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Original Articles

Study of integrated risk regionalisation method for soil contamination in industrial and mining area

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ABSTRACT

Industrial and mining areas have been included as key governance plots of China's soil management and protection. In this study, we developed an assessment method for soil integrated risk in industrial and mining areas, with a comprehensive consideration of pollution risk, pollution sources and receptors of soil risk. The method consists of four parts, including soil risk assessment, vulnerability assessment of soil risk receptors, risk level assessment of pollution sources and integrated risk assessment. Using this method, we could produce a complete soil risk regionalisation map that presents the total factor risk level of soil contamination of industrial and mining areas in ArcGIS. This study also took a typical industrial and mining area in China as a case and quantitatively and spatially assessed the integrated soil contamination risk. Results showed: (1) the integrated risk of the study area ranged from moderate level to high level; (2) the risk of pollution sources in the study area ranged from moderate level to high level; (3) vulnerability of soil risk receptors in streets was lower than that in the towns.

1. Introduction

Soil contamination in China has caused wide concern (Chen et al., 2015; Shen, 2015; Brombal et al., 2015). Because of high-intensity development of land resources and high-speed of economic development in past decades, soil contamination has been gradually emerging in China (Lin, 2014; Lu et al., 2015). In recent years, soil quality of China that is mainly measured by the concentration level of soil contaminants has been deteriorating. The over-standard rate of soils pollution for industrial and mining area has been more than 30%. Among which, the over-standard rates of lands contamination for industrial and mining enterprises, industrial wasteland and mining areaswere are 36.3%, 34.9% and 33.4%, respectively (Lu et al., 2014; Wang et al., 2014). Obviously, soil contamination in industrial and mining areas was particularly serious and has caused huge threats and harm. Protection of ecological security and improvement of soil quality are China's current and long-term major concerns. As key objective of China's soil management, a good understanding of the spatial characteristics of soil contamination risks in industrial and mining areas is desirable.

Soil contamination risk generally refers to the harmful effects to ecosystem and human health caused by soil contaminants from various sources. Soil contaminants, pollution sources and receptors of soil contamination risk are the main elements of soil contamination risk. Risk assessment is currently an important soil management method (Li et al., 2014; Karim and Qureshi, 2014; Suter, 2016; Haimes, 2015). Moreover, risk regionalisation, which can effectively reveal the spatial features and evaluate the grade and influence range of soil contamination risk, has also been used in soil management (Fell et al., 2008; Guan et al., 2014). However, a soil contamination risk regionalisation method has not been established for industrial and mining areas. Industrial and mining lands, residential areas, towns and agricultural lands scattered within industrial and mining areas. This, coupled with pollution sources and pollutant emission, makes the soil pollution situation serious and complicated. Pollution sources, soil pollution and soil risk receptors in different types of land should be comprehensively considered (Guan et al., 2016). Therefore, an exploration of spatial risk assessment is essential to provide a scientific basis and support for soil management in industrial and mining areas.

Previous work on removing soil pollution caused by industrial and mining activities has studied grading evaluation criteria, spatial distribution of contaminants and specific cases in different regions of China. Since the 1990s, China began to promulgate soil quality standards applicable to specific types of land use, then in 1996, China

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developed *Environmental Quality Standard for Soils*. Li (2015) and Shen and Teng (2015) reaffirmed the importance of soil safety and pointed out the basic ideas of soil management over the medium and long term, including pollution prevention legislation and risk management. Moreover, Li et al. (2014) summarised available data in literature (2005–2012) on heavy metal polluted soils originating from mining areas in China. The authors also comprehensively investigated soil heavy metal pollution derived from mines by evaluating soil pollution levels and quantifying human health risks. Many studies have chosen typical mining and industrial areas across China as examples, using evaluation methods such as assessment of pollution levels and ecological or health risks. These studies analysed the contamination and risk levels of contaminants as well as possible sources of pollution. Heavy metals are major contaminants with serious risk to human health (Wang et al., 2010; Luo et al., 2011; Wei et al., 2009; Zhang et al., 2009; Li et al., 2014; Song et al., 2015a,b; Briki et al., 2015). In addition, important information on mobility (Mackay et al., 2013), combined pollution (Shen et al., 2005; Pinedo et al., 2013), spatial distribution and risk assessment (Li et al., 2006; Bai et al., 2011; Guan et al., 2014, 2015) have also been provided.

The primary risk assessment methods in previous studies were mainly pollution risk assessment. The frequently used risk regionalisation characterises the intensity and spatial distribution of soil contamination risks and is based on contents and spatial distribution of soil contaminants. However, the status of soil contamination risk receptors and pollution sources has not been systematically introduced in risk regionalisation methods. Obviously, features of receptors such as the type, spatial distribution and vulnerability of receptors can reflect the risk tolerance of social community to soil contamination (Zhao et al., 2012; Chen et al., 2013). Moreover, sewage irrigation of pollutants generated by industrial and mining pollution sources is the main contributors to soil pollution in industrial and mining areas, which means that industrial and mining pollution sources should also be introduced in an integrated assessment of soil contamination risk (Liu et al., 2016).

