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A bottom–up model for quantifying anthropogenic phosphorus cycles in watersheds

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A B S T R A C T

Aiming at tracing the sources of anthropogenic phosphorus flowing into watercourses, this study develops a static model for analyzing the phosphorus flows within a socioeconomic ecosystem. This model consists of four major subsystems: phosphorus ore mining/processing, phosphorous-containing product manufacturing, phosphorus-containing product use and phosphorus-containing waste/wastewater management. Furthermore, based on the principle of mass balance, we provided formulas for calculating phosphorus flows of the ecosystem. Then, we quantified the anthropogenic phosphorus flows using the bottom–up approach for the Chaohu watershed in 2008. The data and parameters are mainly obtained from field surveys, the literature, industrial experts, and official statistics. The results show that approximately 36 thousand tons of phosphorous flowed into watercourses in the Chaohu watershed in 2008, of which 99% came from phosphorus-containing product use (55% from crop farming, 34% from large-scale breeding, 7% from rural consumption, 2% from urban consumption, and 1% from domestic breeding). Therefore, we provided suggestions on mitigating phosphorus loss into watercourses. The study provides a method (model and the calculation formulas) to quantify anthropogenic phosphorus flows at a watershed level, which helps to understand the relationship between human activities and eutrophication.

1. Introduction

Human activities have greatly accelerated the natural phosphorus (P) cycle (Hassan et al., 2005), and global P mobilization had approximately tripled by 2000 compared to its natural flows (Smil, 2000). As a result, P-containing wastewater/wastes discharged by human activities contribute to the eutrophication of surface water (Carpenter et al., 1998). Eutrophication is a process through which lakes become increasingly rich in plant biomass as a result of the enhanced input of plant nutrients, particularly P and nitrogen (Schindler, 1977; Hecky and Kilham, 1988). In recent years, eutrophication has become both a frequent and escalating problem in lakes, rivers, and coastal ocean zones all over the world. The literature shows that for lakes, excessive P, rather than nitrogen, is usually the limiting nutrient for the growth of aquatic plants and, thus, the primarily cause of eutrophication (Oelkers and Valsami-Jones, 2008). Therefore, quantifying P flows throughout socioeconomic ecosystems is vital for the selection of eutrophication mitigation strategies based on the concept of life-cycle nutrient management (Wu et al., 2012).

The origin of the literature on quantifying the pathway of anthropogenic nutrients can be traced to a phosphorus budget for a Swedish municipality with the method of input–output analysis, through which the ecological interplay between the city and countryside was illuminated (Nilsson, 1995). Case studies, such as on an anthropogenic nitrogen cycle in the Netherlands (Olsthoorn and Fong, 1998) and a P budget for the Lake Mendota watershed (Bennett et al., 1999), have also been conducted based on this input–output model. Following these studies, Baker et al. improved this input–output-based model by dividing the ecosystem into subsystems (Baker et al., 2001) and some studies have applied this improved method to estimate the sources of total nutrients in a river/reservoir basin (Hart et al., 2002; Iital et al., 2003), describe the nutrient cycling process and predict its current loss to surface water (Groffman et al., 2002; McDowell et al., 2002; Smith et al., 2003).

As an effective method to connect the utilization of materials with its environmental impacts, substance flow analysis (SFA) has been widely used to quantify the pathways of anthropogenic metals (Lifset et al., 2002). Considering its basic principles, SFA can also be used to analyze the amount and intensity of P use to develop environmental management strategies (Bi et al., 2013; Fan et al.,

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2008). Meantime, a P balance in a river basin was completed using the methodology of material flow analysis (Drolc and Koncan, 2002) and the SFA method was applied to quantify the flows of nutrients throughout a socioeconomic ecosystem (McDowell et al., 2002; Yuan et al., 2011c). However, these studies focused on one or several subsystems, such as the forest industry (Antikainen et al., 2004), food production and consumption (Neset et al., 2008), agricultural and forest sector (Chen et al., 2008), urban environmental sanitation (Montangero et al., 2007), and industrial economy (Jeong et al., 2009).

Overall, the early studies in this field are dominantly characterized by fragmented trials on subsystems, and they help us to understand these subsystems. However, they are not sufficient for decision-makers to select life-cycle strategies for nutrient management. Furthermore, they are usually carried out at a city or country level using the top–down concept due to the availability of official statistical data. There is a lack of statistical data at the watershed level because watershed is usually a geographic concept, rather than a political one. To deal with these problems, conducting an analysis of the whole pathway of nutrients throughout a socioeconomic ecosystem based on the bottom–up concept is indispensable.

