2017)	6
NCAR	National Center for Atmospheric Research	(Jones and O'Neill, 2016)	7
JMP	WHO/UNICEF Joint Monitoring Programme for Water Supply, Sanitation and Hygiene		8
Global model for urban waste	Global model for urban waste	(Morée et al., 2013a)	10
GRanD	Global Reservoir and Dam database	(Lehner et al., 2011)	12
HydroLAKES	A database for global lakes with a surface area larger than 10 ha (Messager et al., 2016)	(Messager et al., 2016)	13
DDM-30	Drainage Direction Map for global stream flows	(Döll and Lehner, 2002)	14
MARINA 1.0	Model to Assess River Inputs of Nutrients to seAs	(Strokal et al., 2016)	15

Table B.2 Description of model inputs and parameters in Figure. B.1. Explanations for abbreviations mentioned in this table are in Box A.1 and Table A.1.

Model input category	Description	Presented in	Varying among		
			Sub-basin	N form	Year
1, 2, 7	These model inputs were aggregated from (0.5° latitude by 0.5° longitude) grids to sub-basins using ArcGIS. An example on how we aggregated the inputs for sub-basins can be found in (Strokal et al., 2015).	Figure 3, Figure 4	x	x	x
3	We used these to derive animal manure production by non-ruminants for sub-basins. We used the distribution of the (0.00833° latitude by 0.00833° longitude) gridded non-ruminant livestock numbers to downscale animal manure production by non-ruminants by countries (see model input category 1) to (0.00833° latitude by 0.00833° longitude) grids. Next, We aggregated from grids to sub-basins using ArcGIS.		x	x	x
4	These model inputs were used to drive average biological N_2 fixation over non-agricultural land for sub-basins. We have data only available for 2000. We applied this value for 2010 and 2050 by assuming that average biological N_2 fixation per unit area (hectare) over non-agricultural land has negligible changes over time. We multiplied the averaged fixation by non-agricultural land area (see model input category 1) by sub-basins to get the total biological N_2 fixation for sub-basins.	Figure 3	x	x	
5	These model inputs were aggregated from (0.5° latitude by 0.5° longitude) grids to sub-basins using ArcGIS. The deposition over agricultural and non-agricultural land were derived using the area weighted method.	Figure 3	x	x	x
6	These model inputs were aggregated from country values to sub-basins based the (0.5° latitude by 0.5° longitude) gridded population (see model input category 7) using population weighted method in ArcGIS. We assigned to the grids incomes (per person) of the country that covers these grids. Next, we multiplied the income by gridded population to get total income for the grids, and aggregated the gridded income to sub-basins. Last, we divide the sub-basin income by total population of the sub-basin to get average income per person for the sub-basins.		x	x	x
8	These model inputs were only available on the country level in 2010. Thus for the Indus sub-basins that covers more than one country, we aggregated the fraction of population connected to sewage systems to sub-basins in ArcGIS using the method that is described in model category 6. The fractions of nitrogen removal during treatment for sub-basins were derived by averaging county fractions using the gridded population within the sub-basins. For the three SSPs in 2050, assumptions in these model inputs were made based on literature. Detailed assumptions can be found in Table 1.	Figure 3	x	x	x
9	These model parameters were calibrated for large river basins at the global scale (Mayorga et al., 2010b).	Table B.3		x	
10	These model parameters were calculated for the Indus sub-basins from Morée et al. (2013b).	Table B.5			
11	These model inputs were aggregated from (0.0833° latitude by 0.0833° longitude) to sub-basins for the Indus River using the approach that is described in (Strokal et al., 2016). Exceptions are the two sub-basins of Indus River: middle stem 2 and delta. We calculated the annual runoff ($Rnat_j$, meter) from land to streams and fractions of water consumption (FQrem, 0-1) by treating the sub-basins middle stem 1, middle stem 2 and delta as one sub-basin. The calculated $Rnat_j$ and FQrem were assigned to middle stem 2 and delta. We did this because of the difficulties to model water discharge by those two sub-basins with dry conditions. In this study, the CWATM model was calibrated using a single objective optimization approach (Burek et al., 2017a). We ran the calibrated model with climate inputs (e.g., precipitation, temperature) from four GCMs (General Circulation Models): GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC5. We used the averaged water discharge from these four runs to reduce the uncertainties that are introduced by the GCMs. To represent the long-term trends and reduce the influence of hydrological extremes in water discharge, we used the 30-year average of water discharge for 2010 and 2050 in this study. For example, the annual water discharge from 1995 to 2025 were averaged to derive water discharge in 2010.	Table B.6, Figure A.1,	x		x
12,13	These model inputs were used for calculating nitrogen retentions in individual reservoirs and lakes. We derived these inputs using the approach that is described in (Strokal et al., 2016). We added in this study lakes for which storage capacity is larger than 0.5 km^3 to calculate nitrogen retentions. For 2050, we assumed the same retention by reservoirs and lakes in 2010.	Table B.7	x		

14	This information was used to make sub-basin delineation, stream order and drainage area of the sub-basins same as it was described in (Strokal et al., 2016).	Figure 1, Figure 2. Figure A.1, Figure A.2	x	
15	These model inputs were taken from the original MARINA 1.0 model based on literature (Strokal et al., 2016).	Table B.8		x

Table B.3 Model parameters used to quantify annual runoff and leaching of organic matter for the Indus sub-basins (see Box A.1 and Strokal et al. (2016) for detailed questions). These parameters do not change over years between 2010 and 2050. These parameters were derived from the MARINA 1.0 model by Strokal et al. (2016) and were derived originally from the Global *NEWS*-2 model describe in Mayorga et al. (2010b) (see Figure B.1). We assumed these parameters do not change over years between 2010 and 2050.

Model parameter	Explanation	Unit	Indus sub-basins	
			DIN	DON
aF	shape constants that are used to quantify $f_F(Rnat_j)$	-	1	0.95
eF	Watershed (land) export constants	-	0.94	0.010
EC_F	the coefficient for P weathering and leaching of organic matter	kg N km^{-2} $year^{-1}$	NA (not applicable)	280
$FEpnt_{F.hum.con.urb}$	the fraction of nitrogen form entering surface waters from urban human waste that is connected to sewage systems	0-1	*	0.14

*This parameter was calculated for each sub-basin as a linear empirical function of nitrogen removal during sewage treatment as described in the MARINA model by Strokal et al. (2016).

