Resource-based agricultural non-point source pollution control using biological agents
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ABSTRACT
Non-point source (NPS) pollution is a major cause of the deterioration of surface water quality. Effectively controlling NPS pollution, especially that from rural areas, is critical in improving the quality and safety of water resources. However, most of the approaches employed for NPS control are low-efficiency or impractical owing to ignorance of the willingness of participants, as well as the high cost. To improve the effectiveness and efficiency, this study newly proposes a resource-based approach for agricultural NPS pollution control via using biological agents. In this approach, the domestic organic waste and livestock manure are economically utilized to produce organic fertilizers and plant protection agents to replace harmful chemical fertilizers and pesticides, respectively. The approach has been applied in the Danjiangkou catchment area in Nanyang City, and the results show that: (1) the most severe pollutants, total P and total N concentrations have been effectively reduced and their values in 2025 are predicted to be the same level as that before significant deterioration; (2) with unpowered sewage treatment and spontaneous participation of farmers, the treatment cost is significantly reduced; (3) the resource-based treatment of domestic waste and livestock manure supports the development of an efficient and sustainable agricultural economy.

Key words | agriculture, biological agent, non-point source pollution, resource-based, South-North Water transfer project

INTRODUCTION
Non-point source (NPS) pollution deteriorates the surface water quality of rivers and lakes. In contrast with point source pollution, which can be easily monitored and controlled, NPS pollution remains underestimated and poorly controlled (Wu et al. 2017). The contribution of NPS pollution to the overall environmental pollution has gradually increased, and NPS pollution is becoming the primary source of surface and groundwater pollution (Ongley et al. 2010; Wu et al. 2018). According to previous research, 30–50% of the Earth’s total surface area is under the influence of NPS pollution (Xin et al. 2017); furthermore, agricultural NPS pollution, which is harmful to the aquatic environment, is considered the most prevalent form of NPS pollution (Fan et al. 2019; Yi et al. 2020). In the Clean Water Act of the United States of America (USA), legislated in 1972, NPS pollution is defined as ‘any source of water...
pollution that does not meet the legal definition of ‘point source’ in section 502(14) of the Clean Water Act (United States 1972). Agricultural NPS pollution, which is mainly caused by fertilizers, pesticides, sewage sludge, and livestock manure, includes nutrients such as N and P, as well as those in pesticides, and other organic or inorganic pollutants (Li et al. 2010; Li et al. 2019). Agricultural NPS pollution is an important cause of water quality deterioration in surface waters (Liu et al. 2020). Owing to the prevalence, extensive dispersion, and uncertain transport paths of NPS pollutants, the mechanism of agricultural NPS pollution is not well-known; however, it does involve a long latent period, which is significantly harmful (Zeng 2019). Agricultural NPS pollution is considered as a world–wide environmental issue (Yang et al. 2017), and it hinders the sustainable rural development in China (Liu et al. 2017). Therefore, the development of an effective approach for controlling NPS pollution is crucial.

Research on NPS pollution was first conducted in the 1960s in several developed countries, such as the USA, Britain, and Japan, and global research interest expanded from the 1970s. In the 1980s, research on agricultural NPS pollution underwent a period of vigorous development. By the 1990s, new pollutants had become the focus of research (Tong et al. 2011; Adu & Kumarasamy 2018). And then numerical researches on NPS were presented, including the pollution source identification, modeling and estimation, control and management and so on (Xiang et al. 2017; Yang et al. 2017). By using ArcHydro (ArcGIS extension model) and a long-term hydrological and NPS pollution model, Wilson & Weng (2010) evaluated the impact of urban land-use change on lake water quality in Calumet, Chicago. Burow et al. (2010) analyzed 5101 samples collected via the National Water Quality Assessment program of the US Geological Survey in 51 research areas from 1991 to 2003, and found that the nitrate concentration was highest in shallow groundwater in the agricultural subsoil. Currently, numerical NPS pollution models are available, and detailed reviews can be found in studies conducted by Yang et al. (2017) and Adu & Kumarasamy (2018). Among these models, the Soil and Water Assessment Tool (SWAT), agricultural non-point source pollution model AnnAGNPS, and areal non-point source watershed environment response simulation (ANSWER) have been commonly applied (Liu et al. 2016).

