Assessment of Agricultural Non-point Source Pollution Loads Applying Improved Export Coefficient Model (IECM) : A Case Study in Taihu Lake Basin

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Abstract. Accurate and comprehensive estimation of agricultural non-point source pollution (ANPSP) is of vital importance in watershed pollution control, while data inaccessibility and complexity of process-based models may be main restrictions in practice. An estimation methodology framework for ANPSP was established based on improved export coefficient model (IECM) in this research. A series of updated, regional coefficients were collected and/or calculated with multiple pollution sources considered (i.e., animal husbandry, farming and forestry, fishery, and rural domestic sewage) to provide a comprehensive estimation of TN and TP pollution loads in Taihu Lake Basin. According to this model, pollution loads of TN and TP in Taihu Lake Basin were 65791.28 and 11400.38 t in 2016, respectively. Animal husbandry was main source of ANPSP, accounting for 31.05% and 66.70% for TN and TP, respectively, which requires more efficient and clean agricultural production modes and strict pollution control measures. IECM-based estimation framework may provide a reference for ANPSP management practice in large scale watershed.

Keywords: agricultural non-point source pollution; Taihu Lake Basin; improved export coefficient model; spatial pattern

1. Introduction

Agricultural non-point source pollution (ANPSP) refers to the pollution generated in agricultural production and life with uncertain sources, which features the complexity of occurrence mechanism and uncertainty of emission direction, thus increasing the difficulty in its accurate estimation and contamination control. It has raised increasing concerns that ANPSP would threaten ecological environment, food safety and public health, as a result of rapid but extensive development in agriculture in the past two decades, with a series of behaviors such as leaching and loss of pesticides and fertilizers, over emission of residual food in fishery, improper discharge of livestock manure, and disorderly disposal of rural household garbage.

Export coefficient model (ECM) is applied in estimation with social-environmental-economical statistics and relatively stable coefficients, avoiding complex field monitoring and process-based simulation. ECM could be used in larger spatial and temporal scales, compared with process-based models, because of its relative robustness and less demand for data amount and accuracy [1]. However, classic ECM has been questioned, as fixed coefficients conflict with great temporal-spatial heterogeneity in certain watersheds. Many researchers have reported dynamic export coefficient model (DECM) in Nansi Lake Basin [2], Three Gorges Reservoir Region [3], etc. Other researchers contribute to improvements to ECM on uncertainties quantification [4] and elimination [5], combination with best management of practices (BMPs) [6], and decision alternatives provision policy makers [7].

Taihu Lake Basin is covered with rivers and lakes, and is one of the most densely populated and highly urbanized areas. Increasing concentration has been raised on ANPSP in Taihu Lake Basin in view of developed agriculture, great consumption of chemical fertilizers, and relatively sensitive ecological environment. Eutrophication, algal boom and deterioration in water quality, caused by excessive amounts of nutrients, have stress the significance of research on mechanisms, estimation, control measures, and policy decision about ANPSP. Polder ecosystems, densely distributed at lowland areas in Taihu Lake Basin, are characterized by complicated hydrological process and intensified artificial interference. WALRUS-paddy model has been developed for run-off process simulation in Chinese lowland polders [8], which have multiple land use and pumping stations [9]. Phosphorus Dynamic Model for Polders (PDP) has been developed to estimate phosphorus export coefficients in 2539 polders in Taihu Lake Basin [10]. Net Anthropogenic Nitrogen Inputs (NANI) has also been applied in nitrogen loads estimation at county scale [11]. However, all studies above rely on data acquisition and/or process-based calculation. It take time and efforts to search for various types of high-accuracy data, most of which are, regretfully and unfortunately, inaccessible.

Therefore, it is of great significance to develop a methodology framework based on simpler methods at such a large scale, using accessible statistical data with equal performance. This study aims to (a) develop a ANPSP estimation methodology framework based on IECM with statistical data in Taihu Lake Basin, and (b) to estimate and analysis proportion of different sources and spatial distribution pattern of nitrogen and phosphorus loads with this methodology framework, thus providing reference for ANPSP management practice.