Table B.4 Model parameters used to quantify nitrogen (N) inputs to agriculture on land and to rivers from uncollected rural human waste (not connected to sewage systems) for the Indus sub-basins (see Box A.1 and Strokal et al. (2016) for detailed questions). These model parameters were taken from the MARINA 1.0 model that is described by Strokal et al. (2016). We assumed these parameters do not change over years between 2010 and 2050. Abbreviations of the model parameters are explained in Box A.1 and Table A.1.

Model parameter*	Explanation	Unit	Indus sub-basins
$frN_{sw.hum.uncon.rur}$	fractions of N in human excretion from rural population (not connected to sewage systems) that are directly discharged to surface waters	0-1	0.23
$frN_{NH3.hum}$	the fraction of N losses from human excretion to the air	0-1	0.24
The remainder is applied in agriculture**	-	0-1	0.53

*These model parameters were only available for China. For the Indus basin, we applied the same values by assuming similar management of uncollected human waste between Chinese and the Indus rivers. **For rural and urban population.

Table B.5 Model parameters used to quantify nitrogen (N) inputs to agriculture on land and to rivers from uncollected urban human waste (not collected to sewage systems) for the Indus sub-basins (see Box A.1 and Strokal et al. (2016) for detailed questions). The parameters were derived from the MARINA model by Strokal et al. (2016) based on Morée et al. (2013b), except for ammonia losses. We assumed these parameters do not change over years between 2010 and 2050. Abbreviations of the model parameters are explained in Box A.1 and Table A.1.

Model parameter	Explanation	Unit	Indus sub-basins
$frN_{agr.hum.uncon.urb}$	fractions of N and P in human excretion from urban population without a sewage connection that are recycled in agriculture, after correcting for N losses to the air	0-1	0.126*
$frN_{NH3.hum}$	the fraction of N losses from human excretion to the air	0-1	0.240
The remainder after correcting for N losses to the air is discharged to surface waters	-	0-1	0.874

*Derived from the MARINA 1.0 model this parameter in 2000.

Table B.6 Annual runoff ($Rnat_j$, meter) from land to streams and fractions of water consumption (FQrem, 0-1) for sub-basins: *middle stem 2* and delta of the Indus River in 2010 and 2050 (see Box A.1 and Strokal et al. (2016) for detailed questions). Three combinations of SSPs (Shared Socio-economic Pathways) and RCPs (Representative Concentration Pathways) were selected. The values are derived from outputs from the CWATM model based on the approach described in Table B.2. Abbreviations of the model parameters are explained in Box A.1 and Table A.1.

Model parameter	Unit	2010	2050		
			SSP1-RCP2.6	SSP2-RCP6.0	SSP3-RCP6.0
$Rnat_j$	m	0.05	0.04	0.04	0.04
FQrem	0-1	0.20	0.26	0.29	0.29

Table B.7 Mean capacities of lakes and dams (their reservoirs) that are included for the Indus River in 2010. Dam information is from (Lehner and Grill, 2013), and lake information is from (Messager et al., 2016). We accounted only dams and lakes with storage capacities higher than 0.5 km^3. The capacities were corrected by multiplying 0.67 according to (Strokal et al., 2016).

River basins	Dams	Storage capacity (km^3)	Lakes	Storage capacity (km^3)
Indus	8	3.95 (0.34-9.34)	2	9.05 (5.68-12.42)

Table B.8 The fractions of N input to rivers as form (F: DIN or DON) from direct discharges of animal manure ($FEpnt_{F.ma}$) and human waste ($FEpnt_{F.hum.uncon}$) (see Box A.1 and Strokal et al. (2016) for detailed questions). The values are from the MARINA model by Strokal et al. (2016). Abbreviations of the model parameters are explained in Box A.1 and Table A.1.

Model parameter	Unit	Indus sub-basins	
		DIN	DON
$FEpnt_{F.ma}$	0-1	0.70	0.30
$FEpnt_{F.hum.uncon}$	0-1	0.70	0.30

