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A Fuzzy-based Methodology for an Aggregative Environmental Risk Assessment of Restored Soil[*1]

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ABSTRACT

Environmental risks pertaining to contaminated soils have been well studied, while little attention has been paid to the risks of the soils after remediation. In this study, a concept model developed based on fuzzy set theory was applied to evaluate the uncertainties of three risk indicators, namely, plant growth, groundwater safety and human health, of a restored site that had been previously polluted by heavy metals. The concept model classified the grade and importance of risk factors by an 11-level ranking system and was able to yield a comprehensive risk result rather than multi-risk results for complex risk indicators. Modeling results showed that the risks to the three indicators were effectively reduced after the remediation. Moreover, great sensitivity of the risks was found related to the weight distribution among the three risk indicators. In general, the risks of both polluted and restored soils to the environment were in the order of groundwater safety > plant growth > human health. The model was proved to solve the problems of multi-risk results due to complex risk indicators that previously encountered by other researchers, which made it helpful in decision-making and management of restored soils.

Key Words: fuzzy set theory, heavy metals, remediated, risk assessment, weight distribution

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INTRODUCTION

Heavy metal pollution in soils has not only severely affected the growth and quality of crops but also endangered human health through either direct contact or food chain (Shomar *et al.*, 2005). Thus, the remediation of heavy metal-contaminated soils has drawn an intensive attention worldwide in recent years. Treatments of heavy metal-contaminated soils rely on a set of technologies, which have already been developed and applied at field scale (USEPA, 1995a). Current remediation technologies, exemplified especially by chemical remediation process (Zhang *et al.*, 2012; 2013), have been proved practically efficient in soil restoration. However, since these technologies could not guarantee a thorough removal of heavy metals from polluted soils, the risk of restored soils to the environment might unexpectedly increase in some ways. For example, metal extraction processes using various chelating agents may cause secondary effects (Peters, 1999; Neilson *et al.*, 2003) by: 1) changing the speciation of heavy metals in soil (Sun *et al.*, 2001; Tsang *et al.*, 2007), 2) increasing the mobility of heavy metals (Barona *et al.*, 2001), 3) losing essential nutrients (*e.g.*, Ca, Mg, and K) with the leaching of heavy metals (Di Palma and Ferrantelli, 2005), and 4) leading to overcompaction, water logging and insufficient aeration by inadequate remediation procedures (Kaufmann *et al.*, 2009). Therefore, the physicochemical properties in restored soils may become more unsteady, which makes the risk assessment process complicated.

Up to date, most attention has been paid to the environmental risk of polluted soils but very limited to restored soils. According to the general risk assessment process of polluted soils, the risk indicators considered in a risk evaluation of restored soil include plant growth, groundwater safety and human health. Nowadays, numerous approaches have been used to estimate the mobile, labile, or bioavailable pools of heavy metals in soil. For example, batch extractions are capable in

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estimating the risk of heavy metal leakage to plant or groundwater. The toxicity characteristics leaching procedure (TCLP) and synthetic precipitation leaching procedure (SPLP) have been used to test the potential leachability of contaminants to groundwater (USEPA, 1995b), as well as to make quick evaluations of restored soils due to their normative comparability (Peters, 1999; Lee *et al.*, 2004; Udovic and Lestan, 2007). Meanwhile, methods such as the isotope exchange kinetics (IEK) method and the diffusive gradients in thin films (DGT) technique could help to determine the phytoavailability of heavy metals in soils (Gérard *et al.*, 2000; Zhang *et al.*, 2001). The European Community Bureau of Reference (BCR) sequential extraction procedure could be used to evaluate plant safety due to the significant correlation between exchangeable fraction and plant uptake of heavy metals (Davidson *et al.*, 1998; Pueyo *et al.*, 2003). Furthermore, a wide variety of models of risk-based corrective action (RBCA), contaminated land exposure assessment (CLEA), and framework for metals risk assessment from the United States Environmental Protection Agency (USEPA) have been employed to evaluate the risk of heavy metals to human health (Voegelin *et al.*, 2003; Fryer *et al.*, 2006; Fairbrother *et al.*, 2007). Specifically, the RBCA is a tiered and analytic framework for conducting risk-based corrective actions for contaminated sites based on protecting human health (ASTM, 2000) and is widely used in USA and Europe. It divides various chemicals into carcinogenic and non-carcinogenic materials, and takes direct ingestion (eating or drinking), skin absorption and breathing as three pathways through which human contact with the polluted soil.

The environmental risk of restored soils is a fuzzy problem because general ways such as pollution index methods and chemical extraction methods could neither describe the fuzziness nor make a comprehensive assessment of all the protective targets (risk indicators). In classification schemes, fuzziness makes it difficult to justify the use of sharp boundaries (Li *et al.*, 2008). Moreover, the closed structure of the traditional assessment methods is hard to bridge the gaps between different risk indicators. Zadeh (1965) developed a fuzzy set theory from the typical set for analyzing the uncertain and fuzzy problems, which has the ability to deal with highly variable, linguistic, vague and uncertain data or knowledge and hence allow for a logical, reliable and transparent information stream from data collection to data usage in environmental application (Adriaenssens *et al.*, 2004). In the past few decades, the fuzziness in the environment has led some environmental researchers to investigate advanced assessment methods based on the fuzzy set theory. More recently, the fuzzy set theory is widely used in land classification, crop yield forecast, drilling waste risk assessment, soil mapping, soil pollution evaluation and soil erosion modeling (Zhu *et al.*, 2001; Shi *et al.*, 2004; Sadiq and Husain, 2005; Genske and Heinrich, 2009).

A fuzzy comprehensive assessment model, as one of the methods based on the fuzzy set theory for the aggregated risk evaluation, is also widely used in environmental researches and has been proved more effective in dealing with the fuzzy characteristic of risks and could lead to a few comprehensive remarks (Sadiq *et al.*, 2007). The main endeavor in the present study was to extend the application of the fuzzy comprehensive assessment into the evaluation of the heavy metal-contaminated soil remediated by chemical washing process. Theoretically, the risk of this kind of soil should decrease after remediation, since a certain portion of heavy metals have been removed. However, the speciation changes of residual metals, *e.g.*, the increased ratio of exchangeable metal content to total metal content, might pose a higher risk to the environment than expected. Due to such uncertainties, special endeavor was made to more precisely describe the risks to different risk indicators by both experimental and modeling means.

In the present study, a comprehensive assessment model based on the fuzzy set theory was developed and applied to evaluate the risks of the restored soil, as well as the polluted one, derived from an *ex-situ* chemical remediation site. In the site where an electroplating factory was previously located, a demonstration project was designed and built to treat the soil which has been seriously polluted by heavy metals Cr, Cu, Ni, Pb and Zn. The polluted soil was remediated by soil washing with low concentrations of ethylene diamine tetraacetic acid (EDTA) salts (Zou *et al.*, 2009), and the combination of Na_2EDTA and oxalate (Qiu *et al.*, 2010) to remove both cationic and anionic heavy metals in the soil. After the remediation, the site will be used as a public gathering venue for local residents and consequently its potential environmental risk should be clarified. Thus, the aim of this study was to make a comprehensive risk assessment to plant growth, groundwater safety and human health by the fuzzy-based model, in which the total content, bioavailability, mobility and toxicity of heavy metals were taken into consideration according to the characteristics of the restored site.