Estimation of non-point source pollution loads by improvising export coefficient model in watershed with a modified planting pattern

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Abstract. Export coefficient model was improved to calculate and compare non-point source pollution loads in an agricultural watershed before and after implanting new cropping pattern. The modification was done by introducing the reduction coefficient in consumption amount and loss load as well as the proportion of bioactive ingredients of fertilizer and pesticide to the export coefficient model developed by Johnes in 1996. The modified export coefficient model was then applied to estimate non-point source pollution load in Gaoxi community, Yunnan Province, China where a water-saving and emission reduction technology was implemented by changing cropping pattern. Study results showed that the improved export coefficient model had a favorable flexibility in calculating the non-point source pollution loads and well applicable to the watersheds where various input data is in short. Moreover, the findings will provide scientific basis to understand the variability of non-point source pollutants in agricultural watersheds and their load estimation in order to optimize the efficiency of pollutants reduction plan implemented through agricultural adjustment.

1. Introduction

Pollutant discharged from agricultural non-point source (NPS) is one of the main causes of surface water pollution [1]. In developed countries like USA, agriculture contributes about 68-83% of NPS pollution load in surface waterbodies. Currently pollution load particularly from agricultural source become one of the main factors responsible for water pollution in some parts of China [1].

NPS pollution being diffuse in nature, it is difficult to control or manage unlike point-source pollution such as industry and sewage water. Therefore quantitative estimation of NPS pollutants load from agricultural watershed is an important tool in pollution management plan. Various simulation methods were applied in calculating NPS pollutant loads during the period of 1960-1970 in USA including physically based model and empirical model. Traditionally, physically based model has been applied to predict and evaluate the impact of land use change on water quality. However, a limited cognitive ability has made it difficult to overcome the complexity and randomness of NPS pollution during model construction. The physically based model has strict demand for input data, which leads the model construction costly and difficulty in calibration in large watershed [2]. At present, the main methods for the calculation of NPS pollutant loads include throughput analysis, export coefficient model (ECM) and non-point source mechanism, and so on [2-4]. ECM is widely accepted model to estimate nutrient such total nitrogen (TN) and total phosphorus (TP) loads in North America, England and Wales [5]. The model is mainly dependent on field data, including coefficient of source intensity (pollutant production coefficient and pollutant emission coefficient), which can be calibrated according to rainfall, topography, transport loss and other factors. The migration and conversion property of pollutants in the aquatic environment of the watershed is also considered.

The model construction fee is less, and easy to operate [6-10]. This model has now become an effective model with the highest accuracy in estimating agricultural NPS load, especially for those watersheds area in short of long-term non-point surface pollution census data [4, 11].

The following study is focused on a watershed of Gaoxi community within Fuxian Lake basin in Yunnan province of China where a pilot project to reduce NPS load contribution through changing cropping pattern. Because, there is a lack of long-term numerical data in the study area, the ECM model is preferred to estimate the NPS pollutant load. ECM model is further modified according to the influence of NPS pollution load during pre- and post-project implementation. The objective of the study is to provide scientific basis to the understanding of the trend of agricultural NPS pollutants load in a watershed with the adjustment of agricultural pattern.

2. Model construction

2.1. Study area

The Gaoxi community situated at central Chengjiang county in Yunnan province and the north shore of Fuxian lake (102°52'24"~102°52'50" E, 24°40'40"~24°41'03" N), with an area about 12.53 km^2 and an altitude of 1755 m. The annual mean air temperature is 16.5℃ and the annual rainfall is about 928.3 mm. The rainfall distribution is extremely uneven showing clear distinction between dry and wet season. The wet season is extended from May to October that accounts for nearly 87% of the total annual rainfall, while the dry season (November to April) contributes only 13 of the total annual rainfall. The land is mainly covered by red soil. The land use in the watershed is dominated by agriculture. For example, during 2013 (before project implementation), the uncultivated farmland in Gaoxi community was 230.1 hm^2, including 216.7 hm^2 of paddy field and 13.3 hm^2 of dry field.

