Estimation of the nonpoint source nitrogen load in a strongly disturbed watershed of the North China Plain

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ABSTRACT

Identification of nonpoint source (NPS) pollution is a great challenge in the North China Plain, which has modified rivers and insufficient data. In this study, a simple and reasonable method was developed to estimate the total nitrogen (TN) load in rural areas of the North China Plain. The method was found to work well and produce results consistent with monitoring data when considering various TN sources and transfer mechanisms. The annual TN loads from rural living, livestock and the farmlands were 121.9×10^3, 45.6×10^3 and 78.5×10^3 kg/yr, respectively. The TN load in the region along the river contributed much more to the NPS pollution than that in areas far from the river, with average TN loads of approximately 3394 and 602 kg km^{-2} yr^{-1}, respectively. Overall, the results indicate that this method is suitable for NPS load estimates in severely disturbed watersheds with insufficient data.

Key words | delivered coefficient, disturbed watershed, hydraulic connectivity, nonpoint source pollution, North China Plain, rural living

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INTRODUCTION

Increasing nitrogen (N) loads have been discharged into rivers as a result of China's rapid economic growth during the last few decades, causing severe problems such as eutrophication (Garnier *et al.* 2010; Somura *et al.* 2012; Shen *et al.* 2013). Nonpoint source (NPS) pollution plays important roles in the excessive N loads, especially in regions in which point source pollution is well controlled. Therefore, N loads from the NPS pollution need to be quantitatively estimated in any attempt to protect the aquatic ecosystem effectively.

Watershed hydrology and nutrient loads are highly dependent on land use, and many studies have concentrated on the NPS from a particular land-use type, especially from the catchments dominated by agricultural lands (Somura *et al.* 2012). Agriculture is closely associated with NPS because of the overuse of fertilizer and the high percentage of land use (Ripa *et al.* 2006; Garnier *et al.* 2010). Some studies have also covered the hydrological responses to different periods of land use (Randhir & Tsvetkova 2011), and land-use changes are regarded as the key factors in altering the watershed system. Furthermore, the N loads from different land-use types vary greatly, most of them originating from the critical source areas (Garnier *et al.* 2010). To quantify the source apportionment and identify the critical source areas from different land-use types have been recognized as the first steps in managing water quality in the rivers (Huang *et al.* 2013).

Mechanistic watershed models such as the Soil and Water Assessment Tool (SWAT) and Hydrological Simulation Program–Fortran (HSPF) have been widely applied to diagnose problems related to polluted water bodies, which has helped researchers address problems in aquatic environments and improve decision-making processes (Chen *et al.* 2013). These models have allowed simulations of hydrodynamic and water quality transformation processes within the watershed. However, there are many challenges in estimating NPS in northern China. Estimates of the contribution of N loads from NPS pollution contribution to total water pollution in China are as high as 81%, which is believed to be higher than the actual contribution (Ongley *et al.* 2010). This is caused by the misuse of estimation techniques (most of which were developed in western countries), data shortages and severely polluted watersheds that are strongly disturbed by human activities (Ongley *et al.* 2010).

Mechanistic models have frequently failed in the watershed because time-series input data and adequate mechanisms modelled for the local watershed are needed. For the mass balance method, error in calculating the point source loads is very common, which will affect the

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results. Export coefficient models and improved methods (Ding *et al.* 2010) are widely used in China; however, it is difficult to select the proper export coefficient because of variability among regions. Moreover, some NPS sources are calculated repeatedly or ignored, especially for pollution in rural areas (Yang *et al.* 2012). Furthermore, rubbish and other hidden NPS sources accumulate along waterways, where they contribute greatly to the NPS. Given the lack of empirical data from different types of NPS in China, the results cannot be easily calibrated.

