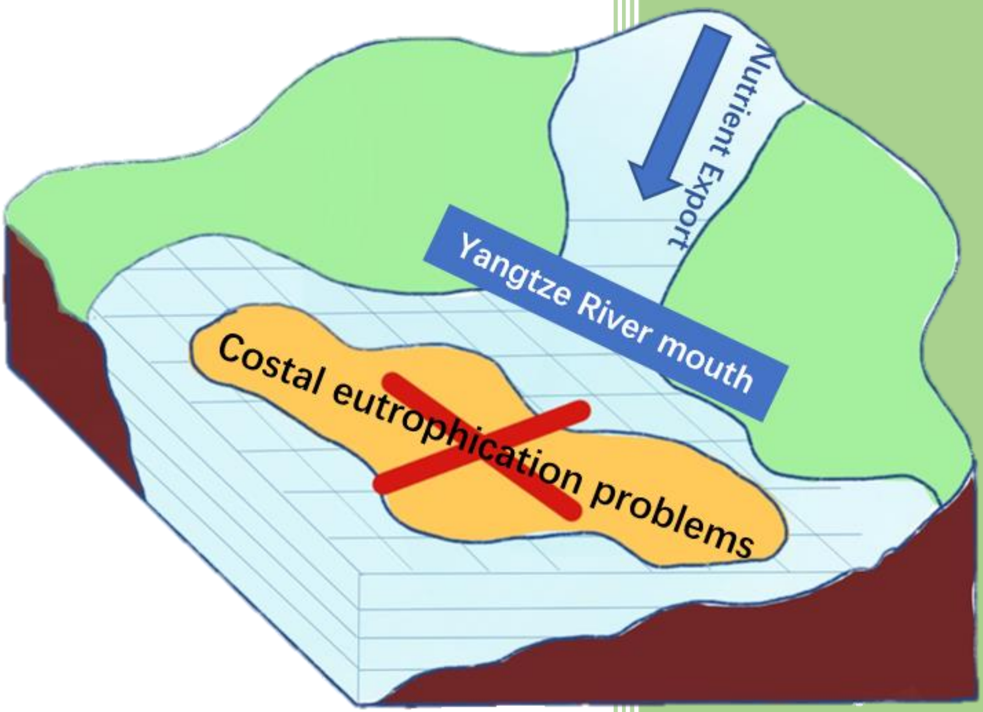
Cost-effective management options to reduce the coastal eutrophication in the Yangtze River mouth



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CONTENT

Summary

China has developed very fast over past several decades. Economic growth, intensive human activities, urbanization, and global change have resulted in increasing amounts of N (nitrogen) and P (phosphorus) in rivers. Rivers export N and P to coastal waters, causing eutrophication. The Yangtze River is the third longest river in the world that has experienced coastal eutrophication problems. However, cost-effective management options to reduce coastal eutrophication problems at the Yangtze River mouth are barely analyzed. Therefore, the research objective of my thesis is to identify the cost-effective management options to reduce coastal eutrophication in the Yangtze River mouth in 2050. I focus on the ten sub-basins whose rivers export increasing amounts of N and P draining into the river mouth. To achieve this research objective, three research questions (RQs) are answered in Chapter 2, 3, 4:

RQ1: What are the main drivers and sources of nutrient pollution in the Yangtze River? (Chapter 2)
RQ2: What are the costs and nutrient removal efficiency of management options to reduce nutrient pollution in the Yangtze River basin? (Chapter 3)
RQ3: What are the cost-effective management options to reduce coastal eutrophication in the Yangtze River mouth? (Chapter 4)

The RQs are answered using literature, the MARINA model in combination with a cost-optimization procedure. MARINA is short for a Model to Assess River Inputs of Nutrients to seAs. The model was developed for China including the ten sub-basins of the Yangtze River. The model is applied for the past (1970,2000) and future (2050) and calculates river export of nutrients (N and P in dissolved inorganic and organic forms). Future trends in the model are based on a baseline scenario: Global Orchestration, which is one of the Millennium Ecosystem Assessment scenarios. The drivers and sources of nutrient pollution in the river are analyzed using model inputs and outputs (RQ1). The management options, their costs and nutrient removal efficiencies are identified using literature (RQ2). MARINA has recently linked to a cost-optimization procedure. This integrated modelling system are updated in terms of the costs, nutrient removal efficiencies and management options (information in RQ2). The updated modeling system is applied to identify cost-effective management options to reduce coastal eutrophication in the Yangtze River mouth in 2050 (RQ3).

My thesis has six main conclusions. **First, economic growth, population booming, and hydrological changes are main drivers of increasing export of nutrient by Yangtze (Chapter 2, RQ1).** For example, the GDP gross domestic product is projected to increase by 80 times between 1970 and 2050GO. The total population is projected to over 400 million by 2050 GO. River discharge will increase by 36% in 2050 GO compare it was in 1970.

Second, diffuse sources are responsible for over half of dissolved inorganic N and point sources are responsible about 80% organic N and P in the Yangtze River mouth in 2000 and 2050 GO (Chapter 2, RQ1). Diffuse sources are from synthetic fertilizer use, animal manure recycling to land, human waste recycling to land, atmospheric N deposition to land, biological N fixation to land. For example, these diffuse sources contributed 88% to DIN river export in 1970 and may contribute to 66% DIN river export in 2050 GO. For DON, these contributions are 64% in 1970 and 15% in 2050 GO. Point sources are from animal manure direct discharge, human waste direct discharge, sewage system discharge, detergent.

These point sources contribute 83%to DIP river export in 1970 and 82% in 2050 GO. For DOP, the contributions are 72% in 1970 and 92% in 2050 GO.

Third, thirteen management options and their costs are identified for reducing future coastal eutrophication (Chapter 3, RQ2). These options are reducing synthetic N and P fertilizer use; recycling animal manure as slurry, solid or after composting; treating animal manure with primary, secondary, tertiary technologies or direct discharge of animal manure; treating human waste with primary, secondary, tertiary technologies or direct discharge of human waste. I updated the nutrient removal efficiencies and included composting as a new option compared to an earlier study for the Yangtze basin. Nutrient removal efficiencies vary between 10-90% depending on management options and nutrient forms. Costs for the options were derived from existing literature and expert knowledge. For examples, costs for fertilizers are 326 $/ton and 1119 $/ton for N and P respectively. Costs for recycling manure are 21 $/ton, 22 $/ton and 45 $/ton as slurry, solid or composting. Costs for treating animal manure are from 0-12 $/ton. Costs for treating human waste are from 0-1.56 $/ton.

Fourth, reducing a 60% gap between the actual and desired levels of nutrients at the Yangtze River mouth will cost around two billion dollars in 2050 (Chapter 4, RQ3). I focus on the 60% gap as an illustrative example. The actual levels of nutrients at the Yangtze River mouth were from the MARINA model for 2050 GO considering differences in the population growth, human activities and hydrology among the ten sub-basins. The desired levels of nutrients at the river mouth were based on an environmental target and derived from an IPCE (Indicator for Potential Coastal Eutrophication). I developed a case relative to GO (Case 1). Under Case 1, reducing the 60% gap between the actual and desired pollution levels will require around 2 billion dollars. Here, cost-effective options for reducing nutrient export by Yangtze are recycling of animal manure (slurry and as solid), treating animal manure with secondary technologies and direct discharges of animal manure to rives (no treatment; only for a few sub-basins). These options are for most of the sub-basins of the Yangtze. Under Case 1, cost-effective options for the ten sub-basins to reduce the 60% gap between the actual and derived nutrient levels at the river mouth are determined by the cost-optimization model. As a result, reductions in the river export of nutrients to reduce this 60% gap at the river mouth range between -4-66% on N and 14-92% on P among sub-basins. This implies that the reductions differ among the sub-basins considering their characteristics (e.g., population, production of animal manure, land use) and the travel distance of nutrients towards the river mouth.

Fifth, cost-effective options may differ when assuming equal reductions in river export of nutrients among sub-basins (Chapter 4, RQ3). Case 2 and Case 3 are developed relative to GO. These cases assume equal reductions (in fractions under Case 2 and in the absolute values under Case 3) in river export of nutrients among the sub-basins to reach the 60% gap at the river mouth. Under Cases 2 and 3 the costs to achieve the environmental target are around 3.5-3.7 billion dollars. The costs of Cases 2 and 3 are much higher compared to the cost of Case 1 (around two billion). This indicates that the equal reduction for the sub-basins may be more costly. This might be associated with the fact that the sub-basins are requested to reduce the same fraction of the nutrients in the river mouth without considering the differences in the population growth, agricultural activities, hydrology and the distance towards the river mouth. These differences are considered under Case 1.

Sixth, the cost-effective options differ among the sub-basins (Chapter 4, RQ3). This holds for Cases 1, 2 and 3 that recycling animal manure to land is the most important cost-effective management option for many sub-basins. This is because recycling animal manure to land can avoid the animal manure directly discharge to rivers, which can reduce the nutrient pollution in the Yangtze River. Some sub-basins need to invest to treat animal manure with secondary technologies in Case 1. These sub-basins are from upstream and middle stream, e.g., Jinsha, Jialing, Main_stem_upper, Dongting. These sub-basins will need to invest to treat animal manure with primary treatment in Cases 2 and 3. Recycling of solid manure after composting becomes an important cost-effective option for sub-basins Jialing, Main_stem_upper, Dongting in Cases 2 and 3.

My thesis provides new insights into the cost-effective management options to reduce river export of nutrients from Yangtze in 2050. These insights can help to formulate cost-effective policies.

Chapter 1. Introduction

1.1 Background

Human activities have changed the functions and structures of our environmental system (Selman et al., 2013; Smith et al., 1999; Smith et al., 2003; Smith et al., 2009). Especially the human activities on the land as agriculture and urbanization have added considerable amounts of nutrients to rivers. River export nutrients like nitrogen (N) and phosphorus (P) further to the river mouth, which has already resulted in costal eutrophication problems in many rivers in the world. (Smith et al., 2009)
The eutrophication problems have become a global concern as it is a primary water quality problem in both fresh and coastal areas (Smith et al., 2009; Tu et al., 2019). Eutrophication can lead to the bloom of harmful algae (HABs) and kill the fishes in the coastal water, as a result, the ability and biodiversity of coastal systems are ruined (Selman et al., 2013). To protect the water quality from eutrophication, there is a need to control nutrient export by rivers (Conley et al., 2009).

Models are usually used to calculate the nutrient export of the nutrients to the river mouth because models are useful in data-scare regions where it is not easy to gather empirical data on rivers from land to sea (Kroeze et al., 2012). Models can predict the nutrient pollution in the future compared to the past data (Kroeze et al., 2012). Two fundamental kinds of models are usually used for calculation of the nutrient export. One is the lumped model, and another is the distributed, process-based models. Both kinds of models are suitable to compute the river export of nutrients to the river mouth, but it depends on the purpose. The lumped model usually calculates the nutrient export on an annual temporal scale based on quasi-empirical data (Kroeze et al., 2012), so the lumped models are mostly used to analyze the past and future trends in river export of nutrients to the coastal water. The distributed model is also called the dynamic model, and this kind of model will be the most appropriate one when to understand the mechanism of water retention or the interaction in the river basin on a short time scale (Kroeze et al., 2012).

Many models exist for nutrients that differ in the spatial and temporal levels. Examples are IMAGE-GNM (Integrated Model to Assess the Global Environment–Global Nutrient Model) (Beusen et al., 2015; Liu et al., 2018), Global NEWS-2 (Global Nutrient Export from WaterSheds) (Mayorga et al., 2010), MARINA (Model to Assess River Inputs of Nutrients to seAs) (Chen et al., 2019; Kroeze et al., 2012; Strokal et al., 2016; Yang et al., 2019), SPARROW (SPAtially Referenced Regressions On Watersheds) (Morales-Marín et al., 2017; Morales-Marín et al., 2018; Smith et al., 1997; Zhou et al., 2018), SWAT (Soil and Water Assessment Tool) (He et al., 2019; Arnold et al., 2012), and NUFER (NUtrient flows in Food chains, Environment and Resources use) (Ma et al., 2012). Some models estimate the nutrient exports in the basins (Global NEWS-2), sub-basins (MARINA) and grids (IMAGE-GNM, SWAT) scale. Many models are annual models, and a few are seasonal models (Chen et al., 2019). Many models are used for rivers (Global NEWS-2, MARINA, IMAGE-GN) and a few are used for lakes (Yang et al. ,2019).

1.2 Problem description

The Yangtze River is the world's third longest river and the largest one in China and it is an important water source for national development. In the past 20 years, cities and towns expanded around 39%

along the Yangtze River and the wastewater discharge to the Yangtze river basin extends 40% of the country's total discharge (China Pictorial, 2018). The water in the Yangtze river has experienced environmental degradation problems (Li et al., 2014). One of the environmental problems which have not been solved yet is eutrophication (Chen et al., 2019).

Since the 1960s, the trend of increases of DIN (dissolved inorganic nitrogen) and DIP (dissolved inorganic phosphorus) and decreases of Si (dissolved silica) have been proven in coastal water around the Yangtze River mouth (Wang, 2006). As a result, there has shown an explosion of HABs (harmful algal blooms) and decreases of macrozoobenthic biomass from the 1980s to today. This phenomenon suggests that the Yangtze River coastal water is at a high level of eutrophication since the 1980s (Wang, 2006). Coastal water eutrophication can cause serious results, such as HABs and hypoxia (Selman et al., 2013) and severe deterioration to the ecosystem's function (Tong et al., 2017). When HABs appear in coastal water, they are usually called "red tide" or "brown tide" because of the color of the algae covering the surface water (Selman et al., 2008). "Red tide" or "brown tide" caused by eutrophication is toxic and it can threaten the health of residents living surround the coastal water, so people always call these water areas "dead zones" (Cheng et al., 2019). Studies have summarized the indicators that cause eutrophication, and they are temperature, nutrients load, light, conductive activities, hydrological conditions and water retention time. According to Billen et al. (2007), nutrient loads are the main factors that influence the coastal environmental areas. The concentration of nutrients in the Yangtze River is very high (Tong et al., 2012). In 2012, the Yangtze River accounts for 66% of nitrogen discharge and 84% of phosphorus discharge in the coastal sea areas (Tong et al., 2012). The major part of the nutrient export by the Yangtze River is from the terrestrial areas riverine discharge (Li et al., 2014). Terrestrial riverine discharge can be divided into point sources and diffuse sources. The nutrient discharges from point sources are usually collected to the wastewater treatment plants, but the diffuse sources can be an uncertain input because its large amount and its difficulty to collect (Tong et al., 2017).

Around the Yangtze River basin, especially in rural areas, human waste and animal manure are sometimes directly discharged to the river (Strokal et al., 2016, 2017). Therefore, to know the nutrient export to the Yangtze River mouth, proper models need to be used and small modifications need to be done to suit the regional situation if necessary. The MARINA model is an integrated model has been applied to large rivers in China including the Yangtze River (Strokal et al., 2016; Yang et al., 2019). The MARINA model quantifies river export of nutrients by sources from sub-basins for the past and future. Sources are, for example, synthetic fertilizer use, human waste and animal manure directly discharged to rivers and so on. (Strokal et al., 2016; Yang et al., 2019). Comparing to other models, the MARINA model already includes a comparable complete data and covers comprehensive sources that cause nutrient pollution. It is an appropriate model to be applied in the Yangtze River basin. The model was validated for the Yangtze River (Strokal et al., 2016).

Cost-effective management options to reduce coastal eutrophication problems at the Yangtze River mouth are barely analyzed. The MARINA model is used to identify the main sources contributing to nutrient export. The MARINA model is also used to explore future trends in river export of nutrients and to analyze the technical potential of the management options (Strokal et al., 2016). However, the economic feasibility of the management options is not well analyzed. Exploring cost-effective management options is needed for three reasons. One reason is that eutrophication problems in the Yangtze River mouth are lack of cost-effective management options. The second reason is models can provide technical information for nutrient pollution reduction, but they do not know the economic feasibilities. The third reason is this integrated modelling approach combining the MARINA model with a cost-optimization process can be a good example for other basins to identify the cost-effective management options to reduce nutrient pollution in rivers and coastal waters.

1.3 Research Objectives and Research Questions

The main research objective of this thesis is to identify the cost-effective management options to reduce coastal eutrophication in the Yangtze River mouth in 2050. To realize this objective, three RQs (research questions) are answered:

RQ1: What are the main drivers and sources of nutrient pollution in the Yangtze River?
RQ2: What are the costs and nutrient removal efficiency of management options to reduce nutrient pollution in the Yangtze River basin?
RQ3: What are the cost-effective management options to reduce coastal eutrophication in the Yangtze River mouth?

RQs are related to each other (Figure 1.1). The first, the RQ 1 gives a review of different sources and drivers that causes nutrient pollution, and this overview can give a clear direction to raise various management options in RQ 2. To find a comprehensive and combination management options in RQ 3, various management options related to different sources with their costs and removal rates will be defined. The last, in RQ 3, using the integrated information from RQ 1 and RQ 2, the cost-effective management options will be found.

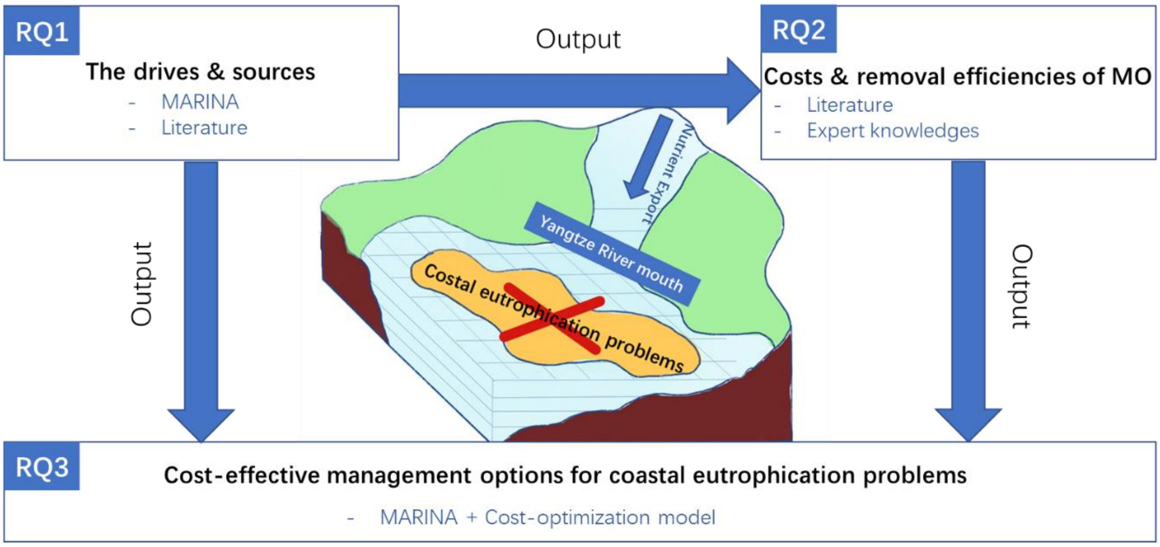


Figure 1.1 A schematic illustration of how research questions (RQs) are connected. *MARINA is short for a Model to Assess River Inputs of Nutrients to seAs. RQ is research question. MO is the management options.*

1.4 Organization of the thesis

In Chapter 2, the input data of MARINA (Model to Assess River Inputs of Nutrients to seAs) model are analyses and the drivers and sources of nutrient pollution in the Yangtze River from sub-basins are identified. This is the basic information in Chapter 2. Then a literature review is used to explain the nutrient pollution by three drivers. The last, the main nutrient pollution forms in the Yangtze River mouth are identified from the output data of the MARINA model.

In Chapter 3, a list of management options in the paper of Strokal et al (2020) is used in this thesis, and the values of costs and removal efficiencies of the management options are updated from the literature.

In Chapter 4, an integrated modelling approach by combining the MARINA model with a cost-optimal process is used to identify the cost-effective management options to reduce the costal eutrophication in the Yangtze River mouth. Three cases studies are conducted to compare the cost-optimization situation with equality situation.

Chapter 5 are conclusions and discussions. six findings as overall conclusions are given considering the information in Chapters 2, 3, 4. In a discussion, a comparison with the results and existing studies is conducted. Limitations and strengths of this research are discussed in several aspects. The last, possibilities of implementation of the thesis results are discussed in technical, practical and economic aspects.

Chapter 2. Drivers and sources of nutrient pollution in the Yangtze River

2.1 Introduction

This chapter is to answer Research Question 1: "What are the main drivers and sources of nutrient pollution in the Yangtze River?". Drivers are social-economic factors (e.g. economic growth rate, population, climate change and hydrology). Drivers may influence inputs of nutrients to rivers and their export to the sea. These inputs of nutrients come from different sources. Examples are synthetic fertilizer use, sewage water discharge, animal manure discharges, etc. The analysis mainly focuses on the past (1970,2000) and the future (up to 2050). The MARINA model: Model to Assess River Inputs of Nutrients to seAs (Version 1.0) is used to do the analysis.

This chapter is structured as follows. First, the methodology is explained in section 2.2, where the literature review and MARINA model are introduced. Second, the drivers are examined using inputs of the MARINA model in section 2.3. In section 2.4, the river exports of nutrients by sources are analyzed using the outputs of the MARINA model. Finally, conclusions are given in section 2.5.

2.2 Methodology

To answer Research Question 1, two research methods will be conducted, literature review and summarization of sources from the MARINA model. A literature review is to give an overview of different drivers and sources cause coastal eutrophication in the Yangtze River mouth, and analyses of inputs from the MARINA model are to ensure the drives and sources from the literature can be used in the MARINA model analysis. Following, these two research methods will be briefly explained.

2.2.1 Literature review

To get more comprehensive understanding of the drivers and sources of coastal eutrophication in the Yangtze River mouth, a literature review is conducted. There are two commonly used literature searching methods: systematic searching and snowball searching. Firstly, the systematic search is to give an extensive search result base on the key concepts. "Snowball" aims to find more literature by checking the citations.

When conducting systematic searching, four main key concepts are used (see Table 2.1). Three bibliographic databases are used: Scopus, Web of Science and Nexis Uni (NEWs). Search queries are created and indicated in Table 2.1. Using this method, 86-108 documents are found for the four keywords. Snowball searching can support the results of the systematic search by focusing on selected articles of the most relevant literature.

Table 2.1. The search results from a systematic search of Research Question 1.

Key concepts	Bibliographic databases	Search query	Search results
Nutrient pollution, Yangtze River, Eutrophication, Sources	**Scopus**	(driver* or source* or indicator* or factor* or cause*) and ("nutrient pollution*" or "nutrient input*" or "nutrient deliver*" or "nitrogen and phosphorus") and ("Yangtze river" or "Yangzi river" or Changjiang)	86 documents
	Web of Science		86 documents
	Nexis Uni (NEWs)		108 documents

2.2.2 MARINA model

MARINA is short for a Model to Assess River Inputs of Nutrients to seAs (Strokal et al., 2016). The model integrates the empirical approaches with process-based data for river export of nutrients (Strokal et al., 2016). The model is developed based on the Global NEWS-2 model (Global Nutrient Export from WaterSheds). The MARINA model follows the modelling approaches of Global NEWS, but for sub-basins considers the direct discharge of human waste and animal manure to rivers, which is not in Global NEWS. These sources are added to the MARINA model using outputs of the NUFER model (NUtrient flows in Food chains, Environment and Resources use) (Ma et al., 2010).

The MARINA model version 1.0 is used in this research. This version calculates the annual river export of nutrient to the river mouth. The model runs for the Yellow, Yangtze, Pearl, Huang, Hai, and Liao rivers (Strokal et al., 2016). The MARINA model is suitable in the Yangtze River basin because it considers the special regional situation in China. For example, a lot of human waste in urban and rural areas are unconnected to sewage systems. As a result, some human waste is directly discharged (untreated) into surface water (Strokal et al., 2016; Yang et al., 2019). The same holds for animal manure that is often directly discharged to surface water (Strokal et al., 2016; Yang et al., 2019).

The MARINA model can analyze the past and future trends. The inputs data of the past (1970 and 2000) are gathered from the literature and existing large-scale models (Strokal et al., 2016; Strokal et al., 2017; Strokal et al., 2014). Input data in the future (2050) is predicted by the scenarios from the MEA (Millennium Ecosystem Assessment). MEA includes four scenarios for 2030 and 2050: Global Orchestration (GO), Adapting Mosaic (AM), Order from Strength (OS), and TechnoGargen (TG) (Alcamo, et al 2005). The differences among these scenarios are in regional or global social-economic development and in proactive or reactive environmental management. The MARINA model uses the GO to predict the river export of nutrient to the Yangtze River mouth in 2050 (Strokal et al., 2016). The GO assumes increase trends in social-economic development and reactive environmental management for China in 2050 (Strokal et al., 2017).

The MARINA model calculates river export of nutrients to the coastal waters (the river mouth) in three steps (Figure 2.1). The first step is to quantify the nutrient export from land (diffuse sources or point sources) to rivers. The second step is to quantify the nutrient export from rivers to the outlets of the sub-basins. The third step is to quantify the nutrient export from the outlets of the sub-basins to the river mouth. These steps are elaborated below.

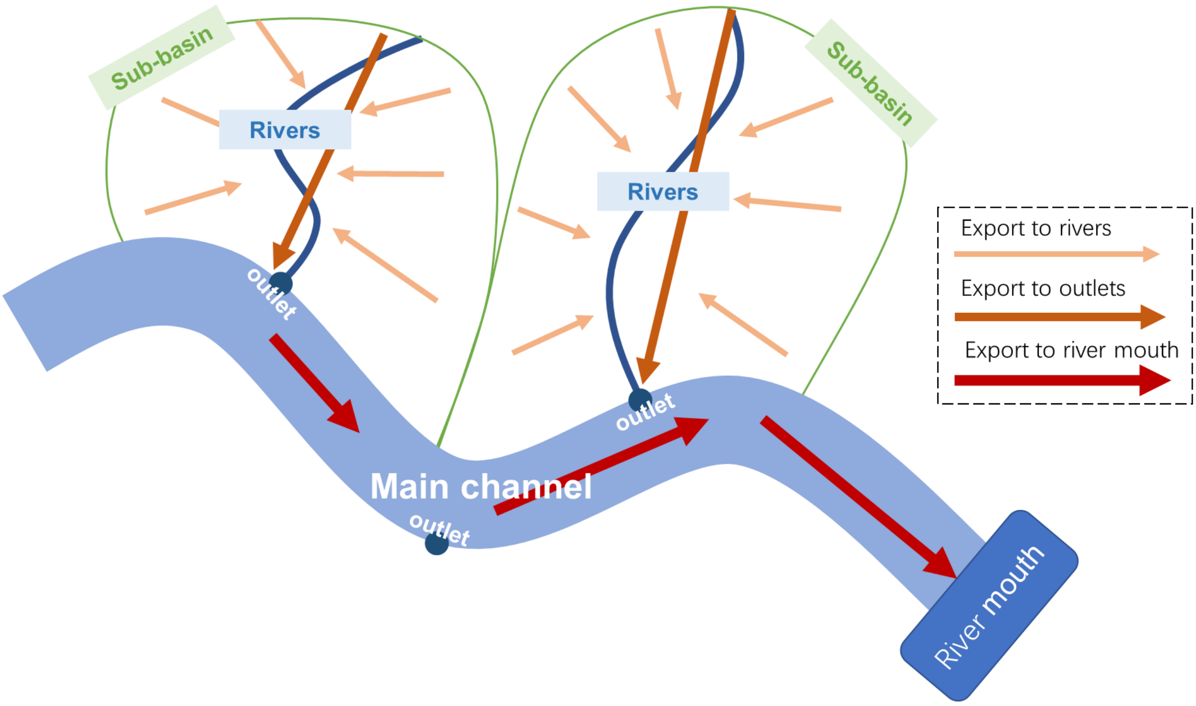


Figure 2.1 Summarized conceptual diagram of the MARINA model (Model to Assess River Inputs of Nutrients to seAs). *Source: the information is summarized based on literature (Strokal et al., 2016,2017).*

Step 1: Quantifying nutrient inputs from land to rivers ($RS_{F,y,j}$, $kton/year$)

Nutrient inputs from land to rivers usually originate from two sources: diffuse sources and point sources. The input of nutrient forms *F* (DIN, DON, DIP, DOP) from diffuse sources *y* to sub-basins *j* ($RS_{dif_{F,y,j}}$, $kton/year$) is quantified using Eq 2.1 according to Strokal et al. (2016) as:

$$RS_{dif_{F,y,j}} = WS_{dif_{E,y,j}} \times G_{F,j} \times FE_{ws,F,j} \tag{2.1}$$

where,

$WS_{dif_{E,y,j}}$ is the nutrient element (*E*: N and P) inputs to land from diffuse source *y* to sub-basin *j* (kton/year).

$G_{F,j}$ is the fraction of nutrient form (F: DIN, DIP, DON, DOP) that stays potentially in the soil after animal grazing and crop harvesting in sub-basin *j* (0-1). $G_{F,j}$ is zero for non-agricultural areas.

$FE_{ws,F,j}$ is the fraction of nutrient element (E: N or P) that enters rivers from land in a form (F: DIN, DIP, DON, DOP) in sub-basin *j* (0-1).

Nutrient inputs to agricultural land include the use of synthetic fertilizers (for N and P), animal manure (for N and P), atmospheric deposition (for N), biological N_2 fixation by legumes (for N). Nutrient inputs to non-agricultural areas include atmospheric deposition (for N) and biological N_2 fixation by natural vegetation (for N). These are all diffuse sources of nutrients in rivers. DIN and DIP are dissolved inorganic N and P, respectively. DON and DOP are dissolved organic N and P, respectively.

The input of nutrient form F (DIN, DON, DIP, DOP) from point sources y to sub-basins j ($RS_{pnt_{F,y,j}}$, $kton/year$) is quantified using equation 2.2 according to Strokal et al. (2016) as:

$$RS_{pnt_{F,y,j}} = RS_{pnt_{E,y,j}} \times FE_{pnt_{F,y,j}} \quad (2.2)$$

where,

$RS_{pnt_{E,y,j}}$ is the nutrient element (*E: N and P)* inputs to rivers from point source *y* in sub-basin *j* (kton/year).

$FE_{pnt_{F,y,j}}$ is the fraction of nutrient element (*E*: N and P) entering rivers from point source *y* as nutrient form (*F:* DIN, DON, DIP, and DOP) in sub-basins *j* (0-1).

Point sources include nutrients input to rivers from sewage systems (after treatment), direct discharges of human waste (untreated) and of animal manure (untreated).

The MARINA model quantifies inputs of DIN to rivers from weathering of P-contained minerals and inputs of DON and DOP to rivers from leaching of organic matter from agricultural and non-agricultural areas (diffuse sources). This is done as a function of runoff using an export-coefficient approach (details are in Strokal et al., 2016).

Step 2: Quantifying the fraction of nutrient form from rivers to the sub-basin outlets ($FE_{riv,F,outlet,j}$, $0-1$).

The fraction of nutrient inputs in rivers as form *F* (DIN, DON, DIP, DOP) that are exported to the outlet of sub-basin j is calculated using equation 2.3 according to Strokal et al. (2016) as:

$$FE_{riv,F,outlet,j} = (1 - D_{F,j}) \times (1 - L_{F,j}) \times (1 - FQ_{rem_j}) \quad (2.3)$$

where,

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

$L_{F,j}$ is the fraction of nutrient form (*F:* DIN or DIP) that is either retained in (P sedimentation) or removed from (N denitrification) rivers in sub-basin *j* (0-1).

FQ_{rem_j} is the fraction of nutrient form (*F:* DIN, DON, DIP, and DOP) that is removed from rivers due to water consumption in sub-basin *j* (0-1).

Step 3: Quantifying the fraction of nutrient form from the outlet to the river mouth.

In the MARINA model, the drainage area of the Yangtze River is divided into 10 sub-basins. Those sub-basins are classified as upstream, middle-stream and down-stream. There are sub-basins with the rivers and sub-basins with the main channel. This implies that rivers export nutrients to the main channel. The main channel exports nutrients further towards the river mouth. Nutrients can be lost or retained during this transport. All this is illustrated in $FE_{riv_{F,mouth,j}}$ (0-1).

The river export of nutrient at the river mouth is presented by equation 2.4 and equation 2.5 according to Strokal et al. (2016):

$$M_{F,y,j} = RS_{F,y,j} \times FE_{riv,F,outlet,j} \times FE_{riv_{F,mouth,j}} \quad (2.4)$$

$$RS_{F,y,j} = RS_{dif_{F,y,j}} + RS_{pnt_{F,y,j}} \quad (2.5)$$

where,
$M_{F,y,j}$ is the river export of nutrient form *F* (DIN, DON, DIP, DOP) to the river mouth from source *y* in sub-basin *j* (kton/year);
$RS_{F,y,j}$ is the nutrient inputs to rivers as form *F* (DIN, DON, DIP, DOP) from source *y* in sub-basin *j* (kton/year);
$FE_{riv_{F,mouth}},j$ is the fraction of nutrient inputs in form *F* (DIN, DON, DIP, DOP) that are exported from the outlet of sub-basin *j* to the river mouth (0-1);

2.3 Drivers and sources

In this section, inputs data of the MARINA model are analysed to identify drivers and sources of nutrient pollution in the Yangtze River basin for 1970, 2000 and 2050. The trends in the following drivers are discussed: economy, population, climate and hydrology (e.g., river discharges). Different sources of nutrients inputs to land are analysed. Outcomes of the literature review are used to support the analysis.

Drivers and sources of nutrients to land and rivers are connected (Figure 2.2). Economic growth, booming population and climate and hydrological changes are three drivers of nutrient pollutions in the Yangtze River mouth. The drivers have can simulate human activities, such as consumption, dam construction, fertilizer usage and so on. Then these activities will increase the input of pollution sources. Beside human activities, climate and hydrological changes will influence the nature-dominant inputs. For example, changes in nitrogen cycling and phosphorus cycling can influence the processes of deposition, fixation, weathering, and leaching.

2.3.1 Drivers of nutrient export to rivers

Human activities and natural changes can both influence the river export of nutrients. Based on the input data of the MARINA model, those drivers can be divided into three categories: economic, population, and climate and hydrology changes.

Economic growth

Economic growth is an important driver of nutrient pollution in the Yangtze River. According to Figure 2.3. With the rapid development of the economy, total GDP (gross domestic product at purchasing power parity) and GDP per capita grow very quickly in the Yangtze River basin as well. People in the future will have more income to consume, which will directly cause an increase in the consumption and production of agriculture products. Even the efficiency of synthetic fertilizer will increase in the future, with less agricultural land, more synthetic fertilizer will be needed to achieve the agriculture products demands. This means synthetic fertilizer using in the future will be more intensive then the past. Nutrient input from synthetic fertilizer to the land will increase. Synthetic fertilizer input to land is a diffuse source of nutrient inputs in the Yangtze River basin. Increased income gives people more chances to consume meat, however, increased meat demand needs more animals, and animal manure leads to nutrient pollution. In some rural parts of the Yangtze River, animal manure is used as fertilizer which can be recycled to the agriculture land (Strokal, et al., 2016; Yang et al., 2019), then those animal manure can be retained in the land and absorbed by the crops and natural plants.

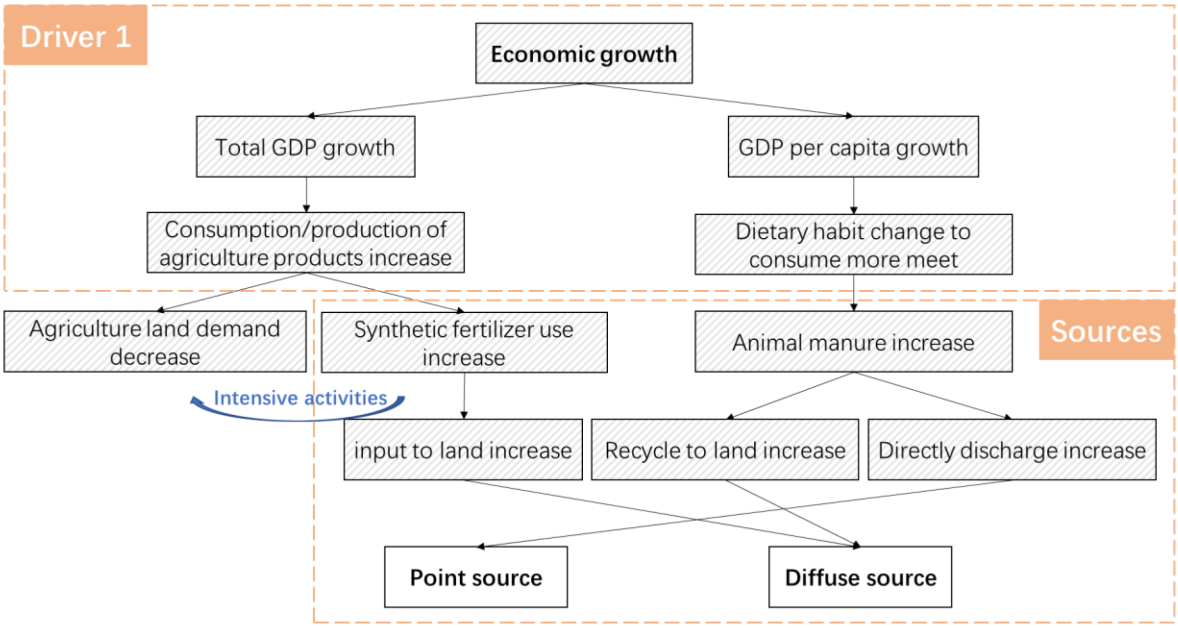


Figure 2.3 Illustrative diagram of how economic growth is linked to sources of nutrient inputs to land and rivers in the Yangtze River basin. *GDP is the gross domestic product at purchasing power parity. Source: information from MARINA 1.0 (Strokal, et al., 2016).*

The GDP per capita is projected to increase by more than 83 times between 1970 and 2050 GO (Figure 2.4). For example, in 1970, GDP per capita was around 464 $ for the Yangtze basin as a whole. This is expected to increase up to around 40000 $ in 2050 according to GO. A larger increase is quantified between 2000 and 2050 than between 1970 and 2000. This is because the GO scenario assumes a globalized world with a global market in the future (Alcamo et al., 2005). This implies that people may become richer in the future.

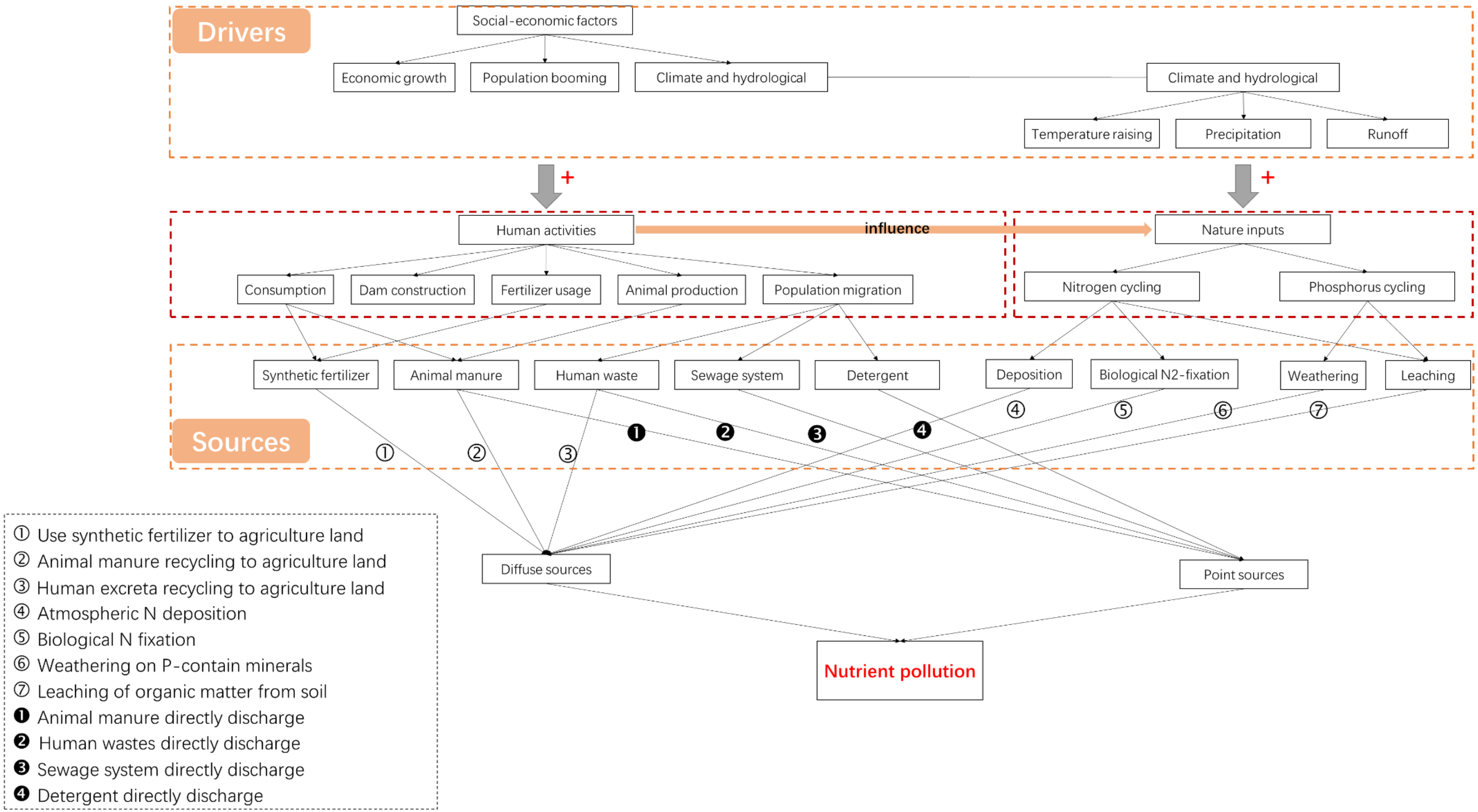


Figure 2.2 An illustrative example of the drivers and sources of nutrient pollution in the Yangtze River basin. *"+" indicates the drivers have the potential to influence the sources of nutrient inputs to land and to rivers. Number in white means the sources are divided into diffuse sources, and the number in black means the sources are divided into point sources. Human activities have an influence on the Nature-dominant inputs because deposition, fixation, weathering and leaching processes also happen on agricultural land. Source: the information integrated in section 2.3.1.*

Growth of GDP brings people more income, as a result, people's consumption of agriculture products will increase. Therefore, the production of agriculture products will also increase (Figures 2.5-2.7). However, the fraction of agricultural land may slightly decrease between 2000 and 2050 GO (Figure 2.5). This indicates that more products will be grown on less agricultural land in 2050 GO compared to 2000, implying intensification of agricultural practices. This intensification is illustrated by an increase in the use of synthetic fertilizer N (at least 1.5-fold increase) and synthetic fertilizer P (at least 4-fold increase) by 2050 GO (Figure 2.6). For example, around 962 kton of N was applied to agricultural land of the entire Yangtze basin from synthetic fertilizers in 1970. This amount was above 6000 kton of N in 2000 and may increase up to around 10000 kton in 2050 (Figure 2.6).

Economic growth is expected to influence the dietary preferences of people towards meat products (Sans & Combris, 2015). The MARINA model shows that protein intake is expected to increase for the Yangtze basin in the future (Figure 2.7). For example, nutrient intake per capita is projected to be 2.3 times more in 2050 GO than it is in 1970. This is evidence that people in the future may consume more protein-contained food, especially the animal-based protein (Sans & Combris, 2015). In this context, consumption and production of meat are expected to increase in the coming years. This will lead to an increase in animal production. As a result, more animal manure will be produced (Qian et al., 2012), contributing to more nutrient pollution to the rivers in the future (Strokal, et al., 2016). If animal manure is not managed properly, most of the animal manure is expected to enter rivers directly without treatment (Strokal et al., 2016; Yang et al., 2019). Animal manure is currently an important source of nutrient input mainly due to direct discharges (point sources).

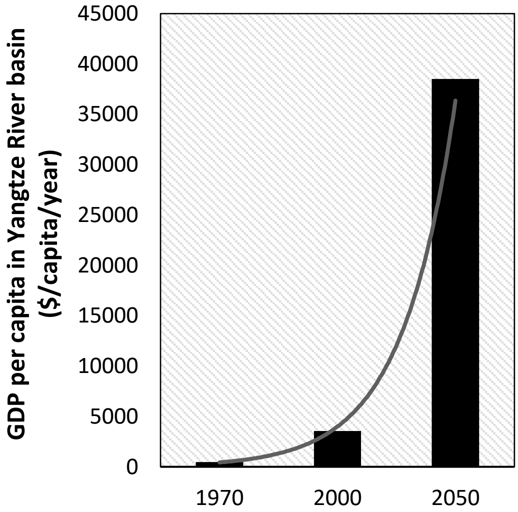


Figure 2.4 Annual GDP per capita (gross domestic products per capita) in the Yangtze River basin in 1970, 2000, and 2050 ($/capita/year)*. 2050 is based on the Global Orchestration scenario. Source: input data from MARINA 1.0 (Strokal et al., 2016)*

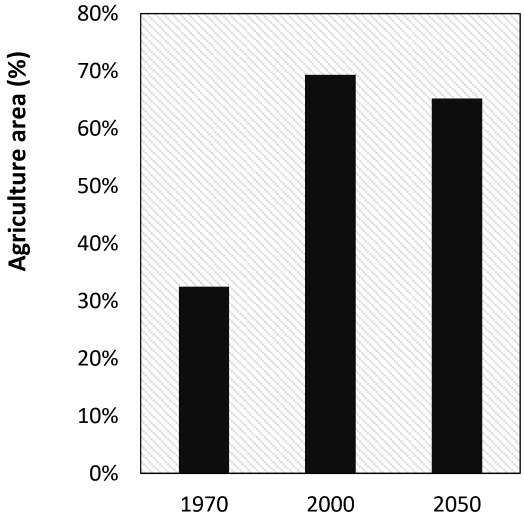


Figure 2.5 The percentage of the agricultural area in the Yangtze River basin in 1970, 2000, and 2050 (%) of the agricultural area in the basin). *The percentage for the Yangtze basin is calculated by dividing the area of agriculture land in the Yangtze River basin (km^2 from all 10 sub-basins) by the total area of the Yangtze River basin (km^2). 2050 is based on the Global Orchestration scenario. Source: input data from MARINA 1.0 (Strokal et al., 2016)*

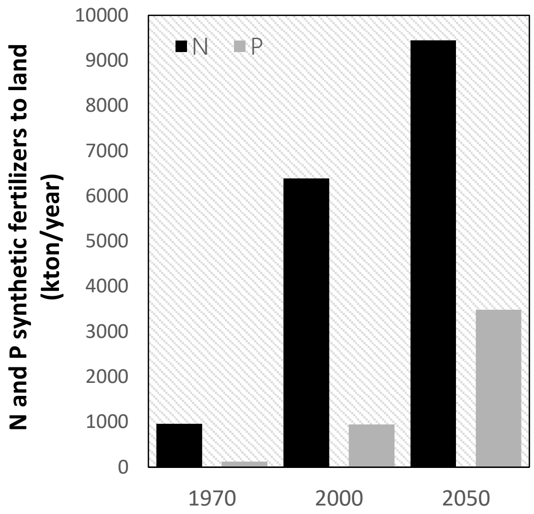


Figure 2.6 Nitrogen (N) and phosphorus (P) inputs to land from synthetic fertilizers in the Yangtze River basin (kton/year). *These values are calculated as the sum of N and P synthetic fertilizers from 10 sub-basins. 2050 is based on the Global Orchestration scenario. Source: input data from MARINA 1.0 (Strokal et al., 2016)*

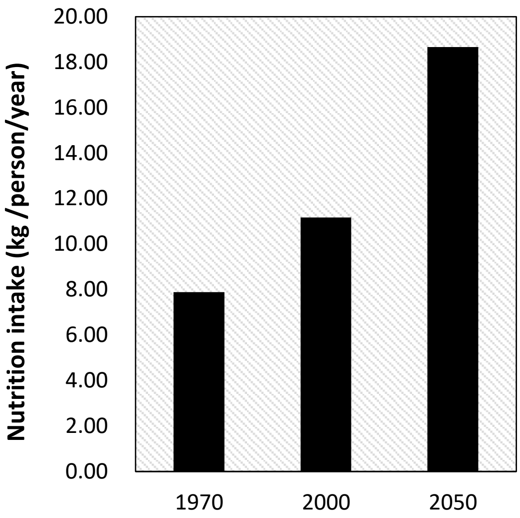


Figure 2.7 Nutrition intake per person in the Yangtze River basin in 1970, 2000 and 2050 (kg/person/year)*. 2050 is based on the Global Orchestration scenario. Source: input data from MARINA 1.0 (Strokal et al., 2016)*

Population Booming

The booming population is another major driver of increases in nutrient pollution in the Yangtze River basin (Figure 2.8). More population causes more human wastes. In the Yangtze River basin, two ways are used to deal with these wastes. Those wastes connected to the sewage system will be treated before discharge, but there still some unconnected waste directly discharge to surface water, which usually happens in rural areas (Strokal et al., 2016; Yang et al., 2019). With the increase of urbanization, more people in rural areas migrate to urban areas, which increases the pressure of urban sewage systems. Those increased population are not 100 percentage connected to the sewage system, so unconnected human wastes can only be discharged directly to surfaces water or be recycled to agriculture lands. No matter what, they both cause nutrient pollution. More than that, increased population also brings increased use of detergent and it is a dominant source of phosphorus. The booming population can result in increased source nutrient input to the river basin, such as human waste, sewage system inputs and detergent.

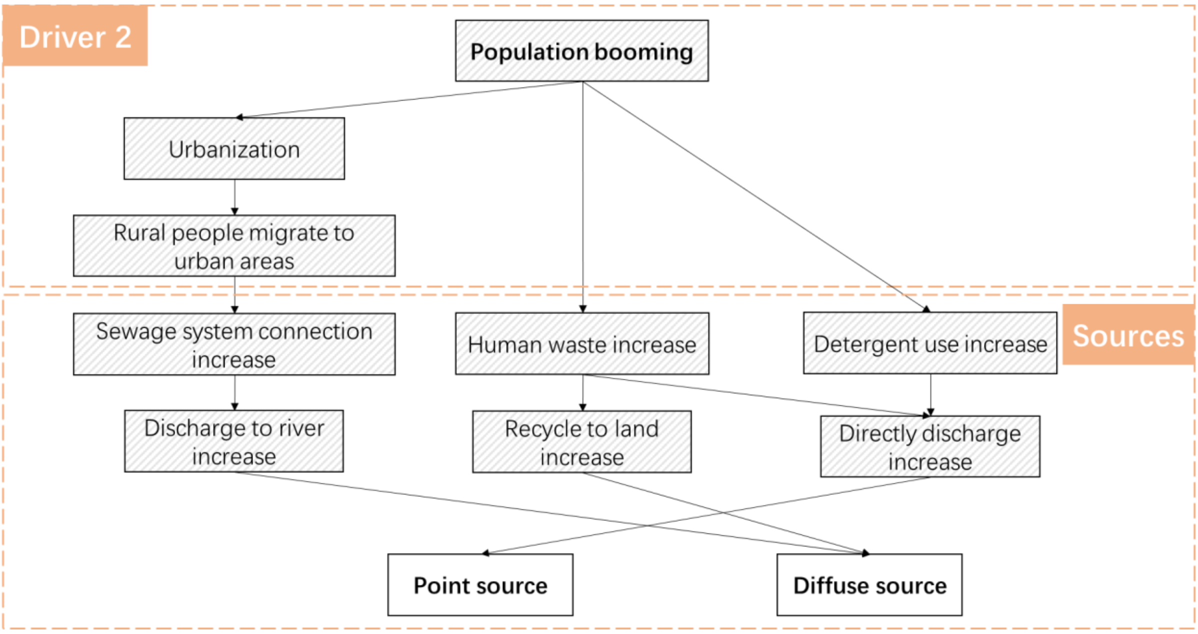


Figure 2.8. Illustrative diagram of how population booming can influence the sources of nutrient inputs to rivers in the Yangtze River basin. *Source: information from MARINA 1.0 (Strokal et al., 2016)*

The total population increased by almost 1.5 times between 1970 and 2000 and may stabilize by 2050 in the Yangtze basin according to GO (Figure 2.9). However, the number of urban people is expected to almost double between 2000 and 2050 GO. This is associated with urbanization trends. More people may move to cities. As a result, more people are expected to be connected to sewage systems (Figure 2.10), this will generate more N and P in rivers from sewage systems (Figure 2.11). For example, sewage system connection rates increased from 5% in 1970 to 16% in 2000 and may reach 40% in 2050 GO (Figure 2.10). This directly leads to the increase of nutrient (N and P) inputs to rivers of the Yangtze river basin (Figure 2.11). This has to do with the fact that the treatment efficiency of removing N and P in waste may remain relatively low in the future in 2050 GO.

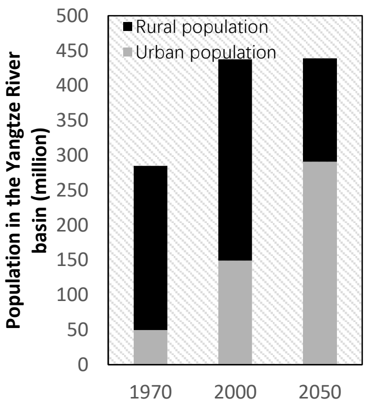


Figure 2.9 Urban and rural population in the Yangtze River basin in 1970, 2000, and 2050 (million). *2050 is based on the Global Orchestration scenario. Source: input data from MARINA 1.0 (Strokal et al., 2016)*

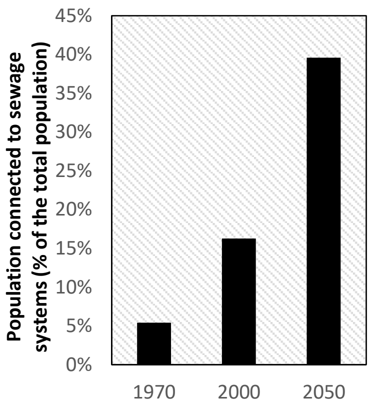


Figure 2.10 Population connected to sewage systems in the Yangtze River basin in 1970, 2000, and 2050 (%). *2050 is based on the Global Orchestration scenario. Source: input data from MARINA 1.0 (Strokal et al., 2016)*

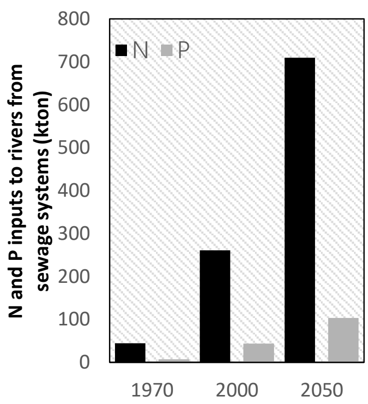


Figure 2.11 Nitrogen (N) and phosphorus (P) inputs to rivers from the sewage systems in the Yangtze River basin in 1970, 2000, and 2050 (kton). *2050 is based on the Global Orchestration scenario. Source: input data from MARINA 1.0 (Strokal et al., 2016)*

Climate and hydrological change

Climate and hydrological change is the third driver of nutrient inputs in the Yangtze River (Figure 2.12). With climate change, the raising of temperature leads to the evapotranspiration of water. These have a negative influence on river discharge. Accompanying with increased extraction of water and construction of dams, river discharge may decrease. However, when precipitation increase, it can counter this negative influence on river discharge. Dams on the river can also retain the water in the repertories and slow down the flow rate of the river, which also have an impact on the nutrient removal rate. Human extraction has the same effect. However, during extraction, some nutrients in the water can be taken out from the river, which means water extraction has two adverse impacts on the nutrient export in the river.

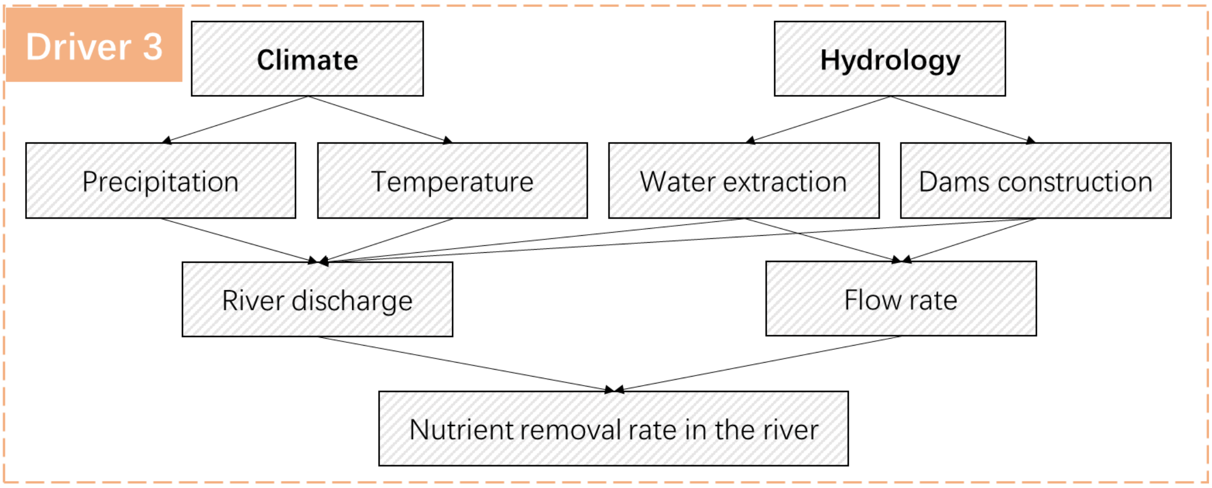


Figure 2.12. Illustrative diagram of how climate change and hydrology influence nutrient retentions in rivers in the Yangtze River basin. *Source: input data from MARINA 1.0 (Strokal et al., 2016)*

The actual river discharge in the Yangtze River basin increased between 1970 and 2000 from 403 km^3 to 437 km^3, and it may also increase from 2000 to 2050, reaching at around 550 km^3 (Figure 2.13). River discharge increase by 36% in 2050 comparing to it is in 1970. The river discharge is influenced by precipitation and the temperature (Li et al., 2018). Human extraction has an impact on river discharge as well. According to Figure 2.14, river extraction in 1970 is only 93 km^3, but in 2000, it increases to 124 km^3. In the future 2050, the water extraction in the Yangtze River may be 140 km^3, which means the water extraction increase by 50% from 1970 to 2050. Why river discharge still increases with growing extraction from human in the Yangtze River can be explained by that the precipitation in the future will increase and have a counter effect as the water extraction.