In China, research on NPS pollution started in the 1980s. Thereafter, studies on urban NPS pollution were conducted in Beijing, Shanghai, Hangzhou, Suzhou, Changsha, Nanjing, and Chengdu, among other cities (Li et al. 2010). Simultaneously, research on rural NPS pollution was successively conducted in the Yuqiao Reservoir, Dianchi Lake, Taihu Lake, Chaohu Lake, Jinjiang River Basin, and Dongjiang River Basin (Chen et al. 2010; Cai et al. 2017; Xue et al. 2019). Since the 1990s, macro characteristics and statistical models (black-box or empirical models) of pesticide and fertilizer pollution have played an important role in agricultural NPS pollution research (Stephenson et al. 2010). Currently, the combination of the NPS pollution model with 3S (GIS, GPS, and RS) technology (Emili & Greene 2013; Yaghi & Salim 2017) and the water quality models of watersheds have become new research hotspots in water quality management (Zhang et al. 2015). However, research on NPS pollution in China is still limited, mainly concentrated on the assessment of NPS pollution loads, simulation of pollutant transport, and data management with GIS. The deficiencies regarding public policy and administration with low participation of households are the most challenging (Wu & Ge 2019; Zhang et al. 2020). There is still much work to fill the gap between research and its applications in this field.

Owing to the unique context of NPS pollution in China, the theories and experience from developed countries cannot be simply transplanted (Ongley et al. 2010). Agricultural NPS pollution control should utilize various sustainable prevention, treatment, and control technologies, and be informed by the natural conditions and pollution characteristics of the concerned catchment (Yang et al. 2015; Wu & Ge 2019; Yi et al. 2020; Zhou et al. 2020). However, owing to the high-cost and low reward for farmers in China, the agricultural NPS control is low-efficiently pushed forward only by the government. Besides, the agricultural harvest heavily relying on fertilizers and pesticides (Wu & Ge 2019) also hinders the NPS pollution control. Therefore, this study proposes a practical approach for agricultural NPS pollution control using the biological agents for waste utilization. In this resource-based approach, the domestic sewage disposal is conducted with micro-power or without power, and the domestic organic waste, sewage sludge, and livestock manure are economically utilized to produce biological agents to replace the harmful chemical fertilizers and pesticides that contribute significantly
to NPS pollution. Therefore, the best contribution of this research is advancing the NPS pollution control towards being more low-cost, efficient and environment-friendly: (1) the treatment of domestic waste and livestock manure is turned into the production of biological agents; (2) the produced biological agents reduce the application of harmful chemical fertilizers and pesticides, which contribute a lot to the NPS pollution; (3) the biological agents bring income to the farmers, promoting their willingness to participate in NPS pollution control. For agricultural NPS pollution, the farmers' willingness is a knotty problem of long standing.

The proposed approach has been applied in Xichuan County and Xixia County since 2010 when the water quality significantly deteriorated, and the results have successfully demonstrated its value with regard to NPS pollution control. This paper is organized as follows. The methodology for agricultural NPS pollution control using biological agents is first introduced, as well as the SWAT model for pollution prediction. The study area and the issue of NPS pollution are then described. The application results for to the catchment of the Danjiangkou Reservoir in Nanyang City are then analyzed. Finally, conclusions and suggestions are given.

METHODOLOGY

Framework

As shown in Figure 1, NPS pollution in rural areas usually involves domestic sewage and waste from villages in addition to pollutants from farmland. Livestock manure, which is released into rivers, also contributes to NPS pollution. The NPS pollutants converge into lakes or reservoirs through different pathways, such as streamflow, overland flow, and groundwater flow. NPS pollution is a complex issue owing to the diversity of pollution sources and transport pathways (Adu & Kumarasamy 2018).

