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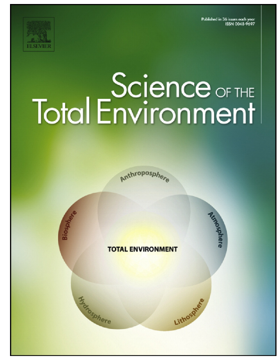

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Increasing Nitrogen Export to Sea: A Scenario Analysis for the Indus River

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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.

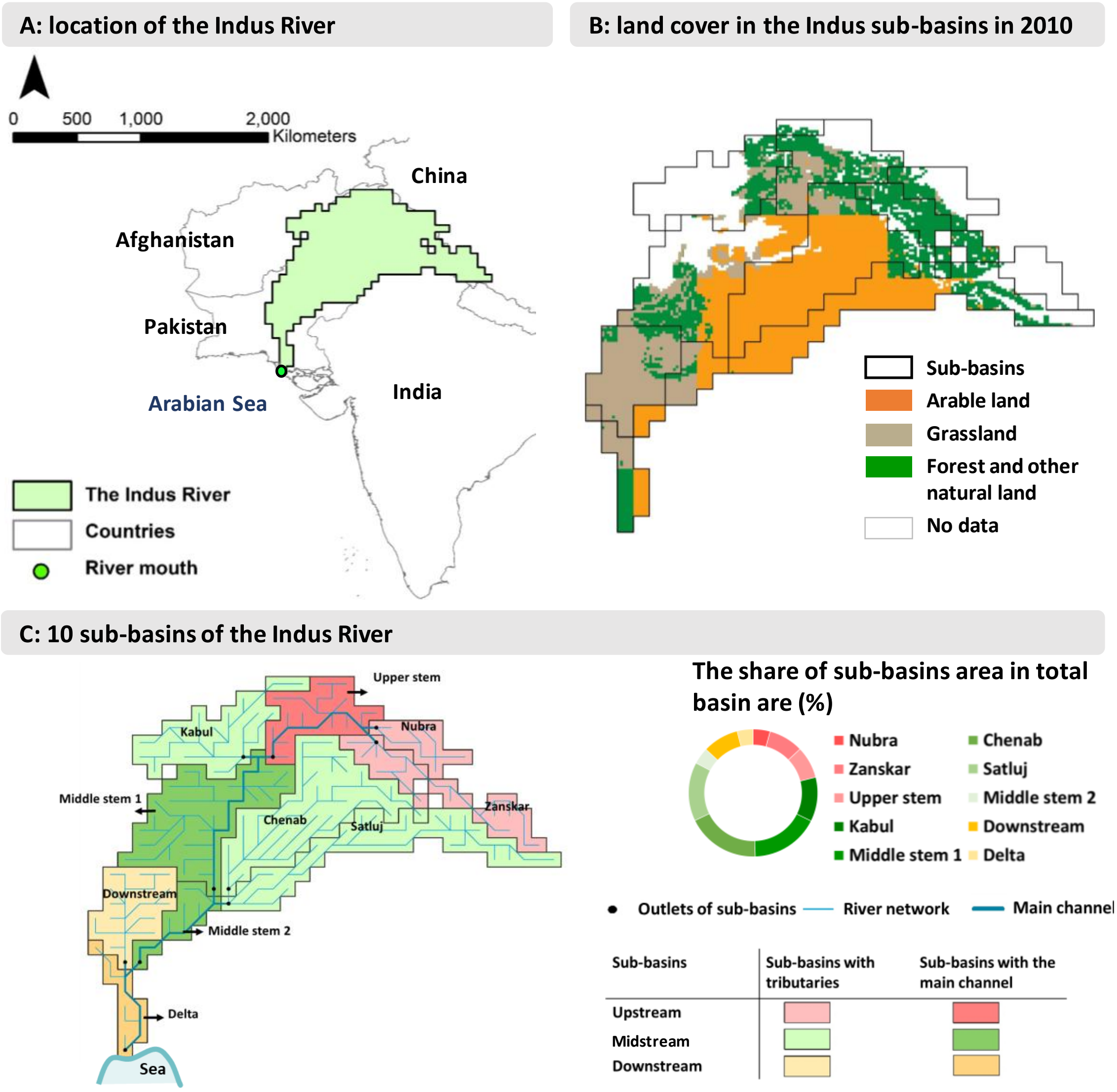

Figure 1 (A) Location of the Indus River; (B) Dominant land use in the Indus-sub-basins; (C) Sub-basins of the Indus River and the shares of the sub-basin areas in the total basin area. Drainage areas of the rivers and their sub-basins are from