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Sustainability likelihood of remediation options for metal-contaminated soil/sediment

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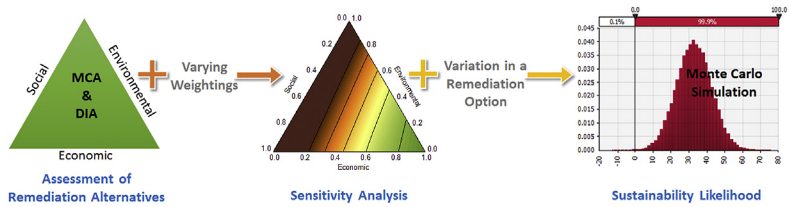
HIGHLIGHTS

- Remediation sustainability depends on site conditions and stakeholder preferences.
- Monte Carlo simulation reveals the uncertainty in sustainability scores.
- *In-situ* remediation generates the highest sustainability probability.
- Both deterministic and stochastic assessments assist decision-making process.

GRAPHICAL ABSTRACT



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ABSTRACT

Multi-criteria analysis and detailed impact analysis were carried out to assess the sustainability of four remedial alternatives for metal-contaminated soil/sediment at former timber treatment sites and harbour sediment with different scales. The sustainability was evaluated in the aspects of human health and safety, environment, stakeholder concern, and land use, under four different scenarios with varying weighting factors. The Monte Carlo simulation was performed to reveal the likelihood of accomplishing sustainable remediation with different treatment options at different sites. The results showed that *in-situ* remedial technologies were more sustainable than *ex-situ* ones, where *in-situ* containment demonstrated both the most sustainable result and the highest probability to achieve sustainability amongst the four remedial alternatives in this study, reflecting the lesser extent of off-site and on-site impacts. Concerns associated with *ex-situ* options were adverse impacts tied to all four aspects and caused by excavation, extraction, and off-site disposal. The results of this study suggested the importance of considering the uncertainties resulting from the remedial options (i.e., stochastic analysis) in addition to the overall sustainability scores (i.e., deterministic analysis). The developed framework and model simulation could serve as an assessment for the sustainability likelihood of remedial options to ensure sustainable remediation of contaminated sites.

1. Introduction

Remediation of contaminated soils and sediments has been a widespread practice in recent decades as a result of

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industrialization. When selecting suitable remedial actions for contaminated sites, previous studies showed particular concerns regarding removal efficiency, effectiveness with time (Al-Tabbaa and Boes, 2002; Rajapaksha et al., 2016), regulatory requirements (Hou et al., 2014b; Wang et al., 2015), cost effectiveness, and timescale of the projects (Apitz and White, 2003; Hou et al., 2014c). In recent years, the concept of sustainable remediation has drawn increasing attention from the regulators, land developers, construction industry, and scientific community (Kim et al., 2013, 2014; Hou et al., 2014e). The measure of sustainability has often been included as one of the decision-making criteria, aiming at maximizing the ultimate benefits from environmental, social, and economic aspects (Bardos et al., 2011; Petruzzi, 2011; Hou et al., 2014c).

Life cycle assessment (LCA) has been intensively adopted to assess the sustainability of remediation process (Lemming et al., 2010; Hong and Li, 2012; Owsianiak et al., 2013), which can capture most impact due to the material and energy flow during the operation of the treatment processes, known as secondary impact. Such impact could adversely influence the sites and surrounding environments, and communities even though the remediation processes could remove the target contaminants and achieve the remedial goals (Bonano et al., 2000; Burger, 2008; Holland, 2011). Meanwhile, LCA lacks the examination of the impact resulting from the use of the remediated site, i.e., tertiary impact, which has significant influence on the outcome of sustainability (Lemming et al., 2010, 2012). The negligence of the tertiary impact may result in negative environmental scores in the assessment, as subsequent utilization of the remediated sites may offset the adverse environmental impact caused by remediation process (Morais and Delerue-Matos, 2010; Hou et al., 2014e).

Moreover, various stakeholders such as regulatory authorities, surrounding communities, landowner, industry, and academia may have different interests and perspectives towards sustainable remediation, which can increase the uncertainty level in environmental measurements and predictions (Balasubramaniam and Voulvoulis, 2005; Hou, 2016). For example, stakeholders can impose significant promoting or impeding forces towards sustainability measures, although they may not show direct effect on the sustainability (Khanna and Anton, 2002; Hou et al., 2014a). Besides, the importance of environmental problems and the sustainability of remedial approaches can be subject to spatial variation with respect to location and scale of remediation. Morgenstern et al. (2000) reported that hazardous waste sites in the U.S. are viewed as a high health risk problem while they are ranked as low concern in some countries such as Ecuador and Thailand. In a study of remediation technologies for chlorinated solvents, site-specific hydrogeological properties and plume dimensions also show profound effect on the life cycle impact (Hou et al., 2014d).