There are several features unique to watersheds in semiarid northern China, where the local watershed is highly regulated by dams and artificial channels. The rainfall-runoff mechanism in farmland is also different from that in western countries because of the field architecture used to conserve water. Artificial channels and hydraulic facilities separate the farmlands into parts that are not hydraulically connected to each other, and the runoff yield and concentration process are regulated completely by human activities (Li & Su 2009). Additionally, the watershed is greatly separated by roads, dams and other buildings along the river; therefore, hydraulic connectivity differs completely between regions along the river and far from the river. Accordingly, quantitative estimation of NPS loads is a great challenge given the complex conditions and insufficient monitoring data.

In this study, we employed a simple and reasonable accounting method to estimate the total nitrogen (TN) loads from different pollutant sources in the North China Plain. We assumed that NPS pollution from farmland would be lower, that rural pollution would be greater than that in other regions, and that NPS pollution in the region along the river was much more severe. This method was designed to: (1) consider the different pollution sources and simple transfer mechanisms, including the excretion, release and delivery processes; (2) consider the different NPS pollution from regions along the river and far away from the river; and (3) calculate the TN loads from different pollution sources and verify them based on measured data. This method should be suitable for NPS pollution estimates in severely disturbed watersheds with highly unsteady flow in the North China Plain.

METHODS AND MATERIALS

Study area

The Fuyang River watershed upstream of the city of Handan is located in the southern portion of the North China Plain in northern China and covers an area of approximately 373 square kilometers (Figure 1). The area is semiarid, with an annual average precipitation of about 550 millimetres per year. The watershed is part of the Hai River Basin, one of the major river systems in China covering Beijing and eight other provinces. The entire basin suffers from the most severe water shortage and pollution in China, with only 305 m^3 available per person. The water quality in rivers in the basin is rated below grade V in water quality standard in China, indicating that it is unsafe for any use (Li *et al.* 2012). The landscape is very flat and the runoff mechanisms are completely regulated by human activities. Moreover, most of the tributaries and some main streams run dry in the watershed. Because of water resource scarcity and channels designed for irrigation and flood control, the river is completely regulated by reservoirs and dams, causing great alterations in the rainfall-runoff mechanisms of the watershed.

There are almost no grasslands or forests in the region. Farmland covers an area of about 279.8 km^2, or about 85% of the total region. The urban and rural regions cover most of the other parts of the watershed, with approximate areas of 74.6 and 8 km^2 respectively. There are 156 rural villages in the watershed, with a total population of about 248,000. The watershed is in the upstream portion of the urban area of Handan, which has no industrial area, so point source pollution is very limited.

Estimation methods

To develop a suitable method of estimating the annual NPS pollution in the region, statistical data, field investigations and some reliable published research results were used. There are mainly two kinds of land-use types, containing the farmland and the rural residential area. It is difficult to estimate the TN loads from each different land use directly because there are no reliable export coefficients. Therefore, the TN loads were estimated directly by the different pollution sources. There were three sources of rural NPS: farmlands, rural residents and livestock sources (Table 1). The accounting method was based on the mass balance model with the excreted, the released and the delivered processes, which considered the excreted, released and delivered coefficients (Table 1).

Farmlands

Chemical fertilizer, organic fertilizer, deposition and irrigation water are the nitrogen sources in the farmland. Fertilizer is commonly used to excess in China, leading to

