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Anthropogenic phosphorus flow analysis of Hefei City, China

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ABSTRACT

The substance flow analysis (SFA) method was employed to examine phosphorus flow and its connection to water pollution in the city of Hefei, China, in 2008. As human activity is the driving force of phosphorus flux from the environment to the economy, the study provides a conceptual framework for analyzing an anthropogenic phosphorus cycle that includes four stages: extraction, fabrication and manufacturing, use, and waste management. Estimates of phosphorus flow were based on existing data as well as field research, expert advice, local accounting systems, and literature. The total phosphorus input into Hefei in 2008 reached 7810 tons, mainly as phosphate ore, chemical fertilizer, pesticides, crops and animal products. Approximately 33% of the total phosphorus input left the area, and nearly 20% of that amount was discharged as waste to surface water. Effluent containing excessive fertilizer from farming operations plays an important role in phosphorus overloads onto surface water; the other major emission source is sewage discharge. We also provide suggestions for reducing phosphorus emissions, for example reducing fertilizer use, recycling farming residues, and changing human consumption patterns.

1. Introduction

Large amounts of phosphorus (P) are required for the growth and development of life. Being a limited resource, this element is of great interest for regional agricultural food production and phosphor resources industry (Matsubae-Yokoyama et al., 2009; Neset et al., 2008). However, the widespread use of phosphorus can be a cause for concern, particularly when excessive amounts accumulate in waterways. P may be introduced to the environment by human activity in the form of point source discharges or diffuse source runoff (Carpenter et al., 1998; Delgado and Scalenghe, 2008). Typical sources include industrial and municipal wastewater discharge and runoff from agricultural lands or urban areas (Carpenter et al., 1998; Shigaki et al., 2008). Phosphorus has been linked with water quality problems in that it contributes to eutrophication (Carpenter et al., 1998; Correll, 1998; Daniel et al., 1994; Sharpley et al., 1994). Phosphorus-induced eutrophication is due above all to its trigger effect on the nutrient cycling of N (Smil, 2000). It has no stable atmospheric gas phases, so unlike other nutrient contributing to eutrophication, nitrogen, the transfer of P could be learned as the state of aqueous phase in ecosystem (Filippelli, 2008).

Since improper nutrient management results in eutrophication, understanding the flow of phosphorus through the urban environment is vital to successful water pollution control strategies and urban sustainability (Kennedy et al., 2007). Quantification of anthropogenic phosphorus entering and leaving city boundaries provide insights into the magnitude and complexity of environmental impacts occurring in cities, particularly with respect to surface water. Traditional problem-solving methods consider water-based transfer only and are based on development of an inventory of nutrient-related activities affecting water quality (Clark et al., 1997; Huang et al., 2007; Kao et al., 2003; Meals, 1996; Yan et al., 1998). This method can provide emission estimates, but is not suited to identification of the actual causes of pollution and emission pathways. Substance flow analysis (SFA) focuses on the relevant processes and the flows of nutrients within a defined area, and estimates the emissions from human activities to the environment (Burström, 1999). It is usually employed to precisely identify the causes for surface and groundwater pollution and formulate the most efficient means to avoid them, and is therefore an effective systematic tool for tracing and quantifying phosphorus flows in the economy and environment (Voet et al., 1995).

Literature on phosphorus flows on either a city or a regional level has been extensively carried out. The flows of phosphorus from the ecosystem to the community and back to the ecosystem in the Swedish municipality of Gavle has been estimated by Nilsson (1995), where the P inflow mainly accumulated in waste dumps — municipal and industrial. In Dianchi basin, China, a quantitative analysis of entire life cycle of societal P flows has been conducted and the critical P cycles associated with intensive livestock, urban centralized sewage systems and P-detergents were of concern for eutrophication (Liu, 2005). A study of a Swedish city's phosphorus utilization was based on food production and consumption chain (Neset et al., 2008), which was

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associated with the largest P flows, such as agriculture, food processing, consumption and waste handling, as well as output flows to the environment. Additionally, research focused on partial phases of phosphorus flow through cities has been investigated by agriculture (Guo et al., 2004), households (Baker et al., 2007; Kelderman et al., 2009) and environmental sanitation (Huang et al., 2007; Montangero et al., 2007; Tangsubkul et al., 2005). In contrast to the significant number of the city or regional level phosphorus studies, few deal with the entire phosphorus life cycle. However, in planning for phosphorus management, the most far-reaching study on the P cycles should be addressed in linkage of flows between the phases of uptake, material transformation and storage, and discharge of waste products.

In our study, we first present an analytical framework based on SFA to define the anthropogenic phosphorus flow, which includes four stages: extraction, fabrication and manufacturing, use, and waste management. We then quantify the flows and inventories of phosphorus in a particular area — Hefei, China during 2008.