Dams in the Yangtze River basin increasing as well (Figure 2.15). In the past, there are only big 19 dams in 1970, but until 2000 it increases more than two times to 45 big dams. There is a trend that more and more dams construction with the development of society. Big dams can retain the water and slow down the flow of the river. On one hand, it can influence the nutrient element removal rate in the river, on the other hand, the repertories can retain some nutrients and reduce the nutrient export in the river mouth.

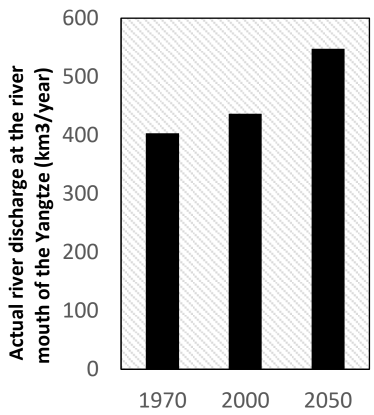


Figure 2.13. Actual river discharge at the river mouth of the Yangtze River basin in 1970, 2000, and 2050 (km^3/year). *2050 is based on the GO (Global Orchestration) scenario. Source: input data from MARINA 1.0 (Strokal et al., 2016)*

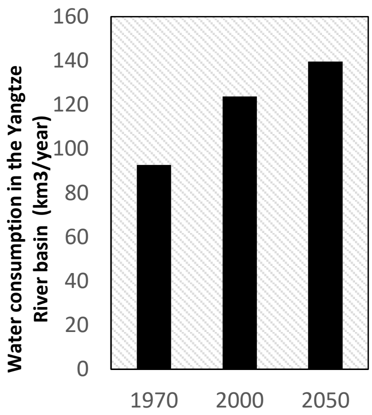


Figure 2.14. Water consumption in the Yangtze River basin in 1970, 2000, and 2050 (km^3/year). *Water consumption is quantified as the difference between natural (before consumption) and actual (after consumption) river discharge at the river mouth of Yangtze. 2050 is based on the GO (Global Orchestration) scenario. Source: input data from MARINA 1.0 (Strokal et al., 2016)*

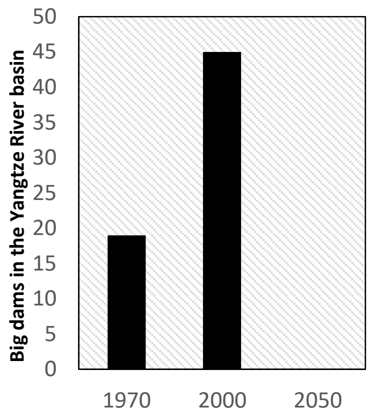


Figure 2.15. Dams in the Yangtze River basin in 1970, 2000, and 2050*. These dams are larger than 0.5 km^3. There is no prediction of 2050. 2050 is based on the GO (Global Orchestration) scenario. Source: input data from the GRAnD database that is incorporated in the MARINA 1.0 model (Strokal et al., 2016)*

2.3.2 Sources

Various sources contribute to N (nitrogen) and P (phosphorus) inputs to land and rivers (Figure 2.15). Considerable amounts of N and P to agricultural land are from synthetic fertilizers especially in 2000 and 2050 GO. Animal manure was an important source of N and P on agricultural land in 1970, but not in 2000 and 2050. This is because of the transformation of the livestock farms from traditional towards more industrial ones (Strokal et al., 2014). Traditional farms recycle most of the manure on the land. Industrial farms are often located far from crop production. Manure is often directly discharged to nearby water systems. This implies the contribution of manure to nutrient inputs to rivers shifted from diffuse sources (application on land) to point sources (direct discharges to rivers) between 1970 and 2000 (Figure 2.16). Sewage systems started contributing considerable amounts of N and P to rivers in 2000 and may continue this trend in 2050 GO. This is a result of an increasing population with sewage connections and relatively poor wastewater treatment (see section 2.3.1). Thus, the contribution of diffuse and point sources to nutrient inputs to land and rivers of the Yangtze basin differs among years.

The dominant source can be identified according to Figure 2.16. For nitrogen inputs, the sum of synthetic fertilizer to land, animal manure recycling to land, atmospheric N deposition and animal manure direct discharging account for a major part of the total inputs as 61%, 83%, 87% respectively in 1970, 2000 and 2050. Biological N fixation to land is a main source in 1970 accounting for approximately 30% nitrogen inputs but it becomes not as important anymore in 2000 and 2050 which only takes less than 10% of the total nitrogen inputs. It is easier to find the main sources of phosphorus inputs because it has a simpler composition. Synthetic fertilizer to land and human wastes recycling to land are the dominant sources, accounting for almost 70% in 1970, 2000 and 2050 and animal manure directly discharge starts to become an important nutrient source since 2000. This can tell that diffuse sources are the main contributor to nutrient inputs. The diffuse sources account for an average of 85%

of the total nitrogen inputs and average of 75% of the total phosphorus inputs (Figure 2.16). Diffuse sources include N inputs to land from synthetic fertilizer (Figure 2.17a), animal manure (Figure 2.17b), human waste (Figure 2.17c), atmospheric N deposition (Figure 2.17d), and biological N fixation (Figure 2.17e). Point sources include N and P inputs to rivers from direct discharges of animal manure (Figure 2.17f) and human waste (untreated, Figure 2.17g), N and P in rivers from sewage systems (Figure 2.17h) and P in rivers from detergents (Figure 2.17i).

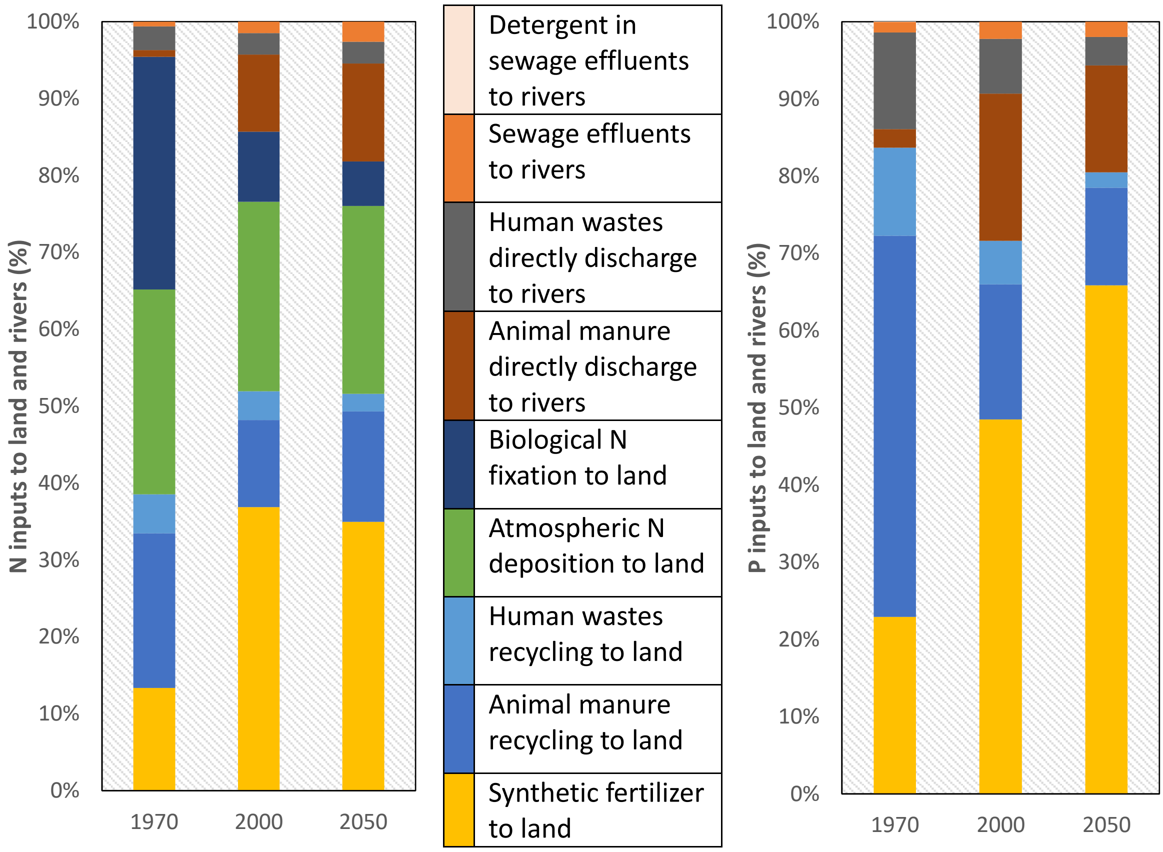


Figure 2.16 Share of nitrogen inputs to land and to the rivers from diffuse and point sources in the Yangtze River basin (% share in the total diffuse and point source inputs). *This percentage is calculated by dividing nutrient inputs from one source by the total nutrient inputs in the Yangtze River basin. N stands for nitrogen and P stands for phosphorus. 2050 is based on the Global Orchestration scenario. Source: information from MARINA 1.0 (Strokal et al., 2016)*

Except for biological N fixation to land, N inputs to land from other diffuse sources are quantified to increase by 1-9 folds in the Yangtze basin during the period of 1970-2050 (Figure 2.17). P inputs to land from the diffuse sources also increased by 1-27 times during 1970-2050. For example, N inputs from synthetic fertilizer were at 962 kton in 1970, increased to around 6000 kton in 2000 and may increase to 10000 kton in 2050 (Figure 2.17a). This increase is caused by intensive synthetic fertilizer use in this period of 1970-2050. Likewise, inputs of N and P to the land of the basin from animal manure have increasing trends from 1970 to 2050 (Figure 2.17b). However, the amount of produced manure is much more in 2000 and 2050 than in 1970. The fraction of manure that is recycled on land in 2000 and 2050 is much lower than in 1970. Nutrient inputs to land from human wastes has also increasing trends between 1970 and 2000, but these inputs may slightly decrease from 2000 to 2050 (Figure 2.17c). This can be explained by an increased connection of human wastes to sewage systems. Nitrogen inputs to land from atmospheric deposition increased between 1970 and 2000 and may further increase by 2050 (Figure 2.17d). However, the trends are different for N inputs to land from biological fixation during 1970 and 2050 (Figure 2.17e). Biological fixation has two types, one is agriculture crops fixation and the other is natural plant fixation. It has been analysed that agriculture crops increase during this period, so biological nitrogen fixation decline may be caused by a decrease of natural plants in this region during the time.

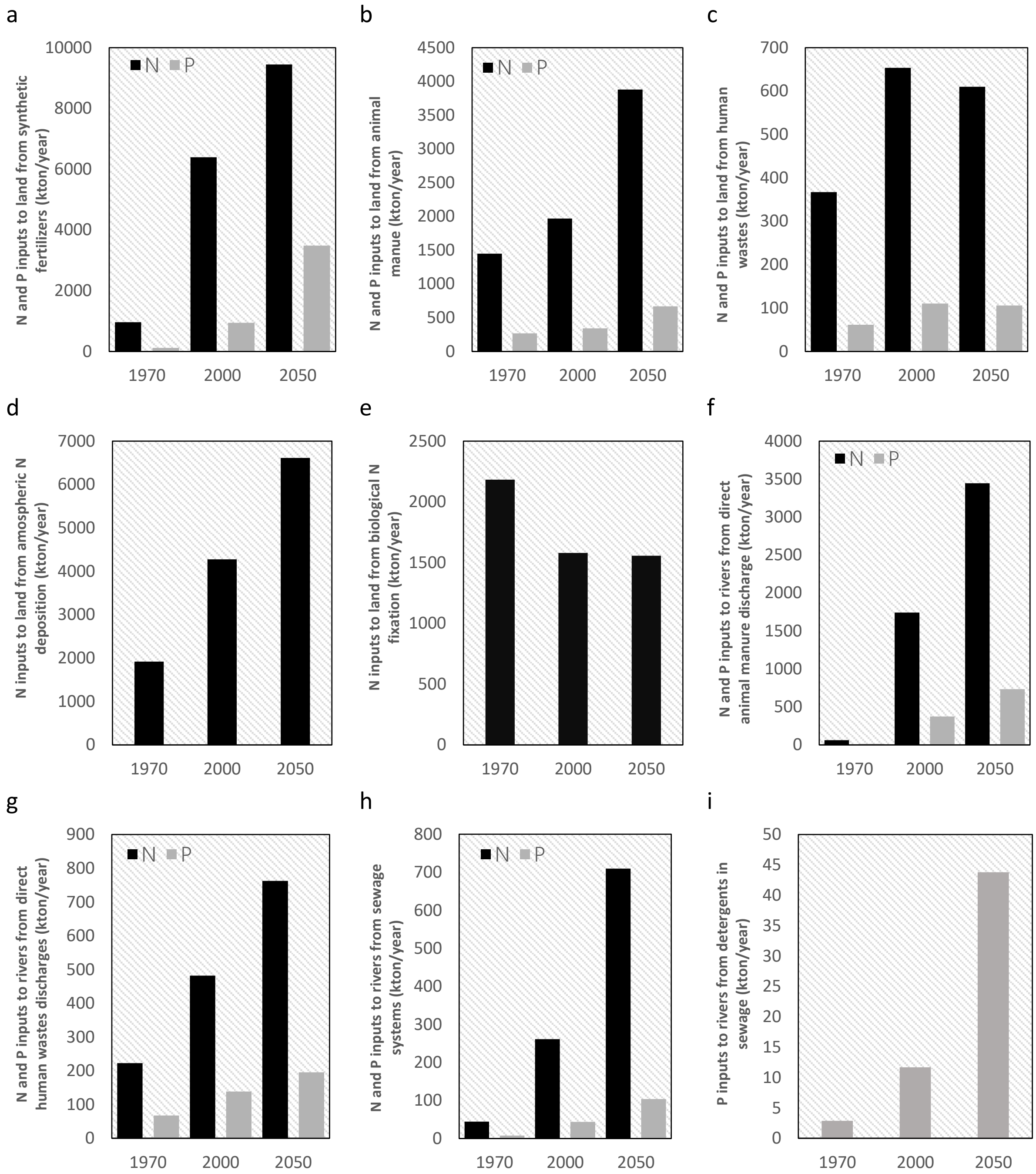


Figure 2.17 Sources of nutrient inputs to land and rivers in the Yangtze River basin (kton/year). *a is N and P inputs to land from sythetic fertilizer (Kton/year); b is N and P inputs to land from animal manure (Kton/year); c is N and P inputs to land from human waste (Kton/year); d is N inputs to land from amospheric deposition (Kton/year); e is N inputs to land from biological N fixation (Kton/year); f is N and P inputs to rivers from animal manure discharge (Kton/year); g is N and P inputs to rivers from human waste discharge (Kton/year). h is N and P inputs to rivers from sweages systems (Kton/year); i is P inputs to rivers from detergent in sewage (Kton/year); N stands for nitrogen and P stands for phosphorus. 2050 is based on the Global Orchestration scenario. Source: information from MARINA 1.0 (Strokal et al., 2016)*

Increasing trends are estimated for N and P inputs to rivers from point sources during the period of

1970-2050 GO (Figure 2.17f-i). For example, N and P inputs to rivers of the basin from direct discharges of animal manure increased by around 50-folds between 1970 and 2000 (Figure 2.17f). In 1970, direct discharge of N and P from animal manure to rivers were close to 60 kton and 10 kton. By 2000, this amount becomes around 1500 kton of N and 500 kton of P in rivers from direct manure discharges. By 2050, these amounts may more than double. This is associated with the growth of animal production and poor manure management. Increasing population and sewage connections can explain increasing trends in N and P inputs to rivers from sewage systems (Figure 2.17h). This also holds for P inputs from detergent usage (Figure 2.17i).

2.4 River export of nutrients

In this section, the outputs of MARINA are analysed for nutrient export by the Yangtze in 1970, 2000 and 2050. River export of nutrients results from 10 sub-basins. River exports of DIN and DON are analysed. The same holds for DIP and DOP.

2.4.1 Nitrogen export by the Yangtze

River export of DIN and DON increased by 1-3 times between 1970 and 2000 and may continue increasing by 2050 (Figure 2.18). In 1970, about 449 kton of DIN and DON were exported to the river mouth. Most of N was exported as DIN. This is different for 2000 and 2050 GO where the share of DIN is equal to the share of DON. In general, DON is projected to become a more important form in 2050 GO.

Diffuse sources were responsible for 88% of DIN river export in 1970. This was 64% for DON. In 2050, diffuse sources will account for 66% of river export of DIN and 15% of river export of DON. Diffuse sources are synthetic fertilizer use, animal manure to land, human waste to land, atmospheric N deposition on agricultural land and nonagricultural land, N fixation on agricultural land and nonagricultural land, organic N leaching from agricultural land and nonagricultural land. Synthetic fertilizer and animal manure were responsible for less than half of DIN exported to the river mouth of the Yangtze in 1970 (Figure 2.19). DON was largely from the leaching of organic matter over non-agricultural areas. In Figure 2.19, leaching and animal manure takes a major part of DON export. The share of the sources in DIN and DON export by the Yangtze is different for 2000 and 2050 GO. More than half of DIN in rivers of Yangtze was from the use of synthetic fertilizers, animal manure recycling on land and animal manure direct discharge in 2000. In contrast, animal manure direct discharges were responsible for over half of the DON in rivers in 2000. The share of synthetic fertilizers in river export of DIN may increase by 2050 according to GO. For DON, this holds especially for direct manure discharges that are expected to contribute over two-thirds of DON in rivers in 2050.

There is a large spatial variability in river export of DIN and DON among sub-basins (Figure 2.18). Over half of DIN export to the river mouth resulted from the middle-stream sub-basins in 1970. The large contribution of these sub-basins is also quantified for 2000 and 2050 GO. In particular, river export of DIN is mainly from the Middle Stem, Han, Poyang, Dongting sub-basins. For river export of DON, the middle-stream sub-basins also contribute largely, but not the extent as for river export of DIN. Activities in the upstream sub-basins are also important for river export of DON (Figure 2.18).

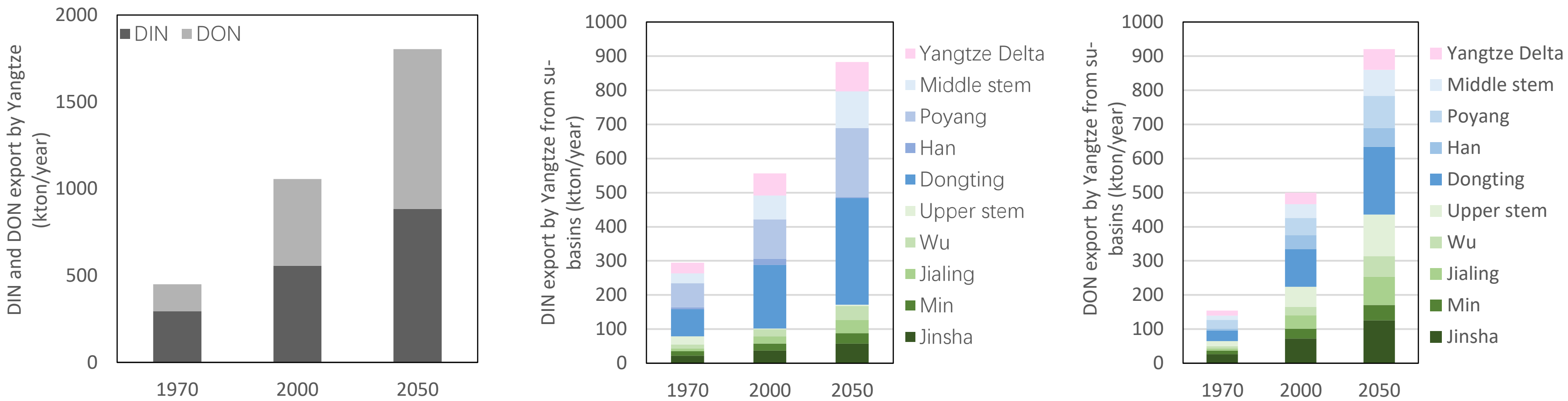


Figure 2.18 Dissolved inorganic (DIN) and organic (DON) nitrogen (N) export by the Yangtze from different sub-basins in 1970, 2000, and 2050 (kton/year). *Source: output data from MARINA 1.0* (Strokal et al., 2016)

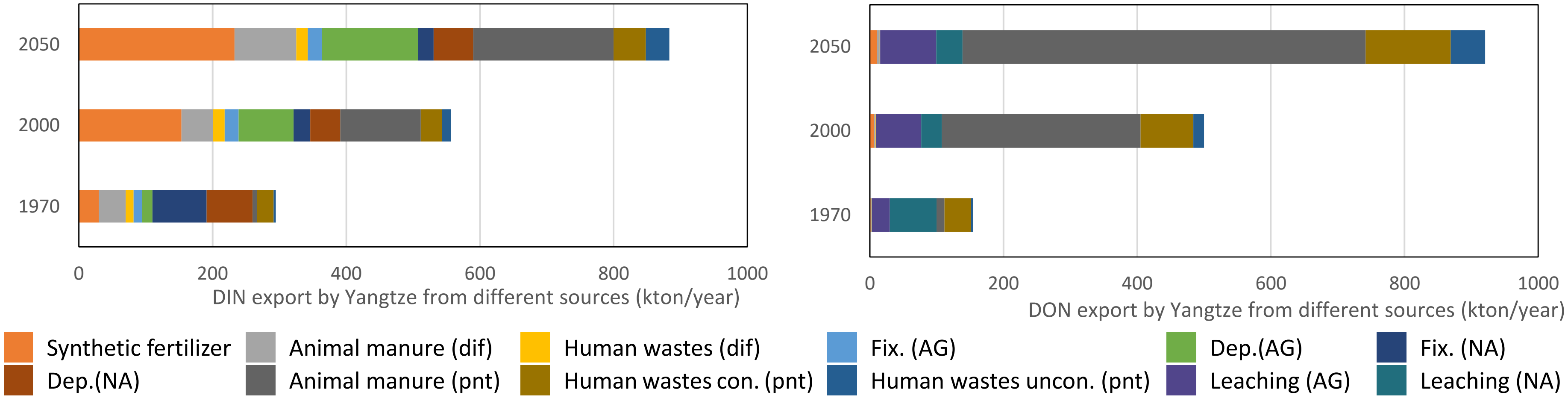


Figure 2.19 Dissolved inorganic (DIN) and organic (DON) nitrogen (N) export by the Yangtze from different sources in 1970, 2000 and 2050 (kton/year). *dif is diffuse source; pnt is point source; Fix is biological fixation; Dep is atmospheric deposition; AG is agricultural land; NA is Natural land; con. is human waste collected by sewage systems; uncon. is human waste that is not collected by sewage systems. 2050 is based on the Global Orchestration scenario. Source: output data from MARINA 1.0 (Strokal et al., 2016)*

2.4.2 Phosphorus export by the Yangtze

River export of DIP and DOP increased by 1-4 times between 1970 and 2000 and may continue increasing by 2050 (Figure 2.20). In 1970, about 38 kton of DIP and DOP were exported to the river mouth. DIP and DOP take the same share. This is different for 2000 and 2050 GO where the share of DOP is 3-4 times higher than the share of DOP. In general, DOP is projected to become a more important form in 2050 GO.

Point sources were responsible for 83% of DIP river export in 1970. This was 72% for DOP. In 2050, Point sources will account for 82% of river export of DIP and 92% of river export of DOP. Point sources are from animal manure directly discharge, human waste directly discharge, sewage system discharge and detergent in the sewage system. Human waste direct discharge export more than half of the DIP to the river mouth of Yangtze in 1970 (Figure 2.21). DOP was largely from animal manure and human waste discharge to rivers. The share of the sources in DIP and DOP export by the Yangtze is different for 2000 and 2050 GO. More than 60% of DIP is from the direct discharge of animal manure and human waste in 2000, but the direct discharge of animal manure and human waste takes more than 90% of DOP export in the river mouth. The share synthetic fertilizers in river export of DIP may increase by 2050 according to GO. For DOP, this holds especially for direct animal manure and human waste discharges that are expected to contribute over 90% of DOP in rivers in 2050.

Differences between DIP and DOP export in sub-basins was shown in Figure 2.20. DIP export is mainly from middle stream sub-basins and delta, and DOP export is mainly from middle stream sub-basins. Yangtze Delta, Poyang, Dongting exports most part of DIP in the river mouth, more than 50% of the total exports. As for DOP, the trend does not change much, Dongting sub-basin is still the main exporter, but Yangtze Delta, Poyang sub-basins is not the main exporter anymore. On the contrary, Wu and Jinsha become more important to DOP export. This means sub-basins like Dongting, Poyang, Yangtze Delta, Wu, and Jinsha need more attention.

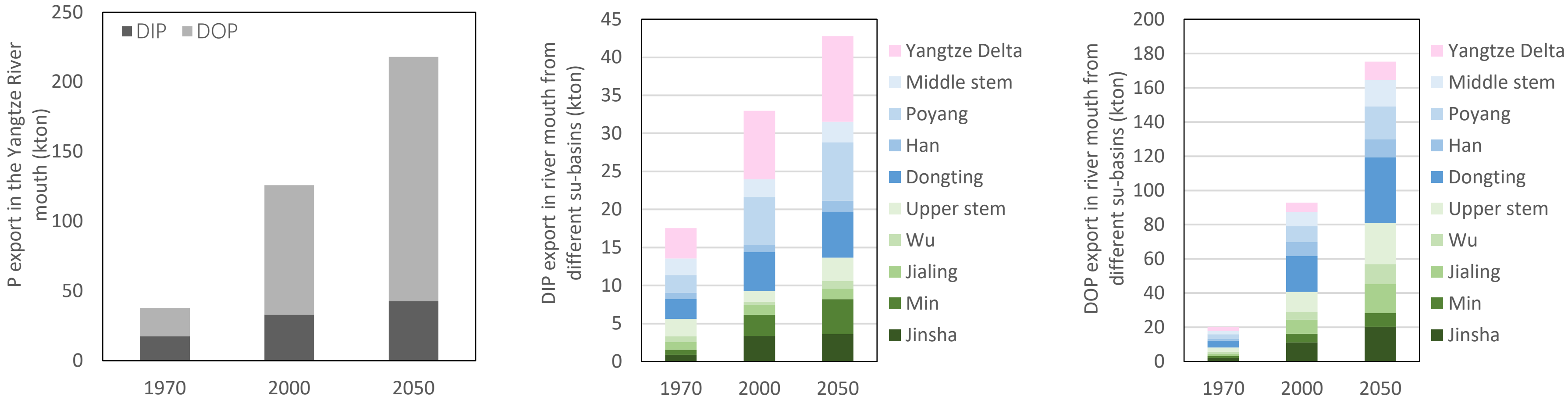


Figure 2.20 Dissolved inorganic (DIP) and organic (DOP) phosphorus (P) export by the Yangtze from different sub-basins in 1970, 2000, and 2050 (kton/year). *Source: output data from MARINA 1.0* (Strokal et al., 2016)

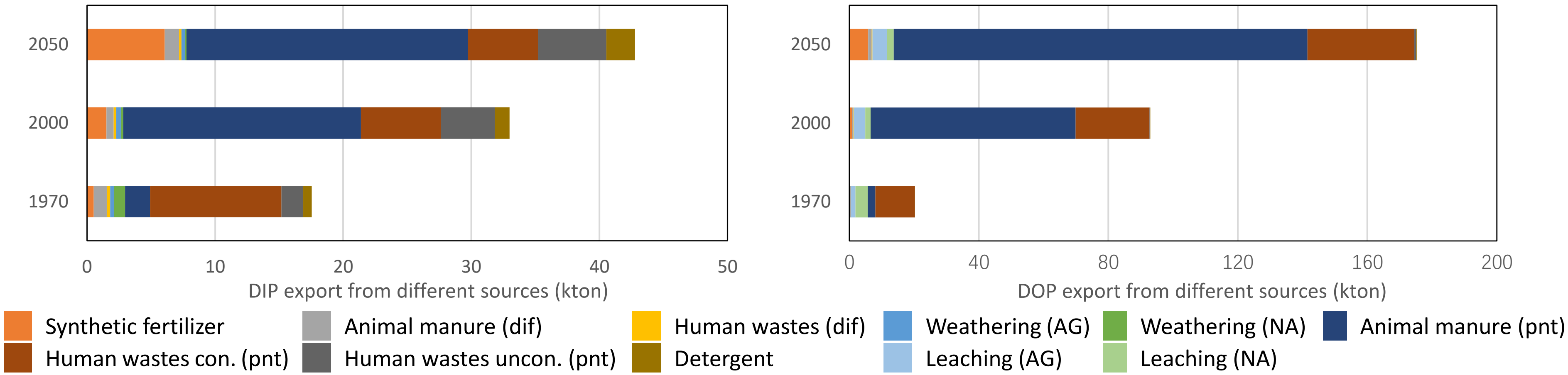


Figure 2.21 Dissolved inorganic (DIP) and organic (DOP) phosphorus (P) export by the Yangtze from different sources in 1970, 2000 and 2050 (kton/year). *dif is diffuse source; pnt is point source; AG is agricultural land; NA is Natural land; con. is human connected to sewage systems; uncon. is human unconnected to the sewage system. 2050 is based on the Global Orchestration scenario. Source: output data from MARINA 1.0 (Strokal et al., 2016)*

2.5 Conclusions

This chapter answered research question 1: “**What are the main drivers and sources of nutrient pollution in the Yangtze River?**”. Input and output data of the MARINA 1.0 model are used to answer this research question. Information from the literature is also used to support the analysis. I focused on 1970, 2000 and 2050. For the future, the Global Orchestration (GO) scenario is used in the MARINA model. Below, I summarize the main findings for drivers and sources.