the Drainage Direction Map (DDM-30) at the resolution of 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:

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

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).

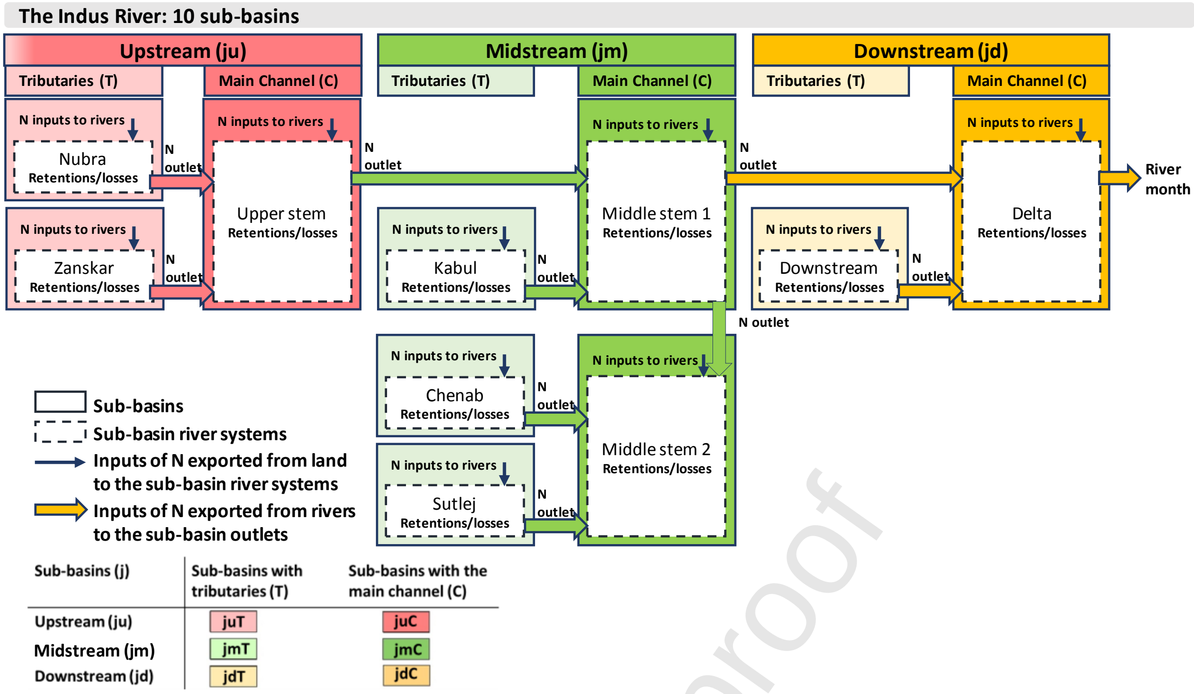

Figure 2 The schematic overview of the sub-basin scale modeling framework for the Indus River in the MARINA 1.0 model (Model to Assess River Inputs of Nutrients to seAs) based on Strokal et al. (2016). The locations of the rivers and their sub-basins are in Figure 1. This is the first time that MARINA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