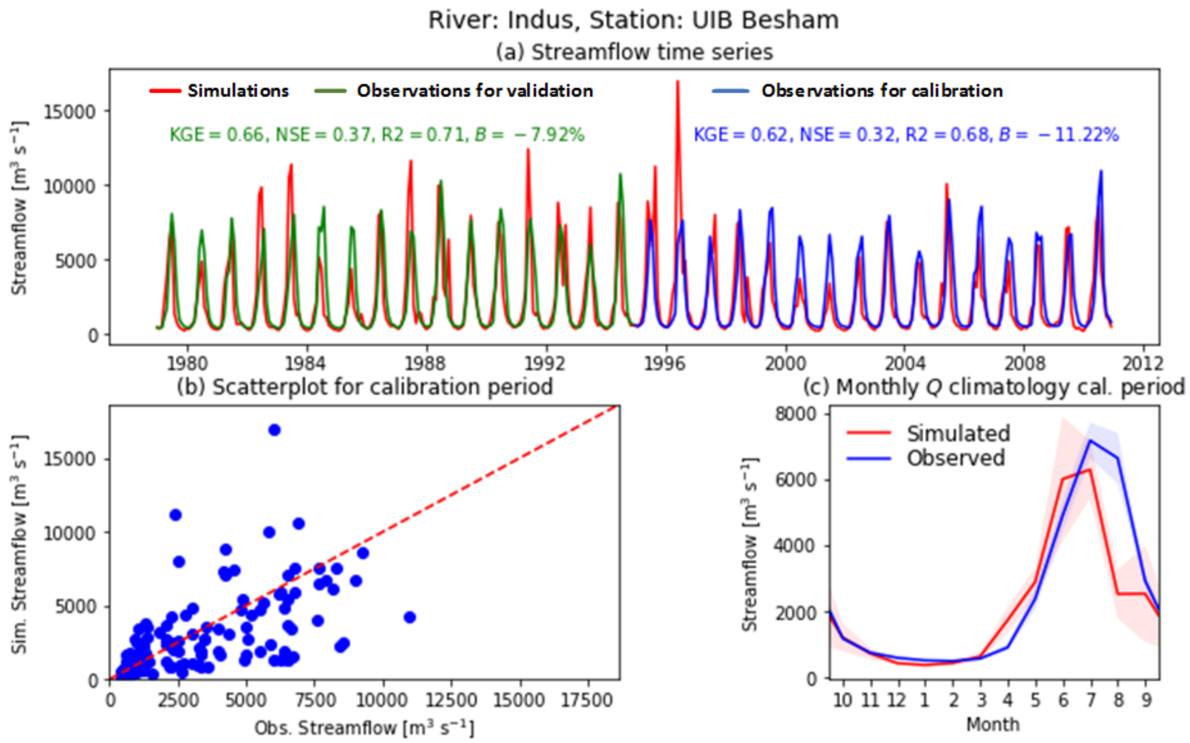

Figure B.2 (a) Calibration (marked as blue line) and validation (marked as green line) of the Community WATer Model (CWATM) simulations against observations in streamflow (river discharge) at the UIB Besham station of the Indus River, (b) Scatterplot for the calibration period (1995 to 2010), and (c) Monthly streamflow (Q) climatology of the calibration period; the shades represent standard deviation. KGE (−∞ to 1) is the Kling-Gupta Efficiency. NSE (−∞ to 1) is the Nash–Sutcliffe Efficiency. R^2 (0-1) is the coefficient of determination. B is the bias estimator. Details in the calibration approach can be found in (Burek et al., 2017a).

Appendix C: Human activities in the Indus basins and modelled results

Model inputs on human activities from the GLOBIOM and EPIC models for the SSPs and RCPs

For model on synthetic fertilizers, animal manure, agricultural N_2 fixation and N in harvested crops we used projections for the SSP-RCP scenarios, obtained by combining the land use projections from the GLOBIOM model (Havlík et al., 2014) and the nitrogen fluxes estimations from the EPIC model (Balkovič et al., 2014) as done in Byers et al. (2018). The land use projections for the various SSP and RCP scenarios were generated by the GLOBIOM land use model as described in Fricko et al. (2017). The main scenario assumptions related to the land use sector as well as the global and regional trends in projected land use change are further described in Popp et al. (2017). The spatially explicit projections required further downscaling of the regional results, as described in Leclère et al. (2017b). Many factors affect the potential development in the share of pixels occupied by cropland and grassland, as well as per hectare fertilizer application and manure dropped on pastures. Future evolution in the demand for various crop and livestock products as population and dietary preferences evolves, which together with trade, market dynamics, increases in crop yield and changes in production systems (all SSP-specific) determine changes in land use, livestock numbers and management. SSP-specific assumptions about the evolution of the environmental impact of agricultural activities (Popp et al., 2017) affect the amount of additional fertilizer applied for a given level of crop yield gain, as illustrated in Valin et al. (2013). RCP further incorporates SSP- and RCP-specific assumptions about additional demand for biofuel, additional area allocated to afforestation, and taxes on greenhouse gas emissions from animal and crop activities as well as land use change. They therefore affect all endogenous variables of the model from demand to land use allocation and management through trade and market dynamics. These effects can play in different direction but overall, the quantity of N applied through mineral fertilization is expected to increase at global scale more in SSP2 and SSP3 (about +80% in RCP4.5 between 2010 and 2050) than in SSP1 (about +50% for RCP4.5 over the same period). The lower increase in SSP1 is because of the relatively faster increases in both crops yield and nitrogen use efficiency increase while population increases more moderately (Leclère et al., 2017a). Increases in fertilizer application is more marked in South Asia and ubiquitous in the Indus basin (Figure C.2 in appendix).

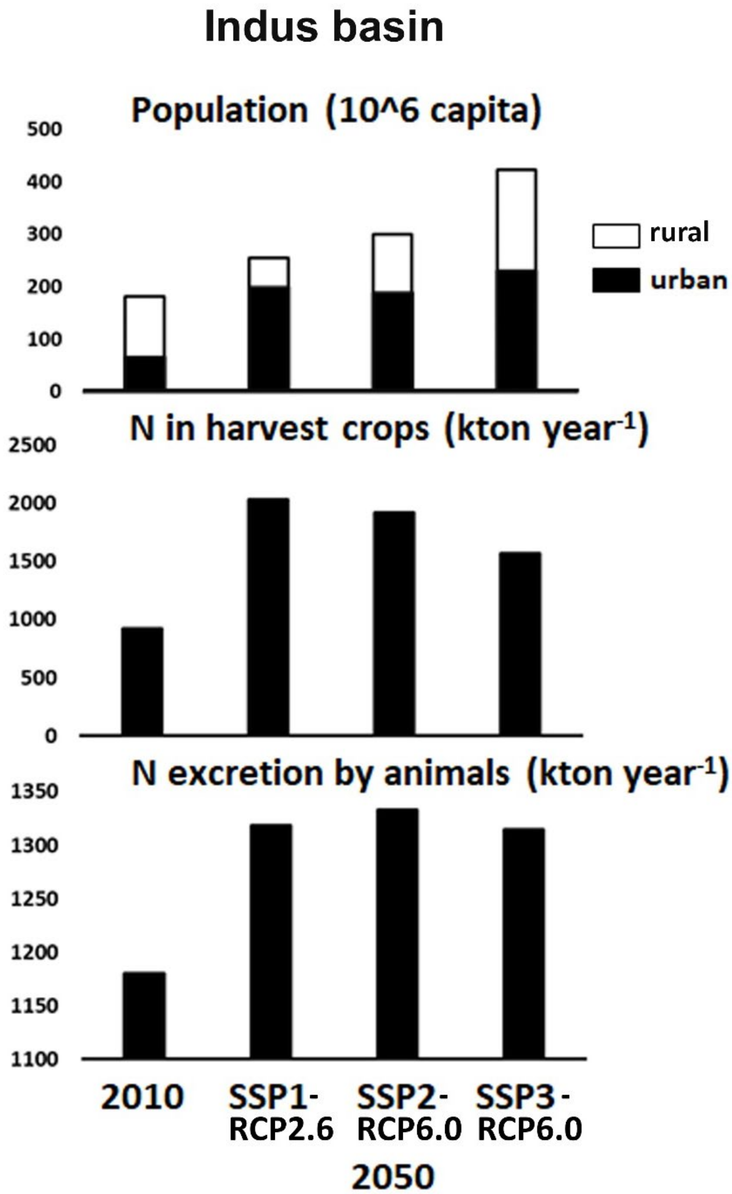

Figure C.1 Population (urban and total) (10^6 capita), nitrogen (N) in harvested crops (kton year^{-1}) and N excretion by animals (kton year^{-1}) in the Indus basin in 2010 and 2050. For 2050 the three scenarios are: SSP1-RCP2.6, SSP2-RCP6.0 and SSP3-RCP6.0. SSPs are the Shared Socio-economic Pathways. RCPs are the Representative Concentration Pathways. Details on the SSP-RCP scenarios are in section 2.3. Data on population is from (Jones and O'Neill, 2016). Data on N in harvested crops and N excretion by animals are from the GLOBIOM/EPIC model system (Byers et al., 2018).

