Journal of Cleaner Production 53 (2013) 13–21

Contents lists available at SciVerse ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Trace anthropogenic arsenic in Taiwan—substance flow analysis as a tool for environmental risk management

Pi-Cheng Chen, Hung-Jen Su, Hwong-Wen Ma*

Graduate Institute of Environmental Engineering, National Taiwan University, 71 Chou-Shan Road, Taipei 10673, Taiwan

ARTICLE INFO

Article history:
Received 29 December 2010
Received in revised form
16 August 2011
Accepted 25 October 2011
Available online 2 December 2011

Keywords:
Substance flow analysis
Health risk assessment
Anthropogenic arsenic
Industrial structure
Risk mapping

ABSTRACT

Site-specific risk assessment is intended for single source analysis, and provides limited options to reduce environmental risk. The links between multiple sources and population exposure deserve better understanding. In this way, the industrial activities can be managed to protect the population from the exposure to the substances in multiple environmental media, food, and drinking water. We took the anthropogenic arsenic in Taiwan into our case study. Substance flow analysis was used to map the circulation of arsenic in Taiwan. Emissions from arsenic related industries were modeled to estimate the health risk for each region. From the life cycle perspective, we found the major inputs were the imported ores and fossil fuels. The outputs would be a great concern to future arsenic exposure, because the use of arsenic-containing products is accumulating arsenic in wastes. Under current steady-state emission, the cancer risk in each region ranged from 10^{-6} to 10^{-3}. The regions of high risk co-exist with fired-power plants, oil refineries, or waste treatment facilities. Several risk reduction strategies were compared. More than 95% of risk could be reduced if all airborne emissions were eliminated. The proposed methodology that integrates substance flow analysis with exposure assessment and risk evaluation offers quick examination on more comprehensive risk reduction alternatives. Further dedicated risk assessment might be required to estimate the more precise risks for the areas or industries that were pre-identified as hot spots.

1. Introduction

Risk analysis and risk reduction are critical issues to sustain cleaner production processes. Different types of risks are of concern in the cleaner production. For example, investment on innovative manufacture or services increases the risk on the business management (Wu and Olson, 2008; Wu et al., 2011). The operation of advanced processes also exposes the workers to health risk in their workplaces. In addition, the environmental risk may arise from the release of hazardous substances. This study focused on the analysis and reduction of health risk caused by the exposure from the substance – arsenic, which can be found emitted from wide variety of industrial processes.

Environmental risk analysis (ERA) has been well developed for site-specific assessment, by which decision maker can approach risk reduction by controlling the emission from specific sources, managing specific environmental media which transport or accumulate arsenic, and avoiding specific pathways through which the population is exposed to arsenic. Recently, increasing concern is about accumulated risk from multiple sources, and additive adverse effects due to the exposure from diverse pathways. The scope of environmental risk assessment would be better extended from single facility to the supply chains associated with hazard substance operation. Therefore, the influence of industrial activities on environmental risk can be better addressed.

In our economy, industries produce products to supply the demand. Some supply chains of arsenic-related products or services are very likely to discharge arsenic, in the forms of air emission, effluent, or waste. Take arsenic for example. Risk of arsenic was attributed to several industrial activities, such as burning of fossil fuel, metal refinery, manufacture of products containing arsenics, and the use of chemicals with arsenic compounds as constituent. In Taiwan, arsenic caused a well-known epidemic incident on the southwest coast. A population of around 140,000 utilizing groundwater containing geogenic arsenic was attacked by black foot disease (Chen et al., 1994). The geogenic arsenic exposure due to the use of groundwater contaminated has been well controlled. However, the industrial sources was found threatened the

* Corresponding author. Graduate Institute of Environmental Engineering, National Taiwan University, 71 Chou-Shan Road, Rm. 314, Taipei 10673, Taiwan. Tel.: +886 2 23630406; fax: +886 2 23928830.
E-mail address: hwma@ntu.edu.tw (H.-W. Ma).

0959-6526/$ – see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jclepro.2011.10.041

population in the cases around the world, such as emissions from manufacturing of insecticide and pharmaceuticals (Thomson, 1979; Sekhar et al., 2003), burning arsenic-contaminated coal (Pacyna, 1987; Matschullat, 2000), producing arsenic sulfide (Terado et al., 1960), and copper smelting (Ayres and Ayres, 1999). The arsenic flow of society was first surveyed in Sweden (Lindau, 1977). He investigated the drivers that added arsenic to the economy, and the arsenic output due to exporting or deposition in the environment. Their results recognized that the major arsenic flow embedded in copper and lead smelting dominated arsenic emission to environmental air and water. In Taiwan, the booming industries of electronics and computers adopted arsenic in their processes. Notably, the semiconductor, photo-electronic industries, and metal related factory have been found to release arsenic into the environment (Chen, 2006; Wang et al., 2007). With the risk of widespread arsenic sources, we need a systematic tool to monitor the potential exposure due to economic activities. The information regarding exposure must be holistic and explicit so that risk managers and chemical control authorities can work together to protect the public's health. However, current practice of site-specific risk assessment was incapable to support the management of risk from multiple sources, to which the perspective of supply chain and industrial structure offer better insight.

