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Green and Sustainable Remediation: Concept and Application

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Abstract. Contaminated soil, sediment and groundwater are one of the major environmental problems faced by U.S. and many other countries across the world. The U.S. Environmental Protection Agency (USEPA) has identified several tens of thousands of contaminated sites that need remediation, many of which are on the national priority list requiring urgent remediation. Over the years, several in-situ and ex-situ remediation technologies have been developed to remediate contaminated soil and groundwater. However, in current practice for the remediation of contaminated sites, the choice of remediation technology at a site is solely based on the potential of the technology to reduce the concentrations to the targeted risk-based levels, cost, time and ease of implementation of the remediation technology at the contaminated site. In this regard, there is often no heed towards quantifying the energy and the resources expended, the air emissions, and other waste streams generated as a result of the remediation activities. Therefore, the broader environmental impacts from the remediation of a contaminated site remain unaddressed. In this study an overview of the concept of green and sustainable remediation is presented. A new framework for quantitative assessment of life cycle sustainability is presented in the context of environmental remediation. Finally, the application of the framework is demonstrated by three case studies pertaining to the remediation of soil, sediment and groundwater.

Keywords. Green and sustainable remediation; life cycle assessment; MIVES methodology; analytic hierarchy process; multi-criteria decision analysis.

1. Introduction

Ever since the industrial revolution, the uncontrolled disposal of wastes and associated environmental pollution including land and groundwater contamination has been a major problem in the U.S. and many other countries. Realizing the significant harmful impacts to the human health and the environment from several landmark events that occurred over the years led to the establishment of strict environmental laws and regulations in the 1970s. Despite these efforts, the problem of soil and groundwater contamination is a serious concern across the world persisting today. In this regard, several remediation technologies ranging from ex-situ to in-situ remediation methods have been developed over the years based on their suitability to different site characteristics including

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contaminated media (e.g. soil, groundwater, sediments), type of contaminants (e.g. heavy metals, organic compounds), extent of contamination (e.g. surficial, sub surficial, deep) and other site characteristics [1]. Moreover, several innovative remediation technologies are being developed and tested for their effectiveness in laboratory and field investigations [2].

The traditional approach for contaminated site remediation is focused mainly on reducing the concentrations of the contaminants of concern to the risk-based remedial goals. In this regard, the choice of the remediation technology to be used at a contaminated site is often based on cost of implementation and remediation timeframe. This approach may seem to solve the apparent problem of contamination at the site, however, the broader environmental impacts from the energy and resource intensive activities during different stages of remediation project often goes unaccounted. For example, the emission of greenhouse gases and other air pollutants from the use of equipment/machinery and transportation of materials used and disposed during remediation activities are not generally addressed in the selection of remedial technologies or strategies. The remediation activities may induce changes in the land which may positively benefit or negatively impact the residents and the community around the site however these local net environmental benefits of contaminated site remediation are rarely considered. Thus, there is a need for a holistic approach to evaluate the net environmental, economic and social impacts from site remediation and identify the most sustainable strategy to clean up a contaminated site.

The concept of "Green and Sustainable Remediation (GSR)" has gained significant momentum in support of addressing the grand challenges (e.g. population explosion, global climate change) faced by today's world. In a functional sense, GSR entails that the primary goal of reducing the contaminant concentrations to targeted risk-based levels to protect the human health and environment be met while foreseeing and minimizing the potential negative environmental, economic and social impacts that may arise from the various activities involved in a remediation project [2]. Several qualitative, semi-quantitative and quantitative tools have been developed by federal agencies as well as private organizations to aid in selecting a technically suitable and a sustainable remediation technology out of several different potential remedial alternatives [2,3]. Most of the published tools and frameworks mainly emphasize evaluating the environmental aspects of remediation while a few others include environmental and economic impacts of remediation. The quantification of economic and social aspects associated with site remediation is difficult and so there is still a lack of tools that can perform a full quantitative sustainability evaluation. In this study a new framework for quantitative assessment of life cycle sustainability (QUALICS) is presented. The methodology involved in the sustainability evaluation and decision-making process is described briefly. The applicability of the QUALICS framework for identifying the most sustainable remediation option at a contaminated site is discussed using three case studies.