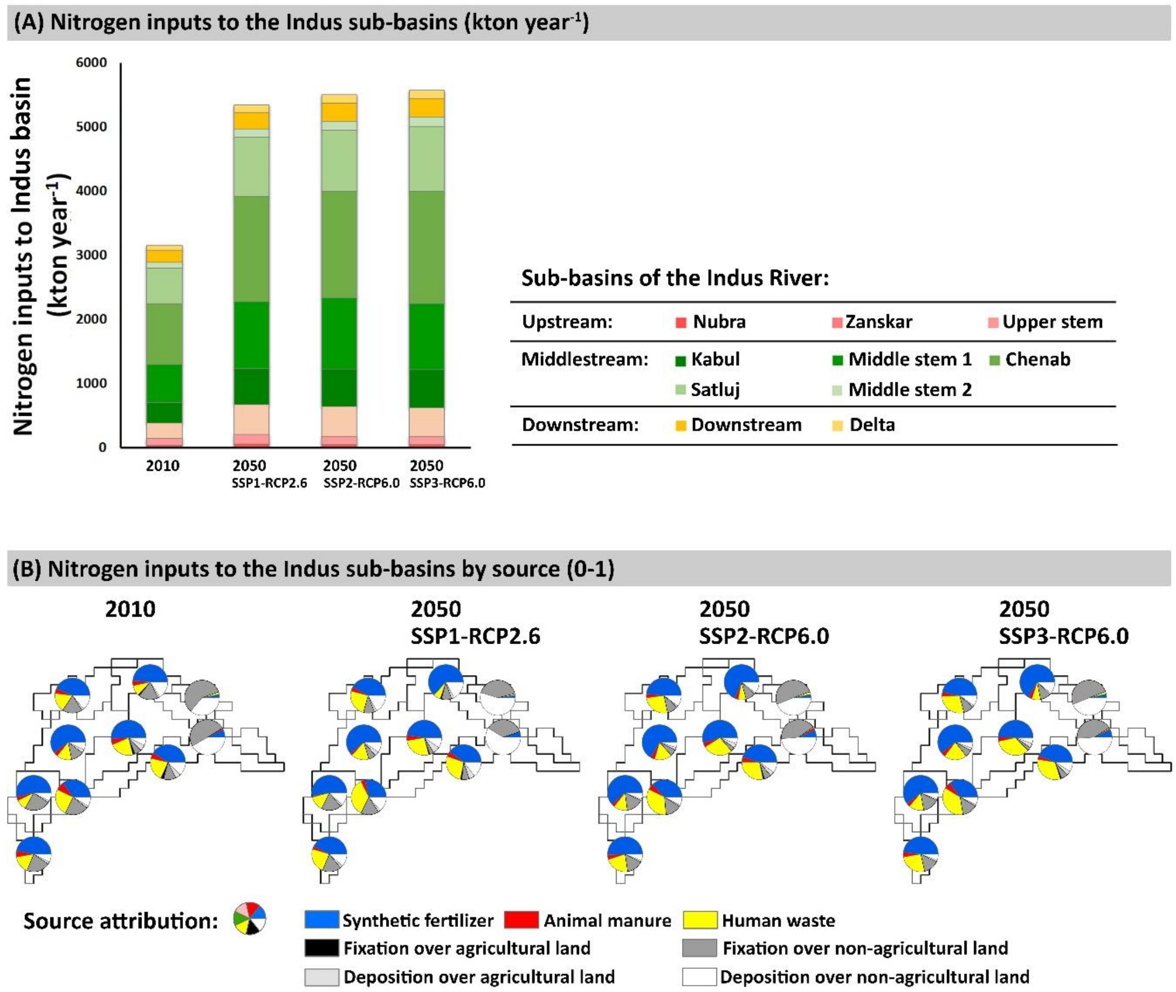

Figure 3 (A) Nitrogen (N) inputs to the Indus sub-basins (kton year^{-1}), and (B) by source (0-1) in 2010 and 2050 for three scenarios: SSP1-RCP2.6, SSP2-RCP6.0 and SSP3-RCP6.0. SSPs are the Shared Socio-economic Pathways. RCPs are the Representative Concentration Pathways. Details on the SSP-RCP scenarios 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).