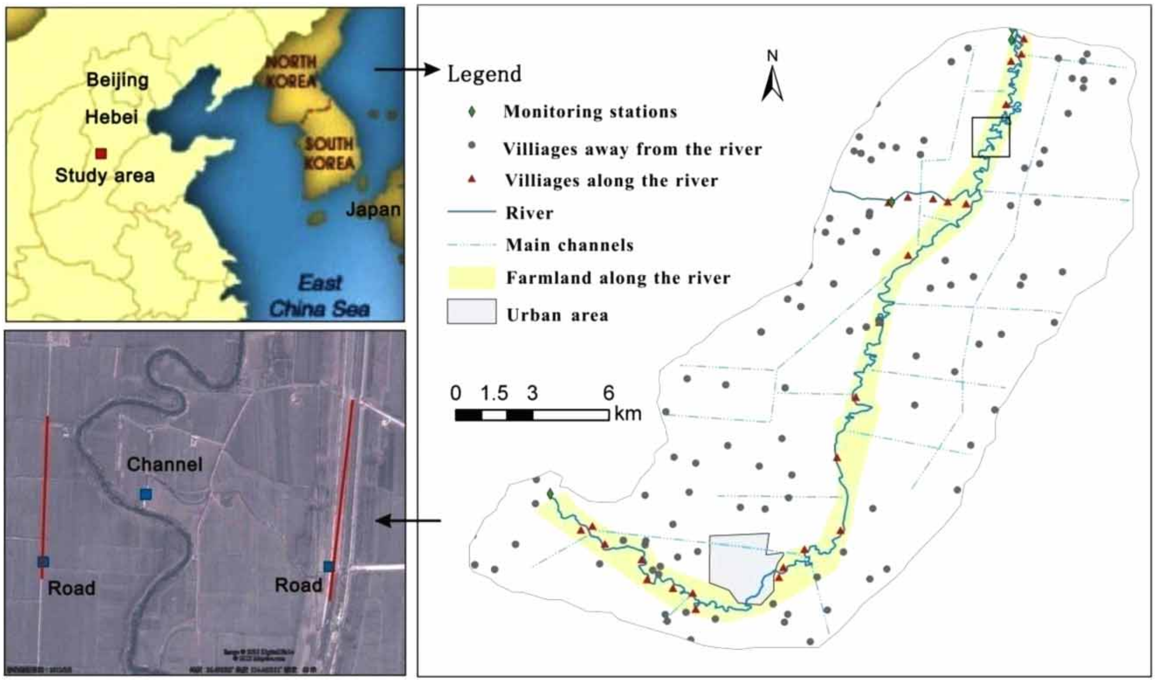

Figure 1 | Location of the study area. As shown in the right figure, the watershed is divided into the region along the river and the region away from the river. The boundary between them is identified by some artificial barriers such as the roads along the river shown in the lower left figure. The rainfall-runoff mechanism is natural in the region along the river, and the NPS in the region far away from the river find it much more difficult to reach the river due to these artificial barriers.

Table 1 | Rural NPS load estimation methods (the delivered loads were based on the release loads and the delivered rate, and three scenarios for different delivered rates were set for these pollution sources to capture the uncertainties)

Pollution source	Excreted load	Released load	Delivered load	Coefficients
Farmland	TN = fertilizer + deposition + irrigation	TN = field research coefficient × area	TN = released load × delivered rate	Field research coefficient 23.05 kg/m^2
Livestock	TN = ∑amount of livestock$_i$ × containment coefficient (i – type of animal)	TN = ∑excreted loads$_j$ × untreated rate$_j$ (j – livestock in different places)		Cattle, 412.5 kg/yr; pig 12.3 kg/yr; chicken and duck 0.27 kg/yr
Rural living	TN = ∑containment coefficient$_i$ × rural population (i – type of rural living, containing the garbage, wastewater and the excrements)	TN = ∑excreted load$_i$ × untreated rate$_i$ (i – type of rural living, containing the garbage, wastewater and the excrements)		Wastewater, 0.35 kg ca^{-1} yr^{-1}; garbage 7.18 g d^{-1}; excrement 3.06 kg ca^{-1} yr^{-1}

Note: ca^{-1} = per capita, d^{-1} = per day.

large losses by ammonia volatilization (Shen *et al.* 2009). Organic fertilizer, deposition, and irrigation sources were difficult to accurately estimate owing to there being limited statistical data and related literature available; accordingly, it was difficult to estimate the loads delivered by the excreted load. Previous studies indicate that the released load from the farmlands in the region is about 23.05 kg/m^2 (Table 1) per year in the plains area in the Hai Basin (Zhu 2011); therefore, we used the average field data from the Hai Basin in this study.