2. Green and sustainable remediation

The concept of GSR addresses environmental contamination in a way that provides the best net overall benefit to the project with respect to environmental, economic and social dimensions of sustainability. The "greenness" of the remediation efforts is accomplished through minimization of use of materials and energy, preservation of natural resources, minimization of waste generation and by-products, and maximization of future reuse options of the specific site addressed by the remediation program. Further, the "sustainable" remediation aspects should incorporate the broader economic and social impacts of the remediation efforts during the project life cycle. This may include minimization of the project costs by using recycled/waste materials, using bio-based technologies (wherever feasible), and minimization of the disruption to the society, among others, around the remediation site [2]. In order to achieve GSR and incorporate this principle in practice, there is a need for sustainability assessment tools for quantifying the sustainability of potential remediation strategies identified for a site.

A sustainability assessment framework is a systematic basis by which the sustainability of a remediation project may be assessed using the sustainability metrics with respect to environmental, economic and social impact indicators. Several international agencies and organizations in the United States and other countries namely the U.S. Environmental Protection Agency (USEPA), Sustainable Remediation Forum (SURF), Interstate Technology and Regulatory Council (ITRC), and American Society for Testing and Materials (ASTM) have been the major drivers in developing frameworks for facilitating sustainability assessment in remediation of contaminated sites [2]. However, most of the frameworks and tools developed lack a holistic life cycle approach while evaluating and quantifying the triple bottom line sustainability of remedial options. The life cycle sustainability assessment would involve quantification of the environmental footprint, quantification of the direct and indirect costs (e.g. administrative costs, social cost of carbon), and benefits (e.g. employment opportunities) through a quantitative life cycle cost analysis, and finally by performing a project specific social sustainability assessment considering the social impacts from the remediation activities across each stage of the project life cycle. A list of all the major sustainability assessment tools (qualitative, semi-quantitative and quantitative) and their limitations has been presented in previous literature [3,4]. Based on these limitations, a new quantitative life cycle sustainability assessment framework has been developed. The methodology of the proposed framework is discussed briefly in the following section.

3. QUALICS framework

The proposed framework for quantitative assessment of life cycle sustainability uses the Spanish Integrated Value Model for Sustainable Assessment (MIVES) [5], and a multi-criteria decision method capable of defining specialized and holistic sustainability assessment models to obtain global sustainability indices [6]. The MIVES method combines the triple bottom line sustainability requirements in terms of weighted aggregation of a certain set of criteria and indicators, the concept of value function (to normalize the metrics to a single comparable unit) and the Analytic Hierarchy Process (AHP) [7] to define the weights to the requirements, criteria and indicators. In particular, the AHP brings in the knowledge and expertise of the experts in the field of research (in this case the field of environmental remediation and sustainable engineering) to decide on the relative importance of the indicators and to finalize the indicators, criteria and requirements to be used for the sustainability assessment. One of the major components of the MIVES methodology is the value function analysis to calculate the sustainability index for the option under consideration. In this study, the option assessed would be a remedial alternative. A schematic representation of the MIVES value function analysis to arrive at a global sustainability index for a remedial alternative is shown in Fig. 1.

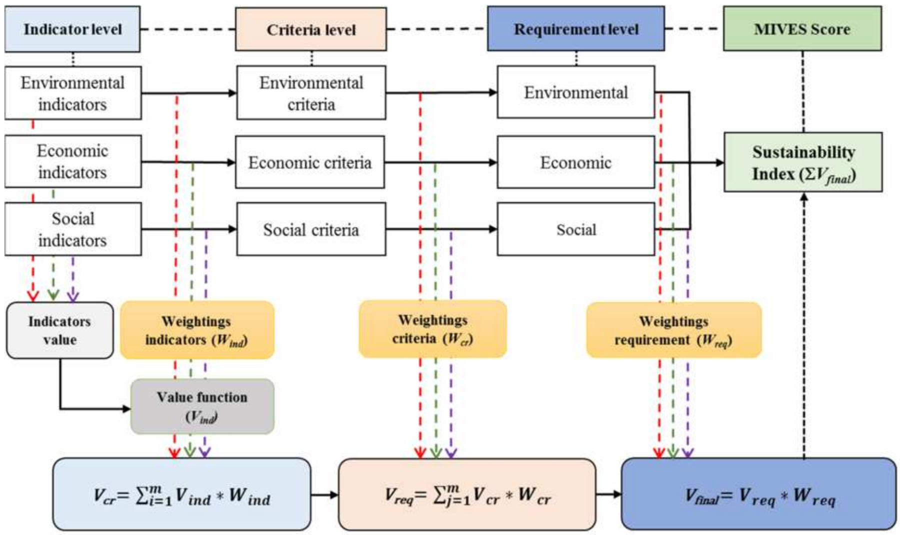

Figure 1. Schematic of the MIVES methodology.