In this study, we developed a method to evaluate and regionalise the integrated soil contamination risk in industrial and mining area. The method considered soil pollution risk, risk of pollution sources and vulnerability of risk receptors. Additionally, we developed an integrated soil environment risk assessment method for industrial and mining areas based on soil risk assessment, vulnerability assessment of soil risk receptors and risk assessment of pollution sources. Finally, this paper used a typical industrial and mining area in Binhai New Area, Tianjin, China, as a case study to explore the application of the method.

2. Methodology

2.1. Research framework

In this section, we describe our evaluation method, which consists of integrated risk assessment and integrated risk regionalisation for soil contamination. The methodological framework of this study is shown in Fig. 1.

2.2. Integrated risk assessment

2.2.1. Risk assessment of soil contamination

Industrial and mining areas are regions of dense human activities. Therefore, human safety is a primary consideration in risk assessment of soil contamination. Adverse effects of soil contaminants on human health in typical industrial and mining area should be assessed to comprehend the risks of soils in these areas.

By characterising the human health effects of soil pollution, human health risk assessment could reflect the impact of contaminants on human health. Generally, human health risks from soil pollution can be reflected as carcinogenic and non-carcinogenic risks.The four-step framework proposed by U.S. Environmental Protection Agency (EPA) is a widely used human health assessment method (U. S. EPA, 2004, 2008, 2014). This method evaluates human health risks from soil pollution in four steps: hazard identification, exposure assessment, dose-response assessment and risk characterisation. China's official guide for soil contamination risk assessment, *Technical Guidelines for Risk Assessment of Contaminated Sites* HJ25.3-2014(abbreviated as*Guideline* below), used the basic framework of this four-step method and developed equations and calculation methods based on China's soil pollution characteristics. In this study, we take the various types of land use in industrial and mining areas and their applicability in China into account, selected the evaluation method framework and risk calculation equations of *Guideline*. Moreover, due to the fact that the *Guideline* cannot be applied to agricultural land, this study introduced and improved MMSOILS model to solve the problem, with specific equations provided below. Finally, in order to facilitate the calculation and regionalisation of comprehensive risk, this section only counts carcinogenic risk from heavy metal contaminants.

Exposure assessment is the core process of human health risk assessment. In this study, we divide industrial and mining area land use types into sensitive, non-sensitive and agricultural lands. According to *Guideline*, sensitive lands refer to areas with dense human activity, such as residential areas, malls, hospitals and schools. Non-sensitive lands refer to areas with strong functional properties, such asindustrial areas, storage spaces and facilities sites. Agricultural lands refer to farmlands, orchards, breeding bases, etc. The calculations and land use selection are done for sampling units. The land use types could be directly determined according to the surrounding environment and the sampling point where the land use nature during the sampling process. The exposure assessment models are as follows:

(1) Sensitive land

In sensitive lands, we consider three routes of exposure, including oral ingestion, skin contact and inhalation.

Oral ingestion:

$$OI_{ca} = \frac{ABS_o}{AT_{ca}} \times \left(\frac{OIR_c \times ED_c \times EF_c}{BW_c} + \frac{OIR_a \times ED_a \times EF_a}{BW_a}\right) \times 10^{-6} \tag{1}$$

Skin contact:

$$SKI_{ca} = \frac{ABS_{sk} \times E_v}{AT_{ca}} \times \left(\frac{SEA_c \times SSF_c \times EF_c \times ED_c}{BW_c} + \frac{SEA_a \times SSF_a \times EF_a \times ED_a}{BW_a}\right) \times 10^{-6} \tag{2}$$

$$SEA_c = 239 \times H_c^{0.417} \times BW_c^{0.517} \times SEAR_c \tag{3}$$

$$SEA_a = 239 \times H_a^{0.417} \times BW_a^{0.517} \times SEAR_a \tag{4}$$

Inhalation:

$$BRI_{ca} = \frac{PM_{10} \times BRR_c \times ED_c \times PR \times (fspo \times EFO_c + fspi \times EFI_c)}{BW_c \times AT_{ca}} \times 10^{-6} + \frac{PM_{10} \times BRR_a \times ED_a \times PR \times (fspo \times EFO_a + fspi \times EFI_a)}{BW_a \times AT_{ca}} \times 10^{-6} \tag{5}$$

(2) Non-sensitive land

In non-sensitive lands, we consider three routes of exposure, including oral ingestion, skin contact and inhalation.

Oral ingestion:

$$OI_{ca} = \frac{ABS_o \times OIR_a \times ED_a \times EF_a}{AT_{ca} \times BW_a} \times 10^{-6} \tag{6}$$

Skin contact:

$$SKI_{ca} = \frac{ABS_{sk} \times E_v \times SEA_a \times SSF_a \times EF_a \times ED_a}{AT_{ca} \times BW_a} \times 10^{-6} \tag{7}$$

Inhalation: