Quantitative Sustainability Assessment of Various Remediation Alternatives for Contaminated Lake Sediments: Case Study

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Abstract

Various technologies have been developed for the remediation of environmentally contaminated sites. The prime goal of remediation technologies is to identify and reduce the contaminants to risk-based allowable concentrations. For a particular problem of contamination, multiple remediation technologies may be feasible. Choosing the most sustainable option among many available technologies is challenging. Generally, the selection of remediation technology is solely based on the cost and time frame of the project. Hence, the environmental impacts as well as the social impacts associated with the project is usually overlooked. In recent years, decision making has become more holistic with the introduction of triple bottom line sustainability assessment framework. It accounts for the environmental, economic and social impacts of the project. In this article, a case study is presented which involves triple bottom line sustainability assessment as well as the integration of the three pillars of sustainability to obtain overall sustainability index for the comparison of various remediation alternatives and arrive at the most sustainable option. This study presents the sustainability assessment framework and its application to select the most sustainable remediation method for contaminated sediments at a site.

Introduction

Contamination of air, water and soil have been a colossal problem since the Industrial Revolution. As industries are growing more sophisticated, the problem of contamination is becoming more complicated. In many case, contaminants are released from the industrial source during storage and disposal of wastes as well as accidental spills[1]. In addition to industry, the source of contamination could be routine human activities such as local waste disposal. Agricultural activities also contribute to contamination such as excessive use of fertilizer or pesticides, wastes from large livestock farms, etc. In the absence of environmental laws and regulations until the early 1970s, the use of chemicals and disposal of wastes occurred without consideration of potential harmful effects on environment[2]. Hundreds of thousands of sites have been contaminated with toxic chemicals as a repercussions of unregulated use of chemicals and waste disposal posing risk to human health and the environment[2]. In the USA alone, thousands of sites have been identified as contaminated and are in need of remediation[3]. Currently, there are 1,343 contaminated sites which are listed under a National Priority List (NPL) by U.S. Environmental Protection Agency (USEPA)[4], at which soil, sediment and groundwater are of major concern.

Various technologies have been developed for the remediation of the contaminated sites. The most common remediation practice is excavation and disposal of the contaminated soil[1]. However, there are many other popular technologies for remediation of soil and groundwater such as soil vapor extraction, soil washing, electrokinetic remediation, in-situ flushing, pump and treat, permeable reactive barriers, monitored natural attenuation, etc as shown in **Table 1**. The selection of remediation technology is based on the type of contaminants and the site characteristics. However, in some cases, more than one remediation technologies may be suitable for a contaminated site. In such case, the choice of remediation technology generally depends upon the cost and timeframe for remediation[3]. This approach does not take into account the environmental as well as social impacts that may arise from the selected remediation option. If the remediation selection and implementation practices are irrational then it may cause more negative environmental impacts than the contamination[5]. The remediation problem is not just about limiting the contaminant exposure or reducing the level of contaminants, it is a process of restoring the site to a state that causes minimal environmental strain as well as provides maximum economic and social benefits.

With sustainable management practices gaining importance, the decision making process is becoming more rational. The concept of "Green and Sustainable Remediation" has been increasingly incorporated in the decision making process[6]. Green and sustainable remediation aims to reduce the contamination to targeted risk-based levels protecting human health and environment, and at the same time decreasing probable secondary or broader negative impacts on environment, economy and society that may arise from remediation activities[3].

Several tools are employed by many organizations to make judgment and arrive at the most suitable and sustainable remediation technology among many potential alternatives. Some of these tools are Life Cycle Assessment (LCA), Spreadsheets for Environmental Footprint Analysis (SEFA), SiteWise™, Leadership in Energy and Environmental Design (LEED), and Envision etc. However, most of these tools emphasize on environmental aspects. Overall sustainability is defined as the holistic consideration of environmental, economic and social impacts of an activity[7] and hence, ignoring any of these aspects makes the judgment questionable. Several agencies like

