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Cost-effective management of coastal eutrophication: A case study for the yangtze river basin

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ABSTRACT

Many water resources are threatened with nutrient pollution worldwide. This holds for rivers exporting increasing amounts of nutrients from the intensification of food production systems and further urbanization. This riverine nutrient transport causes coastal eutrophication. This study aims to identify cost-effective management options to simultaneously reach environmental targets for river export of nitrogen and phosphorus by the Yangtze River (China) in 2050. A newly developed modelling approach is used that integrates the Model to Assess River Inputs of Nutrients to seAs (MARINA) with a cost-optimization procedure, and accounts for socio-economic developments, land use and climate changes in a spatially explicit way. The environmental targets for river export of nutrients aim to reduce the gap between baseline and desirable nutrient export. Our baseline is based on MARINA projections for future river export of nutrients, while the desirable nutrient export reflects a low eutrophication potential. Results show the possibilities to close the gap in river export of both nutrients by 80–90% at a cost of 1–3 billion $ per year in 2050. Recycling of animal waste on cropland is an important cost-effective option; reducing synthetic fertilizer inputs provides an opportunity to compensate for the additional costs of the recycling and treatment of manure and wastewater. Our study provides new insights on the combination of cost-effective management options for sub-basins of the Yangtze. This can support the design of cost-effective and sub-basin specific management options for reducing future water pollution.

1. Introduction

Water resources are often threatened with pollution. This includes nutrient pollution in rivers from intensive food production systems (e.g., Bluemling and Wang, 2018) and urban environments (e.g., Zhang et al., 2017) in many world regions (Yu et al., 2019). Rivers often export large amounts of the main nutrients nitrogen (N) and phosphorus (P). As a result, many coastal waters are eutrophic (Breitburg et al., 2018). The Yangtze River (Chang Jiang), the third longest river of the world, is an example of this issue. Increasing exports of N and P by the Yangtze are a result of intensive human activities in sub-basins. Agriculture is a major cause of nutrient pollution in the Yangtze, with a considerable contribution from direct manure discharges (Wang et al., 2018; Strokal et al., 2016). Sewage systems are also important sources of N and P in rivers of downstream areas. In particular, the middle- and downstream areas contribute to nutrient pollution of the coastal areas (Strokal et al., 2016). The Yangtze is expected to export more nutrients in the coming decades driven by population growth, urbanization, and intensification of agricultural production, unless major policy interventions are implemented effectively (Liu et al., 2013).

Existing modelling studies for China often focused on exploring the technical potential of management options to reduce river pollution

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from food production systems and urban areas (Li et al., 2017; Wang et al., 2017a). These studies used models that integrate socio-economic aspects with flows of nutrients from land to sea while accounting for retentions of nutrients in rivers (Bai et al., 2015; Li et al., 2017; Liu et al., 2018; Wang et al., 2018). An example is the MARINA model (Model to Assess River Inputs of Nutrients to seAs, version 1.0) that has been widely used for China (e.g., Strokal et al., 2017). This model enables analyzing future river export of N and P in different forms by sub-basin and source. Some other studies explored scenarios to reduce future river pollution, and found that recycling of waste resources (e.g., manure on land), improving nutrient use efficiencies in agriculture and wastewater treatment are important options to avoid future river pollution in large Chinese rivers (Li, et al., 2019a, 2019b; Li, et al., 2019a, 2019b) including the Yangtze. These insights suggest technical potentials to avoid pollution. Some studies (Wang et al., 2017b, 2018) identified pollution hotspots from food production and evaluated technical potentials to reduce pollution by increasing nutrient use efficiencies and recycling manure on land. Other studies focused on exploring options to close nutrient cycles in agriculture and urban areas at different scales in China (e.g., Chen et al., 2011; Li et al., 2017; Yang et al., 2019). However, most of the existing studies analyzed technical potentials of reducing river export of N and P, without accounting for economic costs to achieve environmental targets.

The cost-effectiveness of management options to reduce water pollution was analyzed in several studies for other regions (e.g., Lescot et al., 2013; Udías et al., 2014). However, most of these studies focused on individual watersheds (Cools et al., 2011; Cramer et al., 2018; Martin-Ortega et al., 2015) and/or water systems (e.g., lakes) (Jiang and Hellegers, 2016). They accounted for either N (e.g., Cools et al., 2011) or P (e.g., Cramer et al., 2018) originating from human waste (e.g., Jiang et al., 2018; Jiang and Hellegers, 2016) or agriculture (e.g., Albiac et al., 2017). To our knowledge, few studies exist that integrate biophysical (river export of N and P) and economic (cost-optimization) modelling at the river basin scale while accounting for socio-economic development and sub-basin characteristics including hydrology and land use. Such a study is, however, needed to identify the combination of cost-effective management options for reducing river export of both N and P to avoid coastal eutrophication.

The main aim of this study is to identify cost-effective management options to simultaneously reach environmental targets for river export of total dissolved N (TDN) and P (TDP) by the Yangtze in 2050. To meet this aim, a modelling approach is developed that integrates MARINA 1.0 (Strokal et al., 2016) and a cost-optimization procedure.

2. Materials and methods

2.1. Study area

The Yangtze River is an important source of freshwater for human needs such as irrigation. The drainage area of the river covers around 1.8 million km^2 and drains into the Yellow Sea. The drainage area is divided into ten sub-basins according to the MARINA model (Strokal et al., 2016) (Fig. A.1). The ten sub-basins are classified as up-, middle- and downstream sub-basins. Upstream sub-basins represent around half of the total area of the basin. Middlestream sub-basins cover around 40% of the total area, and a downstream sub-basin covers 10%.

2.2. A novel modelling approach

Our modelling approach combines biophysical and economic data and insights to identify cost-effective options for reducing coastal eutrophication (Figure A.1). Cost-effective management options are defined here as the combination of least-cost management options that could achieve pre-defined environmental targets (Girard et al., 2015). In other words, our integrated modelling approach searches for cheapest options to reach environmental targets under which low coastal eutrophication is expected (see Sections 2.3 on options and 2.4 on the environmental targets).

To this end, the approach integrates a substance flow analysis (river export of nutrients) using the MARINA model (version 1.0) with a cost-optimization procedure. In this approach, socio-economic developments, land use and climate changes are accounted for in a spatially explicit way (e.g., at the sub-basin scale) (Strokal et al., 2016). The model runs at the sub-basin scale for the past and future. For each sub-basin, the model quantifies river export of nutrients by source as a function of socio-economic developments (e.g., population, economy), human activities on land (e.g., agriculture, urbanization), sub-basin characteristics (e.g., hydrology, land use) while taking into account nutrient losses and retentions in soils (e.g., volatilization, denitrification, leaching and accumulation) and in rivers (e.g., due to dams, sedimentation, water consumption). Integrating the MARINA model with a cost-optimization procedure enables to identify cost-effective management options to reduce coastal eutrophication while accounting for differences in the socio-economic developments, climate and hydrology among sub-basins. As a result, the least-cost combination of sub-basin specific management options can be identified. Below, the MARINA model (Section 2.2.1) and cost-optimization that is adjusted for river export of nutrients from sub-basins are described (Section 2.2.2). Box 1 presents the equations that combine the MARINA model with the cost-optimization procedure.

2.2.1. MARINA 1.0

MARINA quantifies river export of dissolved inorganic (DIN, DIP), dissolved organic (DON, DOP) nitrogen (N) and phosphorus (P) by source from sub-basins in 1970, 2000 and 2050 The model was validated for China (Strokal et al., 2016) (Appendix C). River export of nutrients is quantified in three steps. First, inputs of nutrients to rivers are quantified considering nutrient retentions on the land. Second, nutrient export to sub-basin outlets is quantified considering retentions in and losses from rivers (e.g., denitrification, sedimentation, river damming and water consumption). Third, nutrient export to the river mouth from each sub-basin is quantified. Nutrient retentions and losses during river export are considered (details are in Strokal et al. (2016), Appendix A, Figs. A.1, B.1-B.6 for model inputs).

