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Reducing river export of nutrients and eutrophication in Lake Dianchi in the future

Chuan Ma[a], Maryna Strokal[a], Carolien Kroeze[a], Mengru Wang[a], Xiaolin Li[b], Nynke Hofstra[c] and Lin Ma[d,*]

[a] Water Systems and Global Change Group, Wageningen University & Research, P.O. Box 47, 6700 AA, Wageningen, The Netherlands

[b] Southwest Forestry University, College of Ecology and Soil & Water Conservation, Kunming, China

[c] Environmental Systems Analysis Group, Wageningen University & Research, P.O. Box 47, 6700 AA, Wageningen, The Netherlands

[d] Key Laboratory of Agricultural Water Resources, Center for Agricultural Resources Research, Institute of Genetic and Developmental Biology, The Chinese Academy of Sciences, 286 Huaizhong Road, Shijiazhuang 050021, Hebei, China

*Corresponding author. E-mail: malin1979@ms.sjziam.ac.cn

Abstract

Lake Dianchi is severely polluted with nitrogen (N) and phosphorus (P). The effects of implementing environmental policies and technologies on future lake quality are not well understood. We analyse effects of environmental policies and technologies on future river export of nutrients into Lake Dianchi. We develop scenarios for 2050 and analyse these with the existing MARINA-Lakes model (Model to Assess River Inputs of Nutrient to lAkes). The scenarios differ in assumptions about future nutrient management in agriculture, sewage systems and mining. In the *SSP3* (Shared Socio-economic Pathway 3) scenario, river export of nutrients to Lake Dianchi is projected to increase 1.4–4.4 times between 2012 and 2050. In the *Current Policies* scenario, rivers may export fewer nutrients than in *SSP3*, but this may not avoid eutrophication. Effects of improved nutrient management on river export of nutrients differ among nutrient forms, sub-basins and sources (e.g., urbanization in the north, agriculture in the middle and south). Pollution levels can be reduced below the 2012 level in an *Optimistic* scenario assuming advanced wastewater treatment, improved nutrient management in agriculture and no mining. However, even this may not completely prevent eutrophication. Preventing eutrophication requires even more efforts, for example, in implementing circular-oriented management options.

Key words: eutrophication, Lake Dianchi, MARINA-Lakes model, scenarios

INTRODUCTION

Lake Dianchi is located in Yunnan province, China. Lake Dianchi is the sixth largest lake in China and the largest freshwater lake in Yunnan. The lake is an important source of drinking water for many cities. Water from the lake is also used for industrial and agricultural activities (Gu *et al.* 2016). However, the water quality of the lake has been deteriorating since the 1970s (Liu & Qiu 2007). As a result, the lake has been suffering from serious eutrophication problems such as harmful algal blooms over the past years. Algal blooms happen frequently in this lake due to high concentrations of phosphorus (P) and nitrogen (N) (Tong *et al.* 2017).

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High concentrations of N and P in the lake are largely related to intensive human activities on land. These human activities include residential and industrial sewage, fertilizers usage in agriculture and P mining (Huang *et al.* 2014; Li *et al.* 2019). Rivers export these nutrients to Lake Dianchi. However, large amounts of nutrients stay in the lake because of the limited outflow from the lake. As a result, eutrophication in the lake has occurred (Huang *et al.* 2014; Zhou *et al.* 2014; Gao *et al.* 2015; Wang *et al.* 2016).

Many studies have been carried out for Lake Dianchi. They mainly focus on monitoring and modelling the current water quality status (Liu *et al.* 2004, 2009; Gao *et al.* 2014; Zhou *et al.* 2015). However, few studies exist on how river export of nutrients from sub-basins influence the water quality of the lake in the future. A study quantified river export of nutrients by source from sub-basins to Lake Dianchi for the year 2012 (Li *et al.* 2019). However, future trends in river export of nutrients are not well studied. In addition, the effects of implementing environmental policies and technologies on the lake quality in the future are not well understood.

The national and local government have introduced a number of policy documents to reduce the eutrophication problem of the lake. The lake is included in a national environmental project called 'Three rivers and three lakes' since 1996. National plans are published every five years. These plans set goals to improve the water quality of the lake to meet the national standard of Water quality for Surface Water (GB3838-2002) (Liu & Wang 2016). In 1999, a local policy 'Zero o'clock action' was published to control wastewater emissions from companies around the lake watershed (Zhang *et al.* 2014). Since 2006, projects such as wastewater collection and treatment, and sediments dredging have been introduced to improve the water quality of the lake. These projects amounted to about 2.8 billion USD (Liu & Wang 2016).

The Chinese government has already realized the importance of controlling nutrient inputs to water systems from agriculture. For example, in 2015, the Ministry of Agriculture published a policy 'Zero Growth in Fertilizer Use by 2020' to reduce over-fertilization of cropland and increase recycling of animal manure to replace fertilizers (MOA 2015). In 2018, Kunming City introduced a local policy 'The implementation plan of the three-year action on the protection and management of Lake Dianchi'. This plan is valid from 2018 to 2020. Approximately 2.05 billion USD is set to be invested in the plan. A better understanding of the effects of these environmental policies on the lake quality is still required.

Several models exist to quantify nutrient flows from land to rivers, seas and lakes in China (Lewis *et al.* 2007; Ma *et al.* 2010; Gao *et al.* 2014; Strokal *et al.* 2016). Water quality models exist with different spatial and temporal levels of detail (e.g., SWAT, SPARROW, IMAGE-GNM) (Parton *et al.* 1998; Beusen *et al.* 2015). The Global NEWS-2 model (Nutrient Export from WaterSheds) is an example that quantifies river export of N and P by source for over 6,000 rivers in the world (Mayorga *et al.* 2010; Seitzinger *et al.* 2010). Another example is the MARINA model (Model to Assess River Inputs of Nutrients to seAs), developed for China based on the modelling approaches of Global NEWS-2 (Strokal *et al.* 2016). The MARINA model quantifies past and future river export of nutrients at the sub-basins scale for large Chinese rivers. MARINA has been used for the future analysis of coastal eutrophication.

Recently, the MARINA-Lakes model has been implemented to Lake Dianchi for the year 2012 (Li *et al.* 2019). MARINA-Lakes has been used to better understand the impact of nutrient loadings on the lake in a spatially explicit way. This has been done for different nutrient forms: dissolved inorganic (DIN, DIP) and dissolved organic (DON, DOP) N and P. Results of the MARINA-Lakes model indicate that agriculture, urbanization and mining are important causes of the lake pollution with nutrients today. There is a need for future analyses to reduce this pollution.

The main objective of this study is to analyse the effects of environmental policies and technologies to reduce river export of nutrients to Lake Dianchi in 2050. To this end, we develop five scenarios and implement them into the MARINA-Lakes model for 2050. We analyse future trends in river export of nutrients by source from sub-basins to Lake Dianchi for the period of 2012–2050. Our analyses

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focus on river export of DIN (dissolved inorganic N), DIP (dissolved inorganic P), DON (dissolved organic N) and DOP (dissolved organic P).