The agricultural NPS pollution framework depicted in Figure 2 employs a series of high-efficiency biological agents for waste, fecal sludge, and soil treatment. It adopts the mode of 'the government leading and coordinating market operation and farmer participation', thereby allowing for the resource-based treatment of domestic waste and livestock manure, the low-energy and sustainable treatment of sewage, and the development of an efficient eco-agricultural circular economy. The produced organic fertilizers with zero agricultural residues can effectively replace chemical fertilizers, while the plant protection agents can effectively replace chemical pesticides. Further, these high-quality agricultural products can increase farmers' income while ensuring agricultural efficiency and food safety.

Biological agents

As shown in Figure 2, the whole framework of NPS pollution control runs on the base of biological agents, which unite all parts of NPS pollution control via a stable circulating system. In this research, the biological agents are some
organic matters that serve for environmental protection, mainly including the deodorizers and antidotes, eco-agricultural synergists, plant protection agents and soil purification agents, and water purification agents, as shown in Figure 3. The biological agents are produced from the domestic waste and livestock manure, and can be used in the domestic
sewage treatment to improve the efficiency, and used in farming to reduce the application of chemical fertilizer and pesticide.

Water purification agents (Figure 3), as an example, can effectively degrade the pollutants in domestic sewage mainly with their biological function. After the addition of the biological agents, the microbes gain or increase the ability to decompose the nutrients and chemical fertilizers. The water purification agents can quickly degrade the hazardous substances, thereby reducing the chemical oxygen demand (COD), biological oxygen demand, and total suspended solids, among others. The sludge can also be purified with organic pollutants reduced to harmless fish food.

Components

The proposed approach is composed of three parts, namely the production of biological agents, treatment of waste and livestock manure, and domestic sewage treatment.

Production of biological agents

The biological agents are produced from the domestic waste and livestock manure as a critical component of our proposed approach. A production flow chart of biological agents is shown in Figure 4. Different biological agents are derived from different fermentation bacteria but share the same production line.

Treatments of domestic waste and livestock manure

(i) Collection: The household garbage is stored at a fixed point, and the household cleaner is responsible for the collection of garbage. The garbage is transported to the garbage transfer station (concentration point) in the village. The waste disposal enterprise will arrange for garbage trucks to collect and transport the garbage to the pretreatment plant, thereby forming an industrial operation mode, as shown in Figure 5.

(ii) Management of livestock manure: the management of livestock manure is conducted by households, with separate storage and enterprise collection. The treatment of livestock manure includes dry manure cleaning, manure composting, and manure fertilizer returning.

(iii) Garbage disposal: domestic organic waste and livestock manure are recycled into organic fertilizers after pretreatment (including sorting, crushing, and deodorization), composting, production, and other processes.

Treatment of domestic sewage

The popular technology of ponding treatment (Liu et al. 2013) involves a biological wastewater treatment process based on natural purification with the joint action of bacteria and algae on organic pollutants. Following this technology, villages, towns, communities, and immigrant villages are equipped with a sewage pipe network, and a three-stage treatment mode is proposed for the unpowered and biological treatment of domestic sewage, as shown in Figure 6.
Due to the limited observation in time and space, the effectiveness of NPS pollution control for those cases when and where pollutants were monitored is assessed using the SWAT model, which is an effective tool in the simulation of pollutant distribution and identification (Ouyang et al. 2008; Liu et al. 2016). Considering nitrogen as an example,
the SWAT can simulate the migration and transformation of nitrogen in different forms, as shown in Equation (1) (for open channel) and Figure 7.

\[
\frac{\partial N}{\partial t} = \frac{\partial}{\partial x} \left( A_x D_L \frac{\partial N}{\partial x} \right) - \frac{\partial (A_x u N)}{\partial x} - \frac{dN}{dt} + \frac{S}{V}
\]

where \(N\) denotes the concentration of any one form of nitrogen (mg/L), \(A_x\) is the cross-sectional area (m²), \(D_L\) is the dispersion coefficient (m²/s), \(S\) denotes the external pollution sources or sinks (g/s), \(u\) is the flow velocity (m/s), \(V\) is the water volume of calculated river reach (m³), \(t\) is time (s), and \(x\) is distance (m).

