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Research article

Uncertainty analysis of primary water pollutant control in China's pulp and paper industry

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ABSTRACT

The total emission control target of water pollutants (e.g., COD and NH_4–N) for a certain industrial sector can be predicted and analysed using the popular technology-based bottom-up modelling. However, this methodology has obvious uncertainty regarding the attainment of mitigation targets. The primary uncertainty comes from macro-production, pollutant reduction roadmap, and technical parameters. This research takes the paper and pulp industry in China as an example, and builds 5 mitigation scenarios via different combinations of raw material structure, scale structure, procedure mitigation technology, and end-of-pipe treatment technology. Using the methodology of uncertainty analysis via Monte Carlo, random sampling was conducted over a hundred thousand times. According to key parameters, sensitive parameters that impact total emission control targets such as industrial output, technique structure, cleaner production technology, and end-of-pipe treatment technology are discussed in this article. It appears that scenario uncertainty has a larger influence on COD emission than NH_4–N, hence it is recommended that a looser total emission control target for COD is necessary to increase its feasibility and availability while maintaining the status quo of NH_4–N. Consequently, from uncertainty analysis, this research recognizes the sensitive products, techniques, and technologies affecting industrial water pollution.

1. Introduction

There are numerous factors influencing industrial pollutant emission. Significant uncertainty exists due to the combination of energy and environment variation, industrial macro-economic fluctuation, and technical system evolution. Firstly, changes in the direction, effort, and options of mitigation policies and regulations may bring political uncertainty. Secondly, in industrial macro-economic predictions, economic uncertainty in terms of sector scale and structure exists. Thirdly, the simulation of technical systems may cause technical parameter uncertainty. These three perspectives of uncertainty lead to different scenarios in the development of sectors, which may eventually impact the total amount control in water pollution abatement. Therefore, pollutant emission has a high sensitivity to parameters of different mitigation roadmaps such as macro-output, structure fluctuation, pollution prevention, and end-of-pipe treatment.

Regardless of the system, uncertainty is an inevitable factor for decision-makers to consider since knowledge gaps exist due to limited information (Chen et al., 2007). An explicit definition of uncertainty is described as the incapability of predicting and prescribing systems, behaviours, or characteristics since quantitative and qualitative information is ambiguous and inappropriate (Zimmermann, 2000). In present researches about uncertainty analysis in water pollution control, the main focus is on non-point source pollution control (Athanassoglou, 2010; Chen et al., 2007, 2014; Dong et al.; Gong et al., 2011; Khanna et al., 2000; Lacroix et al., 2005; Liu et al., 2012a, 2012b; Llopis-Albert et al., 2014; Peña-Haro et al., 2011; Shen et al., 2010, 2008; Tan et al., 2011; Vezzaro et al., 2012; Vezzaro and Mikkelsen, 2012; Zheng et al., 2014). Uncertainty analysis is generally used as a support for major modelling with different possibilities and a reference for policy-making. Uncertainties are taken as a major restriction for non-point source pollution control according to their origins, complexity, quantification approaches, and impact on management decisions and policies (Zheng et al., 2014). Some researches study the issues according to chance-constrained programming (Tan et al., 2011; Shen et al., 2008; Liu et al., 2012b; Dong et al., 2015; Peña-Haro et al., 2011). Some studies are also related to the cost-

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effectiveness of farm management in Europe with the consideration of climate variability (Lacroix et al., 2005), water environmental capacity (WEC) (Chen et al., 2014; Liu et al., 2012a), and different land use types (Shen et al., 2010). There is little research on industrial water pollution control (Peng et al., 2013; Yue et al., 2014; Zhao et al., 2009), and there is almost no research on the categories of uncertainty analysis on a concrete sector, which is the focus and innovation of this article.

Present Chinese researches (Du, 2006; Zhang, 2012; Zhang et al., 2012) on industrial energy saving and pollutant mitigation mainly focus on the conventional limited-scenario analysis, and skip the uncertainty analysis of parameters from the model and scenario building. This passage contributes to introducing uncertainty analysis into industrial water pollution control, recognising major uncertain factors via random sampling, and providing references for total pollution control planning and management.

The classification of uncertainty can be summarized differently according to the research targets. In the field of non-point source pollution, uncertainty is generally categorized into structural uncertainty, input data uncertainty, and parameter uncertainty (Beck, 1987; Hojberg and Refsgaard, 2005; Lindenschmidt et al., 2007; Shen et al., 2010, 2008). In stormwater quality modelling, there are two primary types of uncertainty from the input data, measurements and simplification of reality which related to the replication of pollution (Bertrand-Krajewski, 2007; Freni et al., 2008; Gaume et al., 1998; Haddad et al., 2013; Haydon and Deletic, 2009). Conclusively, uncertainty analysis in water quality management is generally classified quantitatively from parameter uncertainty (Scavia et al., 1981), model uncertainty (Reckhow, 1979) and natural randomness (Chen et al., 2007). Based on the classification above, this research categorizes the uncertainty analysis on industrial water pollutant control into macro-output, mitigation roadmap, and technical parameter uncertainty.