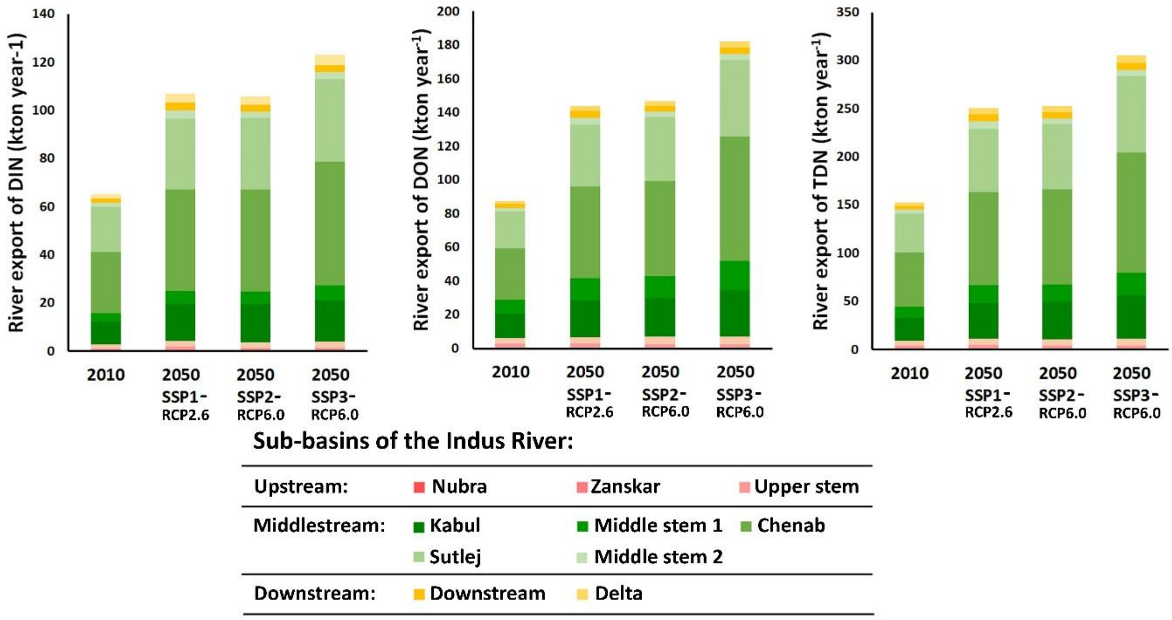

Figure 4 River export of dissolved inorganic (DIN, kton year^{-1}) and organic (DON, kton year^{-1}) nitrogen, and total dissolved nitrogen (TDN, kton year^{-1}) by the Indus sub-basins in 2010 and 2050. For 2050 the three scenarios are: SSP1-RCP2.6, SSP2-RCP6.0 and SSP3-RCP6.0. SSPs are the Shared Socio-economic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

