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Modification of uncertainty analysis in adapted material flow analysis: Case study of nitrogen flows in the Day-Nhue River Basin, Vietnam

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ABSTRACT

Nitrogen flows impacted by human activities in the Day-Nhue River Basin in northern Vietnam have been modeled using adapted material flow analysis (MFA). This study introduces a modified uncertainty analysis procedure and its importance in MFA. We generated a probability distribution using a Monte Carlo simulation, calculated the nitrogen budget for each process and then evaluated the plausibility under three different criterion sets. The third criterion, with one standard deviation of the budget value as the confidence interval and 68% as the confidence level, could be applied to effectively identify hidden uncertainties in the MFA system. Sensitivity analysis was conducted for revising parameters, followed by the reassessment of the model structure by revising equations or flow regime, if necessary. The number of processes that passed the plausibility test increased from five to nine after reassessment of model uncertainty with a greater model quality. The application of the uncertainty analysis approach to this case study revealed that the reassessment of equations in the aquaculture process largely changed the results for nitrogen flows to environments. The significant differences were identified as increased nitrogen load to the atmosphere and to soil/groundwater (17% and 41%, respectively), and a 58% decrease in nitrogen load to surface water. Thus, modified uncertainty analysis was considered to be an important screening system for ensuring quality of MFA modeling.

1. Introduction

Modeling of water quality is greatly needed for managing aquatic environments. Uncertainty is a critical factor when the model is applied and various types and sources of uncertainty have been identified in previously proposed modeling approaches (Beck, 1987). The first is data inaccuracy caused by unreliable empirical measurements made in the process of data collection. The second is data gaps due to shortages of information that occur when employing data from different fields (Björklund, 2002; Steen, 1997; Huijbregts, 1998; Radwan et al., 2004; Antikainen, 2007). Each of these sources of uncertainty is common in developing countries. Sources of uncertainty due to inaccuracy and gaps in data were explored to establish a low-waste emission system for the agro-industry (Oenema et al., 2003). A calculation of the nitrogen budget in a case study of the Netherlands using different data sources indicated relatively large uncertainties, including greater than 30% variation in denitrification and leaching values. Walker and Beck (2012) addressed resource management and environmental issues that manipulate nutrients, water and energy flows under data uncertainty condition in the Upper Chattahoochee Watershed in North East Georgia, USA. The results showed that the largest degree of uncertainty was 35% and was associated with anthropogenic energy flow. The third and most important source of incorrect conclusions is structural bias. Such bias can be caused by simplification in material flow analysis (MFA) modeling, especially when temporal or spatial variations are significant (Björklund, 2002). Radwan et al. (2004) stressed the importance of and need for investigating uncertainty due to the model structure in modeling of river water quality. When water quality model results were compared with measurement results, the errors were 2% for dissolved oxygen, 20% for biochemical oxygen demand, 17% for NH_4–N and 15% for NO_3–N in the case study. Reichert and Omlin (1997) stated that 'neglecting the uncertainty in the model structure leads to an underestimation of the uncertainty in model predictions'. Thus, for quantifying uncertainty, classification of individual uncertainties of the various sources is essential.

In the context of nutrient management in environmental sanitation systems, the adapted MFA methodology has been proposed as

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one of the most appropriate methods for reconciling with uncertain and limited data (Montangero and Belevi, 2008). This methodology could also trace critical sources of nitrogen by determining pollutant stocks and fluxes among environmental processes and human activities by systemizing and reusing applicable results from previous research. Therefore, the MFA was applied to visualize and assess environmental quality in terms of nitrogen under the influence of human activities in the old quarter of Hanoi (Montangero et al., 2007) and in two small communes in Ha Nam Province, Vietnam (Do-Thu et al., 2011). Importance of uncertainty analysis in MFA has been demonstrated by various researchers. For example, nutrient flows in Danube countries and significance of uncertainties due to data inaccuracy were assessed by applying MFA coupled with a Monte Carlo simulation. The uncertainties related to nutrients (N and P) were analyzed by traditional sensitivity analysis, and the relative errors identified in air emissions of N and P from agriculture were about 150–200% (Buzas, 1999). In addition, adapted MFA has been successfully applied in multi-provincial areas, such as the Thachin River Basin in Thailand, to provide an overview of origins and flow paths of point and non-point pollution sources (N and P) for the entire basin (Schaffner et al., 2009, 2010a, 2010b). The results showed that aquaculture (point source) and rice farming (non-point source) were the key sources of N and P in this river basin, and comparison with water-quality and flow measurements revealed that such sources were responsible for approximately 80% of the underestimation caused by gaps and inaccuracies in data. Sources of uncertainty were mentioned in these reports, but methods for identifying and resolving the uncertainty were lacking.