2. Methodology

2.1 Research area

Taihu Lake Basin, as one of the most industrialized and urbanized regions in China, is situated in Yangtze River Delta, Eastern China (119.13-121.92º E, 30.08-32.13º N). Although the total land area of the basin accounts for only 0.4% of China, population and GDP by 2016 accounted for 4.4% and 9.9%, respectively [12]. The last thirty years have seen rapid economic development, as well as consequently a series of ecological environment problems. A comprehensive consideration of hydraulic zoning, pollution control zoning [13], and administrative zoning, 27 administrative-based regions have been established in our research area (Fig. 1) for data processing convenience and estimation reasonableness. Specifically, in view of that there are regional differences in statistical standards, all urban districts in the city were regarded as one unit for data processing.

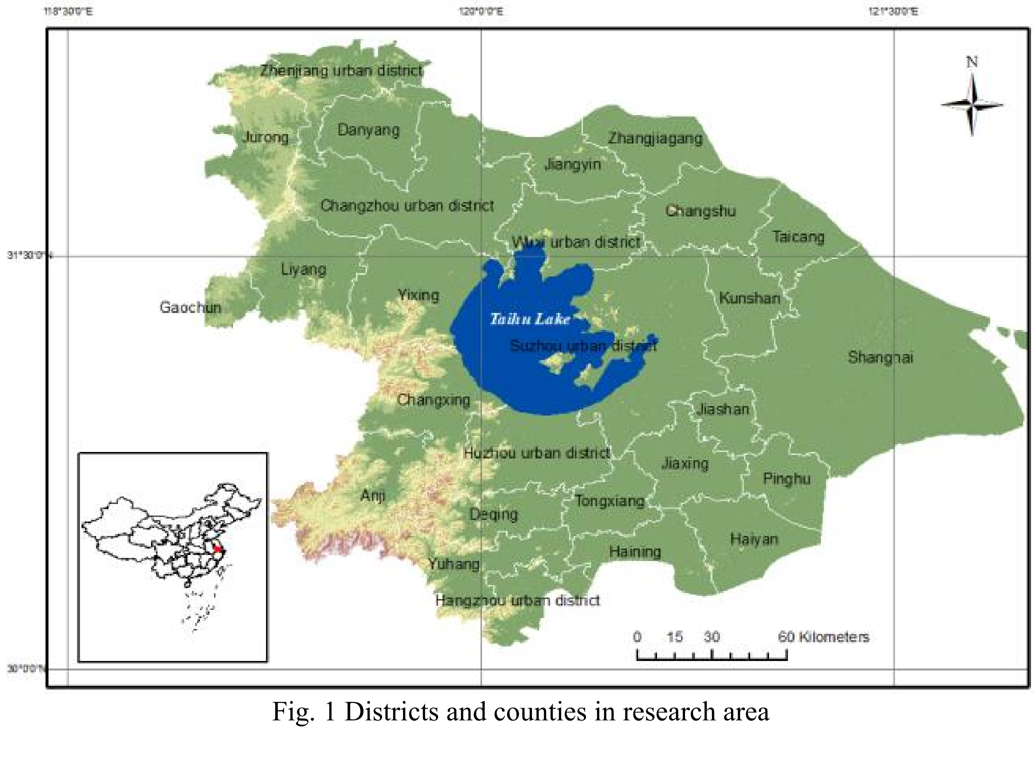

Fig. 1 Districts and counties in research area

2.2 Data description

County-level statistical data in 2016 was collected from statistical yearbook. Area of land, rural population, consumption of chemical fertilizers, basic indicators on farming, animal husbandry, and fishery were included. Monitoring and estimation data of ANPSP was collected from The health status report of Taihu Lake (2008-2018) [14] and other published studies. Coefficients for calculation were mainly provided by Manual for the Second National Survey of Pollution Sources (Agricultural Sources) and other relative reports and literature.

2.3 Estimation framework

ANPSP was calculated using the following formulas (Table. 1).