Economic growth, population, and hydrological changes are three important drivers influencing future river export of nutrients in the Yangtze. For example, the GDP (Gross Domestic Product at purchasing power parity) increased by more than 80 folds between 1970 and 2050 GO. The total population in the Yangtze River basin is projected to increase 1.5 times between 1970 and 2050 GO. In 2050, urban population is projected to be a six-fold of that in 1970. Increase population and more cities will bring more nutrient pollution to the Yangtze River Basin in 2050. **Hydrological change** are not only a social-economic factor but also a natural factor as it is influenced by temperature, precipitation, and runoff. River discharges reflect changes in hydrology that is influenced by climate. River discharges are projected to increase by 36% in 2050 compared with 1970. Water consumption is projected to increase by 50% during this period.

Diffuse sources are responsible for over 60% of DIN in the Yangtze in the past and future. Diffuse sources include synthetic fertilizer inputs to agricultural land, animal manure recycling to agricultural land, human wastes recycling to agricultural land, atmospheric deposition, biological fixation, weathering on P-contained minerals, and leaching of organic matter from the soil. Diffuse sources are the main contributor of N and P (80%) inputs to the Yangtze River basin. DIN is an important pollution form in 2050. The most amount of DIN is from diffuse sources, and they take about 70% of the TDN export in 2050.

Point sources are responsible for over 80% of DIP, and over 70% of DOP in the Yangtze in the past and future. Point sources include human wastes directly discharging, animal manure directly discharging, sewage systems directly discharging and detergent directly discharging. Nutrient inputs from point sources also increase year by year. Point sources only account for 20% of the total N and P inputs to the Yangtze River basin in 2050. DOP is the dominant type of phosphorus exports and point sources are the main contributors of DOP, 90% of DOP is from direct discharge of animal manure and human waste as point sources. Organic nutrient exports are mainly from point sources. More than 80% of the DON and DOP are from point sources in 2000, it will continue to increase in 2050.

River export of the nutrients differs among the ten **sub-basins.** Middle streams and upstream sub-basins (e.g., Middle stem, Poyang, Dongting, Upper stem, and Jinsha) export generally more N and P to the river mouth from their human activities. For example, Dongting in the middle stream is responsible for average 30% of N export and 20% of P export to the Yangtze River mouth.

Chapter 3 Management options to reduce nutrient pollution in the Yangtze River basin

3.1 Introduction

This chapter is to answer Research Question 2: “What are the costs and nutrient removal efficiency of management options to reduce nutrient pollution in the Yangtze River basin?”. To answer this research question, I referred to a list of management option in the MARINA model and updated recycle animal manure to land as a new management option. The value of the cost and removal efficiency of each management option are also updated in the content from the literatures.

This chapter is structured as follows. First, the methodology is explained in section 3.2, where the literature review is the main research method. Second, management options are introduced using the integrated information from the MARINA model in section 3.3. In section 3.4, the cost of each management option is illustrated. Finally, conclusions are given in section 2.5.

3.2 Literature review

The literature review is conducted in this chapter. The literature review is to gather relevant information from different bibliographic databases to ensure theoretical support.

The literature review is the main approach to gather information about management options. Two search methods: systematic searching and snowball searching used in Chapter 2 are conducted in this chapter.

When conducting systematic searching, four key concepts from the Research Question are used for searching (Table 3.1). Three bibliographic databases: Scopus, Web of Science and Nexis Uni (NEWs) are mainly used. As a result, 127-635 documents are found in these bibliographic databases (Table 3.1). Then, a snowball searching method is conducted to find the most relevant documents.

Table 3.1 An illustrative example of the search result from a systematic search of Research Question 2.

Key concepts	**Bibliographic databases**	**Search query**	**Search results**
management options, cost, nutrient pollution, Yangtze River	**Scopus**	("Management option*" OR treatment* OR solution* or strateg*) AND ("nutrient pollution*" OR "nutrient input*" OR "nutrient deliver*" OR nitrogen OR phosphorus) AND ("Yangtze river" OR "Yangzi river" OR changjiang)	127 documents
	Web of Science		118 documents
	Nexis Uni (NEWs)		635 documents

3.3 Management options

Thirteen management options are identified in this section (Table 3.2). These options are classified into four categories: (1) reduce fertilizer use, (2) recycle animal manure on land, (3) discharge animal manure after treatment (mainly liquid), (4) discharge human waste after treatment (Table 3.2). Two options (MO) are for reducing fertilizer use: MO 1 (reduce synthetic N fertilizer use) and MO 2 (reduce synthetic P fertilizer use). These options are meant to reduce nutrient inputs to rivers from diffuse sources. MO 3, MO 4, MO 5 are three options for recycling animal manure on land as slurry (MO 3), solid (MO 4) and after composting (MO 5). These management options are meant to reduce nutrient inputs to rivers from point manure sources and diffuse manure sources by replacing synthetic fertilizers on land. Four management options are for discharging manure to rivers after the primary (MO 6), secondary (MO 7) and tertiary (MO 8) treatment and no treatment (MO 9). These management options are meant to reduce nutrient inputs to rivers from point manure sources. Four management options are for discharging human waste to rivers after the primary (MO 10), secondary (MO 11) and tertiary (MO 12) treatment and no treatment (MO 13, Table 3.2). These options are meant to reduce nutrient inputs to rivers from point sources such as sewage systems.

Connections between the identified management options and the sources of nutrient pollution in rivers exist (Figure 3.2). MO 1 and MO 2 are to reduce synthetic fertilizer use and the nutrient input from the two management options is to land as diffuse sources. MO 3 is recycling animal slurry to land and the input from MO 3 is diffuse sources. Separation is a pre-treatment process and after separation, the solid fraction is managed by MO 5 (recycle animal manure after composting) and MO 4 (recycle animal manure as solid), and the liquid fraction is treated by MO 6 (treat animal manure with primary technologies), MO 7 (treat animal manure with secondary technologies), and MO 8 6 (treat animal manure with tertiary technologies). The nutrient inputs from MO 4 and MO 5 are diffuse sources and the nutrient inputs from MO 6, MO 7, and MO 8 are point sources. MO 9 is to discharge animal manure to the river without treatment and its nutrient input is a point source (Strokal et al., 2016). MO 10 (treat human waste with primary technologies), MO 11 (treat human waste with secondary technologies), MO 12 (treat human waste with tertiary technologies) depend on sewage treatment plant and their inputs are point sources. As for MO 13 directly discharging human waste is a point source according to Strokal et al. (2016).

***Table 3.2 The list of management options to deal with nutrient pollution in the Yangtze River basin**. MO is short for management option. N is short for nitrogen and P is short for phosphorus. The options are largely based on the list of Strokal et al., (2020). A management option in bold is new compared to the list of Strokal et al., (2020).*

Categories	Management options (MO)
Reduce synthetic fertilizer use (diffuse sources)	MO 1: reduce synthetic N fertilizer
	MO 2: reduce synthetic P fertilizer
Recycle animal manure on land (diffuse sources)	MO 3: recycle animal manure as slurry
	MO 4: recycle animal manure as solid
	MO 5: recycle animal manure after composting
Discharge animal manure after treatment (mainly liquid) (point sources)	MO 6: treat animal manure with primary technologies
	MO 7: treat animal manure with secondary technologies
	MO 8: treat animal manure with tertiary technologies
	MO 9: animal manure without treatment (directly discharge)
Discharge human waste after treatment (point sources)	MO 10: treat human waste with primary technologies
	MO 11: treat human waste with secondary technologies
	MO 12: treat human waste with tertiary technologies
	MO 13: human waste without treatment (directly discharge)

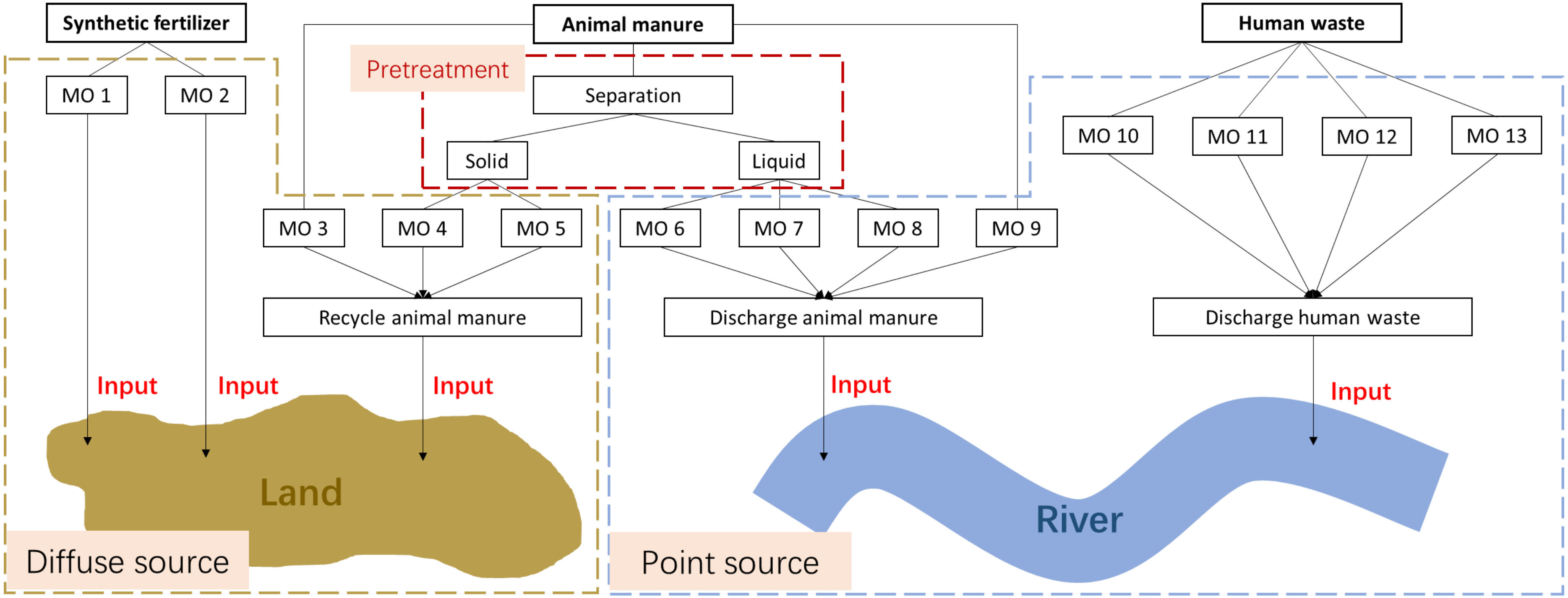


Figure 3.1 Illustrative example of the connection between thirteen management options and sources of nutrients in rivers. *MO is short for management option. Solid is the solid fraction after separation during pre-treatment and liquid is the liquid fraction after pre-treatment. Input is the nutrient input after treating by management options. Inputs to land are diffuse sources and inputs to rivers are point sources. There is a connection between animal manure management options MO 3, 4, 5, 6, 7, 8, and the detailed information can refer to section 3.3.2 Source: integrated information from section 3.3.*

3.3.1 Reduce synthetic fertilizer use

Two management options are **MO 1 (reduce synthetic nitrogen (N) fertilizer use) and MO 2 (reduce synthetic phosphorus (P) fertilizer use).** N and P are the main elements in synthetic fertilizer that contribute to nutrient pollution in the Yangtze (Strokal et al., 2016). To reduce synthetic fertilizer use can simultaneously reduce N and P input to land and thus to the Yangtze.

Two reasons why China becomes the largest consumer of synthetic fertilizer in the world (Gao et al., 2006; Ju et al., 2009; Kahrlet al., 2010). One reason is that not like the United States (U.S), the farmland for Chinese farmers is not abundant and the high-quality farmland is scarce (Gao et al., 2006; Ju et al., 2009; Kahrlet al., 2010). For example, some of the farmlands are on mountain slopes. As a result, China's agriculture depends on intensive inputs of synthetic fertilizer (Gao et al., 2006; Ju et al., 2009; Kahrlet al., 2010). Another problem of synthetic fertilizer application in China is the nutrient efficiency use (the fraction nutrient harvest as products) explained by Cui et al. (2018). Comparing to grains, vegetables and fruits are with higher value and can bring more income (Gao et al., 2006; Ju et al., 2009; Kahrl et al., 2010). Considering the economic value, farmers in China shift to vegetables and fruits planting. However, these crops are more synthetic fertilizer intensive than grains, and the nutrient use efficiency declines in this situation (Gao et al., 2006; Ju et al., 2009; Kahrlet al., 2010). Nutrient use efficiency in China is much lower than it is in the U.S., and the studies tell the fact that there is an over-application of synthetic fertilizer in China (Cui et al., 2018). The studies suggest that China can reduce the application of synthetic fertilizer of 20%-30% for grain crops while also balance the increasing agriculture product demands (Gao et al., 2006; Ju et al., 2009; Kahrlet al., 2010).

Some regulations are issued to solve the problems caused by synthetic fertilizer use. China's Ministry of Agriculture (MOA) released an action plan "Action to Achieve Zero Growth of Chemical Fertilizer Use by 2020" in 2015 (Jin & Zhou, 2018). The object of this action plan is to control the annual growth rate of synthetic fertilizer less than 1% from 2015 to 2019 (MOA, 2015). Until 2017, the annual growth rate of synthetic fertilizer has declined in three years. Under this background, it is reasonable to take reducing synthetic fertilizer use as one management option.

3.3.2 Recycle animal manure to land

Recycle animal manure as slurry (MO 3), as solid (MO 4) and after composting (MO 5) are three management options in this section.

Animal manure which contents a high level of nutrient (nitrogen and phosphorus) and low level of heavy metal is a good source of organic fertilizer (Li et al., 2017). This means animal manure is not a waste but an untreated resource (Yan et al., 2017). However, most parts of animal manure are discharged directly to rivers instead of being recycled on the land (Strokal et al., 2016). The fact is that the recycling rate of animal manure is declining with the development of animal production (Ju et al., 2005).In ancient China, animal manure was used as organic fertilizers on the land for crop production (Ju et al., 2005).

In modern China, livestock production started to industrialize in line with increasing population and food demand (Strokal et al., 2016). As a result, large amounts of manure are directly discharged to Chinese rivers. As a response, science 2001, various legislation and laws have been introduced to reduce the environmental impacts of animal manure (Li et al., 2017). For example, the latest law "Action to Achieve Zero Growth of Chemical Fertilizer Use by 2020" issued in 2015 encourages shifting synthetic fertilizer application to animal manure application to the land (Jin & Zhou, 2018). This action plan requires 60% recycling of animal manure to arable lands (Yan et al., 2017).

Knowledge of how to apply the animal manure to agriculture land is essential for sustainable recycling animal manures. Developed countries have a lot of experience in recycling animal manure to land (Yan et al., 2017). Five animal manure management technologies exist as presented by Yan et al. (2017) for the Netherlands (Table 3.3). In the Netherlands, manure is applied to land mainly as slurry (90%). The slurry is usually a mix of faeces and urine from animals (Foged et al., 2011) and generally slurry contents more than 90% of water. Some animal manure (5%) goes to solid-liquid separation in the Netherlands (Tabel 3.3). Small amounts of manure (approximately 2%) are treated with membrane filtration and biological treatment. In addition, small amounts (about 1%) of dry poultry manure is exported (Tabel 3.3). For China, manure recycling on the land as slurry and solid are identified as management options based on the study of Yan et al., (2017).

Table 3.3 Manure management technologies in the Netherlands. *The sum of the percentage is not 100% is because these are the estimated data from Yan et al. (2017). Source: (Yan et al., 2017).*

Technology	**Percentage of total animal manure treated by the technologies**
Untreated slurry	90%
Solid-liquid separation of slurry	5%
Membrane filtration of the liquid fraction	1%
Biological treatment (nitrification/ denitrification)	1%
Dry poultry exported	1%

Management option 3: Recycle animal manure as slurry
The slurry is usually from the swine and dairy farms. The slurry is transported by tankers or pipes, which makes the transportation cost high (Yan et al., 2017). As a result, it is better to recycle animal manure as slurry to land when the animal farm is close to the agricultural land (Yan et al., 2017). The transportation distance should better not exceed 200km according to Yan et al. (2017).

Ammonia volatilization is a problem when applying slurry directly. This problem is invisible but can bring a lot of problems, like odor and nitrogen loss (Joint et al., 2008). However, a lot of low-emission application technologies to avoid ammonia volatilization (Joint et al., 2008) are developed to solve this problem, such as surface broadcast, trailing hose, trailing shoe and shallow open-slot injection (Resources, 2008). According to Yan et al. (2017), the ammonia emission can be reduced from 50%-90% compared to the traditional splash-plate surface spreading of manure (Yan et al., 2017). For sure, new techniques are more expensive than the traditional ones, but with less loss of ammonia, the slurry can be more N reliable as a fertilizer (Joint et al., 2008).

Management option 4: Recycle animal manure as solid
After machinery separation, the slurry can be separated into a liquid fraction and solid fraction. The separated solid fraction with less water content can also be recycled to the land. The solid animal manure is more concentrated, and the transportation fee is less than the slurry. This can ensure the solid fraction of animal manure be transported to further distance.

Management option 5: Recycle animal manure after composting
Recycle animal manure after composting is a promising option because it can solve the odor and bacteria problems caused by recycling animal manure directly (Naidoo et al., 2017). According to TSFAMC (Technical Specification For Animal Manure Composting) definition, composting is a process of organic matter degradation by microbial fermentation under human controlled conditions (e.g., moisture, the C: N ratio, airing) (AGRI, 2019). By composting (e.g., animal manure becomes a suitable product for land use. Composted manure does not have the odor and easier to transport over longer distances. This is especially relevant for the Chinese situation where crop production is far from livestock production.

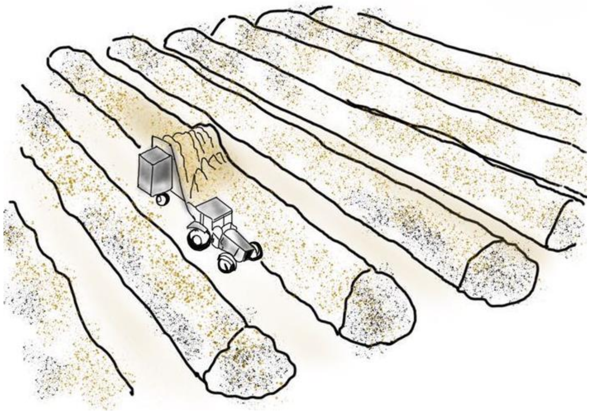
Composting is usually connected with the dry animal manure system for there is a requirement of moisture of the composting materials (Bass et al., 2012). The most suitable moisture rate for composting is about 50%. In this paper, for simplification, composting is to manage the solid fraction of animal manure after machinery separation. Comparing with directly recycling the solid fraction of animal manure to the land, the volume of the manure after composting can be smaller.

TSFAMC (Technical Specification For Animal Manure Composting) introduces three main types of aerobic composting: windrow composting, trough composting and reactor composting. According to (Li & Peng, 2011), a static heap composting is also commonly used. Pictures are related to each composting technology in figure 3.2, these pictures are modified according to the description in the book of Li (2011). These technologies are different from each other and the characters are summarized in Table 3.4. After composting, the N can lose by 60% according to a Chinese expert.

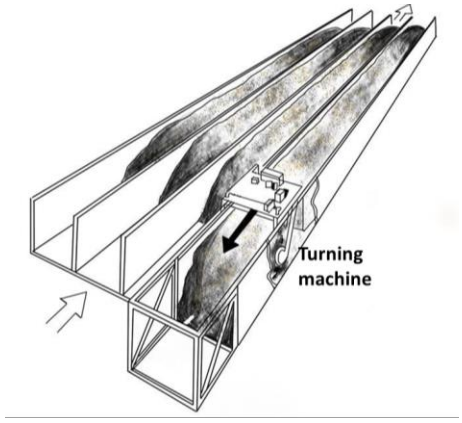
Table 3.4 Comparation of four types of composting. Source: (Li & Peng, 2011), (AGRIC, 2005).

Composting types	Characteristics	Composting time
Windrow composting	• Natural aeration and machinal turning. • Space consuming, need large land areas. • Labor need increases with the increase of aeration frequency. • Commonly used on farms	40~60 days
Trough composting	• Natural aeration and machinal turning. • Limited land required if has a good composting structure. • Need labor for monitoring. • Commonly used on farms	30~40 days
Reactor composting	• Extensive machinal turning and aeration. • Very limited land requires. • Need labors for a consistent level of management. • For commercial application	7~12 days
Static heap composting	• Forced airflow through piles or windrows. • Less land required with effective pile volume. • Preparing is important and needs labors for monitoring. • It can be effectively used on farms.	21~40 days

Figure 3.2 Illustrative pictures of Windrow composting, Trough composting, Reactor composting and static heap composting. *Source: modified pictures from (Li & Peng, 2011).*

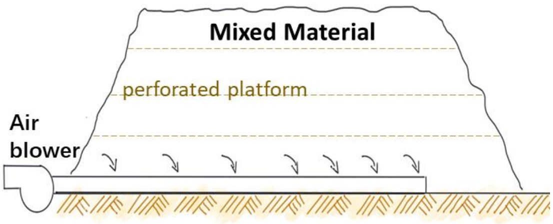


Windrow composting: it is a composting process in piles or in windrows by natural aeration or specially designed windrow turner. The height of the windrow is about 1~3m, the width of the windrow is between 2~8m and the length of a windrow can range from 30m to 100m depends on the composting material and composting position.



Trough composting: It is a composting process happens in troughs. There are tracks on the troughs to help turner machines to turn the mixed materials. Usually, there are aerated conduits in the bottom of the troughs to bring airs in the troughs. The whole process of trough composting is shorter than windrow composting and it lasts 30-40 days.

Reactor composting: It is an integrated airtight reactor including mixing, aerating, reacting and odor treatment. The bioreactor composting needs the shortest time then the other three composting and it is 7-12 days.



Static heap composting: it is a composting process in piles or windrows with a methional aeration (AGRIC, 2005). The mix of composting material is put on a perforated platform to ensure adequate air source. The main difference of static heap composting and windrow composting is that the composting material is not turned but have a special aeration system to produce air.

3.3.3 Discharge animal manure after treatment

Besides recycling animal manure to the agriculture land, the liquid fraction can also be discharged after treatment. Animal manure treatment systems can solve problems like odor, ammonia volatilization of the liquid animal manure. The main target of the manure treatment system is to reduce odor and nutrient content (Humenik, 2001). Strokal et al (2020) divide these technologies of animal treatment system into three categories: primary technologies, secondary technologies, and tertiary technologies. Primary technologies are technologies that are mechanical oriented treatment, such as solid-liquid separation, partial nitrification/denitrification, and flocculation/denitrification (Yan et al.,2017). Secondary technologies are the biological oriented treatment like nitrification/denitrification, ammonium stripping, and phosphate precipitation. Tertiary technologies are advanced treatment and tertiary treatment includes reverse osmosis, anammox and phosphate precipitation. The nutrient removal efficiency of the primary technology is the lowest and the removal efficiency of the tertiary technology is the highest (Strokal et al., 2020).

In this section, four management options are introduced. Animal manure treated with primary technologies (MO 6), secondary technologies (MO 7) tertiary technologies (MO 8) and no treatment (MO 9) are included (Table 3.5). The removal efficiencies of MO 6, MO 7, MO 8 and MO 9 are referred to the value from Strokal et al. (2020). These removal efficiencies are in an estimated value range from the literature, but in this paper, average values between the range are used as specific values of the removal efficiencies. In MO 6 (treat animal manure with primary technologies), N (nitrogen) removal efficiency is 10% and P (phosphorus) removal efficiency is 35%. In MO 7 (treat animal manure with secondary technologies) N removal efficiency and P removal efficiency increased to 60% and 60% representatively. In MO 8 (treat animal manure with tertiary technologies), N removal efficiency reaches 90% and P removal efficiency also reaches 90%. In MO 9, animal manure is directly discharged, so the removal efficiency of N and P are 0%.

Table 3.5 Removal efficiencies of nitrogen (N) and phosphorus (P) during treatment for manure management options (mainly liquid, %). *The range value is the estimated range of removal efficiency and the average value is the average number calculated from the range value. MO is short for management option. Source: (Strokal et al.,2020).*

Manure management option	**Examples of treatment technologies and associated processes**	**N removal efficiency (%)**		**P removal efficiency (%)**	
		average	**range**	**average**	**range**
MO 6: Primary technologies	Mechanical oriented treatment: Solid-liquid separation Partial nitrification/denitrification Flocculation/sedimentation	10	<20	35	<50 or <20 (without flocculation)
MO 7: Secondary technologies	Nitrification/denitrification Ammonium stripping Phosphate precipitation	60	50-70	60	50-70
MO 8: Tertiary technologies	Reverse osmosis Anammox Phosphate precipitation	90	80-99	90	80-99
MO 9: Directly discharge to rivers	-	0	0	0	0

Management option 6: Treat animal manure with primary technologies

According to Strokal et al, the primary treatment is first to separate the solid and liquid fraction from animal manure. The liquid fraction is further treated to remove N and P. Two ways are commonly used in primary treatment to remove the solid, sedimentation and flocculation (Humenik, 2001). In the sedimentation tank, the biosolids or general biomass can be removed (Humenik, 2001). Flocculation is adding chemicals to remove P or suspended solid. In the primary treatment process, the liquid fraction will also be treated by partial nitrification/denitrification (Strokal et al., 2020). After primary treatment, the N removal efficiency is limited less than 20% and the P removal efficiency is less than 50% (Strokal et al.,2020). And if there is no flocculation, the removal efficiency of P can even less than 20% (Humenik, 2001).

Management option 7: Treat animal manure with secondary technologies

The primary technology is cheap, but the removal efficiency of N is very low. Therefore, based on the primary technology, the secondary technology is usually used to further treat the liquid animal manure. The biological process happens in the secondary technology which promotes the process of nitrification and denitrification. Nitrification and denitrification are an important process to remove nitrogen. Nitrification can oxidize N to nitrate nitrogen and denitrification can transfer nitrate nitrogen to N_2O and N_2 with less environmental impact. Besides, ammonia stripping and phosphate precipitation also used in the secondary treatment. The ammonia stripping can remove ammonia from swage and phosphate precipitation is to remove phosphorus from the liquid fraction (Foged et al., 2011; Liao et al., 1995). The removal efficiency in the secondary treatment is higher than the primary treatment. The nitrogen and phosphorus can be both removed 50%-70% (Table 3.5) (Strokal et al., 2020).

Management option 8: Treat animal manure with tertiary technologies

Tertiary technologies include many technologies, such as anammox (Kartal et al., 2010; Qiao et al., 2010) and phosphate precipitation. Reverse osmosis (RO) is also used in tertiary treatment (Yan et al., 2017) to further separate the concentrate solid and clean water. After being treated by termitary technologies, the N and P both can be removed from 80% to 99% (Table 3.5).

Management option 9: Discharge animal manure directly to rivers

Directly discharging of animal manure is another management option to treat animal manure. No cost is attached to this management option, but the removal efficiency of N and P is 0 because the animal manure is not treated before discharging.

3.3.5 Discharge human waste with treatment

It is assumed that in 2050, more human waste will be connected by sewage systems according to GO (Global Orchestration). This means more human waste will be treated before discharging to rivers. In swage systems, the wastewater can be treated by physical, biological and chemical ways to reduce organic and nutrient pollution (Van Drecht et al., 2009). Different ways can be used to treat wastewater and they are classified into three categories: primary technologies, secondary technologies and tertiary technologies (advanced treatment). Human waste after primary treatment cannot meet with the discharge standard, therefore secondary treatment is needed to meet the emission standard. The discharge standard is the national standard in China according to GB 18918-2002 (GB means national standard in Chinses). GB 18918-2002 divides the effluent from the sewage system into four classes: 1A, 1B, 2, 3. 1A is the highest standard and 3 is the lowest (Jin et al., 2014). Tertiary technologies will be used to reach a higher discharge standard. In this section, four management options are distinguished with different nutrient (N and P) removal efficiencies.

The removal efficiencies of these four management options to treat human waste are different from each other (Table 3.6). Obviously, tertiary treatment has the highest removal efficiency of N and P, but it is the most expensive and time-consuming one.