Several approaches have been employed to deal with data uncertainty in MFA studies. The simplest is trial and error, i.e. comparing results with those of similar studies or with other sources of data to assess reasonableness of the findings (Brunner and Baccini, 1992; Hekkert et al., 2000; Lassen and Hansen, 2000). When solving uncertainty in this manner, inconsistency in data has been considered as an error in budget calculation. Weisz et al. (1998) developed a cross-checking approach that employed an operating matrix for material inter-relations between the economy and nature. This matrix was a helpful tool for establishing MFA on a national scale. Although it enables use of a large amount of data and can fill in data gaps, problems remain in applying the matrix to cases of data scarcity. Budget calculations in the above-mentioned studies could be revised; however, uncertainty in MFA has not yet been fully analyzed.

This study aimed to analyze problems related to uncertainty of input data and model structure by using adapted MFA for model improvement. For this purpose, on the basis of a method proposed previously, new criterion sets for plausibility tests and a detailed procedure for reassessment were suggested in MFA. One of the most severely polluted river systems in Vietnam, the Day-Nhue River Basin (DNRB), was chosen as the case study. A number of studies have been conducted on the current status of water quality for the Day and Nhue rivers (Trinh et al., 2006, 2007, 2012a,b; Hanh et al., 2009); however, research that addresses the environment of the entire basin (atmosphere, surface water and soil/groundwater) has not yet been conducted. As the key factors in uncertainty analysis, an evaluation of the interactions between different activities and various environmental elements in the entire DNRB is described here, and the critical sources of nitrogen in the system are identified.

2. Methodology

2.1. Study area

The DNRB covers 7665 km^2 of Ha Nam, Nam Dinh, Ninh Binh Provinces, and a part of Hanoi City and Hoa Binh Province (Ministry of Natural Resources and Environment; MONRE, 2006), with a total population of approximately 10.5 million (GSO, 2010). At present, this river system is under considerable pressure from socioeconomic development activities and urbanization, and the basin is experiencing an annual population increase of about 5% (MONRE, 2006). However, the region's infrastructure is incompatible with rapid development (Ministry of Construction; MOC, 2009). Establishment and operation of industrial zones, craft villages, factories and agricultural areas have caused significant changes to the natural environment, especially to water quality. The basin includes more than 156,269 industrial, commercial and service establishments (MOC, 2009). The number of craft villages is increasing in all provinces in the basin, with the largest number located in Hanoi City. Agriculture is also an important activity in this basin. Approximately 50% of land in the Day–Nhue basin is used for farming and animal production. Given the existing infrastructure resources, solid wastes and wastewater are not yet controllable (MOC, 2009).

2.2. Data collection

A field survey was conducted in 2010 to collect general background information (social, industrial and agricultural) and environmental conditions for 2008–2010 in the study area. The most important data were the data collected from the Vietnam General Statistical Office (GSO, 2008–2010). Other information was in the government reports and documents or results of projects that have been done in the DNRB (MOC, 2009; MONRE, 2006); these were collected from Departments of Natural Resources and Environment of five provinces in the river basin (DARDs, 2010) and from research institutes and non-government organizations. Input data such as population, area, number of animals and crop yields is referred to as 'parameters'. The parameters were categorized into two types, certain and uncertain. In the subsequent analysis, the probability distribution, mean and standard deviation were assumed for each parameter on the basis of the authors' knowledge about the data source and the characteristics of the study site (Table 1). The normal distribution provides a good model for parameters; when a parameter has a strong tendency to take a central value, positive and negative deviations from this central value are equally likely. The lognormal distribution is appropriate to represent non-negative and positively skewed physical quantities, such as pollutant concentrations, and is particularly suitable for representing large uncertainties (Montangero and Belevi, 2008). For parameters that do not have a clear distribution pattern, a uniform distribution is assigned. This categorization was originally introduced in this study and would be useful in uncertainty analysis and model revision, because only uncertain parameters are subject to revision when evaluating a model. On the other hand, Monte Carlo simulation was run automatically through whole simulation, probability distribution of model output was, therefore, generated as a result.

2.3. Model establishment

Flows among the environmental and human-related processes in the draft of MFA system were cross-checked with observations and short interviews with local residents and then compared with the proposed flows. For example, in Fig. 1, eleven processes related to human activities (industrial production, agriculture and solid waste disposal) and three processes corresponded to natural environments (atmosphere, water and soil/groundwater) in the river basin are associated in terms of nitrogen using arrows.

After drafting model structure, model equations were added or updated on the basis of the collected data. Two types of equations were used in this model: balance equations and model equations (Brunner and Rechberger, 2004). Model equations consisted of the certain and uncertain parameters. A stock change rate (budget) of