Table 1: Main formulas of estimation framework in this study

Content	Formula	No.
ANPSP	$Q_{total} = Q_{ani} + Q_{far} + Q_{fis} + Q_{wat}$	(1)
Animal Husbandry	$Q_{ani} = \sum_{i} 365 \quad f_i / 100000 \quad \cdot N_i \cdot T$	(2)
Farming and Forestry	$Q_{far} = \sum_{i,j} M_{i,j} \times a_j \times f$	(3)
Fishery	$Q_{fis} = \sum_{m=1} \sum_{n=1} C_{m,n} \cdot S_{m,n}$	(4)
	$A_{i,j} = \frac{S_i}{F} \cdot \frac{M_j}{F}, \quad and \sum_{i=1} S_i = \sum_{j=1} M_j = F, \sum_{i=1} \sum_{j=1} A_{i,j} = 1$	(5)
	$C = \sum_{j=1} \sum_{i=1} A_{i,j} \cdot f_{i,j}$	(6)
Rural Domestic Sewage	$Q_{wat} = 365 \times N \times f \times \frac{1}{100} \times T$	(7)

For Formula (1), where Q_{total} represents the total pollution loads of AGPSP ($t \cdot a^{-1}$); Q_{ani}, Q_{far}, Q_{fis}, and Q_{wat} represent pollution loads of animal husbandry, farming and forestry, fishery and rural domestic sewage, respectively ($t \cdot a^{-1}$).

For Formula (2), where f_i represents the export coefficients of animal i ($g \cdot head^{-1} \cdot d^{-1}$); N_i represents the number of animal i for calculation (head); T represents the inflow coefficients (dimensionless), T =0.6.

For Formula (3), where $M_{i,j}$ represents consumption of fertilizer type j (nitrogenous, phosphate, and compound fertilizer) in area i ; a_j represents effective content ratio of fertilizer type j (dimensionless); f represents apparent loss coefficient (dimensionless) [15].

For Formula (4)-(6), where $C_{m,n}$ represents integrated export coefficient of category n (fish, shellfish, shrimps-prawns-crabs, and others) in area m ($g \cdot kg^{-1}$); $S_{m,n}$ represents freshwater aquaculture production of type n in area m recorded in local statistical yearbook ($t \cdot a^{-1}$); $A_{i,j}$ represents the proportion of species i with breeding method j (pond, lake, reservoir, and ditch) in total production of certain category; S_i represents production of species i in certain category ($t \cdot a^{-1}$); M_j represents production using breeding method j in certain category ($t \cdot a^{-1}$); F represents total production of certain category recorded in China Fishery Statistical Yearbook ($t \cdot a^{-1}$); $f_{i,j}$ represents export coefficient of species i with breeding method j ($g \cdot kg^{-1}$).

For Formula (7), Where N represents rural population (10^4 persons); f represents export coefficients ($g \cdot person^{-1} \cdot d^{-1}$); T represents inflow coefficients, T =0.7.

3. Results

3.1 Estimation results of ANPSP

The calculation results of ANPSP loads in Taihu Lake Basin are shown in Table 2. In 2016, TN loads of ANPSP in the basin was 65791.28 t, and average pollution density per unit land area was 1740.86 kg·km^{-2}.TP loads of ANPSP in the basin was 11400.38 t, and average pollution density per unit land area was 301.66 kg·km^{-2}.

The contribution of each pollution source to ANPSP loads is shown in Figure 2. In terms of TN, animal husbandry source, fishery source, farming and forestry source, and rural domestic sewage source accounted for 20428.14 t (31.05%), 6146.06 t (9.34%), 12819.20 t (19.48%), and 26397.88 t (40.12%), respectively. In terms of TP, animal husbandry source, fishery source, farming and forestry source, and rural domestic sewage source accounted for 7064.57 t (66.70%), 1181.60 t (10.36%), 1734.28 t (15.21%), and 879.93 t (7.71%), respectively.