The value function analysis involves establishing representative value functions which convert all the quantitative and qualitative variables into a set of variables with the same units or scales. Each indicator is assigned a weight derived from the AHP methodology involving expert opinion. Thereafter, the value function obtained for each indicator (V_{ind}) is multiplied by the respective weightage (W_{ind}) assigned to the indicator. Each of the indicators can be assigned a criterion. The sum of the products of the V_{ind} and W_{ind} of the indicators given under a criterion becomes the value of the criterion (V_{cr}). Further, each of the values obtained for a criterion is multiplied by the corresponding weights assigned for each criterion to obtain the value for each sustainability requirement (V_{req}) (e.g., environmental, economic and social). The final value (V_{final}) for each sustainability pillar is obtained by taking the sum of the product of V_{req} and the weight (W_{req}) assigned to each of the requirements. The sum of the V_{final} values of the environmental, economic and social pillars give the final sustainability index for a remedial alternative. The same procedure can be followed for every remedial alternative under consideration to arrive at their respective sustainability indices. The most sustainable option among the potential remedial alternatives can be assessed by comparing the sustainability index obtained for each remedial alternative. Because the overall sustainability assessment is based on the weights assigned to the indicators, it is subjective to the preferences given by stakeholders. A detailed explanation on the QUALICS framework is presented by Trentin et al. [8].

4. Application of the QUALICS framework

The applicability of the QUALICS framework is demonstrated using three case studies all of which pertains to environmental remediation. A brief overview of the site characteristics, remedial goals, potential remedial technologies after preliminary remedial evaluation and the final results from the sustainability assessment using the QUALICS framework are discussed for each case study.

4.1. Case Study 1

The site under study is an 87.52-acre site historically used for agricultural purposes since 1874 which was later transformed to an electrical power generating facility in 1969. The site discontinued electricity generation in 2004. The facility operated for 35 years (1969–2004), during which five documented spills occurred. These spills included fuel oil, lubricating oil, diesel fuel, and mineral oil. During the initial site investigation involving 96 soil borings and 6 groundwater monitoring wells, the site was tested for BTEX compounds, Polychlorinated biphenyls (PCBs), ethylene glycol, Volatile Organic Compounds (VOCs), Semi-Volatile Organic Compounds (SVOCs), pesticides, and USEPA priority pollutant metals. The test results showed that the site was largely contaminated with BTEX, PAHs, PCBs, and metals from the previous releases of diesel and mineral oil at the site.

A conceptual site model was developed to identify all potential sources of contamination, contaminated media, exposure pathways, and receptors. The exposure pathways included incidental ingestion, inhalation of particulates, and dermal contact. The potential receptors were residents and construction workers. The baseline risk assessment for carcinogenic and non-carcinogenic risk for the identified contaminants of concern was conducted and the preliminary remediation goals for the site were established. Based on the risk assessment, seven hot spots of approximately 30 m x 30 m were identified for remediation. Feasibility evaluation of different remediation technologies was conducted and three potential remediation technologies, namely electrokinetic remediation (EKR), excavation and disposal, and phytoremediation, were identified. The preliminary design of the three potential remedial options are presented in Trentin et al. [8]. The three remedial options were further assessed for their relative sustainability using the QUALICS framework and data derived from the preliminary design of the three remediation technologies.

The environmental impacts of each remedial option were assessed by performing LCA using SimaPro version 8.5 software. The details on the scope (system boundary) of the LCA, the life cycle inventory and the impact assessment method used for the LCA in this case study are provided in Trentin et al. [8]. The economic impacts were also determined by calculating the direct costs (e.g., cost of materials, equipment, labor, transportation) and the indirect costs (e.g., social cost of carbon emissions) at each life cycle stage. Finally, the social sustainability assessment was performed based on a survey conducted using the Social Sustainability Evaluation Matrix developed by Reddy et al. [9]. The results from these analyses were compiled and used in the value function analysis involving the MIVES in the QUALICS framework and the sustainability indices for each remedial alternative were found to be 0.49, 0.32 and 0.69 for EKR, excavation/disposal and phytoremediation options, respectively. A sensitivity analysis was also conducted by varying the weights of environmental, social, and economic requirements to identify the sensitivity of varying stakeholder preferences on the resulting sustainability indices.

The results from the sustainability assessment showed that the phytoremediation option was the most sustainable option with the least environmental and economic impacts. It was further concluded that phytoremediation was found to be the most sustainable option irrespective of the stakeholder preferences.