The main goal of our research is to construct a comprehensive picture of health risk due to total emissions. We'd like to enhance the methodology of environmental risk assessment in order to highlight the industrial activities of high emission and contributing to significant health risk. The subsequent management measures can then focus on the hot spot of emission, and examine the effects of the scenarios on health risk reduction. The relationship of processes in the supply chain can be identified. We took arsenic in Taiwan as an example; the proposed methodology framework may also apply to other toxic substances.

The solution suggested is to implement risk assessment base on substance flow analysis (SFA). Substance flow analysis (SFA) is a systems analysis tool modeling the flows of compounds or element throughout the economy and the environment (Brunner and Ma, 2009). SFA can inform the national emission inventory by identifying possible missing flows. All important processes involving a given substance should be considered, and thus SFA facilitates assessment of the cumulative risk from multiple sources. For example, after a survey on arsenic flow, the U.S. EPA found potential risk of arsenic exposure from preserved wood furniture, which was treated with chromated copper arsenate (CCA). Finally, the use of CCA in furniture industry was banned. Based on the mass balance rule, the SFA models the economy as a system containing many processes with input and output flows. These physical flows include importing and exporting of substances, flows in the supply chains, and the flows between the economy and the environment. On one hand, arsenic is extracted from the earth along with metal ores and fossil fuels. On the other hand, arsenic returns to the environment through airborne emission, effluence into bodies of water, and landfills. Some studies also use SFA to survey the overall emission of heavy metals like cadmium (Kwonpongsagoon et al., 2007a, b; Månsson et al., 2009), chromium (Hoffmann et al., 2003; Ma et al., 2007), and lead (Tukker et al., 2006). SFA has been widely applied to estimate the annual discharge of toxic substances into the environment (Hansen and Lassen, 2002; Danish EPA, 2004; Mao et al., 2008; Månsson et al., 2009). Some have noted the potential for SFA to assist environmental risk assessment (Guinee et al., 1999; Kwonpongsagoon et al., 2003; Tukker et al., 2006; Morf et al., 2008).

The other way is to correlate emissions with industrial structure by input–output analysis. Various studies have undertaken emission estimation and impact assessment based on the monetary output of specific industries (Suh, 2009). They assumed that the industrial emission increases in proportion to the increment of capitalized output of product or services. The environmental input–output (EIO) model developed by Leontief (1970) is the prototype of these applications. A number of projects have used EIO-based modeling to predict the emissions variation with economic structure change. A number of case studies applied this method to SO_x, NO_x, PM, and other substances (Nijdam et al., 2005; Hendrickson et al., 2006; Hawkins et al., 2007). Currently, some research attempted to model the health impact with economic model. A risk-based approach to health assessment, to assist policymaking, has also been developed on EIO model (Nishioka et al., 2005). Wright et al. (2008) performed a screening-level risk analysis by integrating economic input–output and life cycle assessment and using equivalent of toluene as indicator of relative risk. To disaggregate the regional emissions from national emissions, the multi-region input–output model (MRIO) has been developed (McGregor, et al., 2008; Peters, 2008; Tukker et al., 2009). In this case study, we also adopted the assumption of MRIO for regional emission estimation.

Risk analysis and risk reduction can benefit from the model which enables comparison of scenarios with different risk management measures. Wu and Olson (2009) emphasized the benefit of risk modeling can for risk control, especially the optimization of risk management. Our model combining SFA and risk assessment has two advantages. First, the SFA screening of the most relevant sources enriched the spectrum of risk reduction solutions, e.g., better emission control, waste management, and changing an industrial structure. Second, we estimated the risk in hazard quotients (HQ) and carcinogenic risks which are end-point indicators, rather than the mid-point indicator "relative risk" which was used in most SFA related health impact studies. The areas of higher risk of arsenic can be identified.

2. Materials and methods

2.1. Substance flow analysis

Bouman et al. (2000) specified, "SFA is used to identify the causes of specific pollution problem in the economy and find possibilities for amending or preventing". Following the general procedure of SFA, our implementation involved the following steps: (1) goal and scoping, (2) inventory and modeling (3) interpretation (Hansen and Lassen, 2002). In order to analyze risk in an economy, the spatial boundary was Taiwan. We considered the annual flows in year 2008.

The integration of SFA to risk assessment was implemented in the step of inventory and modeling in following steps:

1. Identify the processes with arsenic input/outputs and the commodity containing arsenic.
2. Link the processes with the substance flows according to the supply chain or life cycle information.
3. Collect the data of commodity flows with corresponding arsenic contents
4. Create the substance flow models and flow charts.
5. Disaggregate the emissions of national flow into regional emissions.
6. Analyze regional risk with local emissions, exposure scenarios, and landscape properties.

We presented the static arsenic flow model in two forms. The first model is a production network which specifies several supply chains of arsenic related products. In principle, the flows associated with a process are categorized as import, export,