METHODS

Study area

Lake Dianchi is located in southwest of China in Yunnan province. The lake is surrounded by highly urbanized areas, intensive agricultural and mining activities. The surface area of the lake is about 309 km^2, with 39 km of length and 13.5 km of width. The annual average depth of the lake is 4.9 m. The maximum depth is 10.1 m, and the volume of the lake is around 13.9 billion m^3 of water (Li *et al.* 2019). The watershed area of the lake comprises 15 sub-basins (Gao *et al.* 2014). These 15 sub-basins are used in the MARINA-Lakes model (see below). In this study, we define Panlong, Caohai, Daqing, Haihe, Baoxiang sub-basins as the northern sub-basins, Xian, Maliao, Luolong, Laoyu, Nanchong and Yuni sub-basins as the middle sub-basins, and Gucheng, Dongda, Cigang and Baiyu sub-basins as the southern sub-basins (Figure 1).

The MARINA-Lakes model

MARINA-Lakes quantifies annual river export of DIN, DIP, DON and DOP by source from 15 sub-basins to Lake Dianchi. This is done as a function of human activities on land taking into account sub-basin characteristics (e.g., land use, hydrology) and nutrient retentions in soils and rivers. Full explanations and equations are in Appendix A and Li *et al.* (2019).

The main equation of the MARINA-Lakes model is:

$$M_{F,y,j} = RS_{F.\mathrm{y,j}} \cdot FE_{riv.F.outlet.j} \cdot FE_{riv.F.mouth.j} \tag{1}$$

where,

F is the form of nutrients: dissolved inorganic (DIN, DIP) and dissolved organic (DON, DOP) nitrogen (N) and phosphorus (P).

$M_{F,y,j}$ is the annual river export of nutrient form F by source y from sub-basin j (kg/year).

$RS_{F.\mathrm{y,j}}$ is the input of nutrient form F to rivers by source y from sub-basin j (kg/year). $RS_{F.\mathrm{y,j}}$ is divided into diffuse ($\mathrm{RSdif}_{F,y,j}$) and point ($RSpnt_{F.y.j}$) sources.

$FE_{riv.F.outlet.j}$ is the fraction of nutrients exported to the outlet of sub-basin j (0–1).

$FE_{riv.F.mouth.j}$ is the fraction of nutrients exported from sub-basin outlets to the river mouth (into the lake) (0–1).

- Nutrient inputs to rivers from diffuse sources ($\mathrm{RSdif}_{F,y,j,}$ $kg/year$)

Diffuse sources include the use of synthetic fertilizers, animal manure and human waste on land. These are diffuse sources of DIN, DON, DIP and DOP in rivers. Atmospheric N deposition and biological N_2 fixation by vegetation are diffuse sources of DIN in rivers. Weathering of P-contained minerals and P mining are diffuse sources of DIP in rivers. Leaching of organic matter from soils is a diffuse source of DON and DOP in rivers (Table 1). $\mathrm{RSdif}_{F,y,j}$ is the sum of nutrient inputs to rivers in the sub-basins from all diffuse sources (kg/year, see Equation (2)).

$$\mathrm{RSdif}_{F,y,j} = \mathrm{RSdif}_{ant.F,y,j} + \mathrm{RSdif}_{expl.ant.F,y,j} + \mathrm{RSdif}_{expl.nat.F,y,j} + \mathrm{RSdif}_{DIP,min,j} + \mathrm{RSdif}_{nat,F,y,j} \tag{2}$$

where,

$\mathrm{RSdif}_{ant.F,y,j}$ is the input of nutrient form (F: DIN, DON, DIP or DOP) to rivers from anthropogenic (ant) diffuse (dif) source y in sub-basin j (kg/year). These diffuse sources include the use of synthetic

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Figure 1 | Lakes Dianchi and its sub-basins. *Source*: MARINA-Lakes model (Li *et al.* 2019).

fertilizers, animal manure and human waste on land, atmospheric N deposition over agricultural land and biological N_2 fixation by crops. They are quantified as nutrient inputs to agricultural land that are corrected for nutrient export from agricultural land (crop harvesting and grazing) and retentions in soils (Li *et al.* 2019, Appendix B).

$RSdif_{expl.ant.F,y,j}$ is the input of nutrient form (F: DIN, DON, DIP or DOP) to rivers from anthropogenic (ant) explicit (expl) diffuse source y in sub-basin j (kg/year). These anthropogenic explicit diffuse sources include weathering of P-contained minerals and leaching of organic matter over agricultural land. They are quantified using an export-coefficient approach (Li *et al.* 2019, Appendix B).

$RSdif_{expl.nat.F,y,j}$ is the input of nutrient form (F: DIN, DON, DIP or DOP) to rivers from natural (nat) explicit (expl) diffuse (dif) source y in sub-basin j (kg/year). These natural explicit diffuse sources include weathering of P-contained minerals and leaching of organic matter over natural land. They are quantified using an export-coefficient approach (Li *et al.* 2019, Appendix B).

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Table 1 | Summary of the sources for model inputs and parameters for 2012 and 2050

Model inputs and parameters	Unit	Sources for 2012	Sources for 2050
Sub-basin area	km^2	Gao *et al.* (2014)	Gao *et al.* (2014)
Population	people	Chen (2013)	Samir & Lutz (2017); Cuaresma (2017)
Synthetic fertilizer use	kg/year	Wang *et al.* (2017)	Estimated based on Wang *et al.* (2017)
Animal manure applied on land	kg/year	Strokal *et al.* (2016); Wang *et al.* (2017)	Estimated based on Wang *et al.* (2017)
Human waste applied on land	kg/year	Strokal *et al.* (2016)	Estimated
Atmospheric N deposition	kg/year	Xu *et al.* (2015)	Xu *et al.* (2015)
Biological N_2 fixation by crops	$kg/km^2/year$[a]	Strokal *et al.* (2016)	Strokal *et al.* (2016)
P weathering	$kg/km^2/year$[a]	Strokal *et al.* (2016)	Strokal *et al.* (2016)
Organic leaching from soils	$kg/km^2/year$[a]	Strokal *et al.* (2016)	Estimated based on Strokal *et al.* (2016)
Mining	kg/year	Li *et al.* (2019)	Li *et al.* (2019)
Animal manure directly discharged (untreated)	kg/year	Wang *et al.* (2017)	Estimated based on Wang *et al.* (2017), see Table 2
Human waste directly discharged (untreated)	kg/year	Wang *et al.* (2017)	Wang *et al.* (2017)
Sewage systems	kg/year	Li *et al.* (2019)	Estimated based on Li *et al.* (2019)[b]
Actual river discharges	$km^3/year$	Jin (2003)	Jin (2003)
Water removal from the river system	0–1	Jin (2003)	Jin (2003)
Nutrient retention in reservoirs[c]	0–1	Strokal *et al.* (2016)	Strokal *et al.* (2016)
Nutrient retention in water systems ($L_{F.j}$)[c]	0–1	Strokal *et al.* (2016)	Strokal *et al.* (2016)

Details are in Li *et al.* (2019) for model inputs for the year 2012. Table 2 provides details of how we derived model inputs for the year 2050 (see also Table B.2 in the Appendix).

[a]We applied the rates for atmospheric N deposition and biological N_2 fixation per km^2 and multiplied with the sub-basin areas to get kg/year.

[b]We estimated a number of people connected to sewage systems in 2050 taking into account the storylines of the scenarios; the connection rate of the population to sewage systems in 2012 is from Li *et al.* (2019).