U.S EPA, Sustainable Remediation Forum (SURF), Interstate Technology and Regulatory Council (ITRC) and American Society of Testing and Materials (ASTM) have been playing crucial role in developing framework for integrating various aspects of sustainability and ensuring the decision making is more transparent and easier[3]. Similarly, various multi-criteria decision making tools like Integrated Value Model for Sustainable Assessment (MIVES) and Analytic Hierarchy Process (AHP) are gaining prominence in decision making in remediation projects. AHP organizes the decision making process in a hierarchy and measure intangibles in relative terms such as priority scales, by making pairwise comparisons of the variables describing the remediation problem relying on the judgments of experts[8]. Pairwise comparison of variables means comparing relative importance of one variable against another under one category e.g. under the category of environmental sustainability, comparing the relative importance of ozone depletion against greenhouse gas emissions. It helps in determining the relative importance of each of the parameters involved in defining the sustainability framework for each remediation option and gives the values in terms of weightages. MIVES is a methodology which incorporates multi-criteria decision making method to define holistic sustainability models and obtain a unique sustainability index value[9].

In this article, a case study is presented that shows a triple-bottom line sustainability assessment using the three pillars of sustainability (environmental, economic and social) to determine the most sustainable remediation technology among various suitable remediation alternatives for contaminated sediments.

Site Background

Site Description

Cedar Lake is an approximately 150-acre lake located just north of downtown Cedar Rapids in Iowa, USA. The site location is shown in **Figure 1**. Cedar Lake is divided into two main sections roughly bisected by a railroad causeway. The portion north of the causeway includes North Lake, which is approximately 80 acres in size, and West Lake, which is approximately 10 acres in size. The portion south of the causeway includes South Lake, which is approximately 60 acres in size.

Cedar Lake is currently fed from three sources: a small creek called McLoud Run, treated cooling water from Cargill Incorporated, and the Kenwood Ditch Outfall as shown in **Figure 2**. The Kenwood Ditch Outfall is a 19-foot by 10-foot box culvert that discharges into South Lake during storm events. This sewer serves as a drainage basin comprising approximately 6 square miles of Cedar Rapids, including residential and commercial areas.

The geology of the site consists primarily of quiet-water sediments within North Lake. South Lake is dominated by the delta deposit near the Kenwood Ditch Outfall, which consists of coarser-grained sand and gravel deposits near the outfall which grade finer with distance.

Currently, Cedar Lake and specifically North Lake, is used by the public for fishing and paddling sports. Because of the industrial sites and railroad lines along the south shore, access to South Lake is more restricted.

Risk Assessment

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. In the Phase II site assessment, samples were collected using a hand auger from the top 2 feet of sediment at sample points located along a grid system across the Lake.

Currently, there is no established risk levels for sediments within the Iowa Brownfield Assessment program. In lieu of official standards, samples were compared to the National Oceanic and Atmospheric Administration (NOAA) Probable Effects Concentration (PEC), NOAA Threshold Effects Concentration (TEC) and the EPA Region III Sediment Benchmarks. The EPA benchmarks were generally equivalent to the TEC, hence only PEC and TEC are discussed in further detail. The TEC is the concentration at which a negative environmental or ecological impact may be observed while the PEC is the concentration at which a negative environmental or ecological impact is likely to be observed. For the risk assessment, the PEC was used as the screening level for defining the areas which require remediation.

As shown in **Figure 3**, multiple samples located within South Lake by the Kenwood Ditch Outfall exceeded the PEC for either pesticides or PCBs. The final 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 90,000 square feet (ft^2) of sediment exceed the PEC for at least one contaminant of concern and will require further remediation.

Methodology

Goal and Scope

The goal of this study is to evaluate the sustainability of various sediment remediation technologies to identify the most sustainable option based on the three pillars of sustainability: environmental, economic and social. Four remediation technologies were selected for the site: monitored natural attenuation, dredging of contaminated sediments, the placement of a conventional sand cap, and the placement of a modified cap utilizing an activated carbon reactive core mat.

Monitored Natural Attenuation

The studies from 1994 and 2017 showed a decrease in concentrations of contaminants as high as one order of magnitude. This indicates that natural attenuation is occurring across the lake and will likely continue to occur. Monitored natural attenuation (MNA) assumes remediation of contaminants will occur through natural processes, including degradation of contaminants through microbial activity as well as natural burial of contaminated sediment. Sediment deposition rate studies in the lake indicate that approximately 1.5 cm/year are deposited within the target area. For the protection of human health and the environment, the benthic zone or the bioturbation zone, which varies from top 2 to 12 inches (5 to 30 cm) of sediment[10,11] must have contaminant concentrations below the PEC. Given the deposition rate and the target depth of clean sediment, assuming there are no other degradation processes occurring, the contaminated sediments would be sufficiently buried within 20 years. Therefore, a monitoring program would need to be in place for at least that length of time.