Table 2. Agricultural non-point source pollution loads of TN, TP (t) in districts and counties in 2016

Province	City	Districts and Counties	TN	of which				TP	of which			
				Animal Husbandry	Fishery	Farming and Forestry	Domestic Sewage		Animal Husbandry	Fishery	Farming and Forestry	Domestic Sewage
Jiangsu												
	Zhenjiang		4981.17	1534.97	371.57	780.50	2294.13	823.81	571.39	63.18	112.77	76.47
		urban districts	1525.67	528.13	91.86	225.79	679.89	269.71	196.60	17.17	33.27	22.66
		Danyang	1955.12	624.99	167.94	248.37	913.82	321.59	232.65	28.19	30.29	30.46
		Jurong	1500.38	381.85	111.77	306.34	700.43	232.51	142.14	17.82	49.21	23.35
	Changzhou		8003.98	2775.00	687.70	1136.17	3405.10	1453.66	1033.00	195.14	112.01	113.50
		urban districts	5910.82	2260.50	465.78	706.45	2478.09	1142.56	841.47	142.95	75.54	82.60
		Liyang	2093.15	514.50	221.92	429.72	927.01	311.10	191.53	52.20	36.48	30.90
	Wuxi		5519.82	1812.67	542.91	742.07	2422.17	961.46	674.76	90.58	115.38	80.74
		urban districts	1798.54	188.43	78.31	183.97	1347.83	162.51	70.14	10.57	36.87	44.93
		Jiangyin	1887.06	971.80	116.06	190.23	608.97	430.25	361.75	15.95	32.25	20.30
		Yixing	1834.22	652.44	348.54	367.87	465.36	368.70	242.87	64.06	46.26	15.51
	Suzhou		9117.90	2680.72	921.01	1174.26	4341.92	1420.61	997.90	223.55	54.44	144.73
		urban districts	3461.52	939.42	517.27	305.65	1699.18	546.06	349.70	125.55	14.17	56.64
		Changshu	1836.39	422.67	135.26	402.81	875.65	238.03	157.34	32.83	18.67	29.19
		Zhangjiagang	1348.34	244.79	62.13	184.01	857.41	143.31	91.12	15.08	8.53	28.58
		Taicang	1583.75	834.68	43.55	158.08	547.43	346.86	310.71	10.57	7.33	18.25
		Kunshan	887.91	239.16	162.80	123.70	362.25	146.35	89.03	39.51	5.73	12.07
	Nanjing	Gaochun	1091.52	362.84	169.15	138.82	420.71	282.71	135.07	63.96	69.66	14.02
Zhejiang												
	Huzhou		9103.04	3145.78	1912.24	809.93	3235.09	1614.07	1171.05	264.62	70.57	107.84
		urban districts	3954.25	1455.52	991.63	260.77	1246.33	746.46	541.83	140.36	22.72	41.54
		Deqing	2285.93	1018.34	627.87	70.67	569.05	490.35	379.08	86.14	6.16	18.97
		Changxing	1768.23	407.27	211.03	335.61	814.33	232.47	151.61	24.47	29.24	27.14
		Anji	1094.63	264.65	81.71	142.88	605.38	144.80	98.52	13.65	12.45	20.18
	Jiaxing		11575.56	2067.17	733.51	4663.83	4111.05	1794.11	769.57	128.45	759.06	137.03
		urban districts	2897.87	519.93	302.65	1203.94	871.36	473.83	193.55	55.29	195.95	29.05
		Jiashan	1527.95	268.29	112.25	611.63	535.78	232.77	99.87	15.50	99.54	17.86
		Pinghu	1364.68	103.15	33.56	716.10	511.87	176.84	38.40	4.83	116.55	17.06
		Haining	1895.57	290.73	116.58	678.69	809.58	265.82	108.24	20.14	110.46	26.99
		Haiyan	1624.91	444.07	78.11	582.88	519.84	293.24	165.31	15.73	94.87	17.33
		Tongxiang	2264.58	440.99	90.37	870.60	862.62	351.60	164.19	16.96	141.69	28.75
	Hangzhou		3362.54	448.05	463.80	217.73	2232.97	352.88	166.79	76.60	35.06	74.43
		urban districts[1]	753.77	29.68	113.05	32.18	578.86	53.58	11.05	17.18	6.06	19.30
		Yuhang	2608.78	418.37	350.75	185.55	1654.11	299.30	155.74	59.42	29.00	55.14
Shanghai		whole city[2]	13035.73	5600.94	344.16	3155.89	3934.75	2697.07	2085.05	75.53	405.34	131.16
		in total	65791.28	20428.14	6146.06	12819.20	26397.88	11400.38	7604.57	1181.60	1734.28	879.93