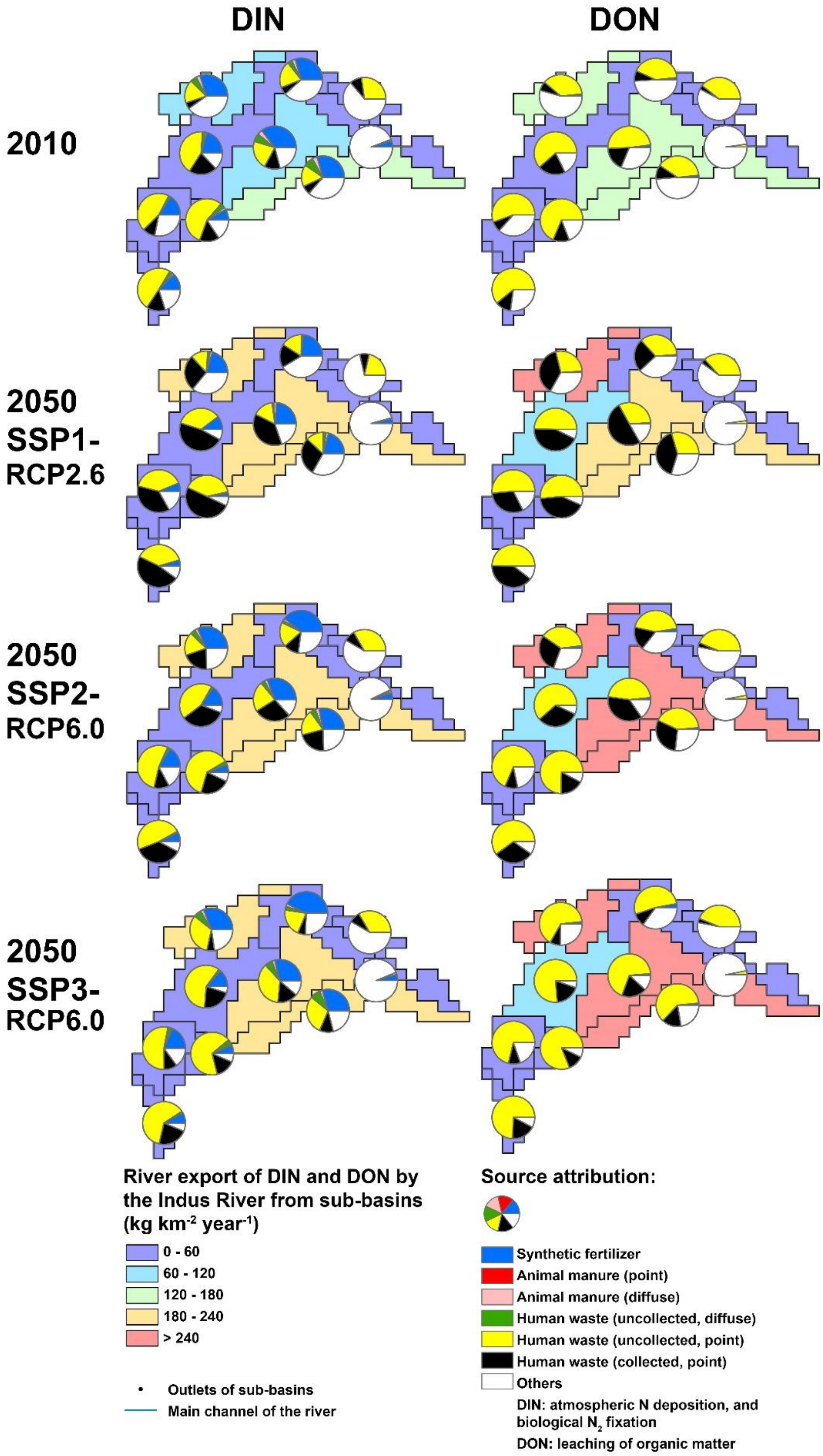

Figure 5 River export of dissolved inorganic (DIN, kg km^{-2} year^{-1}) and organic (DON, kg km^{-2} year^{-1}) nitrogen by the Indus sub-basins by source in 2010 and 2050 for the three scenarios: SSP1-RCP2.6,

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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References:

Amin MN, Kroeze C, Strokal M. Human waste: An underestimated source of nutrient pollution in coastal seas of Bangladesh, India and Pakistan. Marine Pollution Bulletin 2017; 118: 131-140.

Azizullah A, Khattak MNK, Richter P, Häder D-P. Water pollution in Pakistan and its impact on public health—a review. Environment international 2011; 37: 479-497.