Table 3.6 Removal efficiencies of nitrogen (N) and phosphorus (P) during treatment for human waste management options (%). *The range value is the estimated range of removal efficiency and the average value is the average number calculated from the range value. MO is short for management option. Source: (Shi et al., 2010; Van Drecht et al. 2009; Strokal et al., 2020).*

Categories	Treatment technologies	N removal efficiency (%)		P removal efficiency (%)	
		average	Range	average	range
MO 10: Primary technologies	Bar screen; Grit chamber; Sedimentation tank	23	(20-25)	29	(28-30)
MO 11: Secondary technologies	BNR	48	(36-59)	71	(51-90)
MO 12: Tertiary technologies	Ion exchange; Electrodialysis; Reverse osmosis	64	(45-83)	89	(88-99)
MO 13: Directly technologies	-	0	0	0	0

Management option 10: Treat human waste with primary technologies
Primary treatment is also called physical treatment, which is to remove the suspended solids by sedimentation or filtration (Inc et al., 2013). Usually, a bar screen, grit chamber, and sedimentation tank are used in primary treatment (Nathanson & Archis, 2019) (Figure 3.3). After primary treatment, the nitrogen removal rate is estimated as 20%-25% and the phosphorus removal efficiency ranges from 28%-30%. Wastewater after primary treatment will not be discharged directly, but flow to the secondary treatment system for further treatment (Inc et al., 2013).

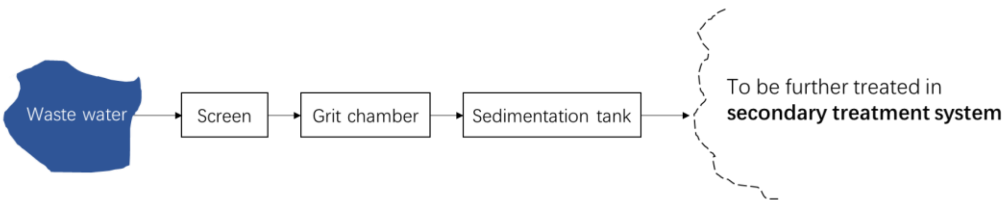


Figure 3.3. The illustrative diagram of primary treatment. *Source: (Nathanson & Archis, 2019).*

Management option 11: Treat human waste with secondary technologies
Secondary treatment is to remove the organic pollutants and the dissolved nutrients (nitrogen and phosphorus) inorganic pollutants. Biological nutrient removal (BNR) processes are usually used in secondary treatment. Typical ways of the biological process include: Activated Sludge (AS), Anaerobic-Anoxic-Oxic (A2/O), Anoxic-Oxic (AO), Oxidation Ditch (OD), sequencing batch reactor (SBR), membrane bioreactor (MBR) (Shi et al., 2010). Table 3.7 illustrated that the nitrogen removal rates among these BNR processes are from 42%-59% and the phosphorus removal rates among these BNR processes are from 66%-78%. Considering the removal rate is estimated in 2006, which should be enlarged with the development of technology. The removal rate of nitrogen is estimated from 36%-59% and the removal rate of phosphorus is from 51%-90% (Van Drecht et al., 2009).

Table 3.7 Nitrogen and phosphorus removal rate in different BNR process in China (%). *BNR is short for biological nutrient removal. DO is short for oxygen ditch. SBR is short for sequencing batch reactor. A2/O is short for anaerobic-anoxic-oxic. AO is short for anoxic-oxic. AS is short for activated sludge. TN is short for total nitrogen. TP is short for total phosphorus. Source: (Shi et al., 2010). Data is from the 2006 database.*

Categories of BNR	TN removal range (%)	TP removal range (%)
OD	59	71
SBR	58	71
A2/O	55	78
AO	58	70
AS	42	66

Management option 12: Treat human waste by tertiary treatment
Tertiary treatment also called advanced treatment, is to remove the pollutants which are not removed in secondary treatment. For example, the nutrient and organic pollutants that are difficultly biodegraded during BNR processes. To removal inorganic pollutions, ion exchange, electrodialysis, and reverse osmosis are three commonly used methods. After advanced treatment, the nitrogen can be removed 45%-83% and phosphorus can be removed 88-95% (Van Drecht et al., 2009).

Management option 13: Discharge human waste directly to rivers
Even it is suggested that human waste should all be connected to the sewage treatment system, there still a situation that people will continue to discharge human waste without treatment. This is because directly discharging doesn't include any costs, which tempts there still are some directly discharge in the future.

3.4 Costs of management options

In this section, the costs for identified 13 management options to reduce nutrients in the Yangtze in the future are discussed.

3.4.1 Cost of reducing the use of synthetic fertilizers

Different types of synthetic fertilizers are used in China. Examples are urea, MAP (monoammonium phosphate), DAP (diammonium hydrogen phosphate) and compound fertilizers (45%) Cl/S 15-15-15. The compound fertilizers content N, P, and potassium (K). The compound fertilizers (45%) S 15-15-15 are produced with potassium sulphate (K_2SO_4), and the efficient element N, P, K share 15%, 15% and 15% of the mass fraction. (45%) Cl 15-15-15 is produced with potassium chloride (KCl) as potassium raw material, and the efficient element N, P, K share 15%, 15% and 15% of the mass fraction. The main differences between the two compound fertilizers are the raw material using and it also influences the price of the two kinds of compound fertilizer.

The costs of applying synthetic fertilizers are estimated as follows. According to Strokal, et al. (2020), the cost of N fertilizer use is 350$/ton and the cost of P fertilizer using is 1110$/ton. I refreshed the representatively synthetic fertilizer types and their cost based on the literature (IPNI, 2007, 2010). The updated price of N synthetic fertilizer is estimated as 326$/ton and the price of P synthetic fertilizer is estimated as 1119$/ton (Table 3.8). These prices are rounded prices from the average value.

3.4.2 Cost of recycling animal manure as slurry

The cost of recycling animal manure as slurry including transportation cost and application cost. Transportation costs depend on the transporting distance, and it will cost more when the distance increase.

Strokal et al. (2020) have estimated the cost of transportation and application of recycling slurry to land is from 3-33 $/ton considering the percentage of liquid in the slurry is 70%. However, in the study from Yan et al. (2017), the slurry contents 90% liquid, which means the cost should be updated. According to the density of solid is 400kg/m^3 and the density of the liquid is 1000kg/m^3. When considering the percentage of liquid in the slurry is 70%, we can calculate the weight of the slurry which is (400*0.3+1000*0.7) =820kg/m^3 (Strokal et al., 2020). However, in this study, the percentage of liquid in the slurry is updated to 90%, and the weight of slurry should be updated to (400*0.1+1000*0.9) =940kg/m^3. This means the weight of one cube of slurry is heavier than it is in the study of Strokal et al. (2020). I decide to set a multiplier and update to the cost of recycling manure as slurry. The multiplier is calculated by dividing the updated value of the weight of one cube slurry by the weight of one cube slurry in Strokal' s study (2020). The multiplier is $\frac{940\text{kg/m3}}{820\text{kg/m3}}$ = 1.15. As a result, the updated cost of recycling animal manure as slurry is estimated range from 3.45 $/ton to 37.95 $/ton. The average round cost is 21$/ton.

3.4.3 Cost of recycling animal manure as solid

The cost of recycling animal manure as solid covering the cost of separation, transportation and application. The animal manure content about 30% solid fraction after separation in this study according to Yan et al. (2017), and the cost will refer to Strokal et al. (2020). The maximum cost of recycling animal manure as solid is 36.39 $/ton and the minimum cost of recycling animal manure as solid is 6.39 $/ton (Strokal, et al., 2020). The average cost of recycling animal manure as solid is 22 $/ ton.

Table 3.8 The cost of synthetic N fertilizer and synthetic P fertilizer. *Values in red are updated value compared to Strokal, et al (2020). N stands for nitrogen and P stands for phosphorus.* Source: (Strokal et al.,2020)

Representative synthetic fertilizer	Components (%)*					Effective element content in fertilizers (%)[a]		Cost for fertilizers			Costs converting as N and P			
	N	P	K	P_2O_5	K_2O	N[a]	N+P[a]	Range (RMB/ton)*	Average (¥/ton)	Average ($/ton)[b]	N ($/ton)[c]		P ($/ton)[c]	
Urea	45	-	-	-	-	45	-	1000-2000	1500	225 [b]	489 [c]		-	
MAP: $NH_4H_2PO_4$	10-12	-	-	48-61	-	-	63	1500-2700	2100	315 [b]	87 [c]		946 [c]	
DAP: $(NH_4)_2HPO_4$	18	-	-	46	-	-	64	2700-3000	2850	428 [b]	188 [c]		1100 [c]	
(45%)S 15-15-15	15	15	15	-	-	-	30	2200-2310	2255	338 [b]	564 [c]		1292 [c]	
(45%)Cl 15-15-15	15	15	15	-	-	-	30	1900-2050	1975	296 [b]	494 [c]		1131 [c]	
											Maximum	87	Maximum	946
											Minimum	564	Minimum	1292
											Average	326	**Average**	1119

*The information is from https://www.chyxx.com/industry/201803/619830.html and (International Plant Nutrition Institution, 2007; International Plant Nutrition Institution, 2010).

[a] The effective elements are nitrogen and phosphorus content in the fertilizers. For example, N[a] is N content percentage (%) in fertilizer and N+P[a] is Nitrogen and P_2O_5 content percentage (%) in the fertilizers.

[b] conversion factor from the Chinese yuan to the US dollar is 0.15 (February 2019).

[c] Converting factor between P2O5 and P is (31*2)/(31*2+16*5)=0.44 (31 is the molar mass of P and 16 is the molar mass of O).

The cost of effective elements can be calculate following:

(225$/ton)/45%(N content percentage)=489$/ton N
(315$/ton)/63%(N+P content percentage)=500$/N+P ton MAP
(428$/ton)/64%(N+P content percentage)=668$/N+P ton DAP
(338$/ton)/30%(N+P content percentage)=1128$/N+P ton (45%)S 15-15-15
(296$/ton)/30%(N+P content percentage)=988$/N+P ton (45%)Cl 15-15-15

Cost of fertilizer N:

489 $/N ton urea = 489$/ton N
87 $/N ton MAP = 500 $/N+P ton MAP * [11% N content / (11%+52% N+P content)].
188 $/N ton DAP = 668 $/N+P ton DAP * [18% N content / (18%+46% N+P content)].

564 $/N ton (45%)S 15-15-15 = 1128 $/N+P ton (45%)S 15-15-15 * [15% N content / (15%+15% N+P content)].

494 $/N ton (45%)Cl 15-15-15 = 988 $/N+P ton (45%)Cl 15-15-15 * [15% N content / (15%+15% N+P content)].

Cost of fertilizer P:

946 $/P ton MAP = (500 $/N+P ton MAP - 87 $/N ton MAP)/0.44
1292 $/P ton DAP = (668 $/N+P ton DAP - 188 $/N ton DAP)/0.44

1100 $/P ton (45%)S 15-15-15 = (1128 $/N+P ton (45%)S 15-15-15 -564 $/N ton (45%)S 15-15-15)/0.44

1131 $/P ton (45%)Cl 15-15-15 = (988 $/N+P ton (45%)Cl 15-15-15 - 494 $/N ton (45%)Cl 15-15-15)/0.4

3.4.4 Cost of recycling animal manure after composting

Management option 5 is to recycle the animal manure after separation to compost. The cost of MO 5 (recycle animal manure after composting) includes the cost of separation, the cost of the composting process and the cost of transportation and application of the final product (Figure 3.3). The costs of separation, transportation, and application are referring to Strokal et al. (2020) (Table 3.9). The cost of transportation is calculated twice, one is to transport separated animal manure to composting plant, and another is to transport the composting product to application.

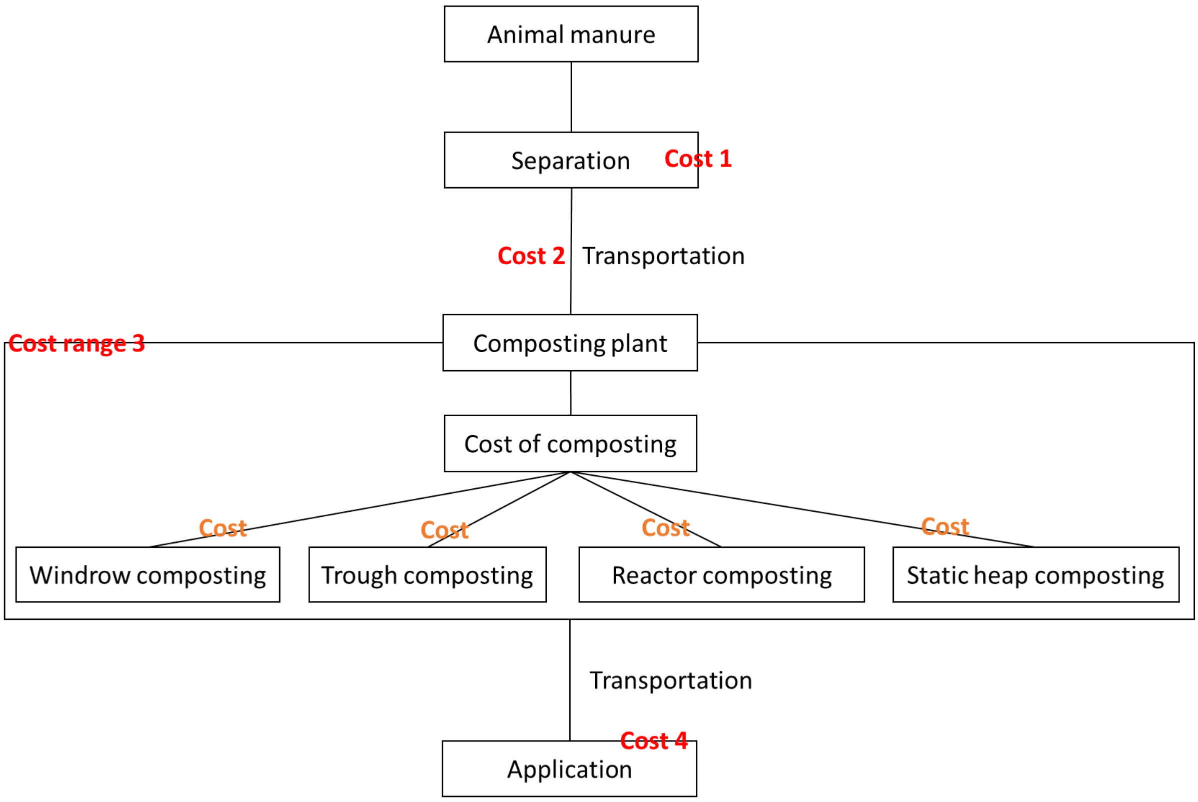


Figure 3.3 The cost composition of recycling animal manure after composting. *Cost 1 is the cost of separation; Cost 2 is the cost of transporting separated animal manure to composting plant; Cost 3 is a cost range of composting process; Cost 4 is the cost of transporting and applying composting product. The Costs in red are the costs composition of MO 5 and the costs in orange are the costs composition of composting process (Cost 3). Source: (Strokal et al., 2020)*

Table 3.9 Cost composition of recycling animal manure after composting. Source: (Strokal et al.,2019)

	Cost ($/ton)	Remark	Source
Cost 1	3.39	Separation	(Strokal et al., 2020)
Cost 2	0-29	Transportation	
Cost 4	3-33	Transportation + Application	

Cost of the composting process (Cost 2)

Fritsch & Collins (1993) has provided the estimated cost of composting in different types. They distinguished two kinds of situations. One is the full capacity of 40000 tons poultry litter and the other is the full capacity of 80000 tons poultry litter. There is an indicator that with higher full capability, the cost of composting of each ton poultry is lower. The cost of windrow composting ranges from 3.8-5.22 $/ton and the cost of Through composting ranges from 3.94-4.75 $/ton. The cost of bioreactor composting is from 4.11 $/ton to 5.22$/ton (Fritsch & Collins, 1993). Science the cost was estimated in 1993, the value of the cost should be updated in Table 3.10.

Table 3.10 Costs of three main types of composting. *Considering the cumulative inflation rate is 78.1% comparing 2019 with 1993 (https://www.usinflationcalculator.com/), the cost will multiply a factor 1.78 (100%+78%) in 2019. $/ton is the cost of per ton of composted manure to be composted .Source: (Fritsch & Collins, 1993)*

Composting types	Cost range (1993) $/ton	Cost range (2019) $/ton	Average cost $/ton
Windrow composting	3.8-5.22	6.76-9.3	8.1
Trough composting	3.94-4.75	7.2-8.1	7.7
Reactor composting	4.11-5.22	7.4-9.3	8.4

Refer to the expert's knowledge in China, the estimated cost of windrow composting, static heap composting and reactor composting in Table 3.11. The static heap composting is the cheapest, but it takes the longest time, about 40 days. Reactor composting and windrow composting cost almost the same for approximately 10 $/ton, the reactor composting only use 7 days.

Table 3.11 Cost of three composting technologies estimated by an expert in China. *$/ton is the cost of per ton of animal manure to be composted*

Composting types	Cost ($/ton)	Composting Time (days)
Windrow composting	10.6	15
Static heap composting	6.7	40
Reactor composting	10.5	7

Combining the information from literature and expert knowledge, the cost of each composting technology can be calculated. The cost of windrow composting and reactor composting are the average cost from the table. Then the cost of windrow composting is (10.6+8.1)/2=9.35 $/ton and the cost of the reactor is (10.5+8.4)/2= 9.45$/ton. The cost of trough composting is 7.7$/ton and the cost of static heap composting is 6.7 $/ton. The cost range of composting process is from 6.7$/ton to 9.45$/ton (Table 3.12)

Table 3.12 Cost of the composting process (Cost 2). *$/ton is the cost of per ton of animal manure to be composted.*

	Composting types	**Cost ($/ton)**	**Cost range ($/ton)**
Composting	Windrow composting	9.35	6.7-9.45
	Trough composting	9.45	
	Reactor composting	7.7	
	Static heap composting	6.7	

The total cost of recycling animal manure after composting is to sum of Cost 1, Cost 2, Cost 3 and Cost

4. The cost ranges from 13-77 $/ton. The average cost of MO 5 (recycle animal manure after composting) is 45 $/ton.

3.4.5 Cost of treating animal manure

Strokal et al. (2020) use expert knowledge to estimate the cost of primary treatment, second treatment, and tertiary treatment. Table 3.13 shows the cost of each management option. The separation cost is only added to the cost of primary treatment because separation usually happens at the first step. The cost of primary treatment is 2-8$/ton. The cost of secondary treatment ranges from 5$/ton to 8$/ton. The most expensive one is tertiary treatment and the cost is from 8$/ton to 16$/ton (Strokal et al., 2020). The cost of directly discharging animal manure without treatment is 0 $/ton and no nutrient pollution will be removed.

Table 3.13 The cost of management option to treat animal manure. *$/ton is the cost of per ton of animal manure to be treated. The cost of MO 5, MO 6, MO 7 and MO 8 are directly referred to the paper of Strokal paper (2020). Source: (Strokal et al., 2020)*

Management option (MO)	Cost ($/ton)	
	Range	Average
MO 6 primary treatment	2-8	5
MO 7 secondary treatment	5-8	7
MO 8 tertiary treatment	8-16	12
MO 9 directly discharge	-	0

3.4.6 Cost of treating human waste

The cost of treating human waste refers to the paper of Strokal (2020). The cost of MO 10, MO 11, MO 12 and MO 13 are directly from (Strokal et al., 2020) (Table 3.13). Strokal considers the operation fee, the investment cost and the capacity of the sewage treatment plant into the cost of treating human waste. In table 3.14, the values are average costs of 0.26 Euro/m^3 for the primary treatment. The costs of secondary and tertiary treatment are 0.42 Euro/m^3 and 0.72 Euro/m^3 respectively (Strokal et al., 2020). Euro/m^3 can convert to $/ton considering human waste density. Assuming the ratio for solid and liquid of human waste is 0.3:0.7, the cost of primary treatment is 1.09$/ton. The cost of secondary treat and tertiary treatment is 1.17$/ton and 1.56$/ton representatively (Strokal et al., 2020). When human waste is discharging without treatment, the cost will be 0 $/ton.

Table 3.14 The cost of management option to treat human waste. *$/ton is the cost of per ton of human waste to be treated. Source: (Strokal et al., 2020)*

Management option (MO)	Cost ($/ton)	
	Range	Average
MO 10 primary treatment	1.01-1.17	1.09
MO 11 secondary treatment	0.97-1.27	1.17
MO 12 tertiary treatment	1.34-1.78	1.56
MO 13 directly discharge	-	0

3.5 Conclusions

This chapter answered the research question 2: "What are the costs and nutrient removal efficiency of management options to reduce nutrient pollution in the Yangtze River basin?". To answer this question, the earlier study (Strokal et al., 2020) are used. The information on the costs and nutrient removal efficiencies in the study of Strokal et al. (2020) are updated. Furthermore, one management option is added to the management list. For this, literature and expert knowledge are used. Below are the main aspects of this chapter.

Thirteen management options are identified to reduce future coastal eutrophication in the Yangtze River mouth. These management options are: MO 1 (reduce synthetic N fertilizer use); MO 2 (reduce synthetic P fertilizer using); MO 3 (recycle animal manure as slurry); MO 4 (Recycle animal manure as solid) ; MO 5 (Recycle animal manure after composting); MO 6 (treat animal manure with primary technology); MO 7 (treat animal manure with secondary technology); MO 8 (treat animal manure with tertiary technology); MO 9 (discharge animal manure without treatment); MO 10 (treat human waste with primary technology); MO 11 (treat human waste with secondary technology); MO 12 (treat human waste with tertiary technology); MO 13 (discharge human waste without treatment).

Nutrient removal efficiencies vary between N and P in management options. For example, for MO 6, N and P removal efficiencies range from 10% to 35% (primary treatment). The removal efficiencies of N and P for MO 7 range from 50% to 70% (secondary treatment). The highest removal efficiencies of N and P are in MO 8 and range from 80% to 99% (tertiary treatment). The removal efficiency of N and P for MO 9 is set at zero. Removal efficiencies of N and P for management options related to human waste treatment range from 20%-30% for MO 10 (primary treatment), 36%-90% for MO 11 (secondary treatment) and 45%-99% for MO 12 (tertiary treatment). MO 13 with a removal efficiency of N and P is 0% (discharges to rivers without treatment). It is set that 60% of N in solid manure is lost during the composting process in MO 5 (recycle animal manure after composting).

Costs vary among management options. Costs of implementing MO 1 and MO 2 are 326 \$/ton and 1119 \$/ton, respectively. Costs of implementing MO 3 and MO 4 are recalculated at 21\$/ton and 22\$/ton, respectively. Costs of implementing MO 5 range from 13-77 \$/ton considering the cost of separation, transportation, the composting process and application. In this study, I applied the average cost for MO 5 (45\$/ton). Costs of implementing MO 6, MO 7, MO 8, MO 9, MO 10, MO 11, MO 12, MO 13 (0-12 \$/ton) are directly referred from the earlier study of Strokal et al., (2020).

Chapter 4: Cost-effective management options to reduce future coastal eutrophication in the Yangtze River mouth

4.1 Introduction

This chapter is to answer the research question “What are the cost-effective management options to reduce coastal eutrophication in the Yangtze River mouth?” A cost-effective combination of management options is defined as the cheapest way to reduce a 60% gap between the actual and desired levels of total dissolved nitrogen (TDN) and phosphorus (TDP) at the river mouth simultaneously in 2050. The actual levels of nutrients are from the MARINA model for 2050 according to the Global Orchestration (GO) scenario (Chapter 2). MARINA model: Model to Assess River Inputs of Nutrients to seAs (Strokal et al 2016; Strokal et al., 2020). GO is considered as a baseline scenario in this study. The desired levels of nutrients are based on environmental targets of TDN and TDP at the Yangtze River mouth that are calculated from the Indicator for Coastal Eutrophication Potential (ICEP).

Section 4.2 describes the methods. Section 4.3 compares three cases to identify a cost-effective combination of management options. Section 4.4 concludes with the answers to the research question.

4.2 Methods

To identify the combination of cost-effective management options, the MARINA model and a cost minimization model are integrated using the GAMS (The General Algebraic Modeling System) programming. The MARINA model is used to calculate the river export of nutrients from various sources and ten sub-basins to the river mouth of Yangtze. A cost-optimization model is used to find the optimal combination of cost-effective mitigation options to reduce coastal eutrophication in 2050. I followed the new approach from Strokal et al. (2020) where the MARINA model and a cost-optimization procedure were integrated. I take this approach as a start. However, I improved the approach in several ways: (1) I added composting as a new option to deal with manure treatment (see Chapter 3); (2) I updated cost estimates for the options (see Chapter 3); (3) I updated the environmental targets for coastal eutrophication reduction (see this Chapter), and (4) I updated the programing codes from Strokal et al., (2020) that now incorporate the composting and constraints for the sub-basin reductions of river export of nutrients (see this chapter). For the last two aspects, I developed three cases.

In general, five steps are used to estimate this optimal combination of management options to reduce coastal eutrophication in the river mouth of the Yangtze in 2050 (Figure 4.1). These five steps are:

Step 1: Define the baseline of nutrient pollution in the river mouth in 2050. This baseline reflects the actual nutrient export by the Yangtze to the river mouth in 2050 according to GO. Nutrients are considered as total dissolved nitrogen (TDN) and total dissolved phosphorus (TDP). TDN is the sum of dissolved inorganic (DIN) and dissolved organic (DON) nitrogen. TDP is the sum of dissolved inorganic (DIP) and dissolved organic (DOP) phosphorus.

Step 2: Desired level of nutrient pollution at the river mouth. The desired level is the river export of N and P to the Yangtze River mouth under a low eutrophication potential by setting ICEP (Indicator of Coastal Eutrophication Potential) equal to zero.

Step 3: Gap closure and environment target. Cap is the difference between the baseline level and the desired level. Cap closure means how much close to the Cap. By setting a different percentage of Gap closure, related environmental targets for total dissolved nitrogen (TND) and total dissolved phosphorus (TNP) at the Yangtze River mouth can be calculated. In this study, a 60% of the gap closure is applied.

Step 4: Combine the output in step 2 and step 3 and the information on management options in Chapter 3, balanced equations are stated. The river export of N and P should not exceed the environmental target level of TDN and TDP at the Yangtze River mouth. Pollution source influent to management options equal to the pollution sources generated in 2050 according to the MARINA model.

Step 5: Three cases are set for cost-effectiveness analysis by setting the same total environmental target of 60% Gap closure for three cases as an example. The result of Case 1 is directly from the model. Case 2 adds constraints of an equal reduction rate of N and P for each sub-basin. Case 2 adds constraints of an equal reduction amount of N and P for every sub-basin. Three cases are used to discuss how equality influence cost.

Below, I describe the five steps in 4.2.1-4.2.5. Section 4.2.4 presents an overview of the integrated model where the MARINA model is combined with a cost-optimization procedure. Section 4.2.5 presents the description of three cases for cost-effective managements of coastal eutrophication in 2050.

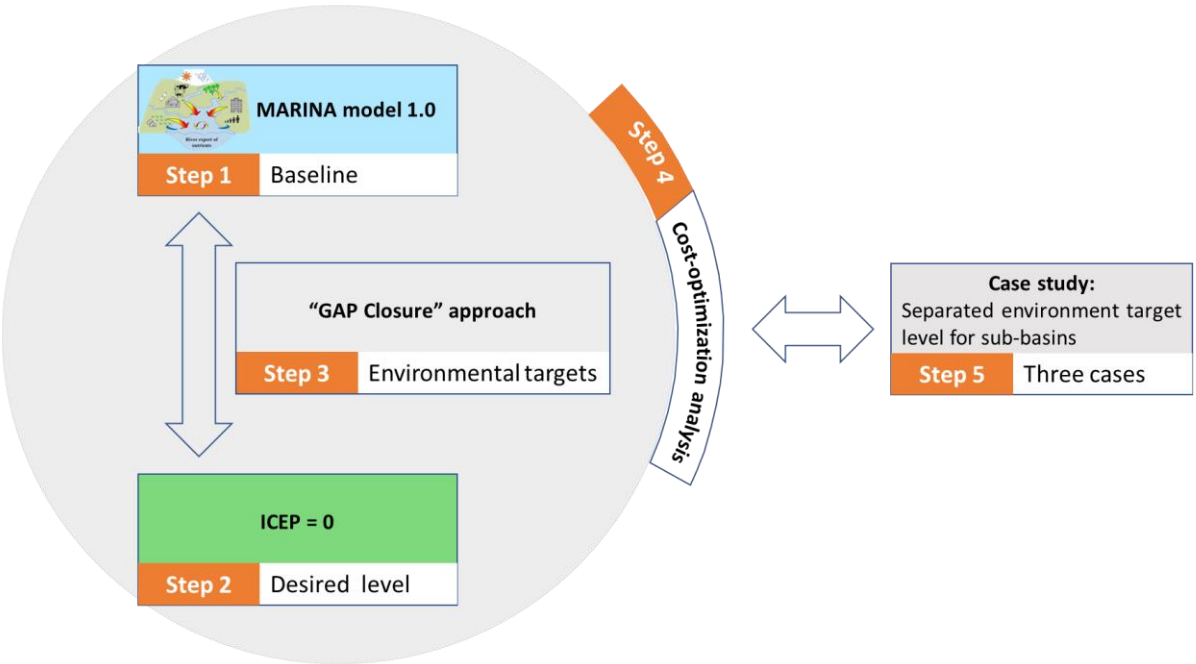
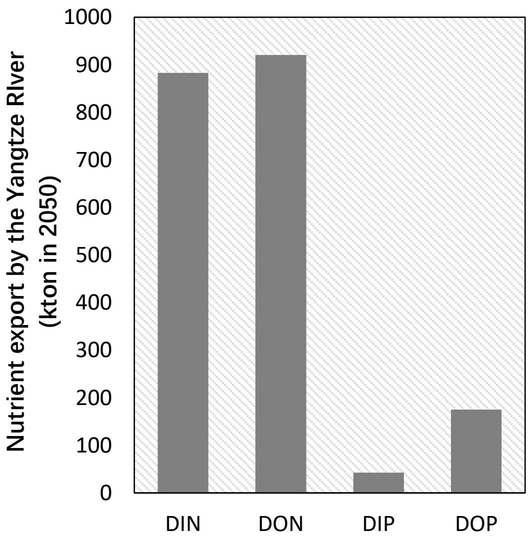


Figure 4.1 Five steps to identify the cost-optimal management options to reduce future coastal eutrophication in the Yangtze River mouth*. MARINA is short for Model to Assess River Inputs of Nutrients to seAs. ICEP is short for Indicator of Coastal Eutrophication Potential.Source: integrated information in section 4.2.*

4.2.1 The baseline of nutrient pollution at the river mouth

The actual river export of nutrients in 2050 is calculated using the MARINA model according to the GO scenario (see also Chapter 2 on model and scenario descriptions). The actual levels for the river export of nutrients in 2050 are shown in Figure 4.2. The actual river export of TDN (BL_{TDN}) and TDP (BL_{TDP}) in 2050 is 1804 kton and 218 kton, respectively.