Nutrients in rivers result from diffuse and point sources (Fig. A.1, Fig. 1). Seven diffuse nutrient sources are considered: (i) inputs of nutrients to land from animal manure (for DIN, DON, DIP, DOP), (ii) synthetic fertilizers (for DIN, DON, DIP, DOP), (iii) human waste (for DIN, DON, DIP, DOP), (iv) atmospheric N deposition, (v) biological N_2 fixation by crops and natural vegetation (for DIN), (vi) weathering of P-contained minerals (for DIP), and (vii) leaching of organic matter (for DON, DOP). Point sources include (a) direct manure and human waste discharges to rivers (untreated) and (b) sewage effluents from population connected to sewage systems (for DIN, DON, DON, DOP).

MARINA requires inputs at the sub-basin scale for 1970, 2000 and 2050. These inputs include information about socio-economic development (e.g., population, economy), human activities (e.g., use of synthetic fertilizers and animal manure), and sub-basin characteristics (e.g., river discharges, dams). Model inputs for sub-basins were prepared based on existing studies (Fekete et al., 2010; Strokal et al., 2016). Model inputs for 2050 are based on the scenarios of the Millennium Ecosystem Assessment (MEA) (Seitzinger et al., 2010; Strokal et al., 2016).

The Global Orchestration (GO) scenario of the MEA is used (Strokal et al., 2017) as a baseline for socio-economic development in 2050 (Table B.1, Figs. B.1-B.6). For the sub-basins of the Yangtze, GO assumes globalized trends in the socio-economic development and reactive approaches to managing environmental problems. The population is expected to increase slightly between 2000 and 2050. However, more people are expected to move to cities, increasing the demand for food in urban areas. This will generate more waste in urban areas and increase the connection rate to sewage systems. However, wastewater

Box 1

Overview of integrating the MARINA model (version 1.0) and a cost-optimization procedure to minimize the total costs of management options in 2050 to reach environmental targets for river export of total dissolved nitrogen and phosphorus at the river mouth. The cost-optimization procedure is used to identify the cost-effective options to reduce river export of nutrients (eq. 1–3) and MARINA is used to quantify river export of nutrients (eq. 4–11). The integrated approach is summarized in Figure B.7. The GO scenario and MARINA 1.0 are described in Strokal et al., 2016 (details are in Appendixes A and B).

The objective function:

$$\min C = \sum_{j=1}^{10}\Big[\sum_{o=1}^{4}(C_{dif.o}\cdot X_{dif.o.j}) + \sum_{o=1}^{8}(C_{pnt.o}\cdot X_{pnt.o.j})\Big] \quad \text{(eq.1)}$$

Minimizing the total cost of management options in 2050 to reach environmental targets for river export of nutrients (C, \$)

dif: diffuse-source input
pnt: point-source input
o: management option
j: sub-basin

Subject to

$$\sum_{j=1}^{10}(M_{DIN.j} + M_{DON.j}) \le ET_{TDN} \quad \text{(eq.2)}$$

$$\sum_{j=1}^{10}(M_{DIP.j} + M_{DOP.j}) \le ET_{TDP} \quad \text{(eq.3)}$$

Environmental targets (ET) for river export of TDN (DIN+DON) and TDP (DIP+DOP) at the river mouth (kton)

$$M_{F.j} = (RS_{dif.F.o.j} + RS_{pnt.F.o.j} + {}^{GO}RS_{F.other.o.j})\cdot {}^{GO}FE_{riv.F.outlet.j}\cdot {}^{GO}FE_{riv.F.mouth.j} \quad \text{(eq.4)}$$

$$RS_{dif.F.o.j} = (WS_{dif.total.opt.E.j} - {}^{GO}WS_{dif.export.E.j})\cdot {}^{GO}FE_{ws.F.j} \quad \text{(eq.5)}$$

$$WS_{dif.total.opt.E.j} = {}^{GO}WS_{dif.total.E.j} \quad \text{(eq.6)}$$

$$WS_{dif.total.opt.E.j} = \sum(X_{dif.o.j}\cdot CF_{dif.E.o}) + {}^{GO}WS_{dif.E.others.j} \quad \text{(eq.7)}$$

$${}^{GO}WS_{dif.total.E.j} = \frac{{}^{GO}WS_{dif.export.E.j}}{{}^{GO}NUE_{E.j}} \quad \text{(eq.8)}$$

$$RS_{pnt.F.o.j} = \sum\big[(X_{pnt.o.j}\cdot CF_{pnt.E.o})\cdot(1 - RE_{pnt.E.o.j})\cdot {}^{GO}FE_{pnt.F.o}\big] \quad \text{(eq.9)}$$

Quantifying river export of nutrient forms by sub-basin j ($M_{F.j}$, kton in 2050) based on MARINA 1.0

Constraint is based on the nutrient use efficiency in agriculture in 2050

$$X_{dif.o3.j} + X_{dif.o4.j} + X_{pnt.o1.j} + X_{pnt.o2.j} + X_{pnt.o3.j} + X_{pnt.o4.j} = {}^{GO}X_{ma.total.j} \quad \text{(eq.10)}$$

$${}^{GO}WS_{dif.hw.land.j} + X_{pnt.o5.j} + X_{pnt.o6.j} + X_{pnt.o7.j} + X_{pnt.o8.j} = {}^{GO}X_{hw.total.j} \quad \text{(eq.11)}$$

Distribution of total manure (${}^{GO}X_{ma.total.j}$, kton) and human waste (${}^{GO}X_{hw.total.j}$, kton) based on the management options o in 2050 (Table 1)

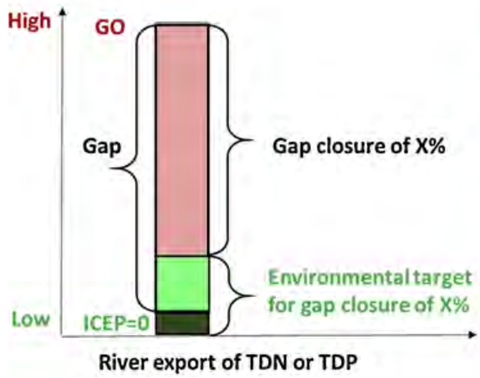
Notations:

$\boldsymbol{C}$ is the total cost of a combination of management options to reach environmental targets for river export of TDN and TDP from all sub-basins and sources simultaneously (\$ in 2050). TDN and TDP are total dissolved N and total dissolved P, respectively.
$\boldsymbol{C_{dif.o}}$ is the cost of management option o for a diffuse-source input to agricultural land to reduce river export of TDN and TDP (\$/kton in 2050).
$\boldsymbol{C_{pnt.o}}$ is the cost of management option o for a point-source input to treatment facilities to reduce river export of TDN and TDP (\$/kton in 2050).
$\boldsymbol{X_{dif.o.j}}$ is the level of a diffuse-source input to agricultural land from management option o in sub-basin j (kton in 2050).
$\boldsymbol{X_{pnt.o.j}}$ is the level of a point-source input to treatment facilities from management option o in sub-basin j (kton in 2050).
$\boldsymbol{{}^{GO}X_{ma.total.j}}$ and $\boldsymbol{{}^{GO}X_{hw.total.j}}$ are the total animal manure and human waste in sub-basin j in GO, respectively (kton in 2050, Figures D.2-D.3).
$\boldsymbol{X_{dif.o3.j}, X_{dif.o4.j}, X_{pnt.o1.j}, X_{pnt.o2.j}, X_{pnt.o3.j}, X_{pnt.o4.j}, X_{pnt.o5.j}, X_{pnt.o6.j}, X_{pnt.o7.j}}$ **and** $\boldsymbol{X_{pnt.o8.j}}$ refer to management options o to distribute animal manure and human waste in sub-basin j (kton in 2050, see Table 1).
$\boldsymbol{{}^{GO}WS_{dif.hw.land.j}}$ is the amount of human waste that stays on land in sub-basin j in GO (kton in 2050, Figures D.2-D.3). N and P content in $\boldsymbol{{}^{GO}WS_{dif.hw.land.j}}$ is calculated (Tables B.1-B.2) and then used together with $\boldsymbol{{}^{GO}WS_{dif.E.others.j}}$ in eq.7.
$\boldsymbol{ET_{TDN}}$ and $\boldsymbol{ET_{TDP}}$ are the environmental targets for river export of TDN and TDP at the river mouth (kton in 2050, Figure 1).
$\boldsymbol{M_{DIN.j}, M_{DON.j}, M_{DIP.j}\ M_{DON.j}}$ are river exports of dissolved inorganic N (DIN), dissolved organic N (DON), dissolved inorganic P (DIP) and dissolved organic P (DOP) by sub-basin j from all diffuse and point sources (kton in 2050).
$\boldsymbol{RS_{dif.F.o.j}}$ is the input of nutrient form (F: DIN, DON, DIP, DOP) to rivers from diffuse sources over agricultural land in sub-basin j (kton in 2050).
$\boldsymbol{RS_{pnt.F.o.j}}$ is the input of nutrient form (F: DIN, DON, DIP, DOP) to rivers from point sources in sub-basin j (kton in 2050).
$\boldsymbol{{}^{GO}RS_{F.other.o.j}}$ is the input of nutrient form (F: DIN, DON, DIP, DOP) to rivers from other sources in sub-basin j in GO (kton in 2050, Figure B.5).
$\boldsymbol{{}^{GO}FE_{riv.F.outlet.j}}$ is the fraction of nutrient form (F: DIN, DON, DIP, DOP) in rivers reaching the outlet of sub-basin j in GO (0-1, 2050, Figure B.6).
$\boldsymbol{{}^{GO}FE_{riv.F.mouth.j}}$ is the fraction of nutrient form (F: DIN, DON, DIP, DOP) reaching the river mouth from sub-basin j in GO (0-1, 2050, Figure B.6).
$\boldsymbol{WS_{dif.total.opt.E.j}}$ is the total input of element (E: N or P) to agricultural land in sub-basin j (kton in 2050). The total input of N and/or P to agricultural land is the sum of N and/or P inputs to land from synthetic fertilizers (optimized), recycled manure (optimized), human waste (Table B.1 according to GO), atmospheric N deposition (Figure B.1 according to GO) and biological N_2 fixation by crops (Figure B.1 according to GO).
$\boldsymbol{{}^{GO}WS_{dif.total.E.j}}$ is the total input of element (E: N or P) to agricultural land in sub-basin j in GO (kton in 2050, Table B.1).
$\boldsymbol{{}^{GO}WS_{dif.export.E.j}}$ is the export of element (E: N or P) from agricultural land via crop harvesting and animal grazing in GO (kton in 2050, Figure B.2).
$\boldsymbol{{}^{GO}WS_{dif.E.others.j}}$ is the input of element (E: N or P) to agricultural land from other diffuse sources in GO (kton in 2050, Figure B.1).
$\boldsymbol{{}^{GO}FE_{ws.F.j}}$ is the export fraction of N or P that is exported to rivers from diffuse sources as form (F: DIN, DON, DIP, DOP) in sub-basin j in GO (0-1, 2050, Figure B.4). $\boldsymbol{CF_{dif.E.o}}$ is a factor for calculating content of element (E: N or P) in a diffuse-source input (e.g., manure, human waste) (kton/kton, Table B.2).
$\boldsymbol{CF_{pnt.E.o}}$ is a factor for calculating content of element (E: N or P) in a point-source input (e.g., manure, human waste) (kton/kton, Table B.2).
$\boldsymbol{{}^{GO}NUE_{E.j}}$ is the nutrient use efficiency of the agricultural system for element (E: N or P) in sub-basin j in GO (0-1, 2050, Figure B.3).
$\boldsymbol{RE_{pnt.E.o.j}}$ is the removal efficiencies of element (E: N or P) during treatment in sub-basin j (0-1, 2050, Table 1).
$\boldsymbol{{}^{GO}FE_{pnt.F.o}}$ is the export fraction of element (E: N or P) that enters rivers after treatment as form (F: DIN, DON, DIP, DOP) (0-1, 2050 Table B.4).

Table 1
Management options, their removal efficiencies for nitrogen (N) and phosphorus (P), and costs to reduce river export of nutrients from diffuse and point sources in 2050. The values of removal efficiencies and costs are the estimates with possible ranges between parenthesis. More details on these estimates are provided in Appendix B (Table B.4).

$X_{dif.o.j}$ $X_{pnt.0.j}$	Used in Box 1	Management options (o)	N removal efficiency* (%, $RE_{pnt.E.o.j}$ in eq. 9 of Box 1)	P removal efficiency* (%, $RE_{pnt.E.o.j}$ in eq. 9 of Box 1)	Costs* ($C_{dif.o}$ and $C_{pnt.o}$in eq. 1 of Box 1)	
					Costs	Unit
Options for diffuse sources: $X_{dif.o.j}$ in eq. 1 of Box 1 (see also Figure B.7)						
1	$X_{dif.o1.j}$	Apply synthetic N fertilizer	–	–	350 (90–600)	10^3 \$/kton of synthetic N fertilizer
2	$X_{dif.o2.j}$	Apply synthetic P fertilizers	–	–	1100 (950–1300)	10^3 \$/kton of synthetic P fertilizer
3	$X_{dif.o3.j}$	Recycle manure as slurry**	–	–	18 (3–33)	10^3 \$/kton of animal manure
4	$X_{dif.o4.j}$	Recycle manure as solid**	–	–	23 (8–38)	10^3 \$/kton of animal manure
Options for point sources: $X_{pnt.o.j}$ in eq. 1 of Box 1 (see also Figure B.7)						
1	$X_{pnt.o1.j}$	Treat manure with primary technologies	10 (< 20)	35 (< 50 or < 20)	5 (2–8)	10^3 \$/kton of animal manure
2	$X_{pnt.o2.j}$	Treat manure with secondary technologies	60 (50–70)	90 (80–99)	7 (5–8)	10^3 \$/kton of animal manure
3	$X_{pnt.o3.j}$	Treat manure with tertiary technologies	90 (80–99)	90 (80–99)	12 (8–16)	10^3 \$/kton of animal manure
4	$X_{pnt.o4.j}$	Discharge manure to rivers (untreated)	0	0	0	10^3 \$/kton of animal manure
5	$X_{pnt.o5.j}$	Treat human waste with primary technologies	23 (20–25)	29 (28–30)	1.09 (1.01–1.17)	10^3 \$/kton of human waste
6	$X_{pnt.o6.j}$	Treat human waste with secondary technologies	41 (36–45)	71 (51–90)	1.17 (0.97–1.27)	10^3 \$/kton of human waste
7	$X_{pnt.o7.j}$	Treat human waste with tertiary technologies	72 (45–99)	91 (83–99)	1.56 (1.34–1.78)	10^3 \$/kton of human waste
8	$X_{pnt.o8.j}$	Discharge human waste to rivers (untreated)	0	0	0	10^3 \$/kton of human waste

*In Box 1, the average numbers are used for the sub-basins of the Yangtze from this table. Exceptions are the Dongting and Poyang sub-basins (see Figure A.1 for the locations). For these sub-basins, the maximum removal efficiencies of the tertiary treatment (99 % for N and P) for human waste are used. Details on cost estimation methods are provided in Tables B.4-B.9. Costs for recycling manure consider annual costs for separation (only for solid manure), transportation and application. Sources of the costs are in Appendix B (Tables B.4-B.9). **Excluding avoided costs of synthetic fertilizers.



Environmental targets for TDN and TDP export by Yangtze (kton)

Gap closure of X% (cases)	TDN	TDP
0%	1916	211
10%	1784	195
20%	1653	180
30%	1521	164
40%	1390	149
50%	1258	133
60%	1126	117
70%	995	102
80%	863	86
90%	732	71
100%	600	55

Fig. 1. Illustration of how environmental targets for the optimization are derived. Environmental targets reflect gap closures of X% (cases). TDN and TDP are the total dissolved nitrogen and phosphorus, respectively. A gap closure of 0% equals the baseline level for TDN and TDP export by the Yangtze in 2050 according to GO (see Section 2). GO is the scenario of the Millennium Ecosystem Assessment from the MARINA model (Strokal et al., 2016). A gap closure of 100% equals the desirable level for TDN and TDP export by the Yangtze (details are in Appendix A, Text A.2).

treatment is assumed to not improve much between 2000 and 2050. Nutrient management in agriculture will remain as in 2000 resulting in large discharges of manure to rivers and over-fertilization of cropland. GO, thus, reflects a worst-case scenario for environmental management, but follows socio-economic trends that reflect recent developments in China.

2.2.2. Cost-optimization

A modelling approach is developed that integrates MARINA 1.0 and a cost-optimization procedure using the General Algebraic Modeling System (GAMS). The cost-optimization procedure is adjusted to river export of N and P by source from sub-basins (Box 1). It includes two main components: the objective function and constraints.

The objective function of the optimization minimizes the total costs of management options in 2050 (C, $) for diffuse and point sources in sub-basins to reach environmental targets for river export of total dissolved N (TDN = DIN + DON) and total dissolved P (TDP: DIP + DOP) simultaneously at the river mouth (Box 1). Diffuse and point sources are included in Table 1. Management options for these sources are explained in Section 2.4.

Several constraints are considered in the optimization including predefined environmental targets (eq.2–3, Section 2.4), river export of DIN, DIP, DON and DOP from sub-basins and sources, nutrient use efficiencies (NUEs) in agriculture (eq. 4–9), and nutrient management options (eq.10–11, Section 2.3). Environmental targets are explained in Section 2.4. River export of DIN, DIP, DON and DOP is quantified using the equations of MARINA 1.0 (eq. 4–9 in Box 1). This is done for sub-basins and sources (see Appendix A, B.1-B.7). Nutrient use efficiencies (NUEs) are also quantified using the MARINA modelling approach: the N and P export from land via crop harvesting and grazing divided by the total N and P inputs to land (synthetic fertilizers, animal manure, atmospheric N deposition and biological N_2 fixation), respectively. Details on the ability of the integrated model to reproduce river export of N and P according to practices in the baseline and uncertainties are in Fig. B.8, Section 4 and Appendix C.

2.3. Management options

Management options are identified for diffuse and point sources to reduce river export of TDN and TDP from sub-basins (Table 1). Management options for diffuse sources include the possibility to reduce the application of N and P synthetic fertilizers and recycling of manure N and P in cropland as organic fertilizer or soil amendment. Costs of using synthetic fertilizers and recycling of manure on cropland depend on many factors such as farm size, distance to manure storage, fertilizer type, application techniques (e.g., surface spreading, injection), the operational cost of machinery, and labor cost (Huijsmans et al., 2004; Jie et al., 2017). In our study, the costs are estimated using available literature in combination with expert knowledge (details in Tables B.4-B.9 in the Appendix).

Management options for point sources include treatment of manure and human waste with primary, secondary and tertiary technologies that reduce direct discharges of untreated manure and human waste to rivers (Table 1). N and P removal efficiencies for treatment technologies are largely based on the literature (e.g., Foged et al., 2012; Jaffer et al., 2002; Jie et al., 2017; Qiao et al., 2010; Tervahauta et al., 2014; van Puijenbroek et al., 2019) (Tables B.4-B.9). The treatment costs of manure and human waste depend on technology type, and labor, land and energy costs (e.g., Gonzalez-Serrano et al., 2005). The available literature with expert knowledge is combined to derive the costs of treatment of manure and human wastes for the Yangtze (Tables 1, B.4-B.9). Costs of direct discharges of untreated manure and human waste were assumed to be zero.

2.4. Environmental targets and scenarios

Environmental targets are quantified for river export of TDN and TDP based on the “Gap closure” approach (Amann et al., 2011) (Fig. 1). This approach has been accepted by science and policy for air pollutants and can reflect different levels of policy efforts to reduce pollution (e.g., https://www.iiasa.ac.at). The “Gap closure” approach is applied for water pollution in this study. The gap is defined as the difference between baseline and desirable levels of river export of nutrients. A gap closure is defined as the percentage reduction of this gap. A gap closure can theoretically range from 0 to 100%. A gap closure of 0% indicates that no efforts are made to reduce river export of TDN and TDP in 2050 (i.e., river export remains as in the baseline). A gap closure of 100% indicates that efforts are made to reduce river export of TDN and TDP in 2050 to fully achieve the desirable level. The baseline for nutrient export by the Yangtze (i.e., 0% gap closure) is from the GO scenario of MARINA 1.0 (Strokal et al., 2017). The desired nutrient export by the Yangtze (i.e., 100% gap closure) reflects the level of nutrients with low potentials for coastal eutrophication. The desirable nutrient export by the Yangtze is derived based on the Indicator for Coastal Eutrophication Potential (ICEP) (Garnier et al., 2010) (details are in Appendix A, Text A.2).

Optimization analyses were performed for two scenarios with cases for environmental targets. Both scenarios have baselines. The baseline

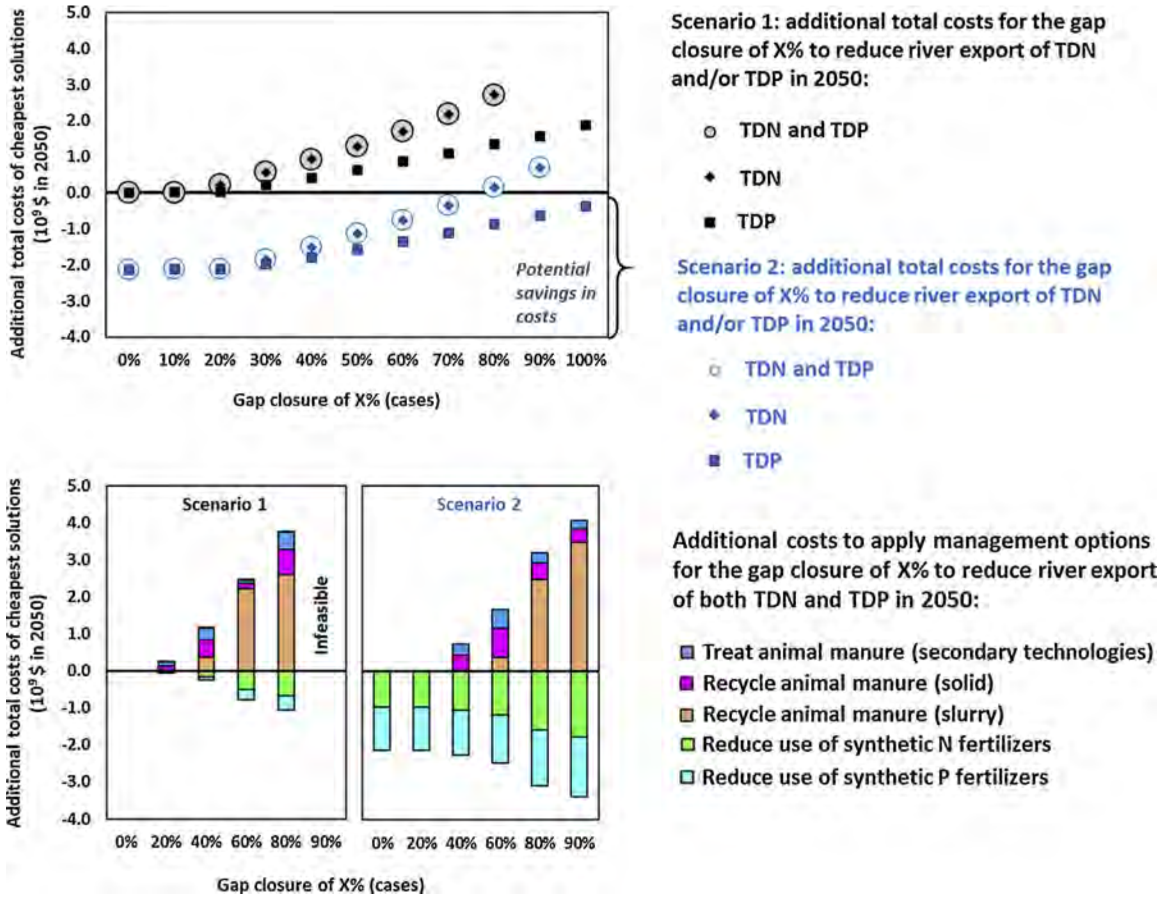


Fig. 2. Costs of closing the gap between baseline and desirable river export of total dissolved nitrogen (TDN) and/or total dissolved phosphorus (TDP) by the Yangtze River (10^9 $ in 2050). Results are shown for cases that have different environmental targets for Scenarios 1 and 2. Costs of management options for human waste are lower than for manure and are shown in Tables D.1-D.2. A 0% gap closure reflects the baseline in Scenarios 1 and 2. The baseline of Scenario 1 is based on the GO projections. The baseline of Scenario 2 assumes improved nutrient use efficiencies relative to GO through a 30% reduction in the synthetic fertilizer use in each sub-basin. See Section 2.4 for descriptions of the scenarios and the gap closure approach.

of Scenario 1 is based on GO (Section 2.2). The baseline of Scenario 2 assumes improved NUEs relative to GO through a 30% reduction in the synthetic fertilizer use in each sub-basin (Fig. B.3). This reduction in the synthetic fertilizer use is assumed to avoid over-fertilization without reducing crop yield (Cui et al., 2018; Ju et al., 2009; Kahrl et al., 2010; Zhang et al., 2013). The two scenarios are developed to better understand the implication of improving NUEs on reducing future nutrient pollution and identifying the cost-effective options. The integrated model is run for the cases with different environmental targets for river export of TDN and TDP under Scenarios 1 and 2. In our analysis, a focus is largely on simultaneous reduction in both TDN and TDP river exports from sub-basins (Section 3, Figs. 2–4). In addition, the integrated model is run separately with environmental targets for TDN or TDP (Fig. 1, Fig. D.1).

3. Results

3.1. Nutrient export by the Yangtze in the baseline (gap closure of 0%)

The Yangtze is projected to export around 1916 kton of TDN and 211 kton of TDP to coastal waters in 2050 under Scenario 1 (Figs. 1,3). Around half of TDN is DIN and two-thirds of TDP is DOP (Fig. 3). This is the net effect of socio-economic development, human activities, and nutrient retentions on land and in rivers (Appendix B and D). In Scenario 2, the river export of TDN (1808 kton) and TDP (206 kton) is somewhat lower than in Scenario 1 (Fig. 3). This is associated with reduced use of synthetic fertilizers on land by 30% in Scenario 2 (Table 2). As a result, less N and P enter rivers from synthetic fertilizers, resulting in lower river export. This holds especially for river export of DIN because synthetic fertilizers are important sources of DIN in rivers. Synthetic fertilizers have a dominant share in diffuse sources from agricultural areas. Diffuse sources include recycled animal manure, synthetic fertilizers, atmospheric N deposition, and biological N_2 fixation (Fig. 3, Table 2). These diffuse sources are projected to contribute around half of DIN and less than one-third of DIP export by the Yangtze in Scenarios 1 and 2 (Fig. 3). Animal manure (untreated) as a point source is projected to contribute to over half of DIP and two-thirds of DON and DOP export by the Yangtze (details on the baseline in (Strokal et al., 2017, Table B.1).

3.2. Cost-effectiveness analysis for the Yangtze basin

Figs. 2 and 3 show the costs of the gap closure of X% and the associated river export of nutrients for the cases in scenarios 1 and 2. Our analysis focuses especially on the gap closure of 20%, 40%, 60%, 80% and 90% for both TDN and TDP (see Fig. D.1 for the gap closure of individual nutrients).

Results show that it is possible to close the gap by up to 80% in a cost-effective way for river export of both TDN and TDP in Scenario 1 (Figs. 2 and 3). However, a gap closure of 100% is challenging, especially, for TDN because of the large contribution of diffuse sources. In general, river export of TDN and TDP decreases whereas the additional cost (on top of the baseline) increases with increasing gap closure. For example, closing the gap by 80% results in a reduction of river export of

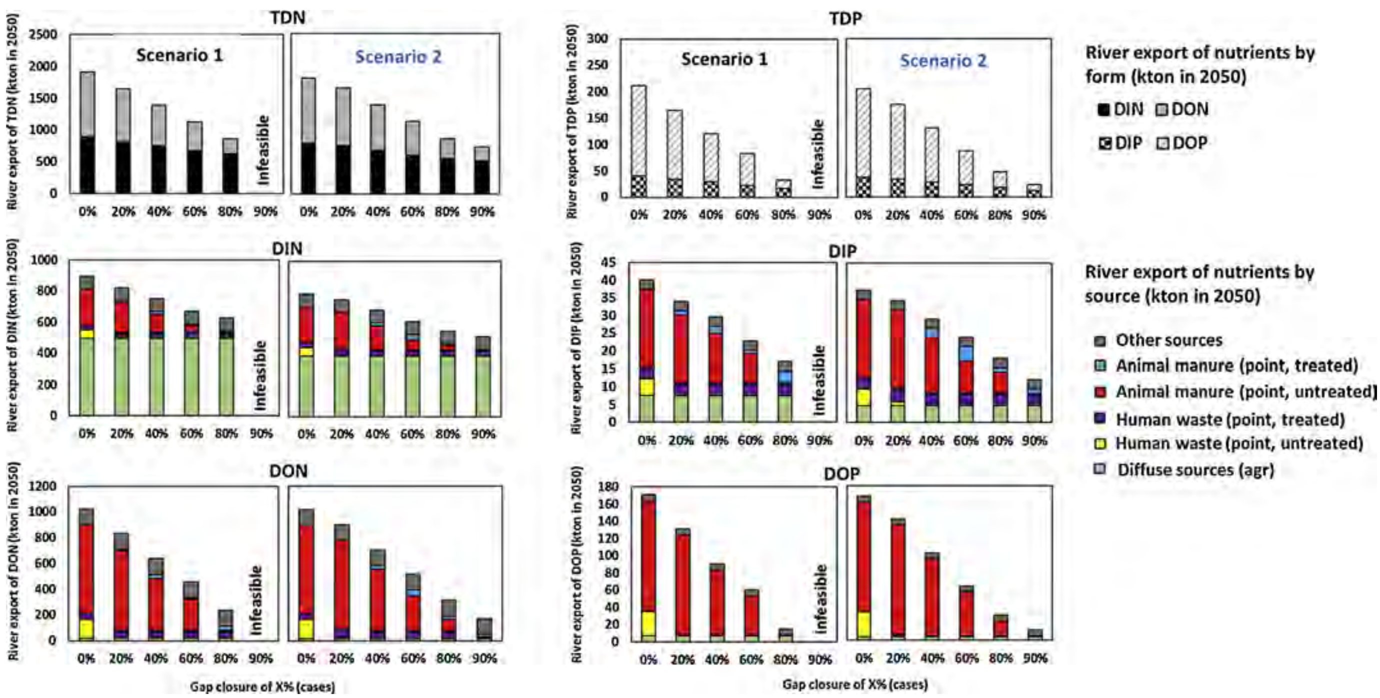


Fig. 3. River export of nutrients by form and source from the Yangtze basin in 2050 (kton) for the cases on gap closures by 0-100% in Scenarios 1 and 2. A 0% gap closure reflects the baseline in Scenarios 1 and 2. TDN and TDP are total dissolved nitrogen and phosphorus, respectively. DIN and DIP are dissolved inorganic N and P, respectively. DON and DOP are dissolved organic N and P, respectively. Other sources include leaching of organic matter (DON, DOP), weathering of P-contained minerals (DIP), detergents (DOP, DIP), atmospheric N deposition over non-agricultural areas (DIN) and biological N_2 fixation by natural vegetation (DIN). "arg" refers to agricultural areas. See Section 2 on the description of the model, scenarios and the gap closure approach.

TDN by 55% and TDP by 85% compared to the baseline (gap closure of 0%) in Scenario 1 (Fig. 3). These reductions are 30% for DIN, 77% for DON, 57% for DIP and 91% for DOP. The associated total cost is around 3 billion $ (Fig. 2). Most of the costs are for manure recycling on land (dominant share) and treatment with secondary technologies (Fig. 2, Table 2). Additional costs are also needed for the treatment of human waste with secondary and/or tertiary technologies (Fig. D.6, Tables D.1-D.2). Direct discharges of animal manure and human waste (untreated) to rivers will be avoided and the use of synthetic fertilizers will be reduced to close the gap by 80% (Table 2, Figs. 2 and 3).

Closing the gap by 90% is possible in a cost-effective way for river export of both TDN and TDP only in Scenario 2 (Figs. 2 and 3). This requires a further reduction in the use of synthetic fertilizers and recycling more animal manure on land (Table 2 and Fig. 2). For example, the total cost is negative in the baseline (gap closure of 0%) and becomes positive (up to 1 billion $ in 2050) for a gap closure of 90% in Scenario 2 (Fig. 2). The negative cost indicates the potential savings that are realized through reductions in the use of synthetic fertilizers due to improved NUEs in Scenario 2 (Table 2, Fig. 2). These savings provide an opportunity to invest in manure recycling and treatment to close the gap by 90%. However, river export of TDP is somewhat higher in cases of Scenario 2 than in cases of Scenario 1, except for a gap closure of 0% (Fig. 3). This is because of higher river export of DOP originating from relatively larger manure discharges to rivers in Scenario 2. This is associated with the fact that manure discharges are more important sources of DON than of DIN in rivers. River export of TDN is similar in both scenarios. This is the net effect of lower river export of DIN (less use of synthetic fertilizers) and higher river export of DON (more manure discharges) in Scenario 2 compared to Scenario 1 (Fig. 3, Table 2).

Results also show that closing the gap for one nutrient may also reduce the losses of the other nutrient without incurring additional costs (Fig. D.1). This is because management options have an impact on manure and human waste that contain both nutrients, affecting simultaneously the flows of TDN and TDP from land to sea (Table 1). However, reducing river export of TDN may largely reduce river export of TDP. For instance, closing the gap by X% for river export of TDN reduces largely river export of TDP, while closing the same gap level for river export of TDP reduces only slightly river export of TDN (Fig. D.1). This is because the amount of TDP is lower than of TDN. TDP in rivers originates mainly from point sources that are easier to control. This explains why reducing TDP is generally easier and its cost is lower than for TDN in both scenarios (Figs. 2 and 3).

3.3. Cost-effectiveness analysis for the sub-basins

According to the baseline in Scenario 1 (gap closure of 0%), around two-thirds of TDN and TDP at the Yangtze mouth are projected to originate from middle- and downstream sub-basins (Fig. 4 for locations, Fig. 5 and Figs. D.2-D.10). This implies that reducing nutrient pollution in the coastal waters preferably requires further efforts in those sub-basins. This holds especially for Poyang (number 8), Dongting (middle-stream, number 6) and Delta (downstream, number 10) sub-basins. These three sub-basins are projected to export up to 70% of DIN (603 kton/year), DON (394 kton/year), DIP (24 kton/year) and DOP (66 kton/year) to the Yangtze River mouth in 2050 in the baseline of Scenario 1 (Table B.1, Figs. D.2-D.10). These loads are the net effect of intensive human activities (agriculture and urbanization) and retentions of nutrients on land and in rivers. For example, nutrients from downstream activities discharge directly to coastal waters. However, nutrients from upstream activities are exported longer distances towards coastal waters. During river transport, nutrients can be retained due to damming and lost due to denitrification processes (Tables B.1, Figs. B.1-B.6, D.2-D.5).

Cost-effective management options for the gap closure of X% differ among sub-basins and scenarios (Figs. 4–5). For example, it is possible to close the gap by 40% (Fig. 4) and 60% (Fig. D.6) at zero or negative costs for most sub-basins in Scenario 2. This is because the assumed reductions in the use of synthetic fertilizers in Scenario 2 compensate the costs of implementing other options. Closing the gap by 80% results

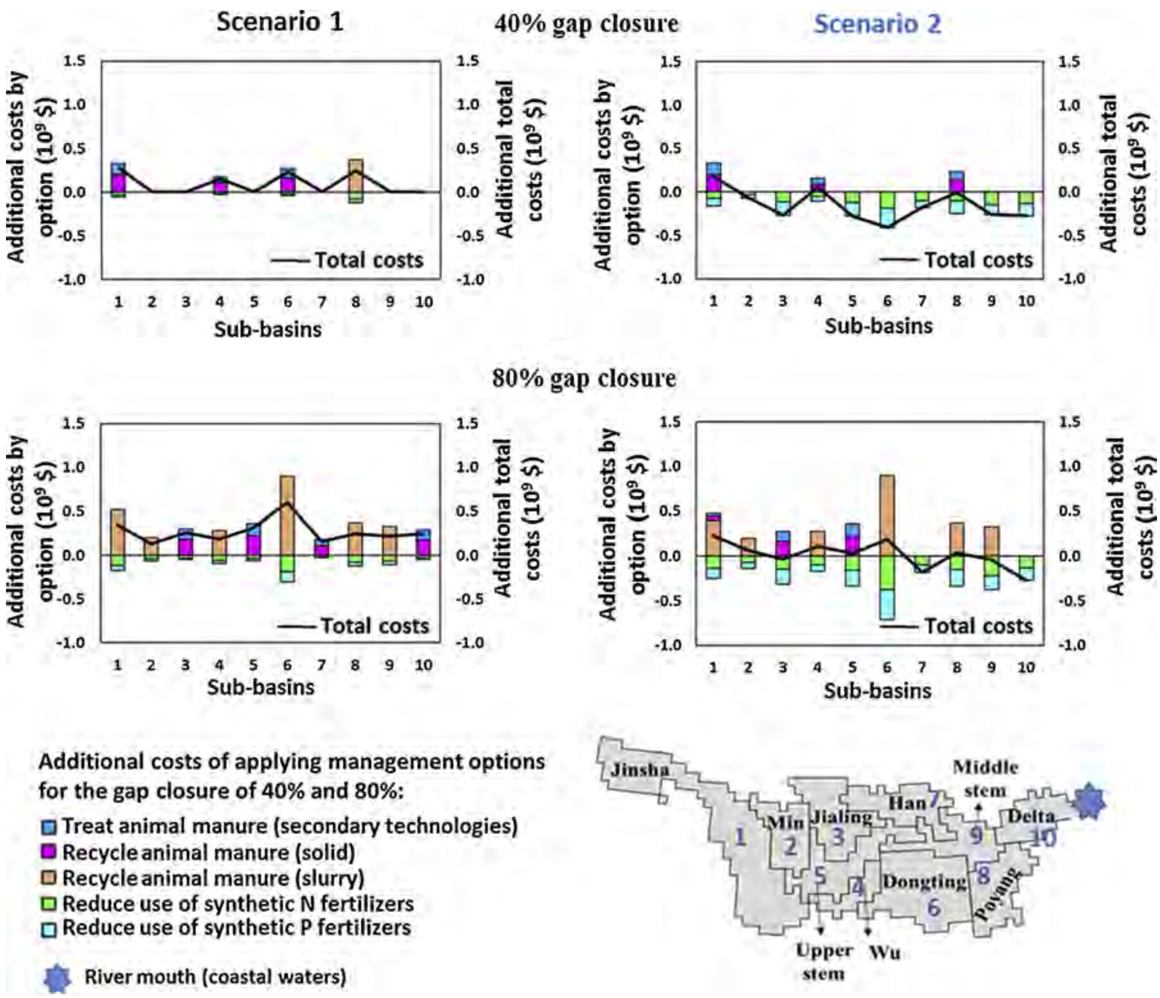


Fig. 4. Costs of applying management options in sub-basins of the Yangtze River for the gap closure by 40% and 80% in Scenarios 1 and 2 in 2050 (10^9 \$). See Section 2 for the description of the model, scenarios and the gap closure approach. See Figures D.2-D.7 and Tables D.1-D.2 for the results for gap closures by 20%, 60% and 90%.

in higher reductions in river export of DIP, DOP and DON from most sub-basins relative to the gap closure of 0% in both scenarios (Figs. 4–5). In contrast, Han (middlestream, number 7) and Delta (downstream, number 10) sub-basins have generally lower reductions for their nutrient forms (Fig. 5). This is associated with the fact that direct manure discharges in those sub-basins may still happen even in Scenario 2, but not in large quantities (details are in Figs. D.7-4.10). The total net costs for these two sub-basins are also lower in Scenario 2 (Fig. 4, D.6). Overall, results indicate that reducing river export of DIN is more difficult because of the large contribution of diffuse sources.

Closing the gap by 80–90% requires investments in manure recycling on cropland as slurry for most sub-basins in the two scenarios (Figs. 4–5 and D.6). Exceptions are the Upper stem (upstream, number 5), Jianling (upstream, number 3), Han (middlestream, number 7 in Scenario 1) and Delta (downstream, number 10 in Scenario 1) sub-basins (Fig. 4). In these sub-basins, investments are needed in manure application as solid manure (after solid-liquid separation) and in treatment of the liquid fractions (secondary technologies). However, these sub-basins could gain savings from reduced synthetic fertilizer use (Fig. 4, details are in Figures D.2-D.6). In general, Dongting sub-basin (middlestream, number 6) has the largest share in the total costs of closing the gap by 60–90% in the scenarios (Figs. 4, D.6). This is because human activities in this sub-basin contribute largely to nutrient pollution at the river mouth (Figs. 5, Appendix D).

4. Discussion

4.1. Policy implications

Our results show that manure recycling to cropland is an effective strategy to substantially reduce coastal eutrophication. Manure has the potential to improve soil quality (Bai et al., 2018b; Melse et al., 2017) and its recycling is suggested as an important policy intervention to reduce water pollution (Khan and Chang, 2018; Ma et al., 2019; MOA, 2015, 2018). Reducing the use of synthetic fertilizers by recycling manure is also highlighted in the recent policy documents such as "Zero Growth in Synthetic Fertilizer Use after 2020". We show that reducing the use of synthetic fertilizers in the Yangtze basin saves costs for investing in manure recycling (see Fig. 2). For example, around 2 billion \$ can be saved when reducing 30% of synthetic fertilizers (see Fig. 2, the difference between the two baselines). In general, controlling point source pollution from urban waste is more feasible because of investments in wastewater treatment plants. However, reducing agricultural diffuse pollution is rather challenging because of nutrient release from land.

Using manure more effectively, to replace synthetic fertilizer, would require adequate incentives to farmers (e.g., manure subsidies or taxes on synthetic fertilizers, (Dalgaard et al., 2014)). Better education is also important through, for example, the Science Technology Backyards in which scientists, students and farmers share their knowledge (Jiao et al., 2016). Livestock farmers can facilitate recycling of manure on