Gaoxi community watershed drains agricultural runoff to Fuxian lake. Fuxian lake located in Chengjiang county is the second deepest fresh water lake in the plateau of southwestern China and the recharge water mainly comes from the inflow rivers [12]. Although Fuxian lake water is categorized as Class I as per China National Water Quality Standard (CNWQS) but with the substantial change in land use and land cover in the watershed poses a threat of significant deterioration of water quality [13]. Study results showed that most of the inflow rivers are polluted and categorized as worse than CNWQS Class V [12]. Gaoxi community initiated a pilot project to reduce the pollution load on Fuxian lake by water-saving and pollution emission measures. The project site has 167.3×10^2 m^2 of farmland inhabited by 721 families and 2380 people. Currently, vegetable is the main crop in the project area. After project implementation, blue berry will become the main crop (118.7×10^2 m^2), followed by pea, green onion, Chinese chives and so on (48.7×10^2 m^2). This change will reduce agricultural NPS pollution loads through two pathways. Firstly, the high-efficient water-saving technology will effectively reduce the consumption of fertilizer and pesticides which will in-turn reduce the loss of agricultural NPS pollutants. Secondly, high-efficient water-saving and integrated water-fertilizer technology will increase the efficiency of fertilizer utilization and improve the migration and conversion process of agricultural NPS pollutants such as nitrogen (N) and phosphorus (P).

2.2. Modification of export coefficient model

The ECM model developed by Johnes in 1996 considered different export coefficients for each component of the land use such as type of crops, the number and distribution of livestock, f number of human population (responsible for emission and disposal of domestic wastewater), plant-fixed and atmospheric deposition of N to improve model sensitivity [14-16]. The mathematical expression of the ECM model is given in equation (1).

$$L = \sum_{i=1}^{n} E_i[A_i(I_i)] + p \tag{1}$$

In this equation L represents the total output load of a pollutant (kg/yr); E_i is the output coefficient (kg/km^2·yr) of pollutant source i; A_i is the area (km^2) occupied by land use type, or number of livestock type, or of people of source i; I_i is input of pollutants (kg) to source i; p is the input of pollutant (kg) from precipitation.

After project implementation, the cropping structure, irrigation pattern, application pattern and amount of fertilizer and pesticide were changed. Other impacting factor (e.g. number of livestock and people) were not changed significantly. The changes in cropping and irrigating pattern will lead to changes in the rate of fertilizer and pesticides, thereby affecting their loss rate. Therefore, we improvise the above ECM model (equation (1)) by considering the amount of fertilizer and pesticide and the proportion of bioactive ingredient in fertilizer and pesticide. The modified ECM model is as follows:

$$L = \sum_{i=1}^{n} E_i\left(1-\alpha_{i1}\right)\beta_i\gamma_i\left(1-\alpha_{i2}\right)A_i \tag{2}$$

where L = total output load of a pollutant (kg/yr); E_i = current consumption rate of fertilizer and pesticide in land i (kg/ km^2·yr); A_i = area (km^2) of land i; α_{i1} = consumption coefficient of fertilizer and pesticide; β_i = proportion of bioactive ingredient of fertilizer and pesticide applied in land i; γ_i = loss load coefficient of fertilizer and pesticide in land i; α_{i2} = loss coefficient of fertilizer and pesticide in land i.

2.3. Confirmation of export coefficient

The output coefficient was determined by literature search and experiment [15]. In the present study, the key components of the export coefficient model has been determined from field investigation, literature search and the annex 9 (analysis methods and partial reference parameters for surface source investigation) of the supplementary technical rules and regulations for water quality assessment of surface water and estimate of pollutant emission of water resources in China. Data concerning the consumption amount of fertilizer and pesticide were collected through on-site investigation.

According to our analysis, the main land use type in this study area was the conventional cropping pattern (crop and forest) irrespective of the high-efficient irrigation strategy. Main crops grown in the study area is vegetable, seedlings and fruits (blueberry and strawberry). The main pollutants include TN, TP and pesticides (organic phosphate and organic chloride).