Nutrients	Nutrient export by the Yangtze River (kton in 2050)
TDN=DIN+DON	1804
TDP=DIP+DOP	218

Figure 4.2 Actual nutrient export by the Yangtze River in 2050 according to the GO (Global Orchestration scenario). *DIN stands for dissolved inorganic nitrogen; DON stands for dissolved organic nitrogen; DIP stands for dissolved inorganic phosphorus; DOP stands for dissolved organic phosphorus. Source: the MARINA model, version 1.0 (Strokal et al., 2016)*

4.2.2 The desired level of nutrient pollution in the river mouth

The desired level of nutrients at the Yangtze River mouth are the levels at which it is possible to avoid eutrophication in the coastal water. This level reflects a low risk of coastal eutrophication in the Yangtze River mouth. ICEP (indicator for coastal eutrophication potential) is usually used as an indicator of coastal eutrophication problems (Garnier et al., 2010) to determine the desirable level. ICEP is based on the ratio of dissolved Si (Silicon) to N or P compared with the ratio needed for diatom growing (Garnier et al., 2010). If there is an excess of N or P over Si, the undesirable non-silicon-based algae will grow instead of the silicon-based algae. A value of zero for ICEP means that the level of the nutrients in the coastal water is not high enough to pose a coastal eutrophication threat which is the desired level of nutrient exports in the river mouth.

Two indicators $ICEP_N$ and $ICEP_P$ are calculated following the approach of Strokal et al., (2020). $ICEP_N$ is estimated when N acts as a limiting nutrient and $ICEP_P$ is estimated when P acts as a limiting nutrient. ICEP can be calculated according to the following equations (Garnier et al., 2010)

$$\mathrm{TN/\ TP} = \frac{N_{flx}}{14} / \frac{P_{flx}}{31} \tag{4.1}$$

$$ICEP_N = \left(\frac{N_{flx}}{(14 \cdot 16)} - \frac{Si_{flx}}{(28 \cdot 20)}\right) \cdot 106 \cdot 12 \qquad \text{TN/TP < 16 (N limiting)} \tag{4.2}$$

$$ICEP_P = \left(\frac{P_{flx}}{31} - \frac{Si_{flx}}{(28 \cdot 20)}\right) \cdot 106 \cdot 12 \qquad \text{TN/TP >16 (P limiting)} \tag{4.3}$$

where,
TN/TP is the ratio of total nitrogen (N) to phosphorus (P).
$ICEP_P$ and $ICEP_N$ are the indicators of coastal eutrophication potential when P and N act as limiting nutrients (kg C/km^2/year).
N_{flx} is the flux of total nitrogen export at the river mouth (kg N/km^2/year).
P_{flx} is the flux of total phosphorus export at the river mouth (kg P/km^2/year).
Si_{flx} is the flux of total dissolved silica in the river mouth (kg/km^2/year).
The value of Si_{flx} can be obtained from the Global NEWS-2 (Nutrient Export from Watersheds) model (Mayorga et al., 2010).

The desired level of the nutrients (P_{flx} and N_{flx}) with low risk for coastal eutrophication can be calculated from equations 4.2-4.3 assuming ICEP at zero. It is assumed that the desired levels of the total N and P fluxes (P_{flx} and N_{flx}) at the river mouth are achieved via reductions in river export of TDN and TDP (see Strokal et al., 2020). Calculating the desired level of the total dissolved nutrient export (DL_{TDN} and DL_{TDP}) in the river mouth is done as follows (Strokal et al., 2020):

$$DL_{TDN} = \left(\frac{ICEP_N}{(106 \cdot 12)} + \frac{Si_{flx}}{(28 \cdot 20)}\right) \cdot 14 \cdot 16 \times \text{Area} \times 10^{-6} \quad (4.4)$$

$$DL_{TDP} = \left(\frac{ICEP_P}{(106 \cdot 12)} + \frac{Si_{flx}}{(28 \cdot 20)}\right) \cdot 31 \times \text{Area} \times 10^{-6} \quad (4.5)$$

Where,

DL_{TDN} is the desired level of the total dissolved nitrogen (TDN) export by the Yangtze River with low risk for coastal eutrophication (kton/year).

DL_{TDP} is the desired level of total dissolved phosphorus (TDP) export by the Yangtze River with low risk for coastal eutrophication (kton/year).

$Areas$ is the basin area of the Yangtze River basin (km^2).

10^{-6} is to convert from unit kg to kton.

When setting ICEP equal to zero using equation4.4 and equqtion4.5, the desired level of TDN is 400 kton and the desired level of TDP is 55 kton in 2050. However, according to Strokal, et al (2016), the technically possible level of reducing TDN in 2050 is 600 kton with the best available technologies. This implies that the desired level of TDN is 600 kton (higher than the level according to ICEP=0 levels). Therefore, we take DL_{TDN}=600 kton and DL_{TDP}= 55 kton in the next steps. This was also done in Strokal et al., (2020).

4.2.3 The gap closure and environment targets

A gap between the actual level and the desired level is defined by the output of 4.2.1 and 4.2.2. The gap is the difference between the actual level and the desired level of nutrient export in the river mouth (Strokal et al., 2020). A gap closure is the percentage of the gap to close between the actual and desired nutrient levels (Strokal et al., 2020). This gap is shown in Figure 4.3. Based on this gap, different environmental targets can be set to achieve different river export levels of nutrients. For example, if a target for the low risk level of coastal eutrophication in the Yangtze River mouth aims to be achieved, the Gap closure will be 100%. This means the environmental target level is equal to the desired level. The percentage (X%) can change depending on how much the nutrients are expected to be reduced.

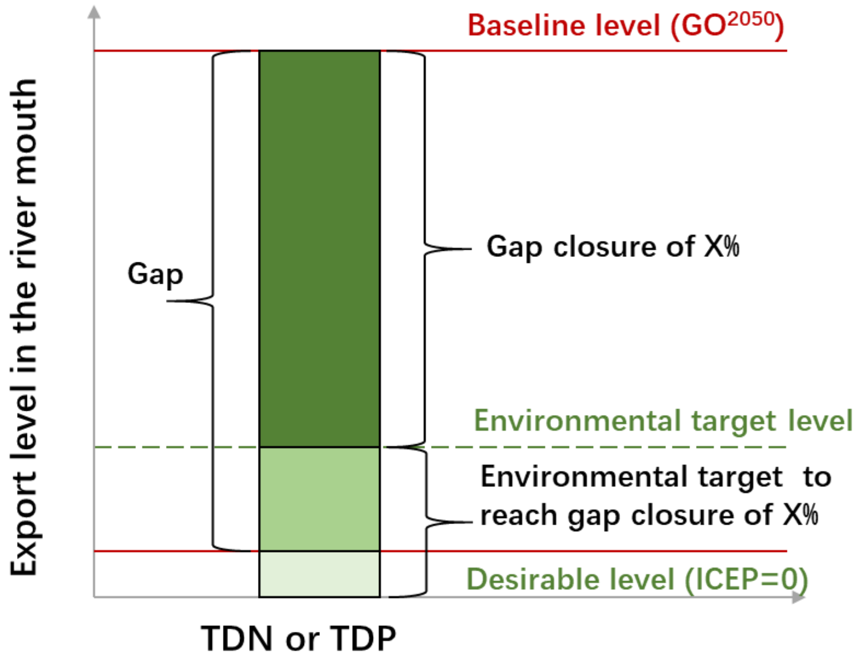


Figure 4.3 Illustration of the gap and environmental targets. *TDN and TDP are the total dissolved nitrogen and phosphorus, respectively. A gap closure of 0% is the baseline level of TDN or TDP export in the river mouth in 2050 according to GO (Global Orchestration scenario of the Millennium Ecosystem Assessment). A gap closure of 100% is the desired level of TDN or TDP export in the river mouth in 2050 when ICEP=0 (Indicator for Coastal Eutrophication Potential). Source: integrated information for step 1 and step 2, following the approach of Strokal et al., (2020).*

The environmental target can be calculated by the following equations:

$$\text{Reduction fraction}_{TDN} = [X\% \times (BL_{TDN} - DL_{TDN})] \div BL_{TDN} \tag{4.6}$$

$$\text{Reduction fraction}_{TDP} = [X\% \times (BL_{TDP} - DL_{TDP})] \div BL_{TDP} \tag{4.7}$$

$$ET_{TDN} = (1 - reduction\ rate) \times BL_{TDN} \tag{4.8}$$

$$ET_{TDP} = (1 - reduction\ rate) \times BL_{TDN} \tag{4.9}$$

where,

$\text{Reduction rate}_{TDN}$ is the fraction of reduced nitrogen divided by the baseline of nitrogen level (%).
$X\%$ is the percentage of the gap closure (%).
ET_{TDN} is the environmental target of the total dissolved nitrogen (TDN) export by the Yangtze to the river mouth (kton /year).
ET_{TDP} is the environmental target of the total dissolved phosphorus (TDP) export by the Yangtze to the river mouth (kton /year).DL_{TDN} is the desired level of the total dissolved nitrogen (TDN) export by the Yangtze River with low risk for coastal eutrophication (kton/year).
DL_{TDP} is the desired level of the total dissolved phosphorus (TDP) export by the Yangtze River with

low risk for coastal eutrophication (kton/year).
BL_{TDN} is the baseline level of total dissolved nitrogen (TDN) export in the river mouth in 2050 according to GO (kton/year).
BL_{TDP} is the baseline level of total dissolved phosphorus (TDP) export in the river mouth in 2050 according to GO (kton/year).

By setting the Gap closure from 0% to 100%, I can calculate environment target levels of nitrogen and phosphorus export by the Yangtze River to the river mouth (Table 4.1). When achieving a gap closure of 0%, the reduction rate$_{TDN}$ is 0% and reduction rate$_{TDP}$ is 0%. When achieving a gap closure of 100%, the reduction rate$_{TDN}$ is 67% and the reduction rate$_{TDN}$ is 75%. Comparing the environmental target levels related to each gap closure with the baseline level, the reduction rates of TDN and TDP related to the gap closures can be calculated.

Table 4.1 Environmental targets for TDN and TDP export by the Yangtze River to the river mouth. *The gap of closure is how much the gap is closed between the desired and actual levels of TDN and TDP at the river mouth. Reduction rate$_{TDN}$ is the ratio of the amount of TDN export by the Yangtze is reduced relative to the baseline level of TDN at the river mouth in 2050. Reduction rate$_{TDP}$ is the ratio of the amount of TDP export by the Yangtze is reduced relative to the baseline level of TDP at the river mouth. ET_{TDN} is the environmental target of the total dissolved nitrogen (TDN) export at the river mouth of Yangtze in 2050 (kton /year). ET_{TDP} is the environmental target of the total dissolved phosphorus (TDP) at the river mouth of Yangtze in 2050 (kton/year). Source: the actual levels of TDN and TDP export by the Yangtze are from the MARINA 1.0 model (Chapter 2) and the desired levels of TDN and TDP at the river mouth are calculated following the approach of Strokal et al. (2020).*

Gap closure of X%	**Reduction rate$_{TDN}$**	**Reduction rate$_{TDP}$**	**ET_{TDN}(kton)**	**ET_{TDP}(kton)**
0%	0%	0%	1804	218
10%	7%	7%	1684	202
20%	13%	15%	1563	185
30%	20%	22%	1443	169
40%	27%	30%	1322	153
50%	33%	37%	1202	137
60%	40%	45%	1082	120
70%	47%	52%	961	104
80%	53%	60%	841	88
90%	60%	67%	720	71
100%	67%	75%	600	55

4.2.4 The cost-effective management options for the Yangtze River

In this research, the most important part is to identify the cost-effective management options to reduce the future eutrophication problems in the Yangtze River mouth in 2050. To this end, the MARINA model (Chapter 3) is integrated with a cost-optimization procedure using the GAMS following the approach of Strokal et al. (2020) (see Section 4.2). 13 management options are identified. These options are MO 1 (reduce synthetic N fertilizer), MO 2 (reduce synthetic P fertilizer), MO 3 (recycle animal manure as slurry), MO 4 (recycle animal manure as solid), MO 5 (recycle animal manure after composting), MO 6 (treat animal manure with primary technologies), MO 7 (treat animal manure with secondary technologies), MO 8 (treat animal manure with tertiary technologies), MO 9 (discharge animal manure without treatment), MO 10 (treat human waste with primary technologies), MO 11 (treat human waste with secondary technologies), MO 12 (treat human waste with tertiary technologies), MO 13 (discharge human waste without treatment). Twelve management options are identified by Strokal et al., (2020). Their costs and removal efficiencies of nutrients during treatment are updated. Composting is added as a new mitigation option to treat raw manure in order to facilitate manure recycling on the land. The details on costs and removal efficiency of management options can refer to Table 4.2.

Table 4.2 Costs and removal efficiencies of management options used in Box 4.1. *Abbreviations can refer to Box.4.1. Source: the MARINA model (Strokal et al., 2020) and the updated values in Chapter 3.*

Management options (MO)	$X_{dif.s.j}$ $X_{pnt.s.j}$	**Costs (10^3\$/kton)** $C_{dif.o}$ **and** $C_{pnt.o}$	**Removal efficiency (%)** $RE_{pnt,E,o,j}$ N	P
Options for diffuse sources: $X_{dif.o.j}$ in (4.10) of Box 4.1		in (4.10)	in (4.18)	
MO 1: reduce synthetic N fertilizer	$X_{dif.o1.j}$	326 (87-564)	-	-
MO 2: reduce synthetic P fertilizer	$X_{dif.o2.j}$	1119 (946-1292)	-	-
MO 3: recycle animal manure as slurry	$X_{dif.o3.j}$	21 (4-38)	-	-
MO 4: recycle animal manure as solid	$X_{dif.o4.j}$	22 (7-37)	-	-
MO 5: recycle animal manure after composting	$X_{dif.o5.j}$	45 (13-77)	60 ($RE_{dif,E,05,j}$)	-
Options for point sources: $X_{pnt.o.j}$ in (4.10) of Box 1		in (4.10)	in (4.18)	
MO 6: treat animal manure with primary technologies	$X_{pnt.o1.j}$	5 (2-8)	10 (<20)	35 (<50 or <20)
MO7: treat animal manure with secondary technologies	$X_{pnt.o2.j}$	7 (5-8)	60 (50-70)	60 (50-70)
MO 8: treat animal manure with tertiary technologies	$X_{pnt.o3.j}$	12 (8-16)	90 (80-99)	90 (80-99)
MO 9: animal manure without treatment	$X_{pnt.o4.j}$	0	0	0
MO 10: treat human waste with primary technologies	$X_{pnt.o5.j}$	1.09 (1.01-1.17)	23 (20-25)	29 (28-30)
MO 11: treat human waste with secondary technologies	$X_{pnt.o6.j}$	1.17 (0.97-1.27)	48 (36-59)	71 (51-90)
MO 12: treat human waste with tertiary technologies	$X_{pnt.o7.j}$	1.56 (1.34-1.78)	64 (45-83)	89 (88-99)
MO 13: human waste without treatment	$X_{pnt.o8.j}$	0	0	0

The object function is to minimize the total cost of reducing nutrient export by the Yangtze from all sources and ten sub-basins to the river mouth. The constraints include the actual TDN and TDP export by the Yangtze in 2050 (from the MARINA model, see Chapter 3 and Section 4.2) and the total environmental target of TDN and TDP at the river mouth (from setting the gap closure of 60%, see Section 4.2.3). The actual TDN and TDP exports by the Yangtze should never exceed their environmental targets. The equations can be found in Box 4.1. Under known targets for river export of TDN and TDP (see section 4.2.3: ET_{TDN}), actual river exports of TDN and TDP (the output of MARINA model: $M_{F,j}$) and the cost and removal rates of nutrients for each management option ($C_{dif,o}$, $X_{dif,o,j}$, see Chapter 3), it is possible to identify the optimal combination of cost-effective management options. The expected result will be the most effective way to achieve the target but with the lowest cost.

Compare to the equations by Strokal (2012), I added composting ($X_{dif,05,j}$) as a management option in the integrated modelling approach. Solid manure previously is only applied to land, but now parts of solid manure are also treated by composting (4.17 in Box 4.1). During composting, N can lose from solid manure, affecting the amount of N in the composted manure (4.17 in Box 4.1).

Equation	No.	Description
The objective function:		
$\min C = \sum_{j=1}^{10}[\sum_{o=1}^{5}(C_{dif,o} \times X_{dif,o,j}) + \sum_{o=1}^{8}(C_{pnt,o} \times X_{pnt,o,j})]$	(4.10)	The object is to minimize the total cost of management options in 2050 to reach the environmental target.
Subject to:		
$\sum_{j=1}^{10}(M_{DIN,j} + M_{DON,j}) \leq ET_{TDN}$	(4.11)	The environmental target is calculated by the ICEP.
$\sum_{j=1}^{10}(M_{DIP,j} + M_{DOP,j}) \leq ET_{TDP}$	(4.12)	
$M_{F,j} = (RS_{F,o,j} + {}^{GO}RS_{F,other,o,j}) \times {}^{GO}FE_{riv,F,outlet,j} \times {}^{GO}FE_{riv_{F,mouth,j}}$	(4.13)	
$RS_{F,o,j} = RS_{dif_{F,o,j}} + RS_{pnt_{F,o,j}}$	(4.14)	
$RS_{dif_{F,o,j}} = [WS_{dif,total,opt,E,j} \times (1 - {}^{GO}NUE_{E,j})] \times {}^{GO}FE_{ws,F,j}$	(4.15)	Nutrient use efficiency does not change, and the value is from GO 2050 in MARINA model
${}^{GO}NUE_{E,j} = \frac{{}^{GO}WS_{dif,export,E,j}}{{}^{GO}WS_{dif,total,E,j}}$	(4.16)	
$WS_{dif,total,E,j} = \sum_{o=1}^{4}[X_{dif,o,j} \times CF_{dif,E,o}] + X_{dif,05,j} \times CF_{dif,E,05} \times (1 - RE_{dif,E,05,j}) + {}^{GO}WS_{dif,E,other,j}$	(4.17)	
$RS_{dif_{F,o,j}} = \sum_{o=1}^{8}(X_{pnt,o,j} \times CF_{pnt,E,o}) \times (1 - RE_{pnt,E,o,j}) \times {}^{GO}FE_{pnt,F,o}$	(4.18)	For simplification, the solid fraction manure takes for 30% of the total treated manure. The solid fraction manure is allocated to MO 4 and MO 5. The liquid fraction manure is allocated to MO 6, MO 7, MO 8
$X_{dif,03,j} + X_{dif,04,j} + X_{pnt,01,j} + X_{pnt,02,j} + X_{pnt,03,j} + X_{pnt,04,j} = {}^{GO}X_{ma,total,j}$	(4.19)	
${}^{GO}WS_{dif,hw,j} + X_{pnt,05,j} + X_{pnt,06,j} + X_{pnt,07,j} + X_{pnt,08,j} = {}^{GO}WS_{hw,total,j}$	(4.20)	
$(X_{dif,04,j} + X_{dif,05,j}) : (X_{pnt,01,j} + X_{pnt,02,j} + X_{pnt,03,j}) = 3:7$	(4.21)	

Box 4.1. Description of the integrated modelling approach where the MARINA model and a cost-optimization procedure are combined to identify cost-effective management options to reduce future coastal eutrophication. *The objective function is to minimize the total cost of management options to achieve the environmental target (60% gap closure between the actural level and the desired level) for TDN and TDP export by the Yangtze to the river mouth (4.10-4.12). The MARINA model is used to calculate the nutrient export by the Yangtze from each management option and from each sub-basin (4.13-4.21). MARINA is short for a Model to Assess River Inputs of Nutrients to seAs. Source: the integrated modelling approach of Strokal et al. (2020), but improved in terms of updated cost estimates, added a composting managment option.*

Abbreviation	
C is the total cost of a combination of management options to reach environmental targets for TDN and TNP exports in the river mouth from all sub-basins and sources simultaneously ($ in 2050). $C_{dif,o}$ is the cost of management option o for one unit of a diffuse source input to agriculture land ($/kton in 2050). $C_{pnt,o}$ is the cost of management option o for one unit of a point source input to treatment facilities ($/kton in 2050). $X_{dif,o,j}$ is the level of diffuse sources input to agriculture land from management option o in sub-basin j (kton in 2050). $X_{pnt,o,j}$ is the level of point sources to treatment facilities from management option o in sub-basin j (kton in 2050). $M_{DIN,j}$ is the inorganic nitrogen (DIN) export in the river mouth from sub-basin j (kton in 2050). $M_{DON,j}$ is the organic nitrogen (DON) export in the river mouth from sub-basin j (kton in 2050). $M_{DIP,j}$ is the inorganic phosphorus (DIP) export in the river mouth from sub-basin j (kton in 2050). $M_{DOP,j}$ is the organic phosphorus (DOP) export in the river mouth from sub-basin j (kton in 2050). ET_{TDN} is the environmental target of total dissolved nitrogen (TDN) export in the river mouth (kton /year). ET_{TDP} is the environmental target of total dissolved phosphorus (TDP) export in the river mouth (kton /year). $M_{F,j}$ is the nutrient forms F (DIN, DON, DIP, DOP) export in the river mouth from sub-basin j (kton in 2050). $RS_{F,y,j}$ is the nutrient input form F (DIN, DON, DIP, DOP) from source y in sub-basin j to rivers (kton/year).	$RS_{dif_{F,o,j}}$ is the nutrient input form F (DIN, DON, DIP, DOP) from diffuse source in the sub-basin j to rivers (kton/year). $RS_{pnt_{F,o,j}}$ is the nutrient input form F (DIN, DON, DIP, DOP) from a point source in the sub-basin j to rivers (kton/year). $^{GO}RS_{F,other,o,j}$ is the input of nutrient form F (DIN, DON, DIP, DOP) from other sources in sub-basin j in GO 2050 (kton/year). $^{GO}FE_{riv,F,outlet,j}$ is the fraction of $RS_{F,y,j}$ exported to the outlet of sub-basin in GO 2050 (0-1). $^{GO}FE_{riv_{F,mouth,j}}$ is the fraction of $RS_{F,y,j} * FE_{riv,F,outlet,j}$ exported to the river mouth in GO 2050 (0-1). $WS_{dif,total,E,j}$ is the total input of element E (N or P) to agriculture land in sub-basin j (kton in 2050). $^{GO}WS_{dif,export,E,j}$ is the export of element E (N or P) from agriculture land via crop harvesting and animal grazing in GO 2050 (kton). $^{GO}FE_{ws,F,j}$ is the export fraction of element E (N or P) that is exported to river mouth from diffuse source as form F (DIN, DON, DIP, DOP) (0-1). $CF_{dif,E,o}$ is the factor for calculating the content of element E (N or P) in a diffuse source (kton/kton). $^{GO}WS_{dif,E,other,j}$ is the input of element E (N or P) to agriculture land from other diffuse sources (other diffuse sources include the nitrogen fixation, nitrogen deposition and human waste to land) in GO 2050 (kton). $CF_{pnt,E,o}$ is the factor for calculating the content of element E (N or P) in a point source (kton/kton). $RE_{pnt,E,o,j}$ is the removal efficiencies of element E (N or P) during treatment in sub-basin j by management option o in 2050 (0-1). $^{GO}FE_{pnt,F,o}$ is the export fraction of element E (N or P) that is exported to river mouth from point source as form F (DIN, DON, DIP, DOP) (0-1). $^{GO}WS_{dif,hw,j}$ is the diffuse source from human waste to land in sub-basin j in GO 2050 (kton).

4.2.5 Three cases for cost-effectiveness analysis

In this thesis, I set three cases to see how different policies influence the cost-effective options (Table 4.3). It is assumed that the outcome of the integrated modelling approach of MARINA (Box 4.1) is a cost-effective management option. All three cases have the environmental target to reduce 60% of the gap between actual and desired river export of TDN and TDP at the river mouth in 2050. However, the three cases differ in the reduction rates for the ten sub-basins of the Yangtze River.

Case 1: Reduction rates differ among the sub-basins. Here, reductions in river export of TDN and TDP from each sub-basin relative to the actual levels are derived from the integrated optimization modelling approach (Box 4.1). In other words, the integrated modelling approach provides these reduction targets. This approach calculates the amount of TDN and TDP that is exported by the Yangtze from each sub-basin to reduce the 60% of the gap at the river mouth. The difference between the optimized amount of TDN and TDP export from each sub-basin and their actual river exports in GO is the percentage reduction that is needed for each sub-basin in order to close the gap by 60% at the river mouth.

Case 2: Reduction rates are equal for the ten sub-basins. Here, I assume that ten sub-basins reduce the same fraction of the TDN and TDP river export relative to GO. This means that 60% of the gap closure must be reached at the river mouth under the condition that all ten sub-basins reduce their river export of TDN and TDP at the same rate. This rate is 40% for TDN and 45% for TDP.

Case 3: Reduction amounts are equal for the ten sub-basins. Here, I assume that the 60% of the gap closure must be reached at the river mouth under the condition that all ten sub-basins have to reduce their river export of TDN and TDP in the same amounts (absolute values). See details in Section 3.

Table 4.3 Summarized description of Cases 1, 2 and 3. *The total target is the environmental target at the Yangtze River mouth, and separated targets are the target for each sub-basin. Source: integrated information in 4.2.5.*

<table>
<tr><th>Case1</th><th>Case 2</th><th>Case 3</th></tr>
<tr><td colspan="3">Total target (the same for three cases): at the Yangtze River mouth</td></tr>
<tr><td colspan="3">Amount of TDN and TDP that is exported by the Yangtze from each sub-basin to reduce the 60% of the gap between the actual level and desired level at the river mouth</td></tr>
<tr><td colspan="3">Separated targets: for each sub-basin</td></tr>
<tr><td>The result derived from the integrated optimization modelling approach</td><td>Reduction rates are equal for the ten sub-basins</td><td>Reduction amounts are equal for the ten sub-basins</td></tr>
</table>

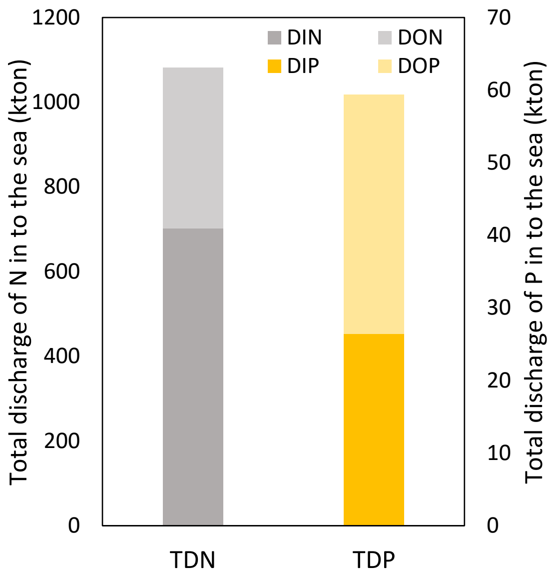
4.3 Cost-effective management of future coastal eutrophication

4.3.1 Case 1

Reducing the 60% gap between the actual and desired river export of TDN and TDP will cost around 2 billion dollars in 2050. This is an additional cost on top of the assumed practices in the baseline scenario (GO). Environmental targets are estimated at around 1082 kton and 120 kton of TDN and TDP export by the Yangtze to the river mouth, respectively (Table 4.4). To reach these targets, -4-67% of the TDN river export and 14-92% of TDP river export are required to reduce in 2050 relative to the baseline GO scenario. These ranges are for the sub-basins exporting TDN and TDP to the river mouth of Yangtze (Table 4.4). The differences in the reductions among the sub-basins are associated with the differences in the socio-economic development (e.g., population, income), agricultural and urbanization activities, hydrology and climate, and the travel distance towards the river mouth (see Chapter 2). Additionally, under Case 1, over half of TDN is estimated to be exported in a form of DIN to the river mouth from all sub-basins in 2050 (Figure 4.4). Almost half of TDP is estimated to be exported in a form of DIP (Figure 4.4).