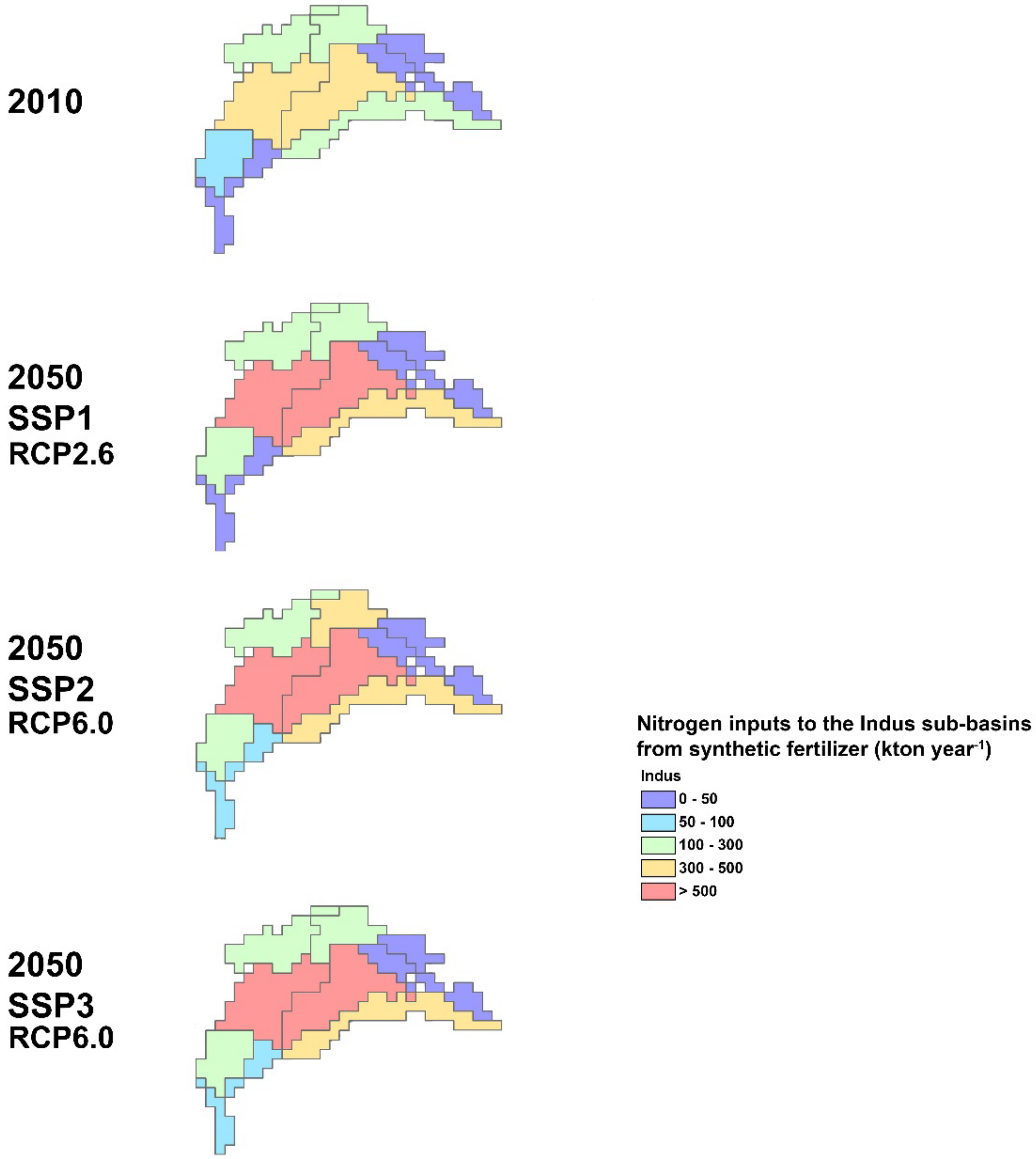

Figure C.2 Nitrogen (kton year^{-1}) inputs to the Indus sub-basins from synthetic fertilizer in 2010 and 2050. For 2050 the three scenarios are: SSP1-RCP2.6, SSP2-RCP6.0 and SSP3-RCP6.0. SSPs are the Shared Socio-economic Pathways. RCPs are the Representative Concentration Pathways. Details on the SSP-RCP scenarios are in section 2.3. Source of fertilizer data is summarized in Figure B.1.