2.3.1. Consumption coefficient t of fertilizer and pesticide (α_{i1}). For pre- project implementation period, the consumption amount of fertilizer and pesticide per unit area, Ei, was determined according to field investigation and the current reduction coefficient is considered as zero. For post- project implementation period, the consumption amount of fertilizer and pesticide per unit cultivation area was modified by the reduction coefficient in the consumption amount and was determined by literature search. Research results in different area showed that the consumption amount of fertilizer was reduced by 30-58% under the integrated water-fertilizer application technology compared to the conventional fertilization technology in the context of similar cropping pattern [16-18]. It was also suggested that the application of nitrogenous fertilizer in pearl, watermelon, soybean and corn was reduced by 23-30%, 66%, 27% and 22-31% respectively. Based on the above study results, we adopted a conservative strategy in studying the consumption amount of fertilizer in area under vegetable and seedlings production. The lowest value is considered as the reduction coefficient such as

20%.

When the integrated water-fertilizer application technology was used for vegetable cultivation, the amount of irrigation water becomes less. Due to the seasonal impact, evaporation and relative air humidity is reduced, the susceptibility of crops to disease is reduced, and ultimately there are fewer requirements for pesticide. It was reported that the consumption amount of pesticide per unit cultivation area was reduced by 15-30% when integrated water-fertilizer use strategy was applied [17]. According to the estimated amount of pesticide application in vegetable field and seedlings, we adopted a conservative strategy like fertilizer, and the lowest value of 15% was considered as the reduction coefficient.

2.3.2. Proportion of bio-active ingredient in fertilizer and pesticide. In the present study, we determined the proportion of bioactive ingredients in fertilizer and pesticide based on literature search and the annex 9 (analysis methods and partial reference parameters for surface source investigation) of the supplementary technical rules and regulations for water quality assessment of surface water and estimate of pollutant emission of water resources in China.

The common fertilizer applied in the study area is urea and compound fertilizer. Nitrogen (N) content in urea is 42%, while the compound fertilizer contains N, phosphorus (P) and potassium (K) in a proportion of 15:15:15. After conversion, 40% of the total amount of fertilizer applied was considered as the pure amount of fertilizer. This parameter is not affected by the water-saving irrigating technology, therefore, the pure amount of N and P before and after the implementation of the high-efficient water-saving technology can be calculated as follows:

α_i for N = (40% +42%) + (40% + 33.3%) = 30% and α_i for P = (40% + 33.3%) = 10%.

The type of pesticide used in the study area includes organic phosphate (60%), organic chloride (20%) and 20% of other kind of pesticide. The bioactive ingredient in organic phosphate was 14%, and that was 11% in the organic chloride. Similarly this coefficient is not changed by the water-saving irrigation strategy, the pure amount of N and P in pesticide before and after the implementation of the high-efficient water-saving technology can be calculated as follows,

β_i for organic phosphate or N (60%×14%) =8.4% and β_i for organic chloride or P (20%×11%) =2.2%,

2.3.3. Loss reduction coefficient (LRC) and loss load coefficient (LLC) of pollutants. According to literature search, the LRC of fertilizer and pesticide per unit area in the study site changed after the implementation of high-efficient water-saving irrigation technology. The data for loss load of fertilizer before project implementation is not available therefore the LLC of pollutant, expressed as γ_i , is determined as follows:

- LLCfor nitrogenous fertilizer: the absorption and utilization rate of nitrogen fertilizer in general crop plants is about 35%. About 65% of the nitrogen fertilizer is lost due to volatilization, leaching and leakage. The loss coefficient was calculated according to the lowest loss rate such as 20%.
- LLC for phosphorus fertilizer: the current absorption and utilization rate of phosphorus fertilizer in general plants is about 20％, and about 15% of phosphorus fertilizer is lost with water. In the present paper, the loss coefficient of phosphorus fertilizer is considered as 15％.
- LLC for pesticide: pesticide is lost mainly due to drift, volatilization, and evaporation in soil, plant and water. In particular, 25% of the consumption amount of pesticide is lost due to drift and volatilization, 3-5% due to soil evaporation and 10% due to plant evaporation. The LLC of pesticide is therefore 40%.

After project implementation, the loss load of pollutant was modified by the reduction coefficient of loss load, α_{i2}, and α_{i2} was determined by literature search. It was suggested that the integrated water-fertilizer technology can effectively reduce the consumption amount of fertilizer and pesticide and the loss load of pollutant [19]. The loss load of TN per unit yield for pear, soybean and corn in trickle fertilization was reduced by 45.2%～56.4%, 14.5%～49.7% and 26.3%～51.8% compared to the conventional irrigation, respectively. Research results showed that precise trickle fertilization can reduce the loss load of TN by 22.8~58.0% [20]. Compared to conventional irrigation, maintenance of surface soil and vegetation, mulching film coverage and precise trickle irrigation can reduce the loss load of TP in pear orchard and vegetable field by 20.6% and 12.6%, respectively [21]. It was also shown that precise trickle fertilization reduced the loss load of TP by 45.0%～75.0% [20]. The results mentioned above were summarized in table 1.