Note: 1. Based on traditional boundary of Taihu Lake Basin, only Xihu, Gongshu, Shangcheng, Binjiang, and Qiantang District in Hangzhou urban district are considered, according to latest notice from Ministry of Civil Affairs; 2. Only freshwater aquaculture is considered, therefore Chongming District is not included.

A similar spatial distribution pattern of TN and TP loads in research area has been observed, indicating their potential similarities of pollution sources (Fig. 3). On the whole, Jiaxing City, eastern Huzhou City (Huzhou Downtown and Deqing County), Changzhou Downtown, and Danyang city are high population load areas, while western Huzhou City (Changxing County and Anji County), Yixing City, Suzhou Downtown and Kunshan City are low pollution load areas. The TN load of Tongxiang City was the highest (3114.97 kg·km^{-2}), and that of Anji County was the lowest (580.40 kg·km^{-2}). The TP load was highest in Deqing County (522.76 kg·km^{-2}) and lowest in Anji County (76.78 kg·km^{-2}).

Specifically, the spatial distribution pattern of pollution sources differs from each other, while that of TN and TP appears similarities in terms of a certain pollution source. The high load areas of animal husbandry sources were Jiangyin City and Deqing County, while the low load areas were Hangzhou Downtown, Wuxi Downtown, Pinghu County, and Anji County. Notably, Hangjiahu Plain appeared high loads of ANPSP originated from farming and forestry source. Huzhou Downtown and Deqing County featured high loads of ANPSP from fishery source.

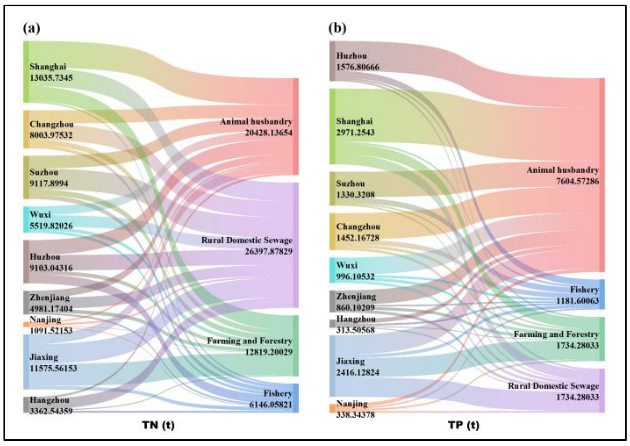

Fig. 2: Proportions of different pollution sources among districts and counties in research area;
(a)TN; (b)TP

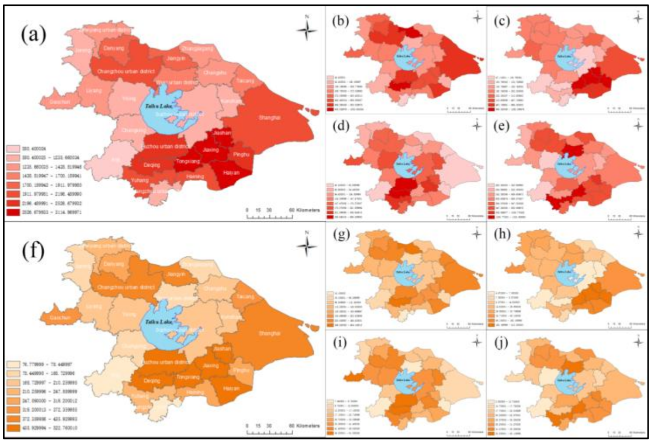

Fig. 3: Spatial distribution of pollution loads (kg • km-2); (a)TN; (b) TN-animal husbandry source; (c)TN-farming and forestry source; (d)TN-fishery source; (e)TN-rural domestic sewage source; (f)TP; (g)TP-animal husbandry source; (h)TP-farming and forestry source; (i)TP-fishery source; (j)TP-rural domestic sewage source