Multi-criteria analysis (MCA) is considered to be an appropriate tool to aid environmental decision-making process, which can incorporate site information as one of the criteria and take preference of stakeholders into account through (sub-)category weighting (Balasubramaniam and Voulvoulis, 2005; Linkov et al., 2006; Balasubramaniam et al., 2007). Due to the unavoidable subjectivity associated with the use of a single set of weighting, varying distributions of weightings according to different scenarios may be used, which can evaluate the sensitivity of the remedial alternatives (Bridges et al., 2006; Alvarez-Guerra et al., 2009). Another advantage of MCA is its applicability for both qualitative and quantitative data (Balasubramaniam and Voulvoulis, 2005), yet the robustness of relying on a single assessment tool may still be questioned (Yatsalo et al., 2007). Therefore, an integrated analysis is recommended to address the uncertainty in criteria values such as scoring and weighting (Balasubramaniam et al., 2007; Kiker et al., 2008).

In this study, we employed MCA and detailed impact analysis (DIA) to quantitatively assess the impact of four remedial options for four contaminated sites, and evaluated the remedial sustainability with an emphasis on the significance of variations in stakeholders' preference. Monte Carlo simulation and sensitivity analysis were used to account for the uncertainty in the likelihood of achieving sustainable remediation under different scenarios. Among the four sites, three were former timber treatment sites or farmland contaminated with heavy metals and chlorinated organics, while the other site was a port with sediment contaminated with heavy metals and hydrocarbons.

2. Methodology

2.1. Site characterization

Four contaminated sites located in New Zealand were selected for investigation. Barrow Box site in Tapanui (45°55′ S, 169°15′ E) is a former sawmill site, where the estimated volume of contaminated soil was over 1600 m^3. Craigpine site in Christchurch (46°08′ S, 168°19′ E) is also a former timber treatment site containing more than 1000 m^3 of contaminated soil. These two sites were contaminated by chromated copper arsenate (CCA) preservatives, pentachlorophenol (PCP), and boron due to historical reason. Wharewaka site in Taupo (38°43′ S, 176°04′ E) was used as a farmland (about 100 m^3 of contaminated soil) as well as an unofficial disposal site for hazardous waste afterwards. Arsenic derived from CCA was detected in the site area, while copper and zinc existed as treatment for sheep foot rot. The Lyttelton Port in Christchurch (43°36′ S, 172°42′ E) has been in operation since 1849, where over 10,000 m^3 of the harbour sediment were contaminated with lead, zinc, copper, mercury, tributyltin (TBT), and total petroleum hydrocarbon (TPH). Detailed site features for further assessments are shown in the Supplementary Information (Table S1).

2.2. Remediation options

Possible remediation options were proposed for sustainability assessment via the preliminary screening based on our previous experimental studies (Tsang et al., 2013; Tsang and Yip, 2014; Wang et al., 2015) and discussion with industrial practitioners. Four available remediation options: (i) *in-situ* containment, (ii) *ex-situ* soil washing, (iii) *ex-situ* stabilization/solidification, and (iv) off-site landfill disposal were examined on each of the four contaminated sites in terms of technical and environmental sustainability via a comparative assessment. Fig. 1 illustrates the breakdown of various treatment options for further analyses. Option 1 involves capping the contaminated soil or sediment with a relatively impermeable

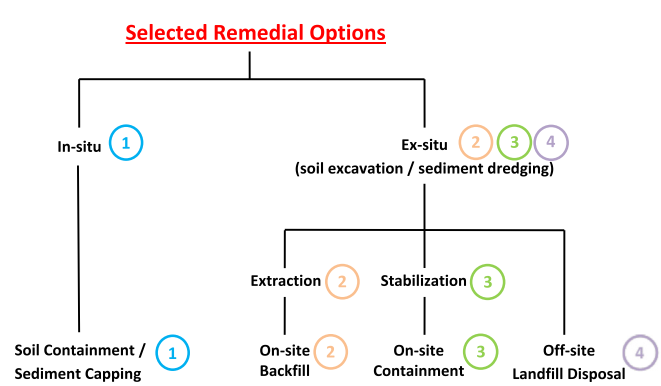

Fig. 1. Treatment options for contaminated land remediation at the concerned sites.