**STUDY AREA**

**Overview of the study area**

The proposed approach for NPS pollution control was applied to the Danjiangkou catchment area (the source of the Middle Route of the South–North Water Transfer Project, SNWTP) in Nanyang City. Four counties were included; that is, Xichuan County, Xixia County, Neixiang County, and Dengzhou City, as shown in Figure 8. The total area of this study catchment is 6,361.93 km², including 67,400 hm² of arable land. Most of the arable land in this area is distributed in narrow regions along the rivers with low elevations and decentralized settlements. The distribution of precipitation is uneven, and the precipitation from May to October accounts for 80% of the total annual precipitation.
In addition to being an important catchment area, Nanyang City is the only junction and core area of the point (head of the canal), line (main canal), and face (reservoir) of the SNWTP. The catchment area in Nanyang City covers 31 towns, 596 administrative villages, and 950,000 people, and accounts for 82% of the total area of the water resource protection zone in Henan Province. The total length of the Middle Route of the SNWTP is 1,267 km from the Taocha Canal head in Nanyang City to Tuancheng Lake in Beijing City. The length of the section in Nanyang City is 185.5 km, which accounts for 1/7 of the total length. Owing to its sensitive regional location, Nanyang City is responsible for ensuring the quality of water sent to Beijing City and for the sustainable management of water resources.

**Agricultural non-point source pollution data**

According to the field surveys, the COD and the amount of N in the form of ammonia related to the domestic sewage in the Danjiangkou Reservoir and its upstream catchment is 7,448 t/year and 860 t/year, respectively. The output of rural domestic waste and livestock manure is 327,000 t/year and 480,000 t/year, respectively; the annual output of N and P from 67,400 hm² arable land is 141,000 t/year, with an annual average volume of applied chemical fertilizers and pesticides up to 140 kg/mu and 1 kg/mu, respectively. Agricultural NPS pollution, from domestic sewage, waste, livestock manure, chemical fertilizers, and pesticides, has become the main factor affecting the water quality in the study area. Table 1 shows the annual average volume of NPS pollution from chemical fertilizers and pesticides in the study area since 2006.

### RESULTS

#### Improvement in environmental protection

**Domestic waste and manure treatment results**

The employed waste and manure treatment system in the study area can produce 210,000 t/y of organic fertilizers, in which the organic matter content is greater than 45%. The resource-based treatment not only deals with the domestic waste and livestock manure, but also significantly mitigates the pollution from chemical fertilizers and pesticides. Organic fertilizers produced from the resource-based treatment system can effectively reduce COD by 35,000 t/y and ammonia N by 845 t/y, and can save almost 100 million yuan/y (in RMB) for the investment in fertilizers. Compared with conventional fertilizers, organic fertilizers can significantly reduce the soil nitrate content (Wang et al. 2018), and the average N loss can be reduced by 30–50% owing to the lower N mineralization rate of organic fertilizers. For example, in Jiuzhong Town in Xichuan County, the application of chemical fertilizers and pesticides has been reduced by 4,000 t/y and 30 t/y since 2010, respectively, and the loss of N and P has been reduced by 216 t/y and 72 t/y, respectively. In Wuliqiao Town in Xixia County, the application of chemical fertilizers and pesticides has been reduced by 4,000 t/year and 20 t/year, respectively, and the loss of N and P has been reduced by 192 t/year and 60 t/year, respectively.