Balkovič J, van der Velde M, Skalský R, Xiong W, Folberth C, Khabarov N, et al. Global wheat production potentials and management flexibility under the representative concentration pathways. Global and Planetary Change 2014; 122: 107-121.

Bouraoui F, Grizzetti B. Modelling mitigation options to reduce diffuse nitrogen water pollution from agriculture. Science of the Total Environment 2014; 468: 1267-1277.

Bouwman A, Beusen A, Billen G. Human alteration of the global nitrogen and phosphorus soil balances for the period 1970–2050. Global Biogeochemical Cycles 2009; 23: GB0A04.

Burek P, Satoh Y, Greve P. Community Water Model: 9. Calibration tool. IIASA WAT Program, 2017a, https://cwatm.github.io/#.

Burek P, Satoh Y, Greve P, Kahil T, Wada Y. The Community Water Model (CWATM)/Development of a community driven global water model. EGU General Assembly Conference Abstracts. 19, 2017b, pp. 9769.

Byers E, Gidden M, Leclère D, Balkovic J, Burek P, Ebi K, et al. Global exposure and vulnerability to multi-sector development and climate change hotspots. Environmental Research Letters 2018; 13: 055012.

Cf OdDS. Transforming our world: The 2030 agenda for sustainable development. 2015.

Crespo Cuaresma J. Income projections for climate change research: A framework based on human capital dynamics. Global Environmental Change 2017; 42: 226-236.

Daud M, Nafees M, Ali S, Rizwan M, Bajwa RA, Shakoor MB, et al. Drinking water quality status and contamination in Pakistan. BioMed research international 2017; 2017.

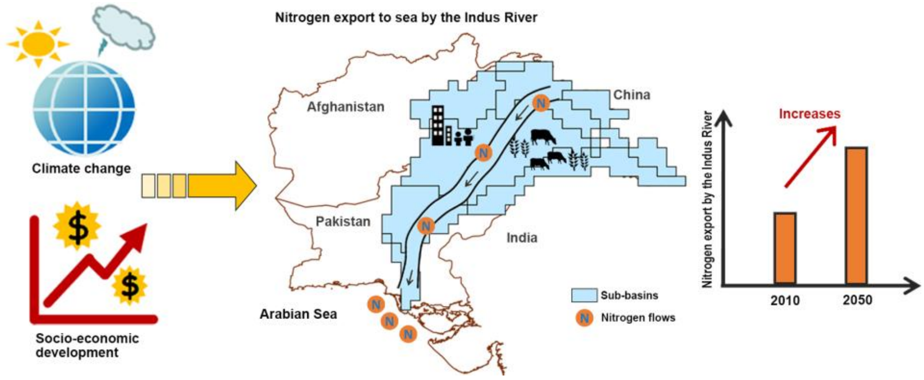
De TK, De M, Das S, Chowdhury C, Ray R, Jana TK. Phytoplankton abundance in relation to cultural eutrophication at the land-ocean boundary of Sunderbans, NE Coast of Bay of Bengal, India. Journal of Environmental Studies and Sciences 2011; 1: 169.

Dewani V, Ansari I, Khuhawar MY. Evaluation and Transport of Nitrogen and Phosphorus by River Indus at Kotri Barrage. Chemical Society of Pakistan 2000; 22: 104-110.