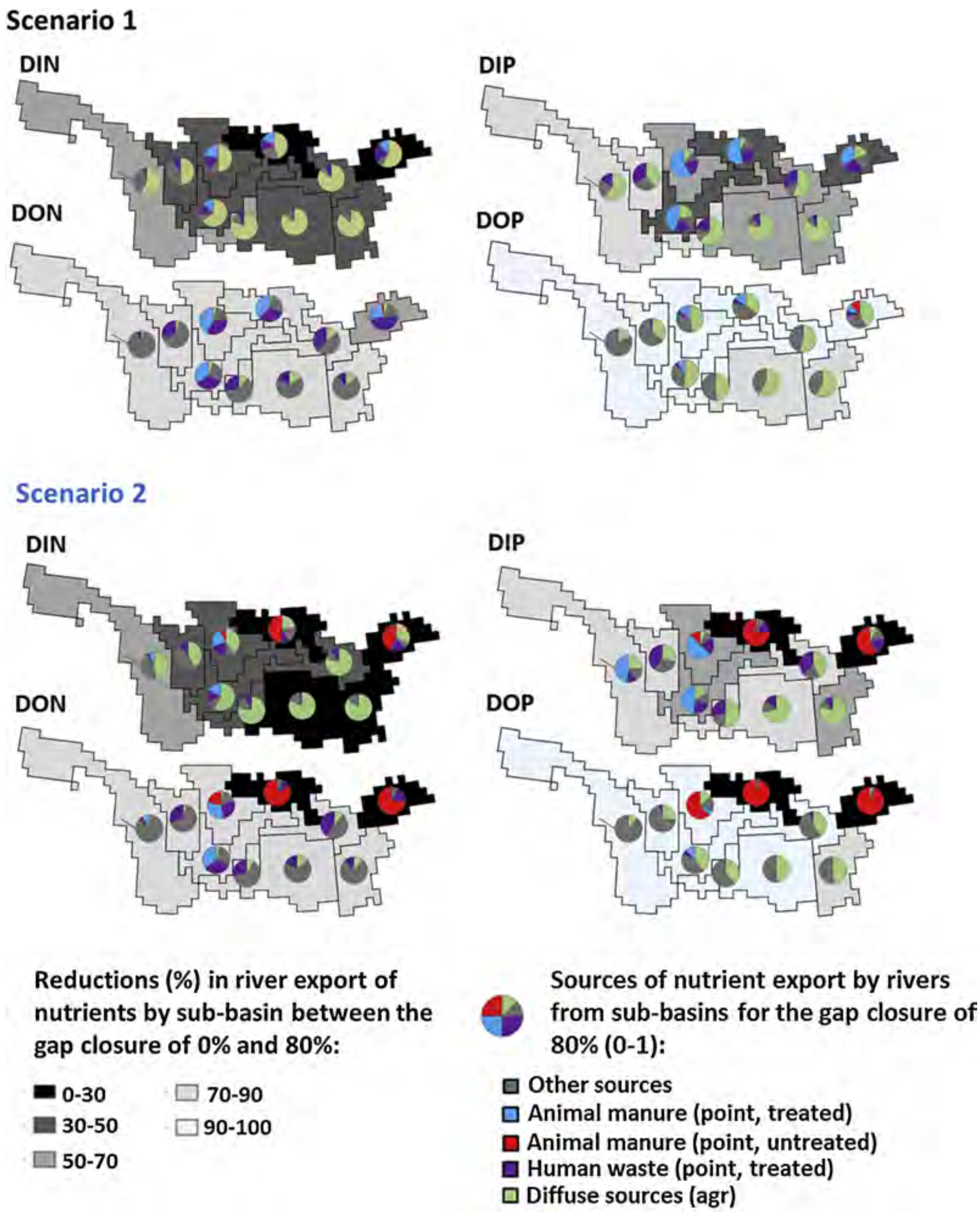


Fig. 5. Reductions in river export of nutrients from sub-basins as a result of a gap closure of 80% (% reduction relative to a gap closure of 0%) and the sources of river export of nutrients in 2050 in the case with a gap closure of 80% (0–1). A 0% gap closure reflects the baseline in Scenarios 1 and 2. DIN and DIP are dissolved inorganic N and P, respectively. DON and DOP are dissolved organic N and P, respectively. Other sources include leaching of organic matter (DON, DOP), weathering of P-contained minerals (DIP), detergents (DOP, DIP), atmospheric N deposition over non-agricultural areas (DIN) and biological N_2 fixation by natural vegetation (DIN). "agr" refers to agricultural areas. Fig. 4 provides names of the sub-basins. See Section 2 for the description of the model, baselines and the gap closure approach. See Figures D.2-D.7 and Tables D.1-D.2 for the results for gap closures of 20%, 40%, 60% and 90%.

land through the cooperation with arable farmers. Implementation of technologies like composting could make the use of manure more attractive for arable farmers (Bai et al., 2018a, 2018b). More initiatives are also needed to facilitate the implementation of best available technologies to treat wastewater. Scientists can develop demonstration sites to increase the awareness about available technologies for local government to implement them. Overall, implementing cost-effective management options requires an effective deployment and uptake of technologies by the different stakeholders and their active cooperation.

4.2. Comparison with other studies

Our study shows that the costs of reducing coastal eutrophication caused by the Yangtze in 2050 amount to 1–3 billion $ (range for the cases of Scenarios 1 and 2). These are the costs of a gap closure of 80–90 % in river export of both TDN and TDP (Figs. 2, D.1-D.10, Tables D.1-D.2). Few studies estimated costs for reducing nutrient export by rivers (Gren et al., 1997), but not for the sub-basins of the Yangtze. Several studies are conducted for Lake Taihu (Le et al., 2010; Peng et al., 2018; Yang and Liu, 2010), which is located in a downstream sub-basin of the Yangtze. Those studies indicate economic losses due to lake eutrophication of 6.5 billion $ in 1998 (Le et al., 2010). They estimated the investment cost of halving total P loads to the lake of around 80 million $ (Peng et al., 2018). Our cost estimates are higher than for Lake Taihu because we consider the entire Yangtze basin. One of our findings is that the cost for reducing river export of N is generally higher than for P. This is consistent with the results of previous studies for the Baltic Sea (Gren et al., 1997) (more details are in Appendix C).

4.3. Novelties

Our study is novel in three main aspects. First, a novel modelling approach integrates substance flow analysis (i.e., river export of nutrients with MARINA 1.0) and cost-optimization while accounting for the socio-economic drivers, land use, and hydrology at the sub-basin scale. Second, our modelling approach accounts for multiple nutrients, which is limited in the current literature (see Section 1). A multi-pollutant focus helps to identify synergies and trade-offs in management options and thus supports the search of optimal solutions. For example, reducing DIN and DON in rivers from manure results in reductions of DIP and DOP (synergy), because of the large contribution of manure to river pollution. Manure recycling reduces point-source inputs of DIN, DON, DIP and DOP, but may increase diffuse-source inputs of these nutrients to rivers (trade-off). Third, the "Gap closure" approach is applied to reduce water pollution. The approach is rather elegant and enables to provide policy-makers with the combinations of cost-effective options to reach environmental targets at different ambition levels: from 0% to 100% reduction in pollution.

4.4. Limitations

The application of our modelling approach is subject to uncertainties associated with simplifications made when preparing model inputs (see Appendix C on uncertainty analysis). Examples are cost estimates. Averaged values are used for the Yangtze basin that are within the range of the existing studies (Tables B.4). A sensitivity analysis is conducted to assess the robustness of the results to different cost estimates. This analysis shows that the main messages of this study remain the same (Appendix C, Tables C.1-C.2). Another limitation is related to the "Gap closure" approach and the selection of management options. The "Gap closure" approach needs desirable (environmental) levels. In our study, ICEP is used to derive the desirable levels for river export of nutrients. Such levels are averaged, but may differ in space and among ecosystems. Our management options can be further divided into more specific technologies such as injections, and types of manure (Bai et al., 2016; Foged et al., 2012; Ma et al., 2019) and human waste treatment (e.g., Foged et al., 2012; Jie et al., 2017; Qiao et al., 2010; Tervahauta et al., 2014; van Puijenbroek et al., 2019). We, however, believe that our management options are relevant for the Yangtze based on the sources of river pollution (Strokal et al., 2017; Wang et al., 2018). In Scenario 2, an optimistic assumption is made to improve NUEs through a 30% reduction in the use of synthetic fertilizers at zero cost (Cui et al., 2018; Ju et al., 2009; Zhang et al., 2013). Despite these limitations, our modelling approach generates useful insights for policy-makers to reduce coastal eutrophication. It provides an opportunity to include more pollutants (Font et al., 2019; Ippolito et al., 2015; van Wijnen et al., 2017) and management options.

5. Conclusions

Our study indicates that closing the gap in river export of both TDN and TDP by 80–90 % is economically feasible. Thus, it is possible to reduce coastal eutrophication at the Yangtze river mouth in 2050. The combination of cost-effective management options differs among the sub-basins of the Yangtze and are largely associated with reductions in the use of synthetic fertilizer, increased manure recycling, and wastewater treatment. The identified cost-effective options can help to meet the Sustainable Development Goals (Ma et al., 2019). Our study can support policy-makers for water pollution control in China and serves as an example for other rivers to identify cost-effective solutions.

Author contribution section

MS and CK initiated an idea to integrate cost-optimization with the MARINA model (version 1.0). MS developed the MARINA model (version 1.0) for China. CK, ZB, LM and OO co-developed this model. TK and MS developed a cost-optimization approach that is used in this study. MS and TK tool a lead in integrating the MARINA model with the cost-optimization approach. MS is the main corresponding author. TK is the second corresponding author. MS took a lead in coordinating, designing and analysing the manuscript and its Appendices. TK, CK, XZ, FW, YW, SL, and TE substantially assisted in developing and supported an idea how to integrate the MARINA model with the cost-optimization approach. TK, JA, OO, ZB, LM helped largely with getting the data for the manuscript. All authors contributed to development of the scenarios. All authors substantially assisted in analysing the results and writing the manuscript. All authors read and commented on the text.

Declaration of Competing Interest

The authors declair no conflict of interst

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The authors declare no competing financial interest.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.resconrec.2019.104635.

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