The pulp and paper industry, as an essential and fundamental industry of raw materials in the domestic economy, is an intensive sector in wastewater discharge in China (Zhang et al., 2012). According to data from the Ministry of Environmental Protection of PRC, in 2012, the wastewater discharge in the pulp and paper industry reached 3.43 billion tons, comprising of 16.9% of the total emission in key industries. COD and NH_4–N emissions were 623,000 tons and 84,000 tons, which accounted for 20.5% and 8.5% of the key industries' total emission respectively. It is predicted that Chinese consumption of paper will significantly increase in the next few years. Coordinated water pollution control is necessary for sustainability in economic and social development. Taking the paper and pulp industry as an example, this article aims at (1) analysing impacts of water pollutant control uncertainty on total COD and NH_4–N emission based on the mitigation targets; (2) recognizing sensitive products, techniques, and technologies via randomly sampling, sensitivity analysis, or nonparametric tests towards industrial key parameters; and (3) raising suggestions from the uncertainty analysis to increase the feasibility and practicality of mitigation targets.

This paper is structured in five sections. Following this introduction, section 2 provides the settings of basic data and scenario building. Section 3 presents an overview of uncertainty analysis and its application on water pollution control in the paper and pulp industry. Section 4 expresses the results of uncertainty analysis in terms of mitigation targets, and discusses the impact of sensitive factors on COD and NH_4–N mitigation in different scenarios. Section 5 summarizes the research and provides suggestions for total COD and NH_4–N control.

2. Material and methods

2.1. Methodology of calculating environmental impacts

2.1.1. Simulation of technology systems in pulp and paper industry

The pulp and paper industry involves various raw materials, production techniques (including production scales), and classifications with a complicated industrial structure. In this research, the simulation of technology systems in China's pulp and paper industry takes raw material-technique-scale-production as a unit, as shown in Fig. 1.

Meanwhile, 14 water pollution abatement technologies in the pulp and paper industry were selected based on a literature research. The cleaner production techniques include advanced alkali recovery, closed screening, dry and wet non-wood feedstock preparation and horizontal continuous cooking, elemental chlorine free bleaching (ECF), total chlorine free bleaching (TCF), oxygen delignification, high efficiency pulp washing, dry timber preparation, enzymatic deinking, white water close reuse and fibre recovery, super batch cooking, modification continuous cooking, floatation deinking for recycled pulp, and medium and high concentration pulping technology.

2.1.2. Calculation of environmental impacts

Environmental impacts in this research include calculating sector emission of water pollutants and energy consumption in the process of mitigation.

Annual recursive mechanism of generation and recharge coefficient was utilized in this research to figure out the total emission of water pollutants. According to the initial research of this study (Wen et al., 2015), in this methodology, the coefficients are decided by the coefficients in the previous year, and the improvement (expressed by technology promotion) of cleaner production technology and end-of-pipe technology, as shown in Eqs. (1)–(3).

$$G^{t+\Delta t}_{(m,i,s,a),p} = G^{t}_{(m,i,s,a),p} \cdot \prod_{ct \in SET^{ct}_{(m,i,s,a)}} \left(\frac{1 - \theta_{ct,(m,i,s,a),p} \cdot \beta^{t+\Delta t}_{ct,(m,i,s,a)}}{1 - \theta_{ct,(m,i,s,a),p} \cdot \beta^{t}_{ct,(m,i,s,a)}} \right) \tag{1}$$

$$E^{t}_{(m,i,s,a),p} = G^{t}_{(m,i,s,a),p} \cdot \left[\sum_{eop \in SET^{ct}_{(m,i,s,a)}} \gamma^{t}_{eop,(m,i,s,a)} \cdot \left(1 - \varphi_{eop,(m,i,s,a),p}\right) \right] \tag{2}$$

$$TE^{t}_{A,p} = \sum_{(m,i,s,a) \in SET^{(m,i,s,a)}_{A}} D^{t}_{(m,i,s,a)} \cdot E^{t}_{(m,i,s,a),p} \tag{3}$$

In Eq. (1), m, i, s, and a represent raw materials, production techniques, production scales, and outputs. The expression (m,i,s,a) stands for the combination of techniques. G illustrates generation coefficients of pollutant p. We generally set Δt to be one year. The end-of-pipe technology is shortened as *eop*. In the first two equalities, abatement rates are expressed as θ and φ, while the promotion rates are shown as β and γ. Eq. (3) outputs the total emission of pollutant p in sector A in time t.

The mitigation process may influence energy consumption while reducing pollution. Such consumption is estimated according