Döll P, Lehner B. Validation of a new global 30-min drainage direction map. Journal of Hydrology 2002; 258: 214-231.
Grigg N, Mobin-ud-Din Ahmad SI, Podger G, Kirby M, Colloff M. Water quality in the Ravi and Sutlej Rivers, Pakistan: a system view. 2018.
Hashmi I, Farooq S, Qaiser S. Chlorination and water quality monitoring within a public drinking water supply in Rawalpindi Cantt (Westridge and Tench) area, Pakistan. Environmental monitoring and assessment 2009; 158: 393.
Havlík P, Valin H, Herrero M, Obersteiner M, Schmid E, Rufino MC, et al. Climate change mitigation through livestock system transitions. Proceedings of the National Academy of Sciences 2014; 111: 3709-3714.
Hofstra N, Vermeulen LC. Impacts of population growth, urbanisation and sanitation changes on global human Cryptosporidium emissions to surface water. International Journal of Hygiene and Environmental Health 2016; 219: 599-605.
Imran S, Bukhari LN, Ashraf M. Spatial and Temporal Trends in River Water Quality of Pakistan (Sutlej and Ravi) 2018. Pakistan Council of Research in Water Resources (PCRWR), 2018, pp. 83.
Katukiza A, Ronteltap M, Niwagaba C, Foppen J, Kansiime F, Lens P. Sustainable sanitation technology options for urban slums. Biotechnology advances 2012; 30: 964-978.
Kazmi SS, Khan SA. Level of nitrate and nitrite contents in drinking water of selected samples received at AFPGMI, Rawalpindi. Pak J Physiol 2005; 1: 20-3.
Koff H, Maganda C. The EU and the human right to water and sanitation: Normative coherence as the key to transformative development. The European Journal of Development Research 2016; 28: 91-110.
Kok K. Multi-scale integration and synthesis of scenarios and adaptation narratives. 2016.
Liaqat UW, Choi M, Awan UK. Spatio - temporal distribution of actual evapotranspiration in the Indus Basin Irrigation System. Hydrological processes 2015; 29: 2613-2627.
Mayorga E, Seitzinger SP, Harrison JA, Dumont E, Beusen AH, Bouwman A, et al. Global nutrient export from WaterSheds 2 (NEWS 2): model development and implementation. Environmental Modelling & Software 2010; 25: 837-853.
Messager ML, Lehner B, Grill G, Nedeva I, Schmitt O. Estimating the volume and age of water stored in global lakes using a geo-statistical approach. Nature communications 2016; 7: 13603.
MOHURD. China Urban-Rural Construction Statistical Yearbook 2001. In: China. MoHaU-RDotPsRo, editor. Ministry of Housing and Urban-Rural Development of the People's Republic of China., 2001.
Morée A, Beusen A, Bouwman A, Willems W. Exploring global nitrogen and phosphorus flows in urban wastes during the twentieth century. Global Biogeochemical Cycles 2013; 27: 836-846.
Nakicenovic N, Lempert RJ, Janetos AC. A framework for the development of new socio-economic scenarios for climate change research: introductory essay. Climatic Change 2014; 122: 351-361.
O'Neill BC, Kriegler E, Ebi KL, Kemp-Benedict E, Riahi K, Rothman DS, et al. The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. Global Environmental Change 2017; 42: 169-180.
O'Neill BC, Kriegler E, Riahi K, Ebi KL, Hallegatte S, Carter TR, et al. A new scenario framework for climate change research: the concept of shared socioeconomic pathways. Climatic Change 2014; 122: 387-400.
Oenema O, Witzke H, Klimont Z, Lesschen J, Velthof G. Integrated assessment of promising measures to decrease nitrogen losses from agriculture in EU-27. Agriculture, ecosystems & environment 2009; 133: 280-288.
Pedde S, Kroeze C, Mayorga E, Seitzinger SP. Modeling sources of nutrients in rivers draining into the Bay of Bengal—a scenario analysis. Regional Environmental Change 2017; 17: 2495-2506.