The proposed monitoring program will consist of annual sampling of the top one foot of the sediment in 20 locations across the affected area. The samples will be shipped in coolers from Cedar Lake to an analytical laboratory in Lenexa, Kansas. It is assumed that the sampling team will come from 50 miles away and that samples will be collected using a geoprobe rig with disposal acetate liners pushed 1 foot into sediment. Waste disposal from each event will consist of the acetate liners and related sampling materials, such as gloves. It is assumed that all soil collected will be shipped to the laboratory for analysis. Therefore, waste generation will be negligible.

Dredging of Contaminated Sediment

The depth of contamination was not fully evaluated during investigation activities due to the collection of a homogenized sample from the top two feet of sediment. A conservative thickness of 5 feet was used for the design of dredging. A total volume of 450,000 cubic feet (ft^3) will need to be removed from the targeted area (90,000 ft^2 area x 5 ft thickness), assuming a sediment density of 169 pounds per cubic foot, a total of 38,025 tons will be dredged and require disposal at a special waste landfill. The nearest landfill to the site is located 9 miles south of the site and all dredged material will be transported there in 20-ton trucks. Assuming the trucks can make 4 trips with 10 trucks per trip average, the remediation would be complete in 48 days. Due to the shallow water depth across the affected area (less than 1 foot), dredging can be completed on land using clam shell buckets to avoid potential resuspension of contaminated material.

Conventional Capping

A traditional cap generally consists of 12 inches of sand over the contaminated sediment to prevent benthic organisms as well as humans from exposure to contaminants. An additional 3 inches of sand is placed on top of the sand layer for overplacement allowance and as a factory of safety for the exposure potential. Above that, a four-inch thick layer of angular gravel ranging in size from one-inch to one and a quarter inches would be placed to keep the sand in place and limit any potential bioturbation and mixing of the cap material due to ebullition. Similar to the sand, an additional 3 inches of gravel would be placed as an overplacement allowance. Due to the location of the target area on a delta that experiences periodic high flows, an armored cap will need to be installed at this location, especially in the area directly adjacent to the Kenwood Ditch Outfall. This armoring consists of a 4-inch layer of angular stones ranging in size from 3 to 4 inches (riprap). **Figure 4a** shows a schematic of the conventional capping system to be implemented at Cedar Lake. The target area is located near shore and has shallow water depths, so sediments can be placed with a backhoe from shore. All cap materials can be sourced from a quarry located approximately 12 miles from Cedar Lake.

Additionally, Cedar Lake is located within a 100-year floodplain in Cedar Rapids and is used as a detention basin during storm events and high flow conditions. Therefore, the net storage of the lake must remain the same. Since 195,500 ft^3 of sediment is being introduced into South Lake, this same storage volume must be removed from a different portion of the lake. Since North Lake has previously had contaminants of concern above action levels, but it is known that the top two feet are below risk levels as mentioned earlier in the risk assessment, one foot of sediment will be removed across 195,500 ft^2 of North Lake in order to maintain a 1 foot clean benthic zone for the protection of human health and the environment in North Lake. The sediments in North Lake are generally silts and clays and are therefore not suitable for use in the cap. These sediments must therefore be disposed of or reused at a different site. For the purposes of this evaluation, the sediments to be dredged to maintain storage volume will also be disposed of as special waste due to the historic potential contamination.

Modified Cap with a Reactive Core Mat

The modified cap is similar in design to the conventional cap however, a reactive core mat consisting of granular activated carbon in between two pieces of geotextile fabric would be placed directly over the contaminated sediment. The reactive core mat contains 0.4 pounds per square foot of granular activated carbon[12] to adsorb any potential contaminants, thereby limiting the exposure risk due to ebullition and bioturbation. Directly overlying the half-inch thick reactive core mat would be 12 inches of sand to act as the benthic zone for aquatic organisms. Since the granular activated carbon limits potential contaminants from passing through the sand, the overlying gravel is not needed and only the rip rap armor for high flow will be placed. **Figure 4b** shows a schematic of the modified capping system.