[c]Nutrient retentions for 2012 and 2050 are taken from Strokal *et al.* (2016) for the Jinsha sub-basin, and we applied it for all other sub-basins of Lake Dianchi because of data limitation.

$RSdif_{DIP,min,j}$ is the input of dissolved inorganic phosphorus (DIP) to rivers from mining activities (rock processing as diffuse source) in sub-basin j (kg/year). These inputs are quantified using the information on the production of DIP during mining activities (Li *et al.* 2019, Appendix B).

$RSdif_{nat,F,y,j}$ is the input of nutrient form (F: DIN, DON, DIP or DOP) to rivers from natural (nat) diffuse (dif) source y in sub-basin j (kg/year). These natural diffuse sources include atmospheric N deposition over natural areas and biological N_2 fixation by natural vegetation. These inputs are quantified as inputs to natural land that are corrected for retentions in soils (Li *et al.* 2019, Appendix B).

- Nutrient inputs to rivers from point sources ($RSpnt_{F.y.j}$, kg/year)

Point sources of nutrients in rivers include direct discharges of untreated animal manure and human waste. These are point sources of DIN, DIP, DON and DOP in rivers. Mining is a point source of DIP in rivers (Table 1). Nutrient inputs to rivers from point sources are quantified using Equation (3).

$$RSpnt_{F.y.j} = RSpnt_{E.y.j} \cdot FEpnt_{F.j} \tag{3}$$

where,

$RSpnt_{F.y.j}$ is the input of nutrient form (F: DIN, DIP, DON and DOP) to rivers from sewage systems ($RSpnt_{F.sew.j}$, $kg/year$), direct discharges of untreated animal manure ($RSpnt_{F.ma.j}$, $kg/year$) and of untreated human waste ($RSpnt_{F.hw.j}$, kg/year), and from mining as a point source ($RSpnt_{DIP.min.j}$, for

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DIP only, kg/year). Details about the equations to quantify these point source inputs to rivers are given in Appendix B (see also Li *et al.* 2019).

$RSpnt_{E.y.j}$ is the input of nutrient element (E: N or P) to rivers from point source y in sub-basin j (kg/year).

$FEpnt_{F.j}$ is the fraction of nutrient element that enters rivers from point sources in form F (DIN, DIP, DON and DOP) (0–1).

- Nutrient retentions in rivers ($FE_{riv.F.outlet.j} \cdot FE_{riv.F.mouth.j},\ \ 0-1$)

The nutrient export fractions are quantified using Equation (4).

$$FE_{riv.F.outlet.j} = (1 - L_{F.j}) \cdot (1 - D_{F.j}) \cdot (1 - FQrem_j) \quad (4)$$

where,

$L_{F.j}$ is the fraction of nutrient form (F: DIN, DIP) retained in and lost from river systems in sub-basin j due to denitrification (for DIN) and sedimentation (for DIP) (0–1).

$D_{F.j}$ is the fraction of nutrient form (F: DIN, DIP) retained in reservoirs in sub-basin j (0–1).

$FQrem_j$ is the fraction of nutrient form (F: DIN, DIP, DON, DOP) removed from sub-basin j through water consumption (0–1). Details are in Li *et al.* (2019).

In Lake Dianchi, all sub-basins drain directly into the lake, thus $FE_{riv.F.mouth.j} = 1$.

- Model inputs

The nutrient export to Lake Dianchi in 2012 is quantified using the MARINA-Lakes model from Li *et al.* (2019). The model inputs and their sources are provided by Li *et al.* (2019) for 2012 (see also Table B.1 in the Appendix). Here, we summarize the sources of the main model inputs and parameters for Lake Dianchi in Table 1. Table 2 gives more details on how we derive model inputs for 2050 (see section on scenarios below).

Scenarios

SSP3 (Shared Socio-economic Pathway 3) is used as a worst-case for Lake Dianchi (O'Neill *et al.* 2014; Fujimori *et al.* 2017; Riahi *et al.* 2017). Four alternative scenarios are developed based on the SSP3 scenario: CP, AT, IAM and OPT scenarios. These four alternative scenarios are described below. Table 2 summarizes the main descriptions of the scenarios.

SSP3 was interpreted for the Chinese food system for 2050 (Wang *et al.* 2017). For Lake Dianchi, SSP3 assumes that population will increase relatively fast until 2030. However, by 2050 the total population may decrease, reaching the level of 2012. Population in China is expected to decrease between 2030 and 2050 as the net effect of the 'One-Child' policy (Goodkind 2017; Zhang 2017). The production of animal manure is projected to increase by 90% between 2012 and 2050 in all sub-basins. This is because more people will move to cities, the demand for food in cities might increase. People are expected to have more preferences for meat products (Wang *et al.* 2017). In this scenario, policies for nutrient management in agriculture, sewage systems and mining are not effectively implemented. As a consequence, synthetic fertilizer use on land is expected to increase by 26% (Wang *et al.* 2017) between 2012 and 2050 for all sub-basins (Table 2). Manure recycling rates will stay at the level of 2012 (52% of the total excretion). Fractions of direct discharges of manure to rivers in this scenario are expected to stay as in 2012. The same holds for untreated human waste. The same fraction of the urban and rural population will be connected to sewage systems in 2050 as in 2012 with the higher number of people in cities. Wastewater treatment technologies might not be improved largely compared to the level of 2012. Mining activities will continue as in 2012.

The CP scenario reflects implementation of the Current environmental Policies for agriculture, mining and urbanization (Table 2). In this scenario, implementation of the following national

Table 2 | Description of the five scenarios to quantify nutrient export by rivers from sub-basins to Lake Dianchi in 2050

Human activities		2012	Scenarios for 2050: SSP3	CP	AT	IAM	OPT
Agriculture	Manure excretion (ton/km^2/year)	3 for N and 1.5 for P	90% increase between 2012 and 2050[a]	As SSP3	As SSP3	As SSP3	As SSP3
	Manure recycling on land (% of the total excretion)	52%[a] for N[1] and P	As 2012	57% for N[1] and P	As SSP3	62% for N[1] and P	As IAM
	Manure discharges to rivers (% of the total excretion)	10%	As 2012	5%[1]	As SSP3	0%[1]	As IAM
	Synthetic fertilizer use (ton/km^2/year)	8.5 for N and 1.3 for P	26% increase between 2012 and 2050[a]	At the level of 2020	As SSP3	30% decrease between 2012 and 2050	As IAM
Sewage systems	Human waste directly discharged to rivers (untreated) from urban and rural population (% of the total human excretion)	For N: 13% for urban and 23% for rural population; For P: 13% for urban and 47% for rural population	As 2012	As 2012	As SSP3	As SSP3	As 2012
	Total population (10^3 people)	103 urban and 368 rural	As 2012[b]	As SSP3	As SSP3	As SSP3	As SSP3
	People connected to sewage systems (% of the population)	94% for urban[c] and 55% for rural[c]	As 2012	97% for urban and 60% for rural	99% for urban, 70% for rural	As SSP3	AS AT
	Nutrient removal efficiencies (%)	35% for N[c], 67% for P[c]	As 2012	65% for N, 83% for P[2]	90% for N and 95% for P	As SSP3	AS AT
Mining	Mining activities (ton/year)	28 ton of DIP[c]	As 2012	Ban	As SSP3	As CP	As IAM

SSP3 is Shared Socio-economic Pathway 3. CP assumes the full implementation of the Current Policies relative to SSP3. AT assumes more urbanization and the full implementation of Advanced Technologies to treat wastewater relative to SSP3. IAM assumes the full implementation of Improved nutrient management in Agriculture and banned Mining relative to SSP3. OPT is an optimistic scenario combining the AT and IAM scenarios. *Source*: MARINA-Lakes model (see Methods section).

[a]Wang *et al.* (2017).

[b]Samir & Lutz (2017); Cuaresma (2017).

[c]Li *et al.* (2019).

[1]Manure recycling rates are quantified as the amount of recycled manure on land divided by the amount of the total manure excretion. The recycled manure is quantified from the total manure excretion that is corrected for N losses to air and direct discharges to rivers. N losses to air are from Li *et al.* (2019). The fraction of direct manure discharges for 2012 is from Li *et al.* (2019) and assumed for 2050 depending on scenario. For CP scenario, we assumed that manure recycling will be increased as a result of decreased direct manure discharges to rivers compared to 2012. For IAM scenario, we assumed that direct discharges to rivers will be fully avoided. As a result, more animal manure will be applied on land.

[2]This nutrient removal efficiencies are derived using literature on the advanced technologies A^2/O and ICEAS (Liu *et al.* 2007; Zhang *et al.* 2008) implemented by a wastewater treatment company in Kunming City, we assumed that the whole sub-basin will implement this technology by 2050 in CP scenario (see also Appendix C for more information about policies and technologies).

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policy is assumed for agriculture: 'Zero growth in Synthetic Fertilizers Use by 2020' (MOA 2015). This current policy also calls for a 60% recycling rate of manure on land. Thus, we assume that the percentage of direct manure discharges to rivers will decrease to 5% in 2050 (Table 2, see also Appendix C). As a result, the amount of manure use on land will increase in 2050 compared to SSP3. The amount of synthetic fertilizers will stay at the level of 2020. The total population will stay at the level of 2012 as in SSP3. However, the fraction of urban (97% in 2050) and rural (60% in 2050) population connected to sewage systems will increase; this is in line with the 'Lake Dianchi protection regulations in Yunnan province' (KLDA 2013). Improved technologies to treat wastewater will be implemented. This implies that nutrient removal efficiencies will be higher in 2050 than in 2012: 65% for N and >80% for P in all sub-basin. All mining activities will be banned (KGO 2017). More information about policies and technologies are in Appendix C (Tables C.1 to C.5).

The AT scenario assumes the full implementation of Advanced Technologies for wastewater treatment. In this scenario, the population size, urbanization, economy and agricultural activities are the same as in SSP3. The only difference from SSP3 is in advanced technologies for wastewater treatment and in an increasing number of people connected to sewage systems. Some technologies could also reach very high nutrient removal efficiencies in theory, such as reverse osmosis (RO) and anaerobic ammonium oxidation (anammox). RO is a pressure driven membrane process to separate dissolved components in permeates, and is more important in industrial applications (Kucera; Wenten 2016). Anammox is a process which directly oxidizes ammonium to dinitrogen gas under anoxic condition, it is promising for N removal from wastewater (Tang *et al.* 2017) (see also Table C.4 in the Appendix). The connection rate of population to sewage systems will be 99% for urban people and 70% for rural people. The nutrient removal efficiencies are 90% and 95% for N and P, respectively (Table 2).

The IAM scenario assumes Improved nutrient use efficiencies in Agriculture and stopping Mining activities. Improved nutrient management in agriculture implies high animal manure recycling on land and less synthetic fertilizer use with the same socio-economic development as in SSP3. This scenario differs from the CP scenario in that it has well-implemented policies in agriculture and mining industry (KPGOYP 2008; MOA 2015; KGO 2017). These policies are extended with advanced technologies to manage manure and nutrients in agriculture. Examples are injection of manure to avoid losses of nutrients to the environment during application (Wang *et al.* 2017). These nutrient management options can increase N and P use efficiencies in food production and thus reduce losses of N and P to rivers. For the sub-basins of Lake Dianchi, all available animal manure is assumed to be recycled on land (100% for N and P). Thus, direct discharges of manure will be avoided. Synthetic fertilizer use on land will be reduced by 30% compared to 2012 to avoid over-fertilization (Table 2). All mining activities along Lake Dianchi are assumed to be stopped.

The OPT scenario combines assumptions of the AT and IAM scenarios. OPT assumes an optimistic world with improved nutrient management in agriculture, no mining activities and implemented best available technologies. The population, urbanization and economy growth will stay as in SSP3. Almost all urban and over two-thirds of the rural population will be connected to sewage systems. Nutrient removal efficiencies will be high in wastewater treatment plants (90% for N, 95% for P). The use of synthetic fertilizer is expected to reduce by 30% in 2050 compared to 2012, and manure cycling rates could increase as in IAM. Mining activities will be forbidden in 2050.

RESULTS

Future trends in river export of nutrients by source

In 2012, rivers exported large amounts of nutrients to Lake Dianchi (Figure 2). We quantify that about 5,000 ton of DIN and over 1,000 ton of DON were exported to the lake from 15 sub-basins (Figure 1).

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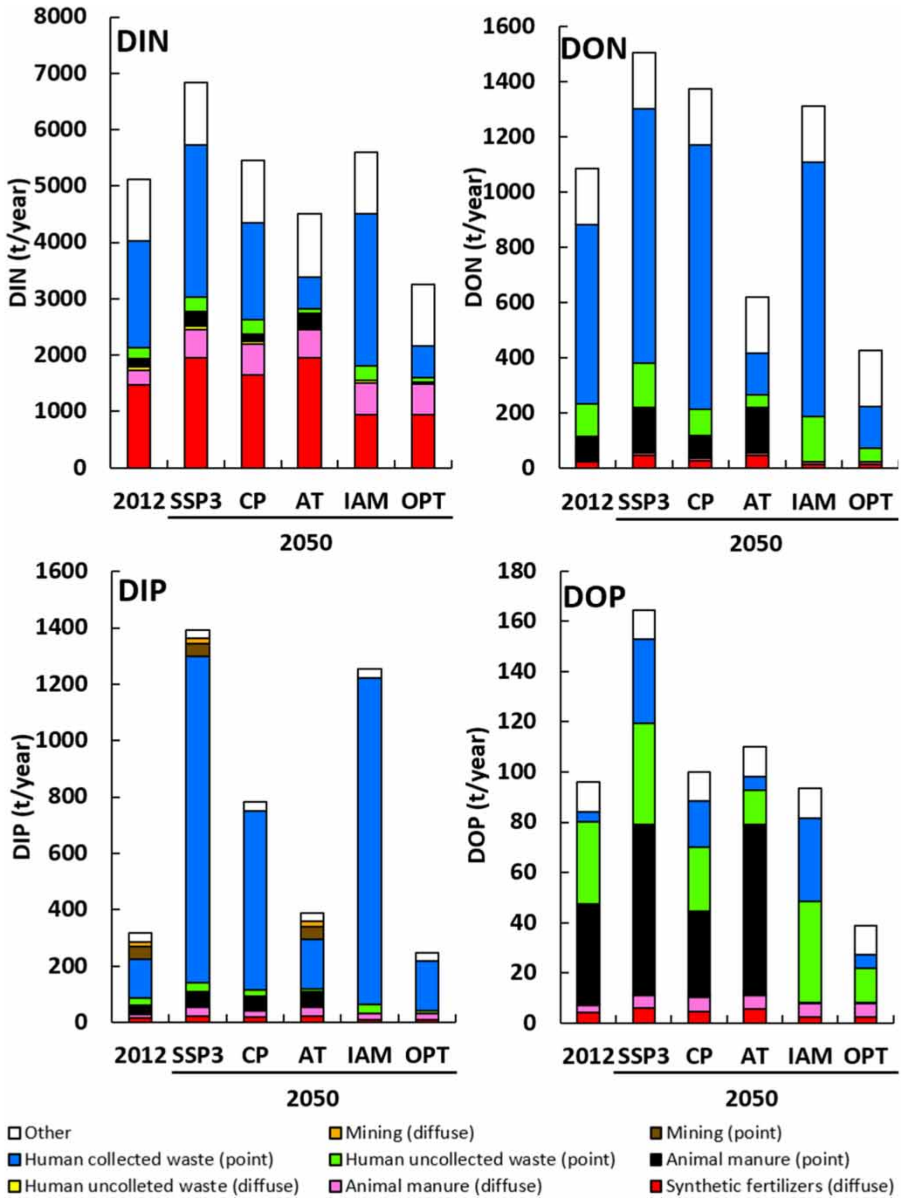

Figure 2 | Annual river export of dissolved inorganic (DIN, DIP) and dissolved organic (DON, DOP) nitrogen (N) and phosphorus (P) by source to Lake Dianchi in 2012 and 2050 according to the scenarios (t/year). SSP3 is a Shared Socio-economic Pathway 3 scenario. CP assumes the full implementation of the Current Policies relative to SSP3. AT assumes more urbanization and the full implementation of Advanced Technologies to treat wastewater relative to SSP3. IAM assumes the full implementation of Improved nutrient management in Agriculture and banned Mining relative to SSP3. OPT is an optimistic scenario combining the AT and IAM scenarios. Other: atmospheric N deposition and biological N_2 fixation for DIN, leaching of organic matter for DON and DOP, and weathering of P-contained mineral for DIP, detergents for DIP and DOP.

In addition, we quantify around 300 ton of DIP and 100 ton of DOP in 2012 (Figure 2). Point sources accounted for over half of the nutrients in the lake except for DIN. Less than half of DIN in Lake Dianchi resulted from sewage systems and around 40% from synthetic fertilizers. Around half of DON in the lake (651 ton) was from sewage systems. For DIP, sewage systems were responsible for over 80% of DIP in the lake. Mining was an important source of DIP in individual rivers in the southern sub-basins. For DOP, direct discharges of animal manure and of untreated human waste (point sources) contributed around 80% of DOP to the lake.

In the future, river export of nutrients is projected to increase by 1.4–4.4 times between 2012 and 2050 in SSP3, depending on nutrient form (Figure 2). River export of DIN and DON is projected to

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increase by 1.4 times, reaching around 8,000 ton and 1,600 ton in 2050, respectively. River export of DIP is projected to increase by 4.4 times, reaching 1,400 ton in 2050. River export of DOP is, however, projected to decrease slightly during 2012–2050 in the SSP3 scenario. The increases in river export of the nutrients are associated with increasing urbanization and intensive agriculture in 2050. Point sources are simulated to remain the main cause of nutrient pollution in the lake (except for DIN where fertilizers are also important). For DIN, sewage systems and synthetic fertilizers are projected to remain important sources of DIN in the lake in 2050. These sources are projected to contribute around 2,700 ton (from sewage) and 2,000 ton (from fertilizers) of DIN to the lake in 2050. Above half of DON is simulated to result from sewage systems in 2050. Mining activities project to continue contributing to river export of DIP from individual sub-basins in the south. Sewage systems are projected to contribute more than 80% of DIP in the lake. For DOP, direct discharges of animal manure are expected to remain the dominant source together with human waste (treated and untreated).

Current Policies (CP) may reduce river export of nutrients to the lake by 2050, but not below the level of 2012 (CP scenario, Figure 2). In 2050, river export of DIN and DOP is slightly higher than in 2012, and river export of DON and DIP is 1.2 and 2.5 times as high as in 2012, respectively. Effects of the current policies on reducing river export of nutrients differ among nutrient forms. Current policies are projected to reduce more DIN and DOP export by rivers than river export of the other nutrient forms compared to SSP3. This is associated with the sources of the nutrients in rivers. Current policies aim largely at reducing over-fertilization of cropland and recycling of manure on land. These are important sources of DIN (fertilizers) and DOP (manure) in rivers. This is different for river export of DIP where sewage systems contribute considerably to DIP in rivers. This also holds for DON in rivers (Figure 2). Mining activities will not add DIP in rivers because they will be completely banned in this scenario.

Implementing advanced technologies for wastewater treatment is more effective to reduce future river export of DIP and DON than of DIN and DOP (AT scenario, Figure 2). In this AT scenario, river export of DON and DIP is lower than in the CP scenario. River export of DIN is comparable to the level in the CP scenario whereas river export of DOP is higher than in the CP scenario. River export of DON is projected to below the level of 2012 in 2050. These trends can be explained by the high nutrient removal efficiencies for N and P in the AT scenario (Table 2). For reducing DIN and DOP in rivers, improving wastewater treatment in sewage systems is not enough because DIN and DOP are largely originated from fertilizers and manure (Figure 2).

Implementing improved nutrient management in agriculture and banning mining is more effective to reduce future river export of DIN and DOP than of DIP and DON (IAM scenario, Figure 2). River export of DIN and DOP is expected to reach the level of 2012 in 2050. This is because DIN and DOP in rivers originate largely from agricultural-related sources such as direct discharges of manure (for DOP) and synthetic fertilizers (for DIN). Reducing manure discharges (point sources) and over-fertilization of cropland by synthetic fertilizers (diffuse sources) according to the improved nutrient management in agriculture will largely reduce river export of DIN and DOP. This is not the case for DON and DIP where sewage systems (point sources) are the main causes.

The OPT scenario indicates that it is possible to reduce future river export of all nutrients to below the level of 2012. This scenario assumes improved wastewater treatment and implemented improved nutrient management in agriculture (Figure 2). For example, river export of nutrients is projected to reduce by a factor of 36% for DIN, 61% for DON, 22% for DIP and 60% for DOP between 2012 and 2050 in the OPT scenario (Figure 2). These reductions are related to the net effect of the management options to reduce pollution from cities (advanced wastewater treatment), agriculture (improved nutrient management) and mining (banned).

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Future trends in river export of nutrients by sub-basin

River export of nutrients differs among sub-basins and nutrient forms (Figures 3 and 4). Caohai and Daqing sub-basins (north) are the two most polluted sub-basins (Figure 1). For example, they exported 0.3–10 times higher DIN to the lake in 2012 than the other sub-basins (except for the Panlong sub-basin). This also holds for other scenarios for 2050 (Figures 3 and 4).

River export of DIN is projected to increase by 2050 in SSP3 (see the previous section). However, the sources of DIN in rivers differ among sub-basins in SSP3 (Figures 1 and 3). DIN is mainly from synthetic fertilizers and manure use on land in middle and southern sub-basins in 2050 SSP3. In the northern sub-basins, DIN in rivers is largely from sewage systems. In the CP scenario, all sub-basins are projected to export lower amounts of DIN compared to SSP3, but higher amounts of DIN compared to 2012 in 2050. In the AT scenario, improved sewage systems is more effective to reduce DIN from the northern sub-basins (Caohai and Daqing, Figure 3). In the IAM scenario, improved nutrient management in agriculture is effective to reduce DIN export from middle and southern sub-basins. In the OPT scenario, DIN reductions in river export from all sub-basins are higher compared to the other scenarios. For example, river export of DIN is projected to reduce by 20–65% (range for sub-basins) in OPT between 2012 and 2050.

Likewise, sources of DON in rivers differ among sub-basins (Figure 3). In SSP3, DON in rivers is mainly from sewage systems in northern sub-basins. In rivers of southern sub-basins, DON is largely from sewage systems and animal manure (untreated) (Figures 1 and 3). In the CP scenario, DON export is not effectively reduced. In this scenario, lower river export of DON is projected from

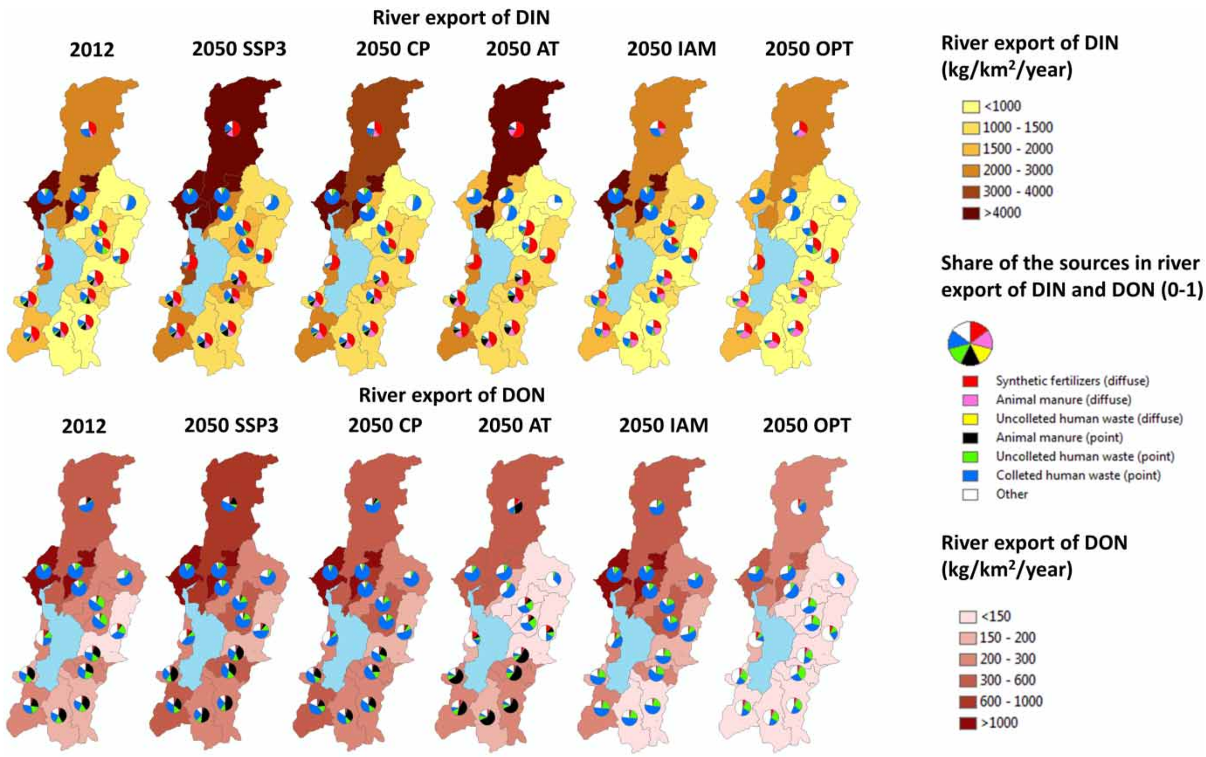

Figure 3 | Annual river export of dissolved inorganic (DIN) and dissolved organic (DON) nitrogen (N) by sub-basin (kg/km^2 of the sub-basin area/year) and the share of the sources in annual river export of DIN and DON (0–1) in 2012 and 2050 according to the scenarios. SSP3 is a Shared Socio-economic Pathway 3 scenario. CP assumes the full implementation of the Current Policies relative to SSP3. AT assumes more urbanization and the full implementation of Advanced Technologies to treat wastewater relative to SSP3. IAM assumes the full implementation of Improved nutrient management in Agriculture and banned Mining relative to SSP3. OPT is an optimistic scenario combining the AT and IAM scenarios. *Source*: MARINA-Lakes model (see Methods section).

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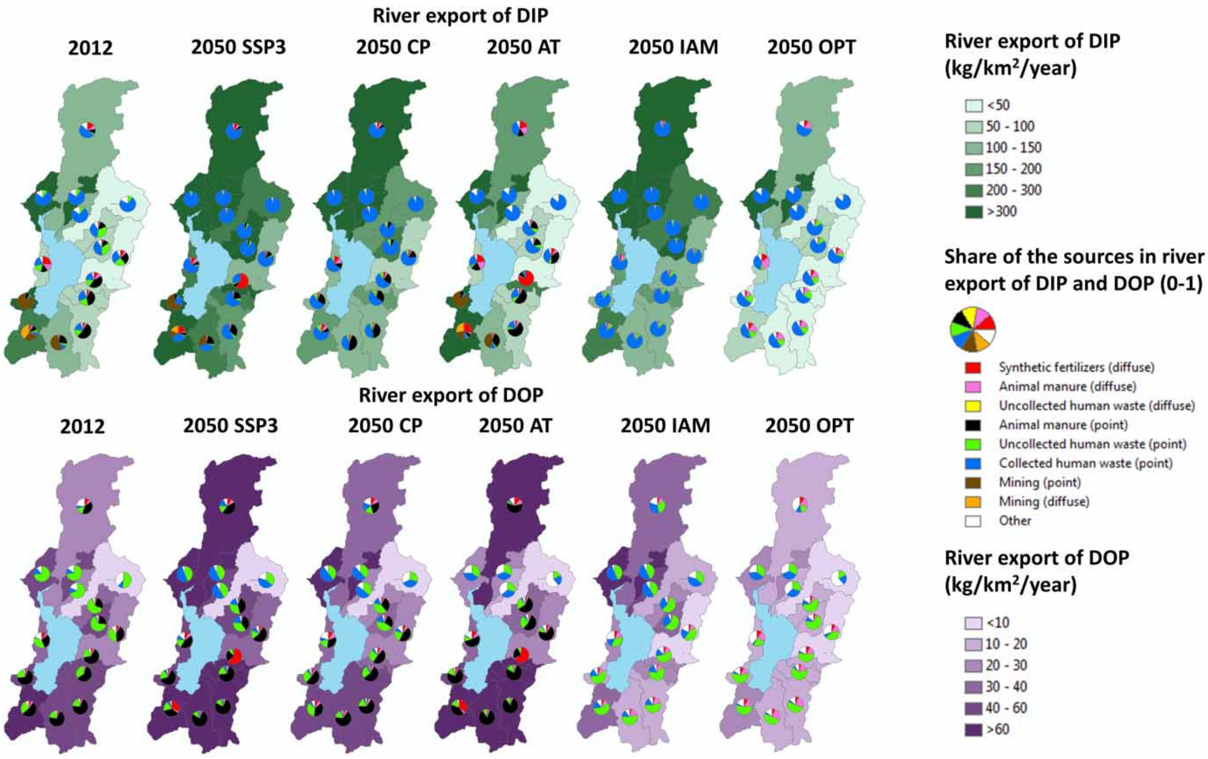

Figure 4 | Annual river export of dissolved inorganic (DIP) and dissolved organic (DOP) phosphorus (P) by sub-basin (kg/km^2 of the sub-basin area/year) and the share of the sources in annual river export of DIP and DOP (0–1) in 2012 and 2050 according to the scenarios. SSP3 is a Shared Socio-economic Pathway 3 scenario. CP assumes the full implementation of the Current Policies relative to SSP3. AT assumes more urbanization and the full implementation of Advanced Technologies to treat wastewater relative to SSP3. IAM assumes the full implementation of Improved nutrient management in Agriculture and banned Mining relative to SSP3. OPT is an optimistic scenario combining the AT and IAM scenarios. *Source*: MARINA-Lakes model (see Methods section).

only a few sub-basins compared to SSP3. This is because more efforts are needed to reduce direct manure discharges and improve wastewater treatment in the CP scenario. In the AT scenario, DON in rivers of sub-basins in the middle-northern part (Figure 1) is expected to reduce in 2050 compared to SSP3. This is because sewage systems in those sub-basins contribute largely to the river pollution. Advanced wastewater treatment in the AT scenario may reduce river pollution in those sub-basins. This is different for southern sub-basins (e.g., Cigang and Baiyu) where improved nutrient management in agriculture (IAM scenario) is more effective to reduce river pollution compared to SSP3. In the OPT scenario, river export of DON is projected to reduce from all sub-basins.

DIP in rivers of northern sub-basins is mainly from sewage systems in SSP3. Mining activities largely contribute to DIP in rivers of southern sub-basins in SSP3. Direct discharges of animal manure are important sources of DIP in rivers of southern sub-basins in SSP3. Overall, the CP scenario is less effective in reducing river export of DIP from most sub-basins. Exceptions are rivers of some southern sub-basins that may export less DIP to the lake. This is because CP assumes some improvements in nutrient management in agriculture and banning of mining that are sources of DIP in those rivers. In the AT scenario, river export of DIP from northern sub-basins (Figure 1) is a factor of 3–6 lower compared to SSP3 and CP. In the IAM scenario, policies (KPGOYP 2008; MOA 2015; KGO 2017) for better agricultural management and banning mining reduce river export of DIP from the southern sub-basins (Figure 4). In the OPT scenario, river export of DIP from all sub-basins is projected to be lower in 2050 than in 2012.

River export of DOP from southern sub-basins is generally higher than from northern sub-basins (Figure 4). This is different for other nutrient forms (see above). The main sources of DOP in rivers are untreated human excreta in northern sub-basins and direct discharges of animal manure to

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rivers in southern sub-basins. By 2050, river export of DOP from all sub-basins may increase in SSP3. Current policies are somewhat effective to reduce river export of DOP from some southern sub-basins. In the AT scenario, DOP export is much higher than in 2012 from most sub-basins. In the IAM scenario, river export of DOP is largely reduced compared to SSP3. This holds especially for some sub-basins in the southern part, where river export of DOP is projected to decrease by a factor of 2 between 2012 and 2050. In the OPT scenario, river export of DOP is 38% to 76% lower in 2050 than in 2012 for all sub-basins (range for the sub-basins).

DISCUSSION

Strengths of our study

Our study provides new insights in future trends in river export of different forms and their sources for Lake Dianchi. Existing studies focus often on the total N and P export to the lake (Chen *et al.* 2002; Cheng *et al.* 2008; Gao *et al.* 2015). Only a few studies distinguish the nutrient forms (Zhang *et al.* 2007; Qian *et al.* 2016; Liu 2017). However, the various nutrient forms in the lake may result from different sources. We show that synthetic fertilizers are important sources of DIN in the lake. This is different for DON, DIP and DOP. Sewage systems are important sources of DIP and DON and direct discharges of manure of DOP in the lake. Mining contributes DIP in southern rivers of the lake (Figure 4). Reduction of all nutrient forms in the lake may contribute to effective reduction of eutrophication (Pinckney *et al.* 2001). Our insights about the sources can help to reduce nutrient forms in the lake effectively. Furthermore, we account for most important sources of lake pollution. Existing studies often focus either on collected human waste (point source) or fertilizer use (diffuse source). For example, direct discharges of animal manure to rivers are often ignored in most of the studies (Wang *et al.* 2017).

Another strength of our study is our analysis of the future for sub-basins and their sources. We quantify river export of nutrients from 15 sub-basins and identify main sources of river pollution in those sub-basins. This helps to better understand the contribution of sub-basins to the total nutrient pollution of the lake. This information is relevant for identifying sub-basins specific management options. Sub-basin specific analyses for future trends in river pollution for Dianchi are limited in existing studies (Kong *et al.* 2012; Gao *et al.* 2014; Zhou *et al.* 2015). In this study, we perform such analyses using the MARINA-Lakes model. This model enables to quantify river export of different nutrient forms by sub-basin and source. To our knowledge, other models for Lake Dianchi that quantify simultaneously river export of nutrients in different forms from sub-basins and sources do not exist.

An important strength of our study is that we developed five different scenarios to analyse the future for Lake Dianchi. The lake has been eutrophic for over decades, and many studies tried to understand the causes and the consequences of the nutrient pollution. However, most of these studies are limited to analyses of past and current trends, and do not explicitly model future trends. National and local governments have invested considerably to improve water quality. However, the effects of the proposed and implemented environmental policies are not always well understood. Several existing studies discussed control measures for eutrophication (Wang 2002; Liu *et al.* 2012), but not at the sub-basin scale and not for different nutrient forms for 2050. We explore several future scenarios for river export of nutrients to Lake Dianchi. We focus, in particular, on effects of the environmental policies and advanced wastewater treatment to reduce nutrient pollution in the lake. We show possible effects of the current policies for agriculture (e.g., Zero Growth in Synthetic Fertilizers by 2020) and mining. These current policies are promising and are expected to reduce future river pollution compared to the SSP3 scenario. However, this may not be enough to avoid eutrophication in 2050.

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We argue that more effort might be needed in reducing both agricultural and urbanization related pollution. Our study may serve as an inspiration for further research on future trends.

Limitations of our study

Our study also has four main limitations. First, we may not include all existing environmental policies and technologies. Policies are often generic without explicit targets. Plenty of technologies exist and their nutrient removal efficiencies vary greatly (Oller *et al.* 2011; Foged *et al.* 2012; Jie *et al.* 2017). Local conditions (e.g., the capacity and the maintenance of the wastewater treatment plants) can influence the removal efficiencies. However, we believe that we considered most relevant environmental policies and accounted for most recent advanced technologies that are relevant for the study area.