Raza S, Zhou J, Aziz T, Afzal MR, Ahmed M, Javaid S, et al. Piling up reactive nitrogen and declining nitrogen use efficiency in Pakistan: a challenge not challenged (1961–2013). Environmental Research Letters 2018; 13: 034012.
Salomon M, Schmid E, Volkens A, Hey C, Holm-Müller K, Foth H. Towards an integrated nitrogen strategy for Germany. Environmental science & policy 2016; 55: 158-166.
Samir K, Lutz W. Demographic scenarios by age, sex and education corresponding to the SSP narratives. Population and Environment 2014; 35: 243-260.
Seitzinger S, Mayorga E, Bouwman A, Kroeze C, Beusen A, Billen G, et al. Global river nutrient export: A scenario analysis of past and future trends. Global Biogeochemical Cycles 2010; 24.
Seitzinger S, Pedde S, Kroeze C, Mayyorga E. Understanding nutrient loading and sources in the Bay of Bengal Large Marine Ecosystem. 2014.
Seitzinger SP, Kroeze C. Global distribution of nitrous oxide production and N inputs in freshwater and coastal marine ecosystems. Global biogeochemical cycles 1998; 12: 93-113.
Singh A, Ramesh R. Contribution of riverine dissolved inorganic nitrogen flux to new production in the coastal northern Indian Ocean: an assessment. International Journal of Oceanography 2011; 2011.
Strokal M, Kroeze C, Li L, Luan S, Wang H, Yang S, et al. Increasing dissolved nitrogen and phosphorus export by the Pearl River (Zhujiang): a modeling approach at the sub-basin scale to assess effective nutrient management. Biogeochemistry 2015; 125: 221-242.
Strokal M, Kroeze C, Wang M, Bai Z, Ma L. The MARINA model (Model to Assess River Inputs of Nutrients to seAs): Model description and results for China. Science of The Total Environment 2016; 562: 869-888.
Strokal M, Spanier JE, Kroeze C, Koelmans AA, Flörke M, Franssen W, et al. Global multi-pollutant modelling of water quality: scientific challenges and future directions. Current Opinion in Environmental Sustainability 2019; 36: 116-125.
Subramanian V. Nitrogen transport by rivers of south Asia. Current Science 2008: 1413-1418.
Suwarno D, Löhr A, Kroeze C, Widianarko B. Fast increases in urban sewage inputs to rivers of Indonesia. Environment, development and sustainability 2014; 16: 1077-1096.
Tahir MA, Rasheed H. Distribution of nitrate in the water resources of Pakistan. African Journal of Environmental Science and Technology 2008; 2: 397-403.
UNEP UNEP-. GEMStat Database of the Global Environment Monitoring System for Freshwater (GEMS/Water) Programme International Centre for Water Resources and Global Change: Koblenz, 2017.
Van Drecht G, Bouwman A, Harrison J, Knoop J. Global nitrogen and phosphate in urban wastewater for the period 1970 to 2050. Global Biogeochemical Cycles 2009; 23.
Van Vuuren DP, Edmonds J, Kainuma M, Riahi K, Thomson A, Hibbard K, et al. The representative concentration pathways: an overview. Climatic change 2011; 109: 5.
Vermeulen LC, de Kraker J, Hofstra N, Kroeze C, Medema G. Modelling the impact of sanitation, population growth and urbanization on human emissions of cryptosporidium to surface waters—A case study for Bangladesh and India. Environmental Research Letters 2015; 10: 094017.
Vermeulen LC, van Hengel M, Kroeze C, Medema G, Spanier JE, van Vliet MT, et al. Cryptosporidium concentrations in rivers worldwide. Water research 2019; 149: 202-214.
Wada Y, Flörke M, Hanasaki N, Eisner S, Fischer G, Tramberend S, et al. Modeling global water use for the 21st century: Water Futures and Solutions (WFaS) initiative and its approaches. Geoscientific Model Development 2016; 9: 175-222.
Wang M, Ma L, Strokal M, Ma W, Liu X, Kroeze C. Hotspots for Nitrogen and Phosphorus Losses from Food Production in China: A County-Scale Analysis. Environmental Science & Technology 2018; 52: 5782-5791.

WWF. Pakistan's waters at risk: water & health related issues in Pakistan & key recommendations. World Wildlife Fund, 2007.



Graphical abstract