The transfer processes of NPS loads between the regions far from the river and along the river were completely different because of the water conservation design of the farmland and poor waterway connectivity. In farmlands far from the river, hydraulic connectivity was limited. As a result, rainwater was partly stored in the channels and ponds for irrigation because of water scarcity. Additionally, some channels that were connected to the main stream were mostly blocked by roads, buildings, rural rubbish and gates (Li & Su 2009). Finally, farmlands were designed to

conserve water. Therefore, most of the NPS loads in this region could not easily reach the river. In farmlands along the river, the released loads were much easier to discharge into the river because there were no obvious barriers that could stop the transfer process.

Accordingly, the N loads in the region along the river and far away from the river were calculated separately. The boundaries could easily be confirmed because they were controlled by the roads and some other barriers (Figure 1). The areas of regions far from the river and along the river were about 239.4 and 40.4 km^2. To reduce uncertainty, the NPS watershed was calculated as a whole and three scenarios were set. In more humid regions in China, the delivery rate was about 25%–30%. In a similar watershed in the Hai basin, about 5%–12% was delivered to the river (Zhu 2011). Therefore, brackets of 5%, 10% and 25% were used to indicate the worst, common and best hydraulic connectivity in different regions in farmlands far from the river, while brackets of 10%, 25% and 50% were used to capture the uncertainty in the precipitation and the hydraulic connectivity of farmlands along the river. The common delivery rate was set as 25% to follow that in more humid regions.

Livestock

The TN loads from the livestock were estimated by the method listed in Table 1. The containment coefficient followed the national standard (Meng *et al.* 2007), and the amount of livestock was obtained from the local yearbook from 2010. The released loads were considered to be the untreated loads that could be transferred directly to nearby waterways. In China, livestock wastes were mainly treated as the organic fertilizer on the farmlands, and the untreated rates would be highly variable in different places. The untreated rate data originated from the national pollution source data in 2010. Similar to the NPS in farmlands, most of the livestock loads were not easy to deliver to the river, and the delivery rate varied.

The delivery coefficient of the livestock pollution varied greatly with different circumstances. In more humid areas such as Shanghai, the delivery rate was about 25%–30% (Yang *et al.* 2012), while in the Yangtze River Delta area about 25% of livestock wastes went into the river (Gu *et al.* 2008), and in the Hai Basin, about 10% entered the river (Zhu 2011). The delivery coefficients for these regions should be less than those for watersheds in humid regions; therefore, brackets of 25%, 10% and 5% were set to capture the variability.

Rural living

The NPS pollution from rural residents was estimated following the methods in Table 1. There were three types of rural residents' sources: wastewater, rural garbage and excrement (Table 2). In rural areas, wastewater is often discharged into the river directly. The TN contamination coefficient of wastewater was set as 0.35 kg ca^{-1} yr^{-1} per capita based on that in the Miyun watershed (Yin *et al.* 2009), which was also part of the Hai Basin.

Additionally, garbage commonly accumulates along waterways in rural areas without being treated, resulting in high pollution levels, especially when rain occurs. Rural garbage pollution has been ignored by many previous studies (Yang *et al.* 2012), even though it commonly accumulates along waterways without being treated, resulting in high levels of contamination. In the Hai Basin, the sewage excreted coefficient is 0.27 kg/day and the TN concentration is about 26.6 g/kg (Feng *et al.* 2009; Zhu 2011). The excreted TN coefficient of the excrement is about 3.06 kg ca^{-1} yr^{-1} per capita (Zhu 2011). We followed the coefficients in this paper. Therefore, we used these parameters in the present study.

In the studied watershed, most of the garbage and wastewater were released without being treated, and agricultural officials estimated that up to 10% of rural sewage and garbage was treated by private facilities; therefore, the untreated rate was set as 90% (Wang *et al.* 2009). While most of the excrement was used as organic fertilizer which has been calculated for the farmlands, previous investigations indicated that about 15% was released (Table 2). The delivery process of NPS from rural villages located near the waterway was completely different from those far away from the river. In rural areas along the river, wastewater could be delivered into the river directly, while the transfer process was driven by rainfall in villages far from the waterway. Therefore, different delivery rates were set for these areas. The numbers of villages far from and near the river were 156 and 26, with populations of about 248,000 and 41,600, respectively.