Second, the MARINA-Lakes model has uncertainties. The sources of the uncertainties are largely associated with model inputs and parameters. For example, some model parameters (e.g., fractions of manure discharges) are generic for all sub-basins and based on expert knowledge and some literature. MARINA-Lakes has recently been implemented for Lake Dianchi for the year 2012 (Li *et al.* 2019). The model has been validated against observations for nutrients in the lake. Validation results are promising and indicate that the model can be used to analyse river export of nutrients to Dianchi (Li *et al.* 2019). We implemented the existing MARINA-Lakes model (Li *et al.* 2019) for 2050.

Third, a few sources might be missing in the MARINA-Lakes model. These include, for example, direct atmospheric N and P deposition on the lake. We account for atmospheric N deposition on land, but not on the lake water. Atmospheric deposition of N and P on water can potentially be a large source of nutrients in coastal water systems (Jassby *et al.* 1994; Paerl *et al.* 2002). However, atmospheric N and P deposition on the lake may not be a primary pollution source. However, this needs more investigation (Ren *et al.* 2019).

Fourth, future trends are uncertain. We developed five scenarios that have the same socio-economic development, but differ in nutrient management in agriculture, cities and mining. Socio-economic development is based on the existing SSP3 scenario (O'Neill *et al.* 2014; Fujimori *et al.* 2017; Riahi *et al.* 2017). For nutrient management, we interpreted relevant policies based on literature and expert knowledge. We assumed the full implementation of the policies and advanced technologies for wastewater treatment plants in all sub-basins in our OPT scenario. Such combinations of policies and the best technologies are simplified in the MARINA-Lakes model. In reality there may be synergies and conflicts that affect reduction options for different nutrient forms. One synergy could be that the recycling of animal manure leads to even more reductions in synthetic fertilizers than assumed in our IAM scenario, and thus fewer nutrients will be exported to rivers. Conflicts might happen when the implementation of advanced wastewater treatment technologies requires additional financial support on top of other management options (e.g., in our AT scenario). Implementing policies and advanced technologies in our optimistic scenario might, thus, be challenging. However, China has been developing fast over past decades, opening an opportunity for further implementation of the effective environmental policies and technologies. We quantify the technical feasibility of implementing solutions. Future research may focus on the political, societal and economic feasibility.

Implications for policies to reduce future eutrophication

Our study shows that it will be difficult to reduce coastal eutrophication in the future, even under the OPT scenario. We compare our quantified nutrient loadings to Lake Dianchi in 2050 with the critical nutrient loadings in 2012 (Li *et al.* 2019). These critical nutrient loadings are the levels of nutrients below which eutrophication may not occur. The critical nutrient loadings were quantified using the lake ecosystem model (PCLake) (Janse *et al.* 2008) and take into account the nutrient cycling in

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the lake and the food web (Li *et al.* 2019). For the northern part of Dianchi (Caohai sub-basin), these critical nutrient loadings are quantified at 3.06 mg N/m^2/day and 0.34 mg P/m^2/day in (Li *et al.* 2019). For the southern part of the lake (other 14 sub-basins), the critical nutrient loadings are quantified at 3.42 mg N/m^2/d and 0.38 mg P/m^2/d. We convert projected nutrient loadings for the year 2050 from kton/year to mg/m^2/d using the surface area of the lake. We compare the N and P quantified in the OPT scenario to the critical loadings. Our comparison shows that the projected N and P loadings exceed their critical loadings by a factor of 27 for N and 25 for P for the northern part of the lake. For the southern part, this exceedance is a factor of 10 for N and 17 for P. It seems that these exceedances are high. However, they are much lower compared to the exceedance between the nutrient loadings in 2012 and the critical nutrient loadings (a factor of 17–82 depending on nutrients and lake part) (Li *et al.* 2019).

Our study indicates that advanced wastewater treatment technologies, improved nutrient management in agriculture and banned mining can help to reduce the gap between the projected nutrient loadings and their critical loadings in the lake (OPT scenario). This is a right direction towards reducing future eutrophication. However, more efforts are needed to avoid eutrophication in 2050. For example, more reductions are needed in the use of synthetic fertilizers than assumed in the OPT scenario. Decentralized wastewater treatment with high nutrient removal efficiencies for rural areas may help to avoid nutrient losses to rivers. We argue that there is a need to focus on circular-oriented management options (e.g., recover and recycle nutrients from waste). Furthermore, controlling internal release of nutrients from lake sediments is also needed. For example, studies show that a gypsum-based technique or the use of alum can prevent phosphorous releases from lake sediments (Varjo *et al.* 2003; Steinman *et al.* 2004). Besides, wetlands or buffer zones around the water systems can prevent nutrient releases to rivers and thus to Lake Dianchi (Yin & Lan 1995; Borin *et al.* 2001; Coveney *et al.* 2002). Efficient use of water from the lake and implementation of water-saving techniques can save water and reduce domestic water use (Xia *et al.* 2007).

CONCLUSIONS

In this study, we analysed the effects of environmental policies and technologies to reduce river export of nutrients to Lake Dianchi in 2050. SSP3 (Shared Socio-economic Pathway 3) is used to reflect a worst-case situation. Four alternative scenarios are developed relative to SSP3. The first alternative scenario assumes the implementation of the current environmental policies in agriculture and sewage (CP). The second and third alternative scenarios assume the implementation of advanced technologies to treat wastewater (AT) and improved nutrient management in agriculture and mining (IAM), respectively. The fourth alternative scenario (OPT) combines AT and IAM.

River export of nutrients is projected to increase 1.4–4.4 times between 2012 and 2050 according to SSP3. In general, agriculture is projected to be an important source of DIN (synthetic fertilizers) and DOP (direct discharges of manure) in rivers of the middle and southern sub-basins. Mining is projected to contribute to DIP in the southern rivers. Sewage systems are projected to contribute to DIN, DON, DIP and DOP in rivers of the northern sub-basins in SSP3. Northern sub-basins (especially Daqing and Caohai) are more polluted because of the high urbanization and high population density. In contrast, middle and southern sub-basins suffer from intensive agricultural activities. Mining occurs within individual sub-basins in the south.

Current policies may reduce river export of nutrients to the lake by 2050 compared to SSP3 (the CP scenario). However, this may not be enough to avoid coastal eutrophication in the future. The AT and IAM scenarios project lower river export of nutrients than in SSP3, but reduction effects differ largely among nutrient forms. River export of nutrients is expected to be below the level of 2012 in an optimistic scenario (OPT). This is because this scenario combines advanced wastewater treatment (AT),

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improved nutrient management in agriculture and banned mining (IAM). However, even under these optimistic assumptions, eutrophication will be difficult to completely avoid. This is because the projected nutrient inputs in 2050 exceed their critical loadings. This exceedance is, however, much lower than for 2012. Our results indicate that more efforts are needed in reducing both agricultural and urbanization related nutrient pollution to avoid eutrophication of Lake Dianchi in the future. Circular-oriented management options such as recover and recycle nutrients from waste could help to avoid nutrient losses to rivers. Controlling internal nutrient loadings from lake sediments may also be important in combination with the other policies.

Insights of our study can support the formulation of management options to reduce future pollution of the lake. For example, improving treatment is important to reduce pollution from the northern sub-basins whereas improving nutrient management in agriculture may be important to reduce pollution from the middle and southern sub-basins. Our study can serve as an example for other lakes experiencing similar environmental problems.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this paper is available at https://dx.doi.org/10.2166/bgs.2020.923.

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