4.2. Case Study 2

The site in this case study dealt with the remediation of sediments at Cedar Lake (composed of North and South Lakes, divided by a railway causeway) in Iowa, USA. Cedar Lake is currently fed from three sources: a small creek called McLoud Run, treated cooling water from a Cargill Incorporated facility, and the Kenwood Ditch Outfall. The Kenwood Ditch Outfall is a box culvert that discharges into South Lake during storm events. A detailed site description is presented in Reddy et al. [10]. A preliminary site investigation found elevated concentrations of both PCBs and pesticides throughout the North Lake and South Lake with concentrations up to 1 part per million (ppm). Multiple samples located within the South Lake by the Kenwood Ditch Outfall exceeded the Probable Effects Concentration (PEC) for either pesticides or PCBs. The final remediation area was determined by using the halfway rule. Half the distance between a sample exceeding the PEC and a sample below the PEC was determined to be the edge of remediation. A total of 8,361.2 m^2 of sediment exceeded the PEC for at least one contaminant of concern and required further remediation.

The studies from 1994 and 2017 showed a decrease in concentrations of contaminants as high as one order of magnitude from natural attenuation. Based on this observation, MNA with a monitoring program for atleast 20 years (based on the sediment deposition rate and contaminant concentrations) was considered as one of the remedial measures for the passive remediation of site. Further, based on the site characteristics and feasibility evaluation of different relevant remedial technologies, dredging of contaminated sediment, conventional capping of the sediment, and modified capping with a reactive core mat were identified as potential remedial alternatives for the remediation of site. A detailed explanation for the preliminary design of all the four remedial alternatives are presented by Reddy et al. [10]. The data from the preliminary design of the remedial alternatives were used for the value function analysis and the evaluation of sustainability indices for the remedial alternatives using the QUALICS framework. A detailed explanation on the life cycle triple bottom line sustainability assessment performed on the four remedial alternatives using the QUALICS framework is presented by Reddy et al. [10].

The sustainability indices of MNA, dredging/disposal, conventional capping and modified capping were determined to be 0.59, 0.26, 0.33 and 0.55, respectively. The results from the QUALICS assessment showed that conventional capping had the highest negative environmental impacts. MNA appeared to have the least negative impact, which is expected as it does not require any dredging or transportation activities. However, MNA is anticipated to pose risk to the benthic organisms and the surrounding environment for a longer duration of time. A sensitivity analysis conducted by varying the weights to different sustainability requirements showed that MNA was the most preferred option across most of the scenarios evaluated. In one of the scenarios where social sustainability was given the highest preference, modified capping with a reactive core mat was identified as the most preferred choice among all the remedial alternatives. Finally, the modified capping with reactive core mat was chosen as the most sustainable option for remediation of the contaminated sediments at the site keeping in mind that Cedar Lake was anticipated to be used for recreational purposes in the future.

4.3. Case Study 3

This site comprised an industrial/commercial area alongside a residential area. The contamination at the site was identified when residents at the site became concerned about potential contamination to their drinking water from an off-site plume and submitted a sample from their private well for analysis. Elevated levels of chlorinated VOCs were found in the groundwater samples from 11 private wells in the residential area and 2 private wells in the commercial area. Elevated concentrations of trichloroethylene (TCE) and tetrachloroethene (PCE) were detected in GW, but not in soil. The site hydrogeology comprised of one unconfined aquifer consisting of unconsolidated outwash sand and gravel deposits from the ground surface to the depth of investigation at approximately 15 m below ground surface. This was the principal source of groundwater for the residences and businesses at and near the site. Human health risk assessment was performed using a conceptual site model by evaluating the contaminated media, exposure routes and potential receptors. Six chemical constituents (1,1-dichloroethane, cis-1,2-dichloroethylene, PCE, TCE, chloroform, and dibromochloromethane) were identified as contaminants of concern at the site. The site-specific screening levels were conferred to be the risk-based remedial goals for the site.

A preliminary remedial option evaluation was performed based on the site-specific contamination and other site characteristics. In this regard, three potential remedial options namely in-situ air sparging with bioremediation (IASB), in-situ chemical oxidation (ISCO) and pump and treat systems (PT) were identified. A preliminary design of each of the remedial option was performed and these data were used for quantitative sustainability assessment using the QUALICS framework. The details regarding the preliminary design are presented in Reddy and Kumar [11]. In this case study, the environmental impact/footprint analysis was performed using a widely recognized quantitative tool developed by the U.S. Navy called as SiteWise. Likewise, the economic impact assessment involved the direct and indirect costs associated with the remedial options across the life cycle of the project. The social sustainability assessment was conducted similarly to the previous to case studies using an online survey of the potential socio-individual, socio-institutional, socio- environmental and socio-economic impacts as the site-specific indicators of social impacts [11].

The sustainability indices were calculated to be 0.83, 0.51 and 0.11 for ISCO, IASB and PT, respectively. Results from the quantitative triple bottom line sustainability assessment showed that in-situ chemical oxidation as technically effective, environmentally feasible, cost-effective and socially viable option for remediating the contaminated site when equal preference is given to the environmental, economic and social concerns associated with the project. However, the authors [11] concluded that a sensitivity analysis is required to assess the possible differences in the relative sustainability of the remedial options based on varying stakeholder preferences.

5. Summary and future work

Environmental pollution and remediation are growing issues in the U.S. and many other countries. Currently, there are well established procedures in practice, at least in the U.S., to identify the hazard, characterize and remediate the contamination at the site to a level that doesn't pose risk to human health and the environment using a suitable remediation technology. However, the remediation activities involve the utilization of significant amounts of energy and resources during the entire project life cycle. In this regard, quantifying the broader or secondary impacts from the remediation activities, while ensuring the reduction of environmental and health risk becomes important to identifying the most effective and sustainable remedial option and consequently to contributing to the global sustainable development. Numerous qualitative and quantitative tools have been developed to assess potential remedial option to identify the most sustainable remedial option for remediation of a contaminated site. However, these tools do not account for the broader environmental, economic and social impacts with a life cycle perspective. In addition, most of the tools focus on only one of the three essential pillars of sustainability (environment, economy and society) usually with more inclination towards environmental impacts.

The applicability of a new quantitative life cycle sustainability assessment framework, QUALICS, was demonstrated using three case studies involving the remediation of contaminated soil, sediment and groundwater at three different sites. The QUALICS framework was used to identify the most sustainable remedial option to be implemented at the site. In addition, sensitivity analysis performed in each of the case studies shows that the results on the sustainability index may vary based on the stakeholder preferences (favoring one sustainability pillar over the other). Future research in this regard should focus on strengthening the analysis of economic sustainability aspects by involving the indirect costs and benefits that are otherwise unaccounted in most of the tools. Further, the tool used for social sustainability assessment in the QUALICS framework is still lacking. Therefore, a well-structured social sustainability assessment tool that can assess the social sustainability in a rational manner for any project needs to be developed.

References

[1] Sharma, H. D., & Reddy, K. R. (2004). Geoenvironmental engineering: site remediation, waste containment, and emerging waste management technologies. John Wiley & Sons.

[2] Reddy, K., & Adams, J. (2015). Sustainable remediation of contaminated sites. Momentum Press.

[3] Reddy, K. R., Kumar, G., & Du, Y. J. (2018a). Risk, sustainability and resiliency considerations in polluted site remediation. In Proceedings of the 8th International Congress on Environmental Geotechnics (pp. 145-163). Springer, Singapore.

[4] Reddy, K.R., & Kumar, G. (2018b). Green and sustainable remediation of polluted sites: New concept, assessment tools, and challenges. Special Issue: XVI DECGE 2018 Proceedings of the 16th Danube - European Conference on Geotechnical Engineering, Skopje, R. Macedonia, 2(2-3), 83-92.

[5] Alarcon, B., Aguado, A., Manga, R., & Josa, A., (2010). A value function for assessing sustainability: application to industrial buildings. Sustainability, 3(1), 35-50.

[6] Pons, O., de la Fuente, A., & Aguado, A. (2016). The use of MIVES as a sustainability assessment MCDM method for architecture and civil engineering applications. Sustainability, 8(5), 460.

[7] Saaty, T. L. (1990). How to make a decision: the analytic hierarchy process. European journal of operational research, 48(1), 9-26.

[8] da S Trentin, A. W., Reddy, K. R., Kumar, G., Chetri, J. K., & Thomé, A. (2019). Quantitative assessment of life cycle sustainability (QUALICS): Framework and its application to assess electrokinetic remediation. Chemosphere, 230, 92-106.

[9] Reddy, K. R., Sadasivam, B. Y., & Adams, J. A. (2014). Social sustainability evaluation matrix (SSEM) to quantify social aspects of sustainable remediation. In ICSI 2014: Creating Infrastructure for a Sustainable World (pp. 831-841).

[10] Reddy, K. R., Chetri, J. K., & Kiser, K. (2018). Quantitative sustainability assessment of various remediation alternatives for contaminated lake sediments: Case study. Sustainability: The Journal of Record, 11(6), 307-321.

[11] Reddy, K.R., & Kumar, G. (2019). Application of triple bottom line sustainability framework to select remediation method at industrial contaminated site. Proceedings of GeoCongress2019 GSP 312, ASCE.