Hefei, as many other cities in developing countries with their high population growth, industrialization and economic development, is facing increased resource consumption and environmental degradation. The city is an agricultural and phosphate industry zone in central China, where the key industries include pigs, poultry, dairy, vegetable gardening, fodder and detergent. In agricultural activities, farmers tend to use more chemical fertilizers in an attempt to enhance yield; the P inputs in the intake of animal food stay high then entail unavoidably large P losses in animal wastes. Accordingly, this creates a huge demand for phosphorus products and boosts the development of phosphate manufacture. The increased losses of nutrients from human-induced activities are definitely of concern regarding water quality of Hefei City (Shang and Shang, 2007). Estimating the phosphorus balance and reducing anthropogenic emission could be the key to water pollution control for Hefei.

Next, we analyze the characteristics of extraction, fabrication and manufacturing, use, and waste management in the study area in order to relate human activity to phosphorus loads in nearby surface water. Finally, we explore approaches to improving the efficiency of phosphorus utilization and reducing emissions. The data were mainly extracted from field surveys, expert advice, official statistics at the local level, and the literature.

The remainder of the paper is organized into four additional sections. The second section presents the methodology including description of the study area, analytical framework, data collection and accounting approach. The third section examines the analysis, describing the current status of phosphorus flows in Hefei and their discharge into surface water. The fourth section discusses analytical results, the data reliability and provides suggestions for phosphorus discharge reduction. The conclusions are presented in the last section.

2. Methodology

2.1. Description of the study area

As the capital of Anhui province in central China, Hefei is located northwest of Chaohu Lake and comprises five inner districts. Rapid economic growth of city started mainly as early as 1980s. It is shown that the growth rate of gross domestic product (GDP) was around 13% from 1980 to 2008 (HSB and NBSSOH, 2009). The Hefei population almost increased two times from one million inhabitants in 1980 to two million in 2008. With the support of fodder and detergent from local phosphate industries, the city depends on importing other phosphate products, such as fertilizer and pesticides, from outside. The statistical data showed that about 5766 tons phosphorus fertilizer and 313 tons pesticides were imported and utilized in planting production in 2008. Intensive agricultural activities consumed huge P resources, most of which are outputting as wastes — that is, excessive fertilizer, crop residues and animal manure. Considering the low recycling rate of urban waste, the breakage of urban–rural phosphorus cycle could be of concern on environmental tolerance.

We choose Hefei as a case study because a) Chaohu Lake is the fifth largest lakes in China and has been subjected to severe eutrophication (Liu and Qiu, 2007); b) excess nutrients especially nitrogen and phosphorus entering surface water then flowing into Chaohu Lake contribute a lot to the lake eutrophication; c) the eutrophication state of the lake western part is the most serious because it is the final place of wastewater from Hefei City (Shang and Shang, 2007).

2.2. Analytical framework

Our aim was to understand the total input, inventory, and output of phosphorus in industrial, agricultural, and personal activities in the Chaohu Lake watershed. It is therefore important to identify all phosphorus activities during the entire production and consumption cycle, which can be summarized as extraction, fabrication and manufacturing, plant production, animal production, household consumption, and local waste management procedures. Baccini and Brunner (1991) defined the traditional MFA (material flow analysis) procedures which are suggested in application of SFA. The procedures are described in details by Baccini and Brunner (1991). More modern approach is named MMFA (Mathematical MFA which is a dynamic model with modern modeling concepts) and applied to many case studies (Huang et al., 2007; Neset et al., 2008). Graedel et al. (2004) further divided the life cycle into four stages within the system definition. Fig. 1 depicts the analytical framework of phosphorus flow incorporating anthropogenic activities. Each stage or box is defined as a process, sector, or stock forming part of the total 'system'.

The system boundaries are defined as the metropolitan area of Hefei City during the year 2008. Fig. 1 illustrates the four stages of the phosphorus cycle: extraction (mining and mineral dressing), fabrication and manufacturing (fertilizer, pesticides, fodder, and detergent), use (plant production, animal production, and household consumption), and waste management (wastewater treatment plants, landfill, incineration and recycling). In order to conduct the closure of P cycles from the lithosphere to the socio-economic system and back to the environment, the framework does not include the energy production system and it could be considered using different system definition in the study of Saikku et al. (2007).

This study focuses on quantifying phosphorus flow through economic, societal, and environmental systems, and does not include phosphorus losses due to natural conditions such as soil erosion. Since the phosphorus content of the atmosphere remains low, phosphorus fluxes from the soil and water into the atmosphere were considered negligible, as was atmospheric deposition on arable land.

2.3. Data collection

The approaches to data collection included statistical reviews, face-to-face interviews, and questionnaires. The statistical data were mainly obtained from local governments (provincial, municipal, and county). Face-to-face interviews with government officials, entrepreneurs, experts, and farmers were used to obtain on-site data and improve our understanding of the statistics. In addition, standardized questionnaires were created to determine the magnitude and circumstances of phosphorous consumption. Considering the differences in living conditions between urban residents and rural farmers, we developed two questionnaires, one for urban residents focusing on food consumption and articles of daily use, another for rural farmers that included questions related to phosphorus input and output values for farming and cultivation in addition to the topics of the urban questionnaire. The urban questionnaire was distributed evenly over the city, while rural survey participants were chosen according to living conditions with the help of local governors. We distributed 352