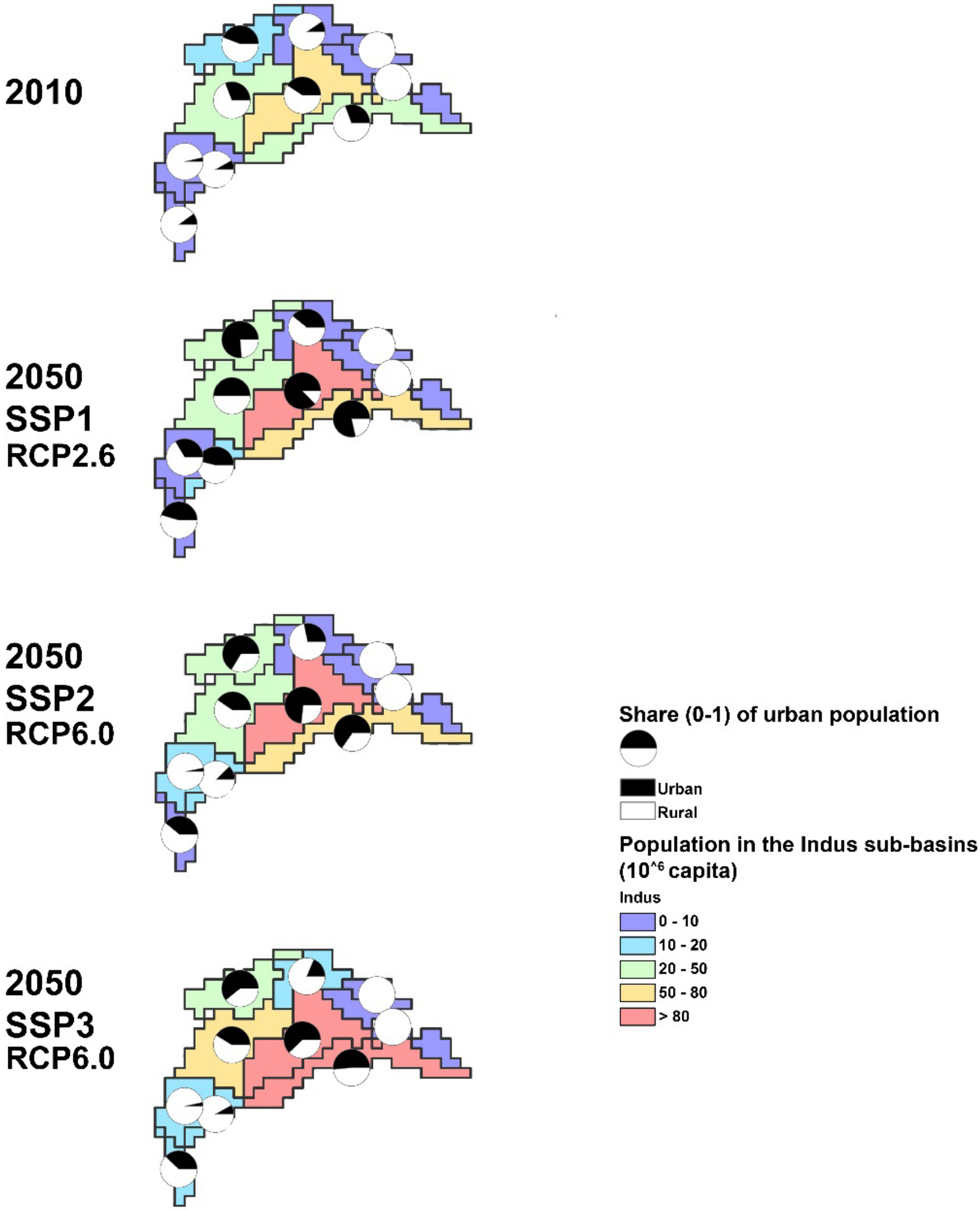

Figure C.3 Population (10^6 capita) and the share of urban and rural population (0-1) in the Indus sub-basins in 2010 and 2050. For 2050 the three scenarios are: SSP1-RCP2.6, SSP2-RCP6.0 and SSP3-RCP6.0. SSPs are the Shared Socio-economic Pathways. RCPs are the Representative Concentration Pathways. Details on the SSP-RCP scenarios are in section 2.3. Data on population is from Jones and O'Neill (2016).

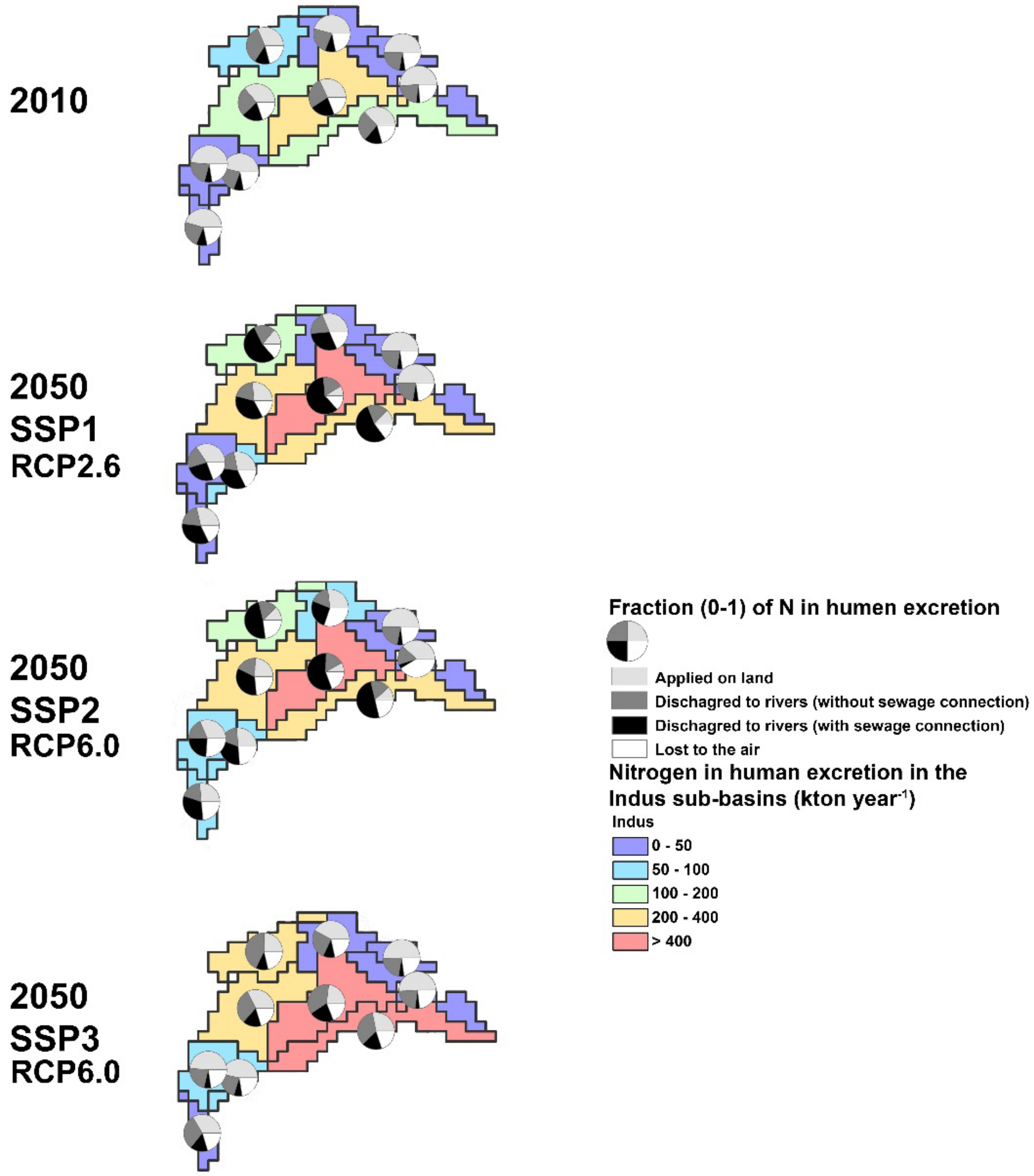

Figure C.4 Nitrogen (kton year^{-1}) in human excretion in Indus sub-basins in 2010 and 2050. For 2050 the three scenarios are: SSP1-RCP2.6, SSP2-RCP6.0 and SSP3-RCP6.0. SSPs are the Shared Socio-economic Pathways. RCPs are the Representative Concentration Pathways. Details on the SSP-RCP scenarios are in section 2.3.