Table 1. Reduction in nutrient loss due to high-efficient water-saving irrigation strategy.

pollutants	reduction rate (%)	
TN	Minimum	14.5
	Maximum	58.0
TP	Minimum	12.6
	Maximum	75.0

When evaluating the loss rate of fertilizer in vegetable field and seedling bed, we adopted slightly conservative strategy, i.e. the lowest value documented in literature was considered as the loss rate of fertilizer, TNα_{i2} = 14.5% and TPα_{i2} =12.6% (table 1). Because the application pattern of pesticide was not changed significantly after project implementation, we didn't consider the effects of high-efficient water-saving measures on the loss load of pesticide.

2.3.4. Current state of fertilizer and pesticide consumption. The consumption amount of fertilizer and *pesticide* in Gaoxi community, Chengjiang county is determined through on-site investigation. The pure amount of fertilizer application in the project area is 2644.5 kg/ hm^2, which is much higher than the average consumption amount of fertilizer in China (434.3 kg/hm^2). The farmers of the project area were dependent on inorganic fertilizer which resulted in an increase in soil acidity. The mean amount of pesticide consumption in the project area is 44.7 kg/hm^2, while the mean consumption amount of pesticide in China is 13.4 kg/hm^2. The consumption amount of fertilizer and pesticides in cultivating blueberry and greening seedlings is relatively less than that of in vegetables production.

2.3.5. Adjustment in cultivation area. Before project implementation, crops grown in the 167.3 hm^2 of study area were mainly vegetables. After project implementation, 118.7 hm^2 of blueberry, 32 hm^2 of vegetable and 16.7 hm^2 of greening seedlings were grown in this 167.3 hm^2 of study area.

3. Results and discussions

The calculated results were shown in table 2.

Seen from table 2, it was clear that:

Before project implementation, the annual consumption amount of fertilizer and pesticide was 1106.06 t and 7.48 t, respectively, whereas, after project implementation, the total consumption amount of fertilizer and pesticide was 277.37 t/a and 3.17 t/a, respectively. The consumption amount of fertilizer and pesticide was significantly reduced by almost 75% and 60%, respectively.

Before project implementation, the total loss of TN, TP, Organo phosphate and organic chloride was 66.36 t/a, 16.59 t/a, 0.25 t/a and 0.07 t/a, respectively. After project implementation, the total loss of TN, TP, organic phosphate and organic chloride was 14.23 t/a, 3.64 t/a, 0.11 t/a and 0.03 t/a. The loss rate of TN, TP, organic phosphate and organic chloride was reduced by 78.6%, 78.1%, 57.6% and 57.6%, respectively.

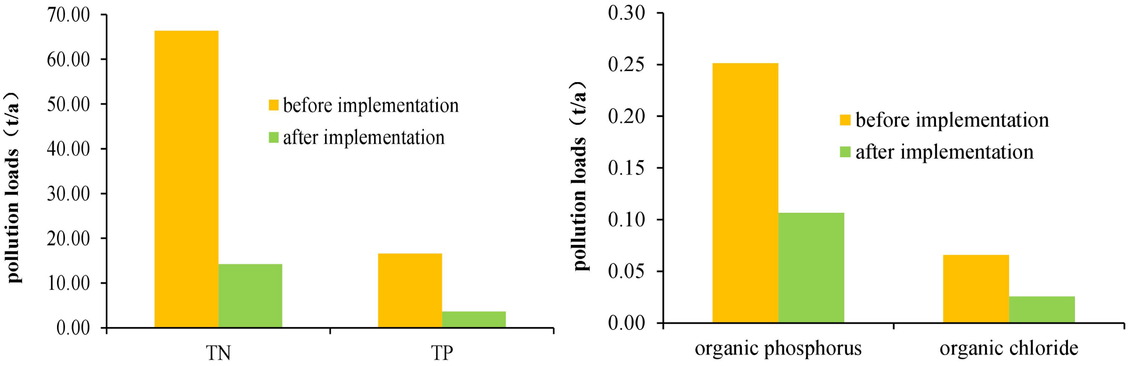
The efficiency of reduction was shown in figure 1.