Table 4.4 Summarized results for Case 1. *Results are based on an integrated modelling approach for total dissolved nitrogen (TDN) and phosphorus (TDP) that is exported by the Yangtze from each sub-basin to reduce the 60% of the gap at the river mouth. The reduction rate differs in sub-basins. Reduction rates are the ratio of the amount of nutrient exports by the Yangtze from sub-basins is reduced relative to the actual level of nutrient exports in 2050 GO. The additional cost is the cost under Case 1 on the top of the assumed practices in the baseline scenario (GO). Details are in Section 4.2.*

The environmental target estimated from reducing the 60% gap between actual and desired river export of TDN and TDP at the river mouth (kton in 2050)			
TDN		TDP	
1082		120	
The actual nutrient level at the river mouth under Case 1 (kton in 2050)			
1082		59	
Reduction rates in river export of TDN and TDP by sub-basins after optimization (reduction rates are relative to 2050 GO, %)			
Sub-basins	TDN	Sub-basins	TDP
Jinsha	56	Jinsha	84
Mintuo	52	Mintuo	77
Jialing	67	Jialing	92
Wu	54	Wu	90
Main_Stem_Upper	66	Main_Stem_Upper	85
Dongting	38	Dongting	82
Han	-4	Han	14
Poyang	29	Poyang	71
Main_Stem_Middle	40	Main_Stem_Middle	86
Delta	9	Delta	21
Additional cost to reduce the 60% gap (billion $) relative to practices in the baseline (2050 GO)			
1.97			



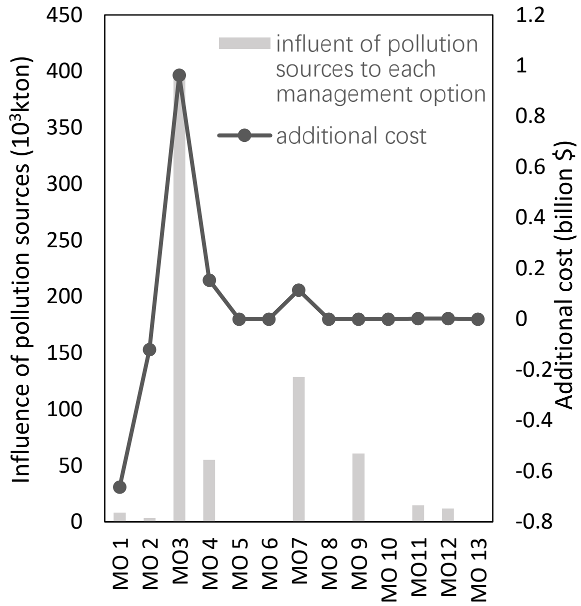


Figure 4.4 Nutrient export by the Yangtze River at the river mouth by form under Case 1 in 2050 (kton). *TDN is total dissolved nitrogen; TDP is total dissolved phosphorus; DIN is dissolved inorganic nitrogen; DON is dissolved organic nitrogen; DIP is dissolved inorganic phosphorus; DOP is dissolved organic phosphorus. Source: see Section 4.2 for Case 1.*

Figure 4.5 Influent of pollution sources to each management option (10^3 kton) and additional costs of these management options in the year 2050 (billion $). *MO is short for management option. MO 1, MO 2, MO 3, MO 4, MO 5, MO 6, MO 7, MO 8, MO 9, MO 10, MO 11, MO 12, MO 13 can refer to Chapter 4.2.4. The left axis shows the amount of pollution sources (animal manure, human wastes, and synthetic fertilizer use) influent to management options. The right axis shows the additional cost of each management option compared to 2050 GO. GO is Global Orchestrion. Source: see Section 4.2 for Case 1.*

Cost-effective management options for the Yangtze basin are MO 3 (recycle animal manure as slurry), MO 4 (recycle animal manure as solid), MO 7 (treat animal manure with secondary technology), MO 9 (discharge directly animal manure without treatment) (Figure 4.5). The sum of the influent of pollution sources to the management options are the amount of animal manure and human waste generated in 2050 according to GO scenario. The animal manure will flow to MO 3, MO 4, MO 5, MO 6, MO 7, MO 8 and MO 9, and the human waste will flow to MO 10, MO 11, MO 12 and MO 13. Most of the pollution sources flows to MO 3 (recycle animal manure as a slurry), about $395*10^3$ kton, which means the animal manure tends to be treated by MO 3 (Figure 4.5). Animal manure treated by MO 3 is influent to agriculture land as diffuse sources. MO 7 (treat animal manure by secondary treatment) treats about $129*10^3$ kton sources is the second-ranked influent of pollution sources management option. After being treated by MO 7, the pollution sources are discharged to rivers in as point sources. MO 4 (recycle animal manure as solid) and MO 9 (discharge animal manure without treatment) manage almost the same amount of animal manures, about $55*10^3$ kton, and $60*10^3$ kton respectively, but MO 9 do not cost money. There flows no animal manure to MO 5 (recycle animal manure after composting). As for the cost distribution, MO 3 is the costliest one compare to other management options (0.96 billion$). Comparably, MO 7 only cost one tenth of MO 3 (0.11 billion $), but animal manure treated by MO 7 is about one third of MO 3. The additional cost of MO 1 (Reduce the use of N fertilizer) and MO 2 (Reduce the use of P fertilizer) are negative, which means less N and P fertilizer are used to achieve the environmental target of 60% gap closure. About 660 ton N fertilizer is reduced and 120 ton P fertilizer is reduced.

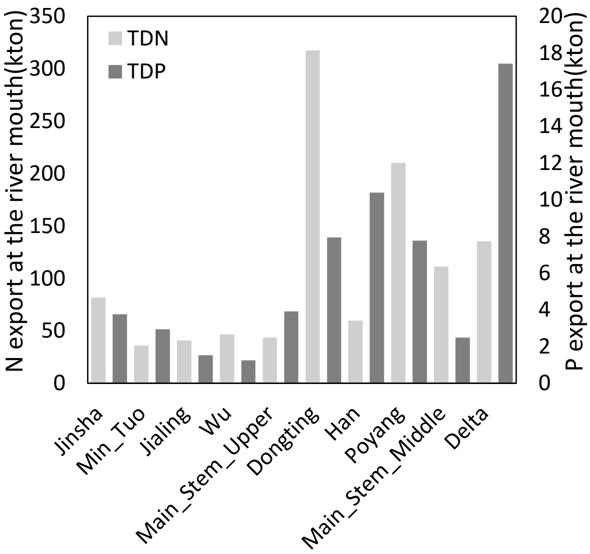


Figure 4.6 Total dissolved nitrogen (TDN) and total dissolved phosphorus (TDP) export by the Yangtze River from each sub-basin in 2050 under Case 1 (kton). *Source: see Section 4.2 for Case 1.*

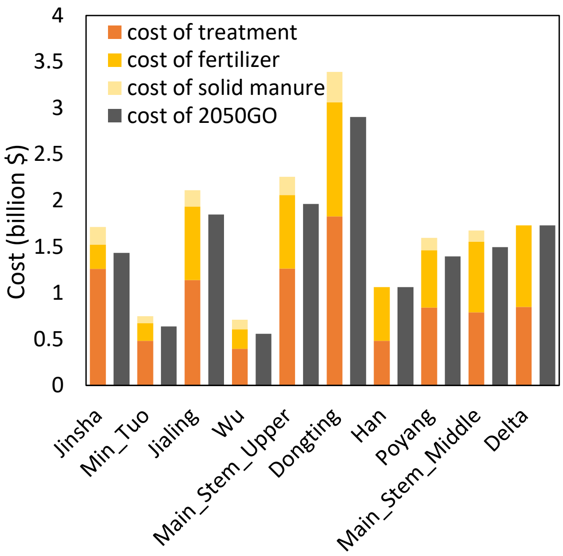


Figure 4.7 Total costs for sub-basins to export TDN and TDP by rivers at the river mouth in 2050 under Case 1 (billion $). *The difference between the costs of the management options (yellowish bars) and the cost of the baseline scenario (GO 2050, black bars) indicates the additional cost needed to close the 60% gap between the actual land desired river export of TDN and TDP from all sub-basins in 2050. Cost of treatment includes the sum of MO 3, MO 6, MO 7, MO 8, MO 9, MO 10, MO 11, MO 12, MO 13. Cost of fertilizer is the sum of cost of MO 1 and MO 2. Cost of solid manure is the sum of the cost of MO 3 and MO 4. MO is the management option. Detailed information about MO can refer to chapter 3. GO is Global Orchestrion. Source: see Section 4.2 for Case 1.*

However, cost-effective options differ among the sub-basins (Figures 4.6-4.7). In general, middle stream and downstream sub-basins are projected to export more TDN and TDP to the river mouth than upstream sub-basins in 2050 under Case 1 (Figure 4.6). For example, Dongting (middle stream) is the biggest contributor to TDN export and is projected to exports about 317 kton of TDN at the river mouth in 2050 under Case 1. Poyang (middle stream), and Delta (downstream) are projected to export 210 kton, and 135 kton of TDN, respectively. Trends in TDP export from the sub-basins are generally lower than TDN exports. The contribution of the sub-basins to the river exports of TDN and TDP reflects the costs needed to reduce the pollution at the river mouth. For example, Dongting sub-basin will need to invest the most to reduce the total pollution in the river mouth compared to the other sub-basins (Figure 4.7), which exceeds the cost by 0.48 billion$ in 2050GO under the baseline. Half of the cost will need to be invested in treatment options including MO 7, MO 11, MO 12. Jinsha (upstream), Jialing (upstream) and Main_stem_upper (middle stream) sub-basins have generally higher costs after the Dongjing for river export of TDN and TDP to the river mouth is less than it is in Dongting (Figure 4.6). Most of the sub-basins also have to invest in treatment including MO 7, MO 11, MO 12. However, in upstream, Jinsha and Jialing do not export many nutrients according to Figure 4.5. Same for middle stream sub-basins, for instance, Main_stem_upper does not export much nitrogen and phosphorus, but it cost about 2.3 billion$ for the management options.

4.3.2 Case 2

Under Case 2, reducing the 60% gap between the actual and desired river export of TDN and TDP by reducing the same reduction rate of nutrient export in sub-basins will cost around 4 billion dollars (3.69 billion $) in 2050 (Table 4.5). This is an additional cost relative to the assumed practices in the baseline scenario (2050GO). The redaction rate of nitrogen is 40% compared to the river export level in 2050GO and the redaction rate of phosphorus is 45%. It is assumed that every sub-basin follows the same reduction rate as separated environmental targets. The separated environmental targets of TDN export by the Yangtze from sub-basins are from 34 kton to 110 kton and of TDP are from 7 kton to 25 kton. To reach these targets, 40% of the TDN river export and 64-87% of TDP river export are required to reduce in 2050 relative to the baseline GO scenario. Following the model, the actual reduction rate at each sub-basin changes, especially for phosphorus. These ranges are for the sub-basins exporting TDN and TDP to the river mouth of Yangtze (Table 4.5). Additionally, two thirds of TDN is estimated to be exported in a form of DIN to the river mouth from all sub-basins in 2050 under Case 2 (Figure 4.8). Almost half of TDP is estimated to be exported in a form of DIP (Figure 4.8).

Table 4.5 Summarized results for Case 2. *60% of the gap closure has to be reached at the river mouth under the Case 2 that all ten sub-basins reduce their river export of TDN and TDP in the same reduction rates. This rate is 40% for TDN and 45% for TDP. Reduction rates are the ratio of the amount of nutrients exports by the Yangtze from sub-basins are reduced relative to the baseline level of nutrients exports by the Yangtze from sub-basins in 2050GO according to the integrated optimal modelling approach. The additional cost is the cost under Case 2 on the top of the assumed practices in the baseline scenario (GO). Details are in section 4.2.5.*

Case 2			
The environmental target estimated from reducing the 60% gap between actual and desired river export of TDN and TDP at the river mouth (kton in 2050)			
TDN		TDP	
1082		120	
The actual nutrient level at the river mouth under Case 2 (kton in 2050)			
TDN		TDP	
1082		53.5	
Environmental target levels of river export by sub-basins at the river mouth (kton in 2050)			
Sub-basins	TDN	Sub-basins	TDP
Jinsha	110	Jinsha	13
Mintuo	45	Mintuo	7
Jialing	73	Jialing	10
Wu	61	Wu	7
Main_Stem_Upper	76	Main_Stem_Upper	15
Dongting	306	Dongting	25
Han	34	Han	7
Poyang	178	Poyang	15
Main_Stem_Middle	110	Main_Stem_Middle	10
Delta	89	Delta	12
Reduction rates in river export of TDN and TDP by sub-basins after optimization (reduction rates are relative to 2050 GO, %)			
Sub-basins	TDN	Sub-basins	TDP
Jinsha	40	Jinsha	76
Mintuo	40	Mintuo	70
Jialing	40	Jialing	70
Wu	40	Wu	86
Main_Stem_Upper	40	Main_Stem_Upper	68
Dongting	40	Dongting	83
Han	40	Han	71
Poyang	40	Poyang	76
Main_Stem_Middle	40	Main_Stem_Middle	87
Delta	40	Delta	64
Additional cost (billion $) relative to practices in the baseline (2050GO)			
3.69			

Cost-effective management options for the Yangtze basin are MO 3 (recycle animal manure as slurry), MO 5 (recycle animal manure after composting), MO 6 (treat animal manure with primary technology), MO 7(treat animal manure with secondary), MO 8(treat animal manure with tertiary technology) technology MO 9 (treat animal manure without treatment) (Figure 4.9). The sum of the influent of pollution sources to the management options are the amount of animal manure and human waste generated in 2050 according to GO scenario. The animal manure will flow to MO 3, MO 4, MO 5, MO 6, MO 7, MO 8 and MO 9, and the human waste will flow to MO 10, MO 11, MO 12 and MO 13. Same with Case 1, most of the sources are influent to MO 3 (recycle animal manure as a slurry), about $416*10^3$ kton, which means the animal manure tends to be treated by MO 3. Following are MO 6 (treat animal manure with primary technology), MO 7 (treat animal manure with secondary technology) and MO 8(treat animal manure with tertiary treatment). About $90*10^3$ kton animal manure is treated by primary technology, $32*10^3$ kton by secondary technology, $17*10^3$ kton by tertiary technology. All solid fraction of animal manure ($60*10^3$ kton) is influent to MO 5(recycle animal manure after composting). All human waste is treated before discharge and most of them go to MO 11 (treat human waste with secondary technology) and MO 12 (treat human waste with tertiary technology). As for the cost distribution, MO 3 still costs most (1.72 billion$). Comparably, MO 6 only costs 0.09 billion $), but animal manure treated by MO 6 is about one fourth of MO 3. The additional cost of MO 1 (Reduce the use of N fertilizer) and MO 2 (Reduce the use of P fertilizer) are negative, which means less N and P fertilizer are used to achieve the environmental target of 60% gap closure. About $4.06*10^3$kton N fertilizer is reduced and $0.81*10^3$kton P fertilizer is reduced. The reduction of synthetic fertilizer use saves about 0.3 billion$.

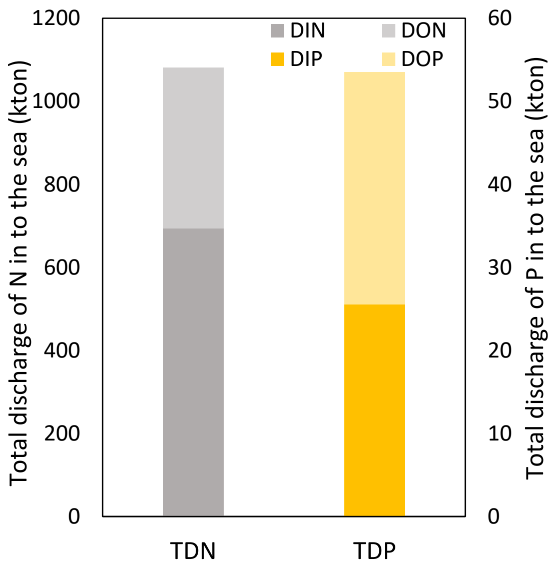


Figure 4.8 Nutrient export by the Yangtze River at the river mouth by form under Case 1 in 2050 (kton). *TDN is total dissolved nitrogen; TDP is total dissolved phosphorus; DIN is dissolved inorganic nitrogen; DON is dissolved organic nitrogen; DIP is dissolved inorganic*

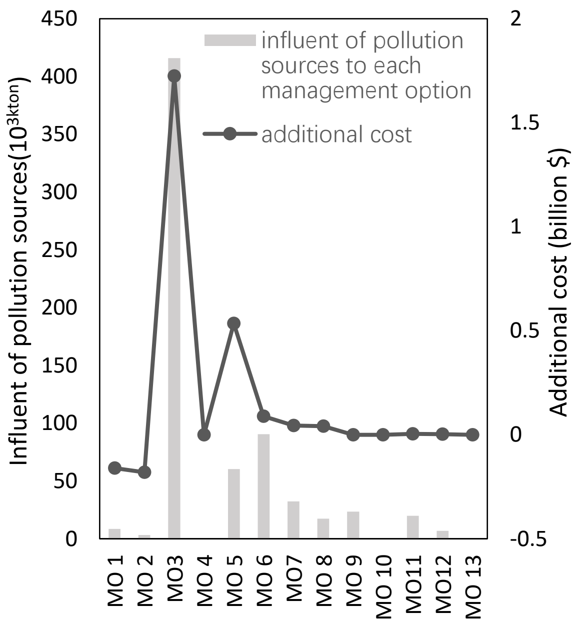


Figure 4.9 Influent of pollution sources to each management option (10^3 kton) and additional costs of these management options in the year 2050 (billion $). *MO is short for management option. MO 1, MO 2, MO 3, MO 4, MO 5, MO 6, MO 7, MO 8, MO 9, MO 10, MO 11, MO 12, MO*

phosphorus; DOP is dissolved organic phosphorus. Source: see Section 4.2 for Case 2.

13 can refer to Chapter 4.2.4. The left axis shows the amount of pollution sources (animal manure, human wastes, and synthetic fertilizer use) influent to management options. The right axis shows the additional cost of each management option compared to 2050GO.GO is Global Orchestrion. Source: see Section 4.2 for Case 2.

Under Case 2, cost-effective options differ among the sub-basins (Figures 4.10-4.11). In general, middle stream and downstream sub-basins are projected to export more TDN and upstream and middle stream are projected to export more TDP under Case 2 (Figure 4.9). For example, Dongting (middle stream) is the biggest contributor to TDN export and is projected to exports about 300 kton of TDN at the river mouth in 2050. Poyang (middle stream), and Delta (downstream) are projected to export 178 kton, and 89 kton of TDN, respectively. Trends in TDP export from the sub-basins are generally lower than TDN exports. TDP export is projected to be equally by sub-basins as a result that for each sub-basin, there is a separate environmental target. The contribution of the sub-basins to the river exports of TDN and TDP reflects the costs needed to reduce the pollution at the river mouth. For example, Dongting sub-basin still needs to invest the most to reduce the total pollution in the river mouth compared to the other sub-basins (Figure 4.11), which exceeds the cost by 1 billion$ in 2050GO under the baseline. Half of the cost will need to be invested in treatment options including MO 6, MO7, MO 8, MO 11, MO 12. Jinsha (upstream), Jialing (upstream) Main_stem_upper (middle stream) and Delta (downstream) sub-basins have generally higher costs after the Dongjing for river export of TDN and TDP to the river mouth is less than Dongting (Figure 4.10). Most of the sub-basins also have to invest in treatment including MO 7, MO 11, MO 12. Han is a sub-basin that exports the least N and P to the Yangtze River mouth, but the cost of Han excesses the Mintuo and Wu. This can be explained that the environmental target for Han is stricter than others.

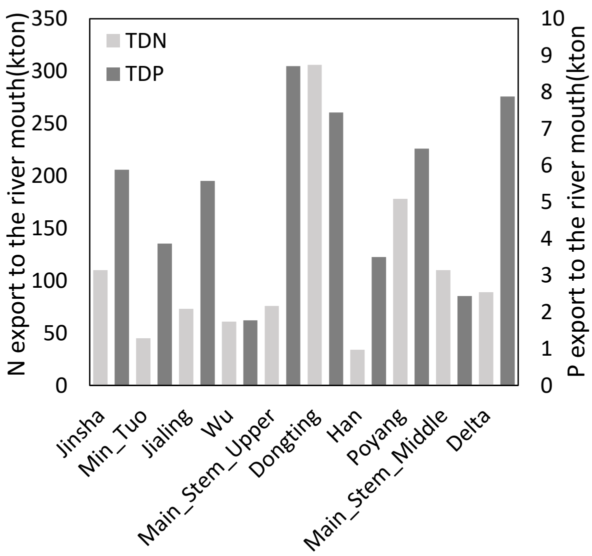


Figure 4.10 Total dissolved nitrogen (TDN) and total dissolved phosphorus (TDP) export by the

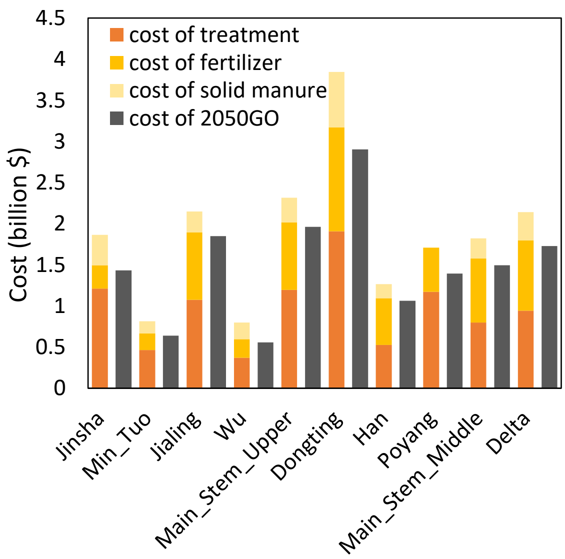


Figure 4.11 Total costs for sub-basins to export TDN and TDP by rivers at the river mouth in

Yangtze River from each sub-basin in 2050 under Case 1 (kton). *Source: see Section 4.2 for Case 2.*

2050 under Case 2 (billion $). *The difference between the costs of the management options (yellowish bars) and the cost of the baseline scenario (GO 2050, black bars) indicates the additional cost needed to close the 60% gap between the actual land desired river export of TDN and TDP from all sub-basins in 2050. The cost of treatment includes the sum of MO 3, MO 6, MO 7, MO 8, MO 9, MO 10, MO 11, MO 12, MO 13. Cost of fertilizer is the sum of cost of MO 1 and MO 2. Cost of solid manure is the sum of the cost of MO 3 and MO 4. MO is the management option. Detailed information about MO can refer to chapter 3.GO is Global Orchestrion. Source: see Section 4.2 for Case 2.*

4.3.3 Case 3

Under Case 3, reducing the 60% gap between the actual and desired river export of TDN and TDP by reducing the same amount of nutrient export in sub-basins will cost around 4 billion dollars (3.56 billion $) in 2050 (Table 4.6). This is an additional cost relative to the assumed practices in the baseline scenario (2050GO). The redaction amount of TDN export is 722 kton compare to the river export level by the Yangtze in 2050GO and the redaction amount of phosphorus is 98 kton. It is assumed that every sub-basin reduces the same amount of TDN and TDP as separated environmental targets. The separated environmental targets of TDN export by the Yangtze from sub-basins are 72.2 kton and of TDP are 9.8 kton. To reach these targets, 16-100% of the TDN river export and 48-93% of TDP river export are required to reduce in 2050 relative to the baseline GO scenario. These ranges are for the sub-basins exporting TDN and TDP to the river mouth of Yangtze (Table 4.6). Additionally, over half of TDN is estimated to be exported in a form of DIN (704 kton) to the river mouth from all sub-basins in 2050 under Case 2 (Figure 4.12). Almost half of TDP (24 kton) is estimated to be exported in a form of DIP (Figure 4.12).

Table 4.6 Summarized results for Case 3. *60% of the gap closure has to be reached at the river mouth under the Case 3 that all ten sub-basins reduce their river export of TDN and TDP in the same reduction amount. The reduction amount for TDN is 72.2 kton and for TDP is 9.8 kton for each sub-basin. Reduction amount is how much of nutrients exports by the Yangtze from sub-basins are reduced relative to the baseline level of nutrients exports by the Yangtze from sub-basins in 2050GO according to the integrated optimal modelling approach. The additional cost is the cost under Case 3 on the top of the assumed practices in the baseline scenario (GO). Details are in section 4.2.5.*

Case 3			
The environmental target estimated from reducing the 60% gap between actual and desired river export of TDN and TDP at the river mouth (kton in 2050)			
TDN		TDP	
1082		120	
The actual nutrient level at the river mouth under Case 3 (kton in 2050)			
TDN		TDP	
1082		53.8	
Environmental target levels of river export by sub-basins at the river mouth (kton in 2050)			
Sub-basins	TDN	Sub-basins	TDP
Jinsha	111	Jinsha	14
Mintuo	3	Mintuo	3
Jialing	49	Jialing	8
Wu	29	Wu	3
Main_Stem_Upper	55	Main_Stem_Upper	17
Dongting	438	Dongting	35
Han	0	Han	2
Poyang	225	Poyang	17
Main_Stem_Middle	111	Main_Stem_Middle	8
Delta	76	Delta	12
Reduction rates in river export of TDN and TDP by sub-basins after optimization (reduction rates are relative to 2050 GO, %)			
Sub-basins	TDN	Sub-basins	TDP
Jinsha	43	Jinsha	81
Mintuo	96	Mintuo	86
Jialing	60	Jialing	91
Wu	71	Wu	93
Main_Stem_Upper	57	Main_Stem_Upper	88
Dongting	16	Dongting	48
Han	100	Han	93
Poyang	24	Poyang	69
Main_Stem_Middle	40	Main_Stem_Middle	86
Delta	49	Delta	70
Additional cost (billion $) relative to practices in the baseline (2050GO)			
3.56			

Cost-effective management options for the Yangtze basin are MO 3 (recycle animal manure as slurry), MO 5 (recycle animal manure after composting), MO 6 (treat animal manure with primary technology), MO 7(treat animal manure with secondary), technology MO 9 (treat animal manure without treatment) (Figure 4.13). Most of the sources are influent to MO 3 (recycle animal manure as a slurry), about $438*10^3$ kton, which means the animal manure tends to be treated by MO 3. Following are MO 6 (treat animal manure with primary technology), MO 7 (treat animal manure with secondary technology) and MO9 (treat animal manure without treatment). About $82*10^3$ kton animal manure is treated by primary technology, $38*10^3$ kton by secondary technology, $25*10^3$ kton by directly discharge. All solid fraction of animal manure ($52*10^3$ kton) is influent to MO 5 (recycle animal manure after composting). All human waste is treated before discharge and most of them go to MO 11 (treat human waste with secondary technology) and MO 12 (treat human waste with tertiary technology). As for the cost distribution, MO 3 still costs most (1.76 billion$). The additional cost of MO 1 (Reduce the use of N fertilizer) and MO 2 (Reduce the use of P fertilizer) are negative, which means less N and P fertilizer are used to achieve the environmental target of 60% gap closure. About $0.7*10^3$kton N fertilizer is reduced and $0.2*10^3$kton P fertilizer is reduced. The reduction of synthetic fertilizer use saves about 0.2 billion$.

Under Case 3, cost-effective options differ among the sub-basins (Figures 4.14-4.15). In general, middle stream and downstream sub-basins are projected to export more TDN and TDP under Case 3 to the river mouth (Figure 4.14). For example, Dongting (middle stream) is the biggest contributor to TDN export and is projected to exports about 429 kton of TDN and 23 kton of TDP at the river mouth in 2050. Poyang (middle stream), and Delta (downstream) are projected to export 225 kton, and 76 kton of TDN, respectively. Trends in TDP export from the sub-basins are generally lower than TDN exports. The contribution of the sub-basins to the river exports of TDN and TDP reflects the costs needed to reduce the pollution at the river mouth. For example, Cost in Dongting is the most to reduce the total pollution in the river mouth compared to the other sub-basins (Figure 4.15), which exceeds the cost by 0.3 billion$ in 2050GO under the baseline. Half of the cost will need to be invested in treatment options including MO 6, MO7, MO 8, MO 11, MO 12. Jinsha (upstream), Jialing (upstream), Main_stem_upper (middle stream) and Delta (downstream) sub-basins have generally higher costs after the Dongjing for river export of TDN and TDP to the river mouth (Figure 4.15). Most of the sub-basins also have to invest in treatment including MO 6, MO7, MO 8, MO 11, MO 12. Mintuo and Wu do not have cost in solid manure. Han is still an exception in Case 3. Han only exports 0.8 kton P but the additional cost of Han reaches 0.3 billion $, even more than the sub-basins where there is more nutrient export.