In the Hai Basin, about 5% to 10% of the released wastewater is transferred into the river, while 20%–30% of the

Table 2 | The excretion coefficient and the untreated rate for pollution from rural residents

Pollution sources	The excretion coefficient	The untreated rate (%)
Wastewater	0.35 kg ca^{-1} yr^{-1}	90
Excrement	3.06 kg ca^{-1} yr^{-1}	15
Rural garbage	7.18×10^{-3} kgd^{-1}	90

Note: ca^{-1} = per capita, d^{-1} = per day.

wastewater is transferred into the river (Zhu 2011). The runoff coefficient from rural residents was 30% in the Miyun Reservoir (Wang *et al.* 2009). Delivery rates of 30%, 10% and 5% were selected for the plains area of Tianjin (Yang *et al.* 2012). In rural areas far from the river, the delivery rates are lower than in the Miyun watershed, which is more hydraulically connected in the mountain area. Therefore, 25%, 10% and 5% delivery scenarios were selected for the rural area far from the river to capture the variability. In the rural area along the river, wastewater and garbage could be delivered into the river directly. Nearly all of the rubbish accumulated in the river in some downstream regions. It was difficult to quantify all of the delivery rates clearly, so 90%, 50% and 25% were set to capture the variability based on field investigations. These rates represented the worst, average and best conditions, respectively.

Verification

The calculated results were compared with those determined by the mass balance method in Equation (1):

$$\text{Rural NPS} = \text{AML} + \text{De} - \text{UNPS} - \text{PS} \tag{1}$$

where AML is the annual measured load, De is the degradation, UNPS is the urban NPS in the watershed, and PS stands for point source pollution.

Urban NPS, point source pollution and the degradation in the river were calculated respectively. The annual measured loads were calculated from the difference between the annual load draining into the watershed and that draining out of the watershed. The degradation was estimated by the degradation rate, which was set as 0.06 per day based on studies of Handan City in the watershed (Guo 2011). The point source data were obtained from the national pollution source survey. Overall, there were limited point sources in this small watershed. The urban NPS was estimated by the export coefficient method, and the coefficient was set as 1100 kg $km^{-2}yr^{-1}$ (Cai *et al.* 2004).

RESULTS AND DISCUSSION

The TN loads from different pollutant sources

In the common delivery rate, the TN loads from livestock pollution were 45.6 tonnes per year (Table 3), contributing about 18.5% of the total NPS in rural areas. In most cases, the excrement returning to the field would help reduce livestock pollution due to both transformation in the soil and farmlands designed to preserve water. Loads from farmlands were comparatively lower than expected. Although the farmlands covered most of the areas in this region, the contribution of the N loads was comparatively limited.

Table 3 | The TN loads from different pollution sources

Pollution sources	Common delivery (10^3 kg/yr)	Low delivery (10^3 kg/yr)	High delivery (10^3 kg/yr)
Livestock	22.8	45.6	114
Farmland along the river	9.32	23.3	46.6
Farmland far away from the river	27.6	55.2	138
Rural residents along the river	30.35	60.7	109.3
Rural residents far away from the river	30.6	61.2	143
Summation	120.67	246	550.9

The loads from rural residents in the regions along the river and far from the river were nearly the same, although their area varied greatly (Table 3). The rural residents were the most important pollution sources because of poor management and living habits. In some regions along the river, the delivery rate could easily reach 90% because all of the rubbish and wastewater were poured into the river directly. In this situation, loads from rural residents contributed more than 60% to the total loads.

In general, the average N load in the region along the river was much more than that far from the river (Table 4). The N loads in the region along the river were much more than those in other regions in the world (Table 4) due to more pollution sources. In contrast, the N loads in the region far away from the river were much less than those in other regions due to the poor hydraulic connectivity.