Again, since Cedar Lake is located within a floodplain and the net change in storage must be zero, sediments from North Lake must be excavated to account for the addition of sediment in South Lake. A total volume of 123,750 ft^3 of sediment is being added to South Lake, therefore a 1-foot thick sediment layer (123,750 ft^3) will be removed from North Lake and disposed of as special waste due to the historic potential contamination.

Sustainability Assessment

One of the most common definitions of sustainable development is given in The Burdtland Report as "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs."[13]. Various frameworks and tools have been developed to assess the sustainability of a project or development activity. In the current study sustainability assessment of the above mentioned four remediation alternatives was performed using the triple bottom line sustainability framework.

Environmental Sustainability

In this study, environmental sustainability was assessed with the help of LCA using software SimaPro 8.5[14]. LCA was performed according to ISO 14044[15]. LCA assesses the environmental impacts associated with the entire life cycle of the project from material acquisition, construction and use, to waste disposal. It analyzes the various life cycle stages of the project and assesses the environmental impacts in terms of various indicators like ozone depletion, global warming, smog, acidification, eutrophication, carcinogens, and more.

In this study, the major life cycle stages involved were material acquisition, operation, use and maintenance, and waste management. The environmental impacts were assessed for each remediation option and a comparison was made between the alternatives on the basis of the degree of environmental impacts obtained from each life cycle stage.

The functional unit for performing an LCA on this project was the total square feet area of the contaminated sediment requiring remediation, which was 90,000 ft^2. The input for material quantities used for the LCA are shown in **Table 2**. **Table 3** shows the location and distance of the site to the quarries and the disposal site. The impact assessment was performed using TRACI (tool for the Reduction and Assessment of Chemical and other environmental Impacts) and BEES (Building for Environmental and Economic Sustainability) methods. TRACI was developed by the US EPA[16] and BEES is a tool developed by the National Institute of Standards and Technology Engineering Laboratory to help in selecting environmentally preferred building products. The inventory used in performing LCA were adopted from the database in the LCA software. For the materials not listed in the database, a dummy material which closely represented the properties of the original material was created for the use in the analysis.

Economic Sustainability

The economic assessment was based on the direct cost associated with the materials and the processes involved in each remediation option. The direct cost includes the cost of the materials, transportation, disposal, sampling and laboratory analysis, operation and labor. Indirect costs associated with the remediation options are also included. For example, the social cost of greenhouse gases like carbon dioxide (CO_2) as well as other emissions engendering environmental impacts. Total direct and indirect costs were determined for each remediation option.

Social Sustainability

Social sustainability is a subjective field which makes it difficult to quantify the social impacts of any activity. However, a few approaches like Social Sustainability Evaluation Matrix (SSEM)[17] have been developed to quantify the social impacts of an activity. In this study, the social impacts of each remediation option was assessed by conducting an online survey among the students in two graduate level courses at UIC (Environmental Remediation Engineering and Sustainable Engineering) and faculties and professionals working in the field of remediation. The survey was sent to all the students enrolled in the courses. Indicators describing the impact of each of the remediation option on social aspects at the individual, community, economic and environmental levels were chosen. Most of the indicators were chosen from the SSEM. The four major areas of social aspects (socio-individual, socio-community, socio-economic and socio-environmental) were further divided into sub-categories or indicators. The survey results were analyzed and the scores were assigned to each indictor under each category in the order of 1-4 (1 being the best and 4 being the worst). **Table 4** shows the various indicators used for social sustainability assessment.

Results and Discussion

Environmental Sustainability

A comparison of the environmental impacts incurred due to each remediation option is shown in **Figures 5 and 6** using TRACI and BEES method, respectively. The impacts are normalized with respect to the highest contributor in each impact category and expressed in terms of percentage. On analyzing the results of both the TRACI and BEES methods, the conventional capping option appears to have the highest negative impacts in most of the impact categories, while MNA has the lowest negative impacts. The reason could be that the MNA does not involve any material acquisition or equipment mobilization. In addition, MNA comprises significantly less transportation than the other remedial options. Conventional capping seems to be the least sustainable option among the four remediation alternatives.

The environmental impact assessment of individual life cycle stages involved in each remediation option showed that most of the negative impacts were contributed by the transportation stage. To discern the impacts of transportation distances, an LCA was performed for all the options with the transportation distances limited to 5 km for each remediation option. **Figure 7** shows the environmental impact assessment of all four remediation options with 5 km transportation distance using TRACI method. The results show that even when the transportation distance is minimal, conventional capping remains the highest contributor towards negative environmental impacts. This result could be due to the the dredging of huge amount of sediments in conventional capping as well as import of huge amount of raw materials such as sand, gravel and armor stones. Hence, even when the transportation distance was kept minimal, the negative impacts associated with the dredging of the sediments as well as import and placement of the capping materials are more than that of the other remediation options.