Following the idea of resource-based treatment in this research, parts of the NPS pollutants have the potential to be beneficial if they are placed in the right position. In this research, the organic waste and livestock manure are

| County       | Consumption | N | N loss | P | P loss | Consumption | Loss |
|--------------|-------------|---|--------|---|--------|-------------|------|
| Xichuan County | 48,000       | 15,000 | 3,300  | 6,790 | 2,038 | 90 | 60 |
| Xixia County  | 32,000       | 10,000 | 2,000  | 8,000 | 2,400 | 122 | 90 |
| Neixiang County | 9,360      | 2,920  | 584    | 716  | 215  | 42 | 28 |
| Dengzhou City | 2,895       | 356   | 71     | 136  | 40   | 13 | 9  |
| **Total**    | 92,255       | 28,276 | 5,955  | 15,642 | 4,695 | 267 | 187 |

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collected and reused on the base of biological agents. Compared with the traditional household biogas digester (Rajendran et al. 2015), the resource-based treatment is more advantageous in both efficiency and sustainability.

In addition, the high-quality agricultural products with zero agricultural residues can improve farmers’ income, agricultural efficiency, and food safety. The saving costs in chemical fertilizers have greatly encouraged farmers to participate in the NPS pollution control. The resource-based treatment of domestic waste and livestock manure supports the development of an efficient and sustainable agricultural economy.

**Domestic sewage treatment results**

Domestic sewage treatment utilizes centralized collection, decentralized treatment, and micro–power, thereby allowing for the effective collection and treatment of domestic sewage in dispersed rural settlements. With the help of biological agents, the average removal rate of domestic sewage using the three-stage ponding system is shown in Table 2.

The sewage effluent enters a solid-liquid separation tank at the front end of the sewage treatment system and then enters the water quality purification tank. In the early stage, deodorants and antidotes are added to activate the genes of bacteria for microbial deodorization, and then a special water purification agent is added to form a treatment layer. Most of the organic matter in the wastewater is removed, and the upper part of the clear liquid is collected in the water quality stabilization tank, which is equipped with a biological matrix.

| Processing stage | COD (mg/L) | BOD (mg/L) | Ammonia N (mg/L) |
|-----------------|------------|------------|------------------|
| Solid–liquid separation tank | Inlet concentration 360 | Outlet concentration 200 | Removal rate (%) 45 |
|                  | Inlet concentration 160 | Outlet concentration 80 | Removal rate (%) 50 |
|                  | Inlet concentration 25 | Outlet concentration 20 | Removal rate (%) 20 |
| Water purification pool | Inlet concentration 200 | Outlet concentration 140 | Removal rate (%) 30 |
|                  | Inlet concentration 80 | Outlet concentration 56 | Removal rate (%) 20 |
|                  | Inlet concentration 20 | Outlet concentration 50 | Removal rate (%) 0 |
| Water stabilization tank | Inlet concentration 140 | Outlet concentration 70 | Removal rate (%) 50 |
|                  | Inlet concentration 56 | Outlet concentration 20 | Removal rate (%) 40 |

After three-stage removal, the quality of domestic sewage can be effectively improved, with the removal rate reaching 80.6%, 87.5%, and 52.0%, respectively for the COD, BOD and Ammonia N. In this no-power treatment system, three different kinds of biological agents are used sequentially in the three stages. Most of the organic matter in the wastewater is removed after the purification pool, while the stabilization tank further clears the wastewater with a relatively longer standing time before reuse. Further, the removal rate of COD and BOD is much better than for Ammonia N owing to the effects of water purification agents, which present almost no impact on the Ammonia N in the water purification pool. It is plausible that the demonstrated domestic sewage treatment is practical although the high removal rate may not be achieved when it is applied to other regions.

**Pollution control assessment**

The Danjiangkou Reservoir is the source of the Middle Route of SNWTP, and its water quality is significantly affected by the NPS pollution in Nanyang City. Owing to the implementation of the resource-based approach, there has been a reduction of TN and TP in the Danjiangkou Reservoir, as shown in Figure 9.

There was a significant deterioration around 2008 while both the TN and TP doubled in concentration (Figure 9). Fortunately, after the NPS pollution control was applied, the deterioration was successfully stopped, and the indicators of TN and TP were sustained at the Level three (1.0 mg/L) and Level two (0.025 mg/L) respectively, according to the Environmental Quality Standards for Surface Water (GB 3838-2002, China). Further, the water quality was gradually restored with a reduction tendency for both TP and TN since 2011.