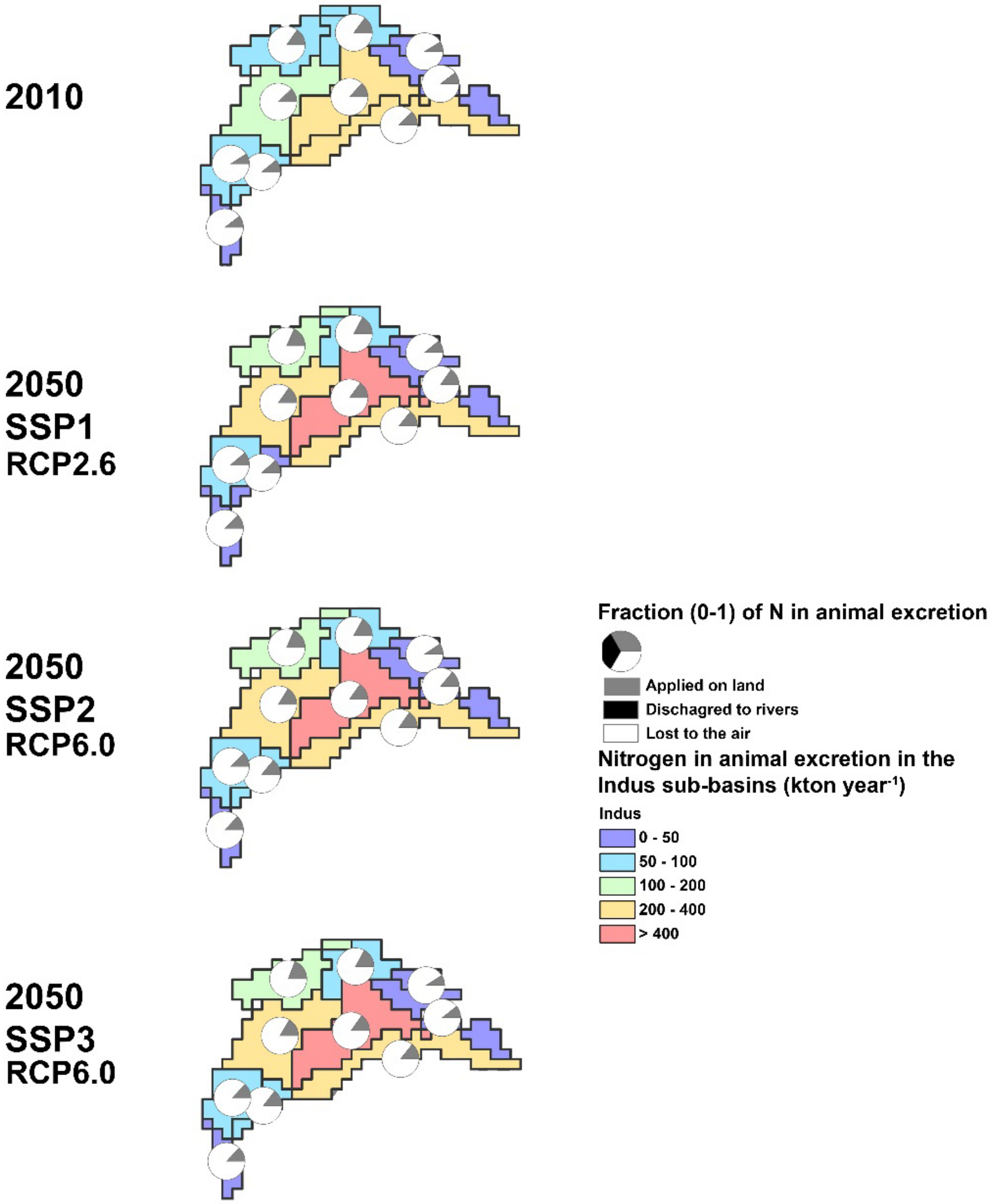

Figure C.5 Nitrogen (kton year^{-1}) in animal excretion in the Indus sub-basins in 2010 and 2050. For 2050 the three scenarios are: SSP1-RCP2.6, SSP2-RCP6.0 and SSP3-RCP6.0. SSPs are the Shared Socio-economic Pathways. RCPs are the Representative Concentration Pathways. Details on the SSP-RCP scenarios are in section 2.3.