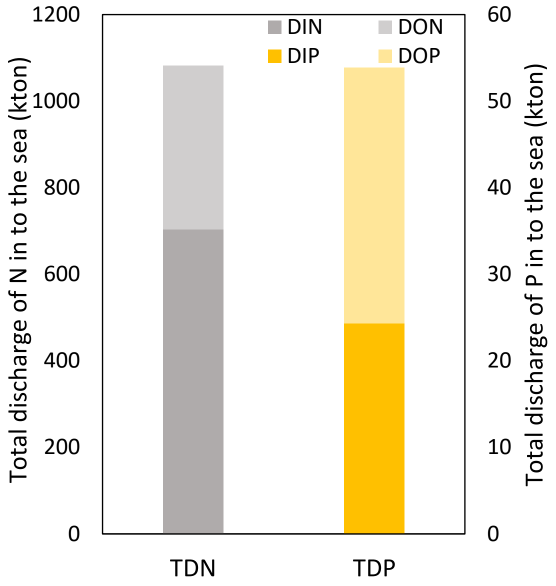


__Figure 4.12 Nutrient forms exported at the river mouth of Case 3 when achieving the environmental target.__ TN is total dissolved nitrogen; TP is total dissolved phosphorus; DIN is dissolved inorganic nitrogen; DON is dissolved organic nitrogen; DIP is dissolved inorganic phosphorus; DOP is dissolved organic phosphorus. Source: calculation data for case 3.

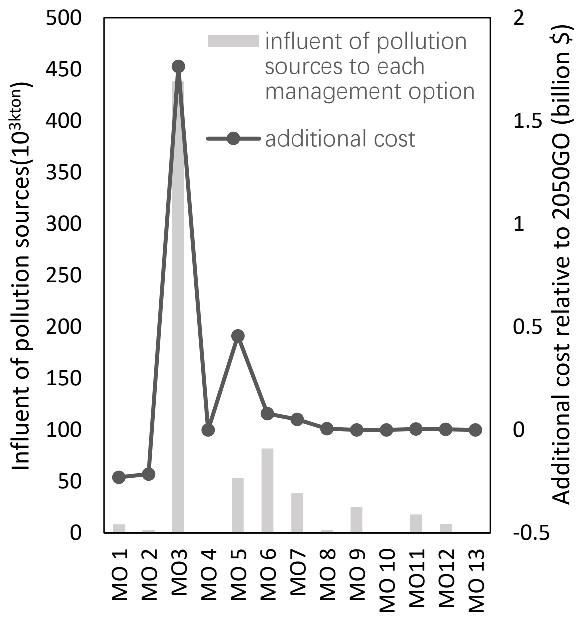
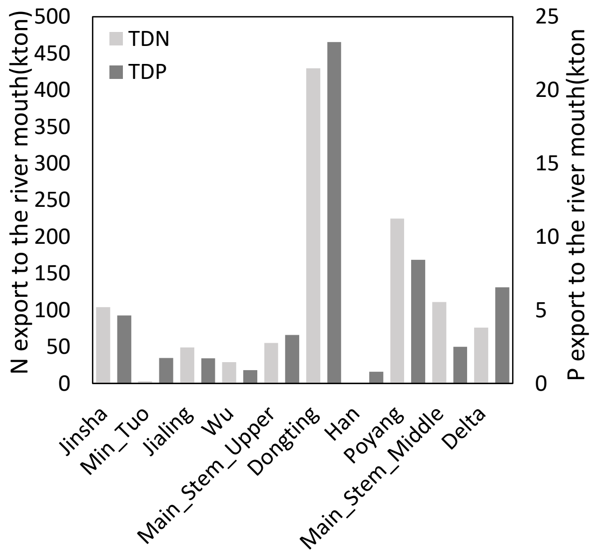


__Figure 4.13 Source influence and cost distribution in 13 MOs.__ MO is short for management option. MO 1, MO 2, MO 3, MO 4, MO 5, MO 6, MO 7, MO 8, MO 9, MO 10, MO 11, MO 12, MO 13 can refer to Chapter 3. The left axis shows the amount of sources influent to management options, and the right axis shows the additional cost relative to 2050GO of each management option. GO is Global Orchestrion. Source: calculation data for case 3.



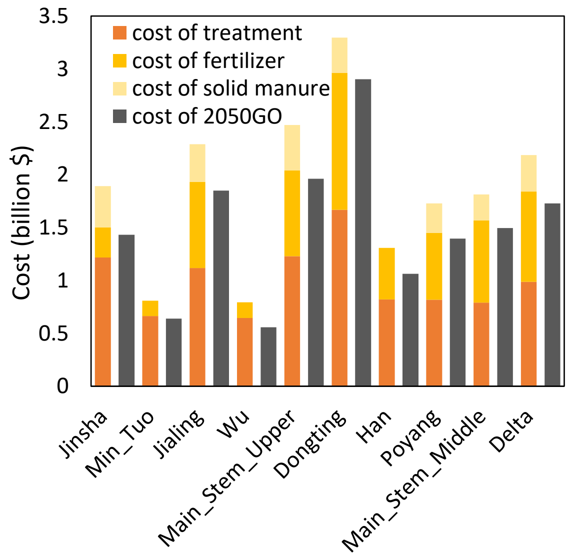


Figure 4.14 Total dissolved nitrogen (TDN) and total dissolved phosphorus (TDP) export by the

Figure 4.15 Total costs for sub-basins to export TDN and TDP by rivers at the river mouth in

Yangtze River from each sub-basin in 2050 under Case 1 (kton). *Source: see Section 4.2 for Case 3.*

2050 under Case 3 (billion $). *The difference between the costs of the management options (yellowish bars) and the cost of the baseline scenario (GO 2050, black bars) indicates the additional cost needed to close the 60% gap between the actual land desired river export of TDN and TDP from all sub-basins in 2050. The cost of treatment includes the sum of MO 3, MO 6, MO 7, MO 8, MO 9, MO 10, MO 11, MO 12, MO 13. Cost of fertilizer is the sum of cost of MO 1 and MO 2. Cost of solid manure is the sum of the cost of MO 3 and MO 4. MO is the management option. Detailed information about MO can refer to chapter 3. GO is Global Orchestrion. Source: see Section 4.2 for Case 3.*

4.3.4 Comparison of the results under Case 1, Case 2 and Case 3

To achieve the same environmental target at the Yangtze River mouth, the additional cost on top of the baseline practices under Case 1 is the smallest. The additional cost of Case 1 is only 1.97 billion $. The additional cost under Case 2 is 3.69 billion $ and under Case 3 is 3.56 billion $. Compare Case 2 and Case 3, the additional cost under Case 3 is slightly less than Case 2. This may seem surprising. The reason may be associated with Han. Han only exports 57 kton of TDN in 2050GO, but Han needs to reduce 72 kton TDN river export to meet the environmental target. 72 kton is higher than 57 kton, so the target is higher than the sub-basin export, which means the environmental target is too strict. Then, the environmental target level of TDN in Han is set as 0 kton in Case 3. As a result, the total cost of Case 3 is less than Case 2. Even Case 2 and Case 3 seems more equal than Case 1, they costs more than Case 1. Only Case 1 can reach the cost-optimal situation, for it finds the cost-minimized way to achieve the same environmental target.

The results of the Case 2 and 3 are much higher than Case 1 is because they do not consider the differences in sub-basins (e.g. population growth, hydrology, agricultural activities and distances to the river mouth). Every sub-basin has the responsibility to reduce TDN and TDP export, and they can take different shares to save the cost.

To achieve the cost-optimal situation in Case 1, MO 3 (recycle animal manure as a slurry) is the cost-minimized way to treat animal manure. The solid fraction of animal manure tends to flow to MO 4 (recycle animal manure as solid). As for the liquid fraction of animal manure, a large part of them is treated by secondary technology and a small part of then are discharged to the river directly. Human waste in Case 1 is treated by secondary and tertiary technology.

4.4 Conclusions

This chapter answer the research question “What are the cost-effective management options to reduce coastal eutrophication in the Yangtze River mouth?" I used an integrated model approach conducting in GAMS and set three cases to prove the model calculation can find the cost-optimal management option. Below, I conclude three main findings of this chapter.

First, reducing a 60% gap between actual and desired river export of TDN and TDP will cost about 2 billion $ in 2050 (Case 1). Cost-effective options are recycling of animal manure on the land as slurry (most important), recycling animal manure on the land as solid, treating animal manure with secondary technologies, and direct discharges of animal manure to rivers. The result also illustrates that N and P fertilize using need to be reduced by about 700 kton and 100 kton respectively comparing to the baseline situation in 2050GO.

Second, cost-effective options may differ when assuming equal reductions in river export of nutrients among sub-basins (Cases 2 and 3)**.** Case 2 and Case 3 have stricter environmental targets than Case 1. That is why reducing 60% of the gap between actual and desirable river export of TDN and TDP cost more under Case 2 and Case 3. The additional cost on top of the baseline practices is 3.69 billion $ in Case 2 and 3.56 billion $ in Case 3. Cost-effective management options are recycling animal manure on the land as slurry (also in Case 1), treating animal manure with primary technology (more than in Case 1) and recycling all solid manure to the land after composting (this is not in Case 1). The additional cost in Cases 2 and 3 are higher than in Case 1. This is associated with the fact that the sub-basins are requested to reduce the same fraction of the nutrients to the river mouth without considering the differences in the population growth, agricultural activities, hydrology and the distance towards the river mouth. These differences are considered under Case 1.

Third, the cost-effective management options differ among the sub-basins (Cases 1, 2 and 3). Most important cost-effective option is to recycle animal manure on the land for many sub-basins in Cases 1, 2 and 3. This is because direct discharges of animal manure are largely avoided. Avoiding these discharges is important to reduce the nutrient pollution in Yangtze. Some sub-basins will need to invest to treat manure with secondary technologies in Case 1. These sub-basins are, for example Jinsha, Jialing, Main_stem_upper, Dongting and so on. Some sub-basins will need to invest to treat manure with primary treatment in Cases 2 and 3. Recycling of solid manure after composting becomes an important cost-effective option for sub-basins Jialing, Main_stem_upper, Dongting in Cases 2 and 3.

Chapter 5 Conclusions and Discussion

Three chapters are used to describe how to identify the cost-effective management options to reduce future coastal eutrophication problems in the Yangtze River mouth. In Chapter 2, three drivers and different sources of nitrogen and phosphorus inputs to the Yangtze River basin are introduced. Chapter 3 describes thirteen management options to reduce the coastal eutrophication problems in the Yangtze River basin with their costs and nutrient removal efficiencies. Chapter 4 uses an integrated modelling approach to identify a cost-effective management option. In this chapter, the results from Chapter 2, Chapter 3 and Chapter4 are discussed and lead to an overall conclusion.

5.1 Conclusions

Finding 1: Economic growth, population booming, climate and hydrological changes are main drivers of increasing export of nutrient by Yangtze basin.

GDPppp in 2050 is more than 30000 $/person/year, which is 80 times more than it is in 1970. With more disposable income, people change their eating habits to meat products. As a result, the nutrient input from animal manure increases. Population booming happens in 2050, especially the urban populations for the reason of rural population migration. Sewage systems in urban areas face more pressure on human waste, and more wastewater are discharged into the Yangtze Basin. Temperature and precipitation change the river discharge in the Yangtze Basin, and the river discharging increase by 36% in 2050.

Finding 2: Diffuse sources are the main contributor of N and P inputs in the Yangtze River. Point sources are the main contributor of organic pollutants.

River inputs of N (nitrogen) and P (phosphorus) in the Yangtze River basin double between 2000 and 2050 in the baseline scenario GO (Global Orchestration). Diffuse sources are responsible for 80% of nitrogen and phosphorus inputs in the Yangtze River basin. DIN accounts for 48% of total N export in 2050 and about 70% of DIN input is from diffuse sources, which exceeds half of the DIN exports. Even though point source only brings 20% of the total N and P inputs, it is a dominant contributor to organic pollutants. More than 80% of DON and DOP are from point sources in 2050. DOP is the main pollution form of P exports.

Finding 3: Thirteen management options and their costs and removal efficiencies are identified for reducing future coastal eutrophication. Composting is used as MO 5 to treat solid animal manure.

These management options are MO 1 (reduce synthetic fertilizer N use), MO 2 (reduce synthetic fertilizer P use), MO 3 (recycle animal manure as slurry), MO 4 (recycle animal manure as solid), MO 5 (recycle animal manure after composting), MO 6 (treat animal manure with primary technologies), MO 7 (treat animal manure with secondary technologies), MO 8 (treat animal manure with tertiary technologies), MO 9 (direct discharge animal manure without treatment), MO 10 (treat human waste with primary technologies), MO 11 (treat human waste with secondary technologies), MO 12 (treat human waste with tertiary technologies), MO 13 (direct discharge human waste without treatment).

The removal efficiency of treating animal manure with primary, secondary and tertiary technologies are updated value compare to the value in Strokal et al. (2019). The values of removal efficiency are estimated average values from the literature. The updated value of removal efficiency of treating animal manure with primary, secondary and tertiary technologies on N is 23%, 48%, 64% respectively and the removal efficiency on P is 29%, 71% and 89% respectively. During the composting process (MO 5), there is a 60% loss of N and the removal efficiency of N when composting is 60%. Cost of reducing fertilizer N use, reducing fertilizer P use, recycling animal as slurry, recycling animal manure as solid and recycling animal manure after composting are recalculated refer to (Strokal et al., 2020) to 326 $/ton, 1119 $/ton, 21 $/ton, 22 $/ton and 45 $/ton, respectively.

Finding 4: Reducing a 60% gap between the actual and desired levels of nutrients in the Yangtze River mouth will cost around two billion dollars in 2050.

The integrated modelling approach finds it is possible to reach the environmental target of reducing 60% of the gap between actual and desired river export of TDN and TDP by an additional cost relative to the baseline in 2050GO of around 2 billion $, which is the result of Case 1. The reduction rates of TDN in the sub-basins to reduce the 60% gap in the river mouth range from -4% to 67%, and of TDP ranges from 14% to 92%. The reductions differ among the sub-basins because the integrated model considers their characteristics. (e.g., population, production activities, land use, etc.).The most effective management options are MO 3 (recycle animal manure as slurry), MO 4 (recycle animal manure as solid), MO 7 (treat animal manure with secondary technology), MO 9 (discharge animal manure without treatment).

Finding 5: Cost-effective management options may differ when assuming equal reductions in river export of nutrients among sub-basins.

Case 2 and Case 3 reach the environmental target of reducing 60% gap between baseline and desired river export by following the same reduction rate or reduce the same amount of nutrients by sub-basins. However, the cost of Case 2 and Case 3 are much higher than the cost under Case 1. This indicates the sub-basins are requested to reduce the same fraction or amount of nutrients to the river mouth do not consider the differences in the population growth, agricultural activities, hydrology and the distance towards the river mouth. These differences are considered in Case 1.

Finding 6: The cost-effective options differ among the sub-basins.
This holds for Cases 1, 2 and 3 that recycling animal manure to land is the most important cost-effective management option for many sub-basins. This is because recycling animal manure to land can avoid the animal manure directly discharge to rivers, which can reduce the nutrient pollution in the Yangtze River. Some sub-basins need to invest to treat animal manure with secondary technologies in Case 1. These sub-basins are from upstream and middle stream, e.g., Jinsha, Jialing, Main_stem_upper, Dongting. These sub-basins will need to invest to treat animal manure with primary treatment in Cases 2 and 3. Recycling of solid manure after composting becomes an important cost-effective option for sub-basins Jialing, Main_stem_upper, Dongting in Cases 2 and 3.

5.2 Discussion

In this section, three parts are discussed. Firstly, reflect on the results of my study and compare them with existing studies. Then the limitation and strength in the thesis research are introduced. The last, a discussion of the implication possibility for science and policy will be given.

5.2.1 Comparison with existing studies

Pollutions drivers and sources in the Yangtze River

Chapter 2 is to answer the research question "What are the main drivers and sources of nutrient pollution in the Yangtze River?". Diffuse sources (including synthetic fertilizer inputs to agricultural land; animal manure recycling to agricultural land; human wastes recycling to agricultural land; atmospheric deposition, biological fixation, weathering on P-contained minerals, and leaching of organic matter from the soil) are the main contributor of nutrient inputs to the Yangtze River basin. Compare the results with other studies, and these studies indicate an increase of nutrients export by the Yangtze to the River mouth since the 1970s. For example, Strokal et al. (2016) indicate that between 1970 to 2050, the river export of nutrients increase by a factor of 2-4. And in 2050, more nutrient pollution will be exported from animal manure and human wastes. It is studied that from 1990 to 2012, an increase of N and P loss happened in food production. (Wang et al., 2018). The diffuse sources account for 80% of the total nutrient inputs. Most of the nutrient export by the Yangtze at the river mouth is as a form of DIN. This is also proved in the study by Chen et al. (2019) that DIN export in the estuary of the Yangtze River increases 4 times from 1970 to 2000.

Chapter 2 indicates Economic growth, Booming population and Climate Change and hydrological change as three drivers of increase of nutrient pollution in the Yangtze River basin. Other studies also indicate that economic growth, population growth, urbanization trend, global change and food production etc. as important causes of nutrient pollution in Yangtze River. (Chen et al., 2019; Strokal et al., 2020; Strokal et al., 2016; Maryna et al., 2017; Wang et al., 2018). Increase in disposable income simulates consumption. As a result, fertilizer use becomes more intensive to support the increasing need for agriculture products. People change to more protein-contained products dietary habits and this brings an increase in animal production. Extending of animal production industry input more animal manure to the basins. Temperature, precipitation and runoff can also change the hydrological condition of the basins. In 2050, the river discharging increase 36% comparing to it is in 1970 and this is a result of an increase in precipitation.

Management options with their removal efficiencies and costs

Chapter 3 is to answer the research question "What are the costs of management options to reduce nutrient pollution in the Yangtze River basin?". To solve the pollution from synthetic fertilizer, animal manure and human wastes, 13 management options are introduced. 12 management options are from Strokal et al. (2020), but the costs and removal efficiencies are updated from the literature (Foged et al., 2011; Humenik, 2001; Jin et al., 2014; Kartal et al., 2010; Qiao et al., 2010; Van Drecht et al, 2009; Yan et al., 2017). Composting is a newly added management option to treat solid fraction of animal manure. Reducing the use of synthetic fertilizer N and P is to deal with the pollution of fertilizer. By reducing fertilizer use, nutrient pollution can be reduced, and cost can be saved. The influent from recycling animal manure as slurry, solid, or after composting are diffuse sources. The influent from treating animal manure with primary, secondary, tertiary technologies or direct discharge are point sources. Human waste is treated by primary, secondary, tertiary technologies or direct discharge to rivers, of which the influents are point sources. Management options whose influents are point sources are with a reduction rate of nitrogen and phosphorus. Management options whose influents are diffuse sources do not have a reduction rate of nitrogen and phosphorus, except for recycling animal manure after composting.

Cost-effective management option in the Yangtze River basin

Chapter 4 answered the question of "What are the cost-effective management options to reduce the coastal eutrophication in the Yangtze River mouth?". Using an integrated modelling approach by combing the MARINA model with the cost-optimization process in Chapter 4, cost-effective management options are identified. MO 3 (recycle animal manure as slurry), MO 4 (recycle animal manure as solid), MO 7 (treat animal manure with secondary technology), MO 9 (discharge animal manure without treatment) are the most effective management options according to the model calculation. This study shows the additional cost relative to the baseline in 2050 GO when reaching the environmental target of reducing 60% of the gap between actual and desired river export of TDN and TDP is about two billion dollars (1.97 billion $). The cost to achieve the same environmental target according to Strokal et al. (2020) is 1.70 billion $. The difference in the estimated cost is caused by the newly added MO 5 (recycle animal manure after composting). MO 5 can deal with the solid fraction of animal manure and during the composting process, 60% nitrogen will loss. When simulating this management option by the integrated modelling approach in GAMS, the additional cost on the top of the baseline in 2050GO will slightly increase. The actual nitrogen and phosphorus levels at the Yangtze River mouth are 1082 kton and 59 kton. According to Strokal (2020), the actual nitrogen and phosphorus levels are 1126 kton and 83 kton respectively. This illustrates that MO 5 can help reduce the nutrient export level at the Yangtze River mouth.

5.2.2 Strengths and limitations

Strengths

This thesis research is novel for three aspects. The first is the costs and removal efficiencies of management options are updated, the second is composting is considering as one management option to treat animal manure, and the third are the three cases studies.

1) Updated the value of costs and removal efficiencies. Strokal et al. (2020) list 12 management options with their costs and removal efficiencies in her paper. In Chapter 3, removal efficiencies of MO 10 (treat human waste with primary technology), MO 11 (treat human waste with secondary technology), MO 12 (treat human waste with tertiary technology) are updated. The cost of MO 1 (reduce the use of N fertilizer), MO 2 (reduce the use of P fertilizer), MO 3 (recycle animal manure as slurry), MO 4 (recycle animal manure as solid) are updated. The updated value is based on a literature review. These updated cost and removal efficiencies are used in the calculation in Chapter 4 and can influence the cost-effective management options and their additional cost relative to the baseline in 2050GO.

2) Updated one management option. One management option, MO 5 (recycle animal manure after composting), is added in Chapter 3. In Chapter 4, it simulates MO 5 (recycle animal manure after composting) by the integrated modelling approach in GAMS to calculate the additional cost to mitigate the costal eutrophication problems in the Yangtze River mouth. Comparing to directly recycling animal manure, composting has many strengths because it can solve the odor and bacteria problems. Ministry of Agriculture and Rural Affair of the People's Republic of China also encourage the agriculture department to compost animal manure (MOA, 2015). Adding composting as a management option can give a better indication to the policy makers.

3) Three cases studies. Another novel aspect is in Chapter 4, I consider two equal situations, Case 2 and Case 3, to compare the costs of them with the cost of Case 1. The environmental target of Case 1 it to reduce 60% of the gap between baseline and the desired level of TDN and TDP export. The additional cost relative to the baseline in 2050GO under Case 1 is much lower than they are under Case 2 and Case 3. Case 2 and Case 3 require the sub-basins to reduce equally in fraction or absolute amount, but the result is not the cost-optimal situation. To discuss different situations of Case 1, Case 2 and Case 3 can provide the policy makers information that Case 2 and 3 do not consider the differences of sub-basins (e.g. population growth, hydrology, physical distance to the river mouth).

Limitations

In this thesis study, there are still some limitations. These limitations are uncertainty in the MARINA model, uncertainty in the integrated modelling approach and in the multi-objective function. Despite these limitations, this model can provide useful information to the policy makers, and it can also be expended to more pollutants and more management options in the future.

1) Uncertainty in the MARINA model

The thesis research is based on the MARINA model, but the MARINA model is a simplification of reality. There still some uncertainties in the model. For example, MARINA model considers the most important nutrient pollution sources in China, but there still some sources are not included, such as industrial pollution and aquaculture pollution (Strokal et al., 2016). However, the model accounts for most important sources of nutrient pollution at the sub-basin scale. Lots of the model parameters are from the Global NEWS-2 model (Mayorga et al., 2010) and some of them are calibrated on a global scale for the reason that there is no enough water quality data. Even so, the MARINA model is validated following the "building TRUST in a model" approach (Strokal et al., 2016). This approach has six options, including comparing modelled nutrient fluxes with existing study, comparing modelled nutrient trends with existing study, comparing model inputs data with other datasets, consulting the experts, and comparing the model results with other studies (Strokal et al., 2016). Considering the results of the six options, the MARINA model can be used to quantify the nutrient pollution export by the sub-basins to the Yangtze River mouth in 2050.

2) Uncertainty in the integrated modelling approach

The values of the costs and removal efficiencies of management options are estimated from a range value in different literature. To simulate these values in the integrated modelling approach in Chapter 4, average values of the costs and removal efficiencies are used, which means the result is the cost-optimal additional cost relative the baseline in 2050 is projected as an average value.

The integrated model approach is a simplification of reality. For example, when modeling the MO 5 (recycle animal manure after composting), only the solid fraction of animal manure is treated by MO 5. This assumption has an impact on pollution sources influent to other management options.

Management options can be divided into more specific management options. For example, the animal manure can be divided into different types, and technologies are more specific, such as injection.

3) Multi-objective function

The optimization model with MARINA focuses on a single objective: minimize the total cost of reducing eutrophication in the Yangtze River. This implies that this approach does not consider the tread-offs in management options between air and water. For example, in MO 5 (recycle animal manure after composting), 60% of the nitrogen is lost during composting. This reduced nitrogen can be transferred to NH_3 in the air. There is an opportunity that NH_3 (ammonia) are deposited to the land or they can be fixated by the plants. Then the lost nitrogen can be back to the Yangtze River basin when precipitation or as a diffuse source. This means that reducing N in manure may reduce N pollution in the rivers but may increase N emissions to the air. This type of the trade-offs can be accounted for in a multi-objective function. This is the next step in research.

5.2.3 Implications for science and policy

The results in this thesis study indicate that recycling animal manure as slurry is an effective management option to mitigate coastal eutrophication problems in the Yangtze River mouth. Reducing the use of synthetic fertilizer is also encouraged for it can save money if replace synthetic fertilizer using by applying animal manure to agricultural land. Reducing 5000 kton synthetic fertilizer use can save a cost of about 1 billion $. It is suggested that all human waste is to be treated by secondary and tertiary technologies. The feasibility of implementing cost-effective options are related to the economic feasibility, the technical feasibility, the practical feasibility.

In the cost-optimal situation, the additional cost relative to the baseline in 2050 GO is about two billion $ and it is very close to the calculation by Strokal et al. (2020). According to Strokal, closing the gap between the baseline and the desired level of TDN and TDP by 80% to 90% is economically feasible (Strokal et al., 2020). Farms in China need more incentives to reduce the use of synthetic fertilizer, for example, subsidies can be set when farmers replace synthetic fertilizer to organic manure fertilizers. Taxes on synthetic fertilizer can also reduce the use of them by farmers. Some management options can attract farmers to join, like composting. Composting can solve the odor problems of animal manure and less volume of the composting product can save the transportation cost to long distances. What's more, the final composting products can be sold to other farmers as compensation. However, more initiatives are needed in China for Chinese farmer are not in a very high educated level. The government need to encourage the knowledge share to the farmers. Overall, the implementation of effective management options still needs the active participation of different stakeholders in China.

The technical feasibility is high. Animal manure contents a high level of nutrient and it is a good source of organic fertilizer (Strokal et al., 2016). It can replace the use of synthetic fertilizer as organic fertilizer when recycling to the land. Recycling animal manure to land can also reduce the nutrient pollution caused by the direct discharge of animal manure. Many management options to recycle animal manure to agriculture land are applied in Europe and China. For example, Yan et al., (2017) indicated that about 90% of the animal manure is recycled as untreated slurry. In this study, we consider this option in detail.

The practical feasibility is still under discussion. Legislations and laws are introduced to mitigate the environmental impact of animal manure in China. For example, the newly issued law “Action plan for zero-growth of artificial fertilizer application by 2020” requires 60% of the animal manure are recycled to agriculture land (Yan et al., 2017). China’s Ministry of Agriculture (MOA) also released an action plan “Action to Achieve Zero Growth of Chemical Fertilizer Use by 2020” to control the annual growth rate of synthetic fertilizer less than 1%. Even though a lot of laws and action plans are available in China, there still needs attention to farms. Farmers in China are not highly educated, so many of them do not know how to apply effective management options. To solve this problem, a “Double High Agriculture” project is provided by the government to help the farmers in managing nutrients, soil and water in the agriculture activities (Wang et al., 2018).

However, the policy makers need to consider how to deal with equality and cost-optimization. The additional cost relative to the baseline in 2050 under Case 2 and Case 3 is doubled the additional cost under Case 1. Case 2 and Case 3 is to reach the environmental target reducing 60% of the gap between the actual level and the desired level by reduce an equal fraction or absolute amount. Case 1 is the result of the integrated model to realize the environmental target reducing 60% of the gap considering the differences in sub-basins (e.g. population growth, agricultural activities, hydrology and so on). This means that equality does not always bring cost-optimization results. In an economic aspect, management options under Case 2 and Case 3 are not efficient. It depends on the social objective of the society, if the society wants to pay more attention to equality, then more cost will be needed (as the results in Case 2 and Case 3). Or they can choose the cost-effective management options (as the result in Case 1) and use the saved money as a compensate to sub-basins. For example, the sub-basins who result in most part of the river export of nutrient pollution in the Yangtze River mouth need to take more responsibility to reduce the pollution, or they pay “clean” sub-basins and ask the “clean” sub-basins to reduce pollution instead. This result in the study give a good indication of the economic optimal situation, but the policy implementations about equal distribution of nutrition reduction are still under discussing.

As mentioned in the limitations, the trade-offs in management options between water and air are not considered in this study, this type of the trade-offs can be taken in to accounted in a multi-objective function. This is the next step in research. A balance of equality and an economic optimal result need further research. The equality does not have specific value like the cost. If we can quantify the equality and compare it to the cost, the result can give a good insight to the policy makers.

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