In addition, the predicted TN and TP from SWAT are also shown in Figure 9. According to the prediction results, the water quality at Taocha in 2025 is predicted to recover to the same level as that before significant deterioration, with the TN and TP reaching Level two (0.5 mg/L) and Level one (0.01 mg/L), respectively. The simulation results from SWAT provide more evidence to the assessment of our proposed approach. Due to the long lag time, the SWAT prediction with some numerical error is used in the
assessment. However, the evident reduction tendency is convincing for the effectiveness of NPS pollution control.

Reduction in treatment costs

With the resource-based treatment, the cost of management and the maintenance of mechanical equipment is significantly reduced. The operation mode allows for the maximum utilization of garbage resources using safe, sustainable, and cost-effective technology. The cost of domestic sewage treatment with no power is less than 0.1 yuan/m³, which is far lower than traditional treatment costs (about 1.0 yuan/m³).

In practice, the management mode of ‘household storage, group collection, village concentration, township supervision, and enterprise transportation’ is adopted for the treatment of domestic waste; the mode of ‘household storage, enterprise transportation and disposal’ is adopted for the treatment of livestock manure; and the maintenance of sewage treatment is the responsibility of qualified operation enterprises. In terms of the chemical fertilizers and pesticides, first, the operation enterprise and farmers reduce the use of chemical fertilizers and pesticides with replacement by organic fertilizers. Second, the use of organic fertilizers and plant protection agents is encouraged with a subsidy of 0.45–0.75 yuan/m² of farmland for farmers. In these operation modes, the farmers are no longer passive followers or ‘spectators’, but active participants. Finally, with the collaboration of farmers, enterprises, and government in NPS pollution control, the cost to the government is also significantly reduced, with a reduction ratio larger than 50%.

CONCLUSIONS

Agricultural NPS pollutants are major causes of the deterioration of surface water quality. They present a complex challenge owing to their prevalence, extensive dispersion, low concentration, and dynamic pollution pathways. NPS pollution is primarily from livestock and poultry farming, crop cultivation, and villages. NPS pollution is generally underestimated and poorly controlled, thereby resulting in long-term damage to the environment. This study proposes a resource-based approach for NPS pollution control using environmental biological agents, aiming at improving the efficiency of agricultural NPS pollution. In the proposed
approach, the systematical operation mode of ‘government leading and coordinating market operation and farmer participation’ is employed to realize the resource-based treatment of domestic waste and livestock manure, unpowered and biological treatment of sewage, and prevention and control of agricultural NPS pollution. After almost one decade of implementation of the proposed approach in Nanyang City, the NPS pollution of Danjiangkou catchment has been successfully controlled. The optimal utilization of garbage resources and sustainable production of biological agents also reduced the operating costs. The application of chemical fertilizers and pesticides has been reduced significantly, along with a reduction in the loss of N and P. Through the collaboration of farmers, enterprises and the government, the cost to the government has been significantly reduced, thereby enhancing the effectiveness and efficiency.

Although the proposed approach provides useful strategies for the control of agricultural NPS pollution, the large scale of livestock and farming with chemical fertilizers and pesticides, as well as the overdispersed housing, significantly hinder the NPS control. In Figure 9, although the proposed approach has initially been implemented since 2010, the water quality improvement was too slight until 2015. To address this issue and speed up the water quality improvement, the environmental protection institutions in the townships and villages should be improved. A corporate and market-oriented operation of rural pollution control should be implemented, and farmers should be further encouraged to actively participate. In terms of NPS pollution from livestock manure, the strategy of pollution control at the source position, such as clean breeding, reducing the volume of manure pollution, and facilitating follow-up treatment and utilization, is essential. Process control and pollution reduction during transport should also be improved, including manure pollution collection and storage, dry manure cleaning, and manure resource utilization.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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