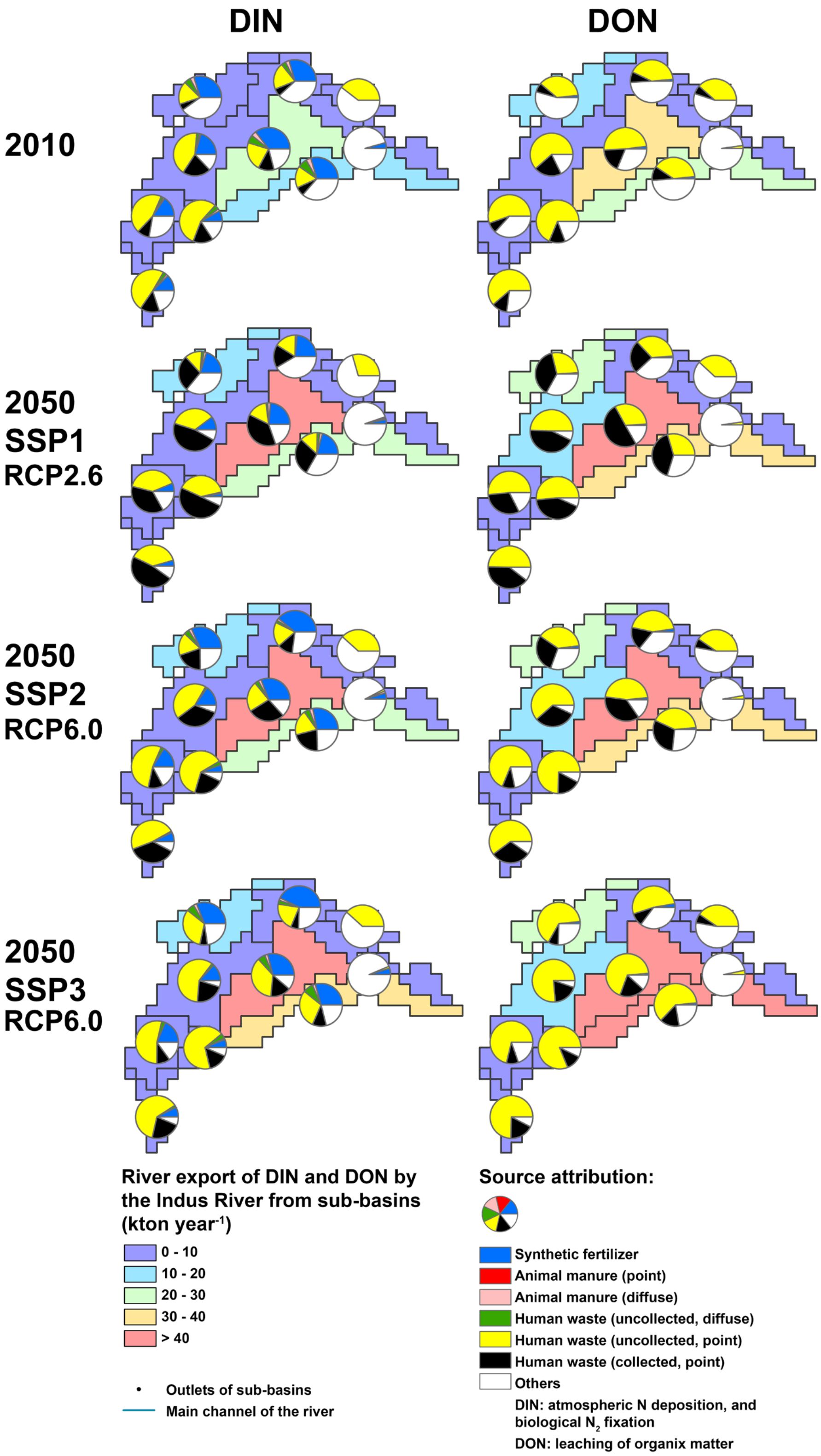

Figure C.6 River export of dissolved inorganic (DIN, kton year^{-1}) and organic (DON, kton year^{-1}) nitrogen by the Indus sub-basins by source in 2010 and 2050 for three scenarios: SSP1-RCP2.6, SSP2-RCP6.0, and SSP3-RCP6.0. SSPs are the Shared Socio-economic Pathways. RCPs are the Representative Concentration Pathways. Details on the SSP-RCP scenarios are in section 2.3. The names and locations of the sub-basins are in Figure 1.

Appendix D: Sensitivity analysis

We tested the sensitivity of the MARINA 1.0 model outputs (i.e calculated river export of DIN and DON by sub-basins) to changes (±10 or 50%) in several important model inputs and parameters (Figures D.1 and D.2). The selected model inputs and parameters included in the sensitivity analysis are: river discharge, water consumption, use of synthetic fertilizers, population, the rural (or urban) population that is not connected to sewage system and the fraction of nitrogen that is not removed during rural (or urban) sewage treatment. We selected river discharge and water consumption because the MARINA 1.0 model was found to be sensitive to changes in hydrology (Strokal et al., 2016). The other model inputs and parameters were selected because they are related to dominant sources of river export of DIN and DON (Figure 5 in the main text).