Verification and uncertainties

The results calculated from the mass balance method (Table 5) were only 5.6% greater than those calculated by the method in this article in 2010. The estimated values by mass balance method should be higher than the actual value because point source pollution is easily underestimated in China, so we believed that the results in this article should be reasonable. In the Hai Basin results calculated

Table 4 | Comparison with the export coefficients from different regions in the world

Regions	Common delivery (10^2 kg km^{-2}yr^{-1})	Low delivery (10^2 kg km^{-2}yr^{-1})	High delivery (10^2 kg km^{-2}yr^{-1})
Region along the river	17.87	8.48	33.94
Region far away from the river	4.82	2.41	6.02
Dry land in Yangtze River watershed (Shen *et al.* 2011)	4.51	–	–
Taihu watershed in southern China (Li *et al.* 2009)	9.02	–	–
Farmland in Meuse in the Netherlands (Pieterse *et al.* 2003)	24.2	–	–
Agriculture (literature median) (Frink 1991)	7.9	3.2	33.3

Table 5 | Comparisons with the annual mass balance results

The N loads (10^3 kg/yr)	2010	2011
Annual measured N Loads	334.3	369.8
Degradation	28.9	30.1
Urban nonpoint source	59.2	65.3
Point source	45.1	47.2
Rural NPS calculated by mass balance method	258.9	287.4
Rural NPS calculated by the method in this paper	246 (120.7–550.9)	246

by the simple export coefficient model in recent years (Ding *et al.* 2010; Ma *et al.* 2011), the farmland source load and the NPS far from the river were overestimated. The NPS in the regions along the river cannot be overlooked, especially for the rural residents' sources.

However, there are still many uncertainties. First, the annual loads can only be calculated as a whole, and dynamic variations cannot be considered. Secondly, variations of the loads can only be estimated based on three scenarios, and some spatial differences cannot be fully considered.

Although simple accounting methods were used, this still has considerable scientific significance. Firstly, the method overcomes the high estimate of NPS by separating the regions into two parts, and the dualistic structure can be adapted to the characteristics of the plain and local hydraulic characteristics. Secondly, the repeating or missing NPS sources were avoided by dividing three processes, and rural living was quantitatively estimated. Furthermore, the NPS was calculated based on statistical data and field investigations, which were more easily acquired than the monitoring data or dynamic data. Our study could provide a well-documented example for load estimation in a disturbed watershed where insufficient data has been provided.

Recommendations

Regions along the river contribute greatly to the NPS because of good hydraulic connectivity. To control the NPS pollution effectively, policies and intervention strategies should concentrate on the NPS along the river.

Control of rural resident pollution should be prioritized because, as the delivery rate rises, the rural resident NPS increases dramatically. Management measures should be strengthened to ban dumping of rubbish and wastewater into the river directly. Moreover, decentralized sewage treatment, garbage collection systems and disposal plants should be constructed. Finally, public sanitary conditions and environmental awareness in rural villages need to be improved.

Livestock pollution control was also very important. Measures that can help reduce the untreated rate and the delivery rate should be implemented. Intensive livestock cultivation should be encouraged because the excreted loads can then be easily treated. Using excrement as organic fertilizer can greatly reduce the release and delivery rate of livestock pollution.

Because of the lower release and delivery rate, NPS pollution from farmlands was not as important as that in humid regions. However, farmlands along the river should be closely monitored. Best management practices employed in western countries could help reduce the NPS in this region. For example, ecological ditches and organized fertilizer application should be implemented to reduce the release and delivery rates.

CONCLUSIONS

In this study, a simple accounting method was developed to estimate the different types of NPS loads in a rural area of the North China Plain. Different NPS sources and processes

were used, to avoid being considered repeatedly. By calculating the areas along the river and far from the river separately, the importance of NPS from different regions was outlined. Three scenarios helped capture the uncertainties.

When the estimated results were compared with the annual measured loads, the developed method was shown to be a good model of rural NPS in the North China Plain and to provide a good example for estimation in other modified and data-poor regions. According to the results, the delivered TN loads along the river were much greater than those in the region far from the river. Rural resident pollution was the most important pollution source, especially when rural conditions were poor. The NPS pollution from farmland in the studied area was less than that in other regions. Overall, the results indicate that great attention should be given to the pollution sources along the river, especially those associated with rural residents.

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