We focus on the life-cycle of phosphorus flows, including its extraction, production, consumption, waste management, water environment, and soil environment in a watershed region. We constructed a SFA-based static analytical model for the anthropogenic P flows at the lake watershed level, and selected Chaohu watershed as a case to quantify the P flows in 2008.

2. Methodology

2.1. Selection of the case lake watershed

We chose Chaohu watershed as the case area because of the following reasons. 1) As the fifth largest lake in China, Chaohu's eutrophication is serious. Furthermore, its eutrophication mitigation is critical and has been paid increasing attention by China's central government. In China's Water Pollution Control Program (2006–2020), Chaohu is regarded as one of the three most important watersheds to mitigate eutrophication. 2) With an area of 13,350 km^2, Chaohu watershed has a relatively clear boundary, which is suitable for field-survey-based data collection and bottom–up analysis. 3) The watershed has approximately 10.2 million residents and the human activities involve the whole process of the P life cycle. 4) There are 33 tributary rivers running into Chaohu in the watershed, which contribute to transporting most P-containing wastewater into Chaohu.

2.2. System boundary

The P flow analysis is limited to the borders of Chaohu watershed, covering two cities and seven counties (Li et al., 2010; Yuan et al., 2011b). The data used in the analysis are based on the year 2008, and the P flows refer to the amounts of P transferred from one process to another during the entire year. Furthermore, the social metabolism of P caused by natural factors, including wind erosion, water erosion and release from sediments, is not taken into account in our model. However, the atmospheric deposition and the surface runoff/erosion from agricultural land are considered. In addition, we neglect the manufacturing process because the manufacturing activity is underdeveloped in Chaohu watershed and so little P is associated with these activities.

2.3. Static analytical model for P flows

According to our investigation, the anthropogenic P life-cycle consists of four sequential life stages shown in Fig. 1. In contrast to the analytical model of the anthropogenic P cycle at the city (Li et al., 2010) and the county (Yuan et al., 2011a, 2011c) levels, we subdivide systems in this study. For example, we subdivide the environment into the water environment and soil environment, because we aim to trace the sources of P flows contributing to eutrophication. Furthermore, every process consists of different sub-processes that are determined based on their predominant P-dependent activities.

2.4. Data collection

Based on the bottom–up approach, a P flow analysis throughout the socioeconomic ecosystem of the Chaohu watershed was completed for the year 2008. Our analysis was based on questionnaires, face-to-face interviews, published literature, and official statistical databases.

We developed two kinds of questionnaires to include parameters related to urban consumption and rural consumption activities, such as the proportions of rural excreta/straw return to farmland, the amount of crop seeds per a given area, feedstuff consumption per livestock individual, and detergents used per capita. The urban questionnaire focused on the consumption of P-containing products and the discharge of P-containing wastewater/waste. The rural questionnaire targeted the inputs and outputs of agricultural activities, such as crop farming and domestic breeding, apart from the consumption contents of the urban questionnaire. Considering economic levels and geographical features, we selected all 2 cities (Hefei and Chaohu) and 3 of the 7 counties (Feixi, Shucheng, and Lujiang). In the two sampled cities, we distributed questionnaires evenly in different districts considering the difference of income and career of residents. In every surveyed county, we chose three towns besides the urban area where the county government is located and three villages for every town concerning economic development. Overall, we chose 2 cities, 3 counties, 16 towns, and 61 villages in the watershed to distribute questionnaires and conduct interviews. We carried out our field survey in July 2009, and it lasted 20 days and employed 16 investigators. All questionnaire receivers were selected rationally, and we distributed 150 questionnaires per city, 50 per town, and 10 per village. Finally, we recovered 1710 questionnaires, of which 1078 were from rural residents and 632 were from urban residents. Based on the information from questionnaires, we used the software Epidata to build the database and completed the data analysis with SPASS 15.0.

At the same time, to obtain objective data and improve our understanding of economic and consumption activities, we conducted face-to-face interviews. Our interviewees included directors of Anhui provincial industrial associations relating to pesticides, livestock breeding, detergent, feedstuff and fertilizer production, provincial/city/county/town officials, technicians and managers of PPM firms, farmers, rural and urban residents, staff of large-scale breeding enterprises, retailers of P-containing products, such as phosphate fertilizers and pesticides, and P-chemical industrial experts. Additionally, we collected data, including the P-content rates in different substances, from product specifications and published literature.

In the end, we also obtained data from a number of statistical databases at the city/county level, such as the amounts of P-containing products, sown crop areas, phosphate fertilizers applied to farmland, crop harvests, milk production, the number of livestock and the human population. These databases include the environmental pollution sources investigation, enterprise pollutant declaration, and statistical yearbooks.

2.5. Mathematical calculations

Based on the principle of mass balance, the system and all of its subsystems follow the equation "input = output + stock". Here the