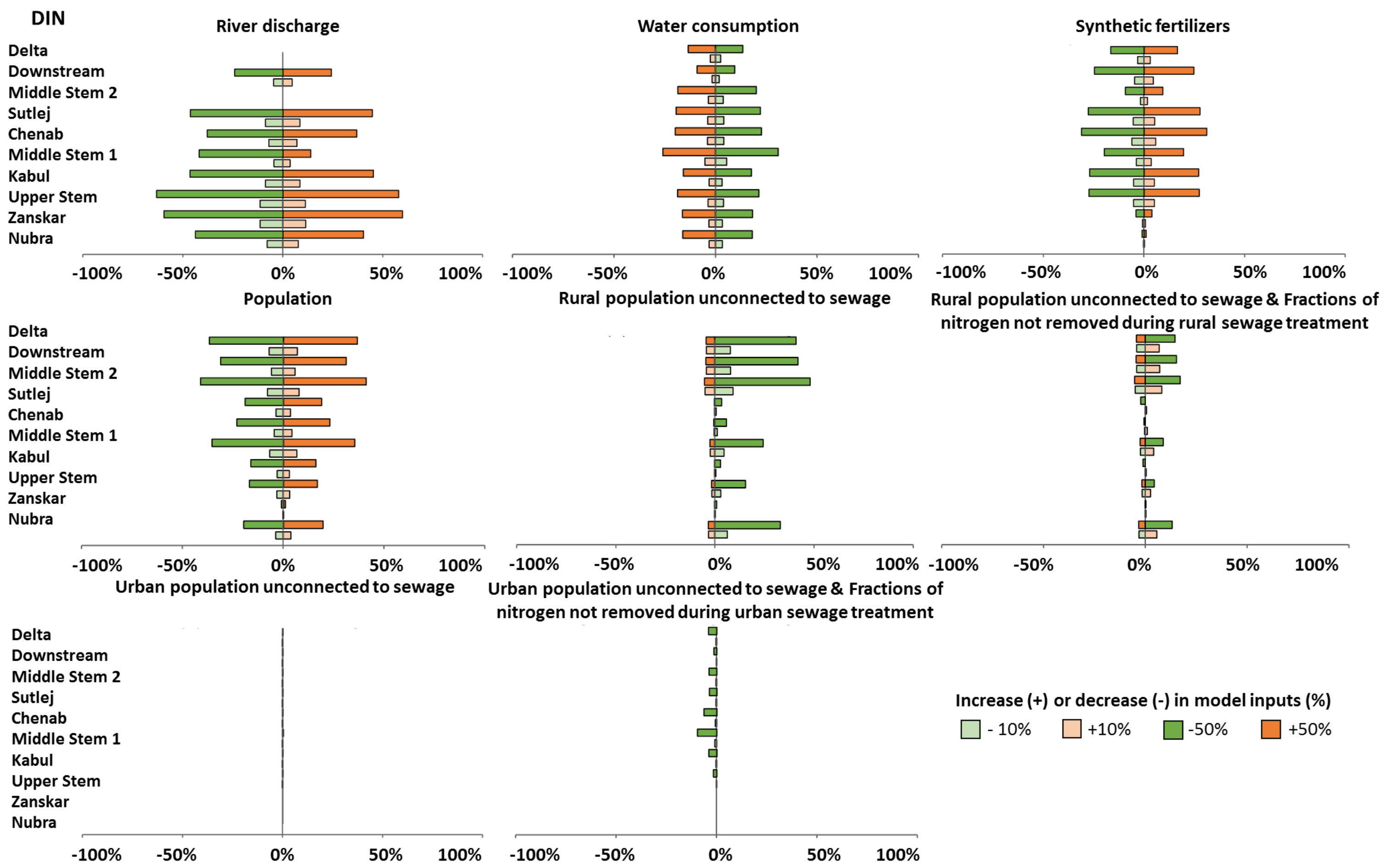

Figure D.1 Sensitivity of river exports of dissolved inorganic nitrogen (DIN) by sub-basins to changes in the selected model inputs (% change) in 2010. Increases in rural population that is not connected to sewage system, fractions of nitrogen not removed during rural sewage treatment, and factions of nitrogen not removed during urban sewage treatment cannot reach 10% to avoid resulting in negative values for other corresponding model inputs or parameters. For example, the maximum value for rural population that is not connected to sewage system is equal to the number of total population in 2010, assuming all population has no sewage connection. Such maximum values are used for the above three model inputs instead of increase their values by 10 or 50%.

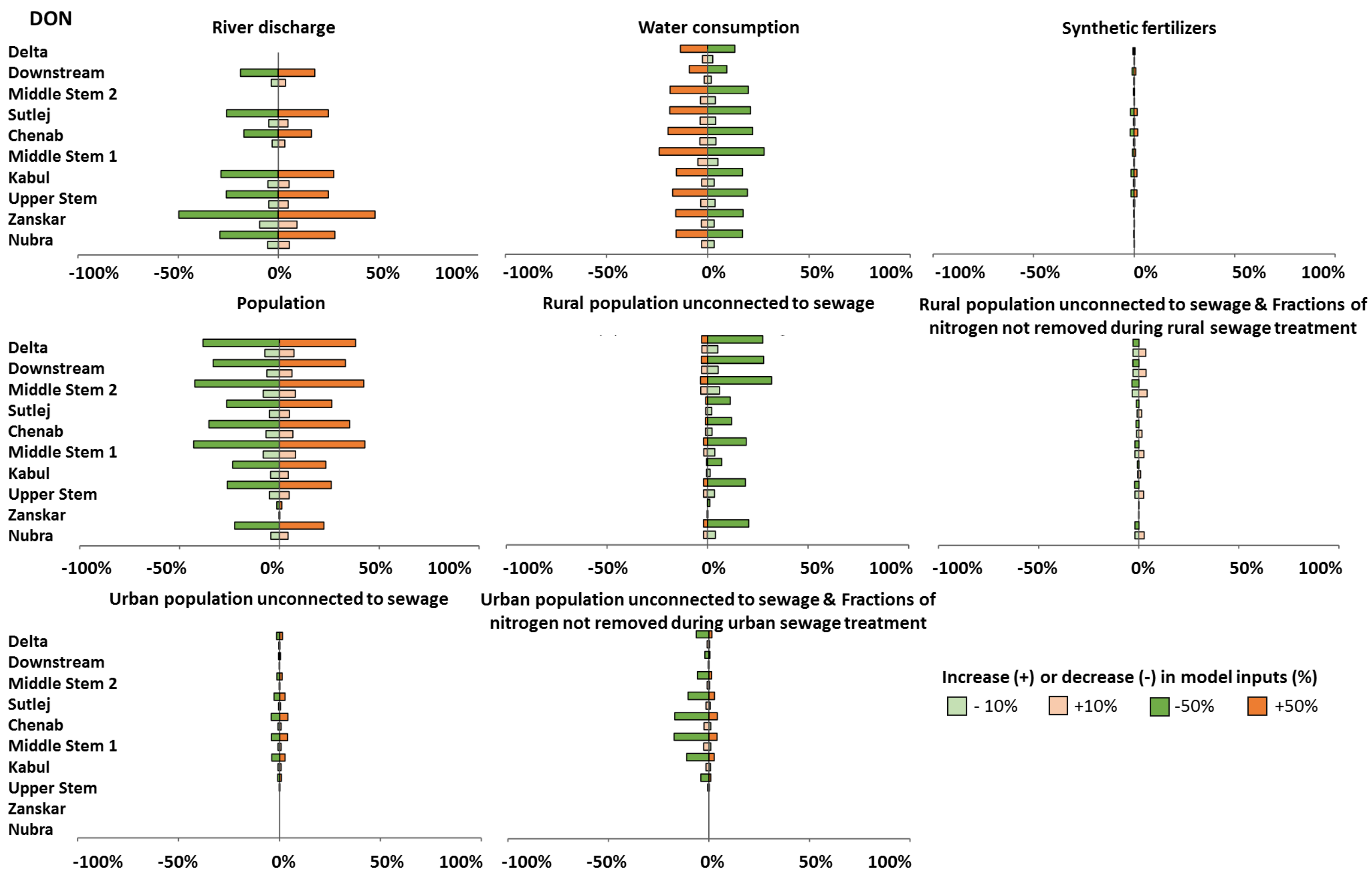

Figure D.2 Sensitivity of river exports of dissolved organic nitrogen (DON) by sub-basins to changes in the selected model inputs (% change) in 2010. Increases in rural population that is not connected to sewage system, fractions of nitrogen not removed during rural sewage treatment, and factions of nitrogen not removed during urban sewage treatment cannot reach 10% to avoid resulting in negative values for other corresponding model inputs or parameters. For example, the maximum value for rural population that is not connected to sewage system is equal to the number of total population in 2010, assuming all population has no sewage connection. Such maximum values are used for the above three model inputs instead of increasing their values by 10 or 50%.

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