It was clear that after project implementation, the non-point source pollution loads resultant from the loss of fertilizer and pesticide tended to decrease. And the main driving force was the great adjustment in cropping structure and application of high-efficient water-saving irrigating pattern. After trial implementation, 32.0 hm^2 of the 167.3 hm^2 of vegetable field was reserved for vegetable

Table 2. Pollution load before and after project implementation.

Pollutants	Plant	Rate of fertilizer or pesticide (kg/hm^2·a)	Bioactive component proportion	Export coefficient	Loss quantity (kg/hm^2·a)	Area (hm^2)	Total Consumption of fertilizer or pesticide (t/a)	Total loss quantity (t/a)
TN	vegetables	6609.9	0.3	0.2	396.6	167.3	1106.06	66.36
TP			0.1	0.15	99.15			16.59
organic phosphorus		44.7	0.084	0.4	1.5		7.48	0.25
organic chloride			0.022	0.4	0.45			0.07
TN	vegetables	5284.5	0.3	0.17	271.05	32.0	169.1	8.68
	blueberry	900	0.3	0.17	46.2	118.7	106.8	5.48
	seedlings	88.2	0.3	0.17	4.5	16.7	1.47	0.08
sub-total					321.75	167.3	277.37	14.23
TP	vegetables	5284.5	0.1	0.13	69.3	32.0	169.1	2.22
	blueberry	900	0.1	0.13	11.85	118.7	106.8	1.4
	seedlings	88.2	0.1	0.13	1.2	16.7	1.47	0.02
sub-total					82.2	167.3	277.37	3.64
organic phosphorus	vegetables	35.7	0.084	0.4	1.2	32.0	1.14	0.04
	blueberry	15	0.084	0.4	0.45	118.7	1.78	0.06
	seedlings	15	0.084	0.4	0.45	16.7	0.25	0.01
sub-total					2.25	167.3	3.17	0.11
organic chloride	vegetables	35.7	0.022	0.4	0.3	32.0	1.14	0.01
	blueberry	15	0.022	0.4	0.15	118.7	1.78	0.02
	seedlings	15	0.022	0.4	0.15	16.7	0.25	0
total					0.6	167.3	3.17	0.03

cultivation, and the remaining 135.3 hm^2 of land was reserved for blueberry and seedlings that are characterized by low unit pollution load. Furthermore, the high-efficient water-saving irrigating technology was adopted in the experimental area. The utilization efficiency of water and fertilizer was effectively increased by integrated water and fertilizer management. Influenced by the integrated function of these two main reasons, especially the great adjustment in cropping structure, the consumption amount of fertilizer and pesticide as well as their loss rate was greatly reduced. This has significantly reduced the agricultural non-point source pollution loads in the study area.



(a) (b)

Figure 1. A comparison of pollution loads before and after project implementation.

4. Conclusions

The ECM model can't be used to calculate the non-point source load in the study area. We therefore constructed an output coefficient model to calculate the agricultural non-point source pollution loads before and after cropping pattern changes by analyzing the main factors that affect the non-point source load output before and after cropping pattern changes and introducing reduction coefficient of the consumption amount of fertilizer (pesticide), bioactive ingredients of fertilizer (pesticide), loss road coefficient of fertilizer (pesticide) in soil and reduction coefficient of the loss load in fertilizer (pesticide).

We constructed an output coefficient model based on our study and calculated the reduction amount in pollution load before and after project implementation. The results showed that the changes in cropping structure, irrigating patter, and the implication pattern as well as implication amount of pesticide had significant effects on non-point source load. TN, TP, organic phosphorate and organic chloride were reduced by 78.6^, 78.1%, 57.6% and 57.6%, respectively.

The modified output coefficient model is well suitable to the comparison and calculation of the agricultural non-point source pollution loads before and after cropping pattern change. It also showed that the modified output coefficient model has good flexibility in calculating the non-point source pollution loads. In the modified model, the main impacting factors or coefficient can be introduced freely.

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