4. Discussion

4.1 Contributions of ANPSP sources

In this study, the IECM was used to estimate the ANPSP loads in the Taihu Lake Basin in 2016 based on the agricultural production data from local statistical yearbooks. TN and TP loads were 65791.28 t and 11400.38 t respectively in Taihu Lake Basin, while TN and TP loads of the upper reaches of the basin are 28376.48 t and 4895.83 t respectively under the same estimation framework. The TN loads in this study are close to those calculated by other researchers in 2017 [16], 2018 [17], and 2020 [18], which proves that the estimation is feasible. The TP loads tend to be higher in this research, compared to estimation by other researchers [19]. It has been pointed out that environmental adsorption of phosphorus is more significant and the conversion loss along the way is greater [20]. In that case, it is doubted that the inflow coefficient of TP is the same as that of TN, which is different from the actual situation.

In this study, the contribution ratio of different pollution sources to TN and TP load was different. Rural domestic sewage sources accounted for a large proportion of TN load (40.12%), which was higher than other research results [11]. This is mainly due to the high inflow coefficients of rural domestic sewage in estimation. Considering being proposed in 2005, the coefficients seems outmoded after around a-decade infrastructure construction and environmental management in research area. Animal husbandry sources account for a large proportion of the TP load (66.70%). Therefore, measures should be taken to reduce the phosphorus load into water to restrain the bloom pollution of Taihu Lake.

4.2 Spatial distribution pattern of ANPSP load

The spatial distribution pattern of TN and TP load of different pollution sources reflects the agricultural composition in different regions. In terms of animal husbandry sources, Huzhou Downtown, Deqing County, Jiangyin City, Changzhou Downtown and Shanghai Municipality had higher pollution load. For example, 100.06 million pigs and 51400 cows were raised by the end of 2016 in Shanghai Municipality, far more than other cities in the study area, which was closely related to the high demand for meat and milk of the dense urban population. Huzhou Downtown and Deqing County city are important livestock and poultry farms in western Zhejiang Province, featuring high quantity of cultured pigs, cattle, sheep, rabbits and poultry. In terms of farming and forestry sources, it is revealed that Jiaxing City serves as an important food and vegetable supply area in Taihu Lake Basin. Compared with Suzhou City in the north, Jiaxing City has a higher proportion of cultivated land, larger planting area of vegetables and melons, higher multiple cropping index, and significantly higher fertilizer application per unit area, so it maintains a relatively high level of ANPSP load [21]. In terms of fishery, the spatial distribution pattern of pollution load is consistent with a study with similar estimation method [22]. Huzhou city, for instance, features largest aquaculture area among the counties in research area. In addition, grass carp and perch are the main cultured species in this area, with a higher consumption of feed rich in nitrogen and phosphorus than river crabs and freshwater shrimps, which aggravates the non-point source pollution load in Huzhou City [22]. ANPSP load of Anji County is the smallest, as a consequence of which the secondary-tertiary industries of the county are relatively developed while the government has invested a lot in non-point source pollution prevention and control, ecological protection, and development of ecological tourism [23].

5. Conclusions

In 2016, the total amount of ANPSP in Taihu Basin was 65791.28 t of TN and 11400.38 t of TP, to which animal husbandry contributes great proportions. Significant spatial differences had been revealed in our research, the estimation results of which was 580.40-3114.97 $kg \cdot km^{-2}$ of TN, and 76.78-522.76 $kg \cdot km^{-2}$ of TP, respectively. Notably addition attention should be payed to Hangjiahu Plain (especially farming and forestry source) due to high loads of TN and TP in this region, indicating that more efficient and clean agricultural production modes and strict pollution control measures should be applied. Our IECM-based methodology framework and estimation results may provide a reference for ANPSP management practice in large scale watershed.

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