Economic Sustainability

Table 5 summarizes the direct and indirect costs for each remediation option. Direct costs were estimated using an online inventory of construction cost data (www.allcostdata.com). MNA is the least expensive option, followed by modified capping. Dredging and disposal technique appeared to be the most cost intensive option. The indirect cost was calculated based on the amount of emissions data obtained from the LCA. The social cost of CO_2 was obtained from the USEPA[18]. The indirect cost followed the same trend as the direct cost.

Social Sustainability

The results of the social survey are summarized in **Table 6**. Each indicator received a score of 1 to 4 from each respondent. The total scores obtained by the indicators in each category were added. The scores from each category (socio-individual, socio-community, socio-economic and socio-environmental) were then summed to get a total score for each remediation option as shown in **Table 6**. Among the four remediation options, MNA received the highest score indicating it has the greatest negative social impact. Modified capping received the lowest score making it the most preferred choice. These results were from responses obtained from students familiar with the remediation and sustainability concepts. Since social sustainability is a subjective field, the results may vary with increase in number of respondents.

Overall Sustainability

As mentioned earlier, overall sustainability is an integration of environmental, economic and social sustainability. The overall sustainability of the four remediation options was assessed with the help of MIVES methodology which uses multi-attribute analysis as shown in **Figure 8**. MIVES method involves various steps: (i) defining the problem (ii) defining the variables in terms of criteria/indicators which best describe the impacts due to the project/activity (iii) establish value functions which converts all the qualitative and quantitative variables into a set of variable with same units and scales (iv) define the weightages to be assigned to each criterion/indicator used in the analysis (v) evaluate the scores obtained in each criterion/indicator (vi) assessment of the results and decision making based on the scores obtained.

Table 7 shows the framework of the MIVES methodology including all the requirements, criteria and indicators used for the overall sustainability assessment of the remediation alternatives in this study. Value function analysis was performed for the assessment of the sustainability index of each of the remediation option. Equal weightages were assigned to each criterion ($W_{criterion}$) and indicator ($W_{indicator}$). The quantitative value of each environmental, economic and social indicator was obtained from the LCA results, economic analysis and social sustainability survey, respectively. After quantification of each indicator, each value was normalized to a dimensionless scale of 0 to 1 using value function of the concave form expressed by **Equation 1** and expressed as value indicator ($V_{indicator}$). In the following step, the $V_{indicator}$ values were multiplied by the $W_{indicator}$ and the product was added to get the $V_{criterion}$ value. Similarly, $V_{criterion}$ was multiplied with $W_{criterion}$ and the product was added to get $V_{requirement}$. The final score V_{final}, termed as MIVES final score, was obtained by adding the product of $V_{requirement}$ and $W_{requirement}$. The final score ranges from 0 to 1.

$$V_{indicator} = \frac{\ln\left(\frac{X}{X_{\max}}\right)}{\ln\left(\frac{X_{\min}}{X_{\max}}\right)} \qquad (1)$$

The weightages assigned to the requirements, criteria and indicators may vary depending on the preferences of stakeholders and may influence the overall sustainability assessment. In this study, four cases as shown in **Table 8** were assessed by assigning different weightages to the three sustainability pillars to examine the effect of their relative importance given the overall sustainability. **Figure 9** shows the results of value function analysis of the four remediation options for each of the four weighting scenarios. **Figure 9a** shows the results of Case A where equal weightage was given to each of the three sustainability pillars. In this scenario, MNA appeared to be the most sustainable option followed by modified capping. **Figure 9b** shows that modified capping is the most sustainable option when the social sustainability pillar is given the highest preference. MNA has the highest sustainability index followed by modified capping for Case C and Case D, as shown in **Figure 9c** and **9d**, respectively.

Decision making depends on the relative importance of the environmental, economic and social aspects of the project which again depends upon the preference of stakeholders[8,19]. For example, in this study, although the MNA option was ranked highest in the MIVES scale for most of the weighting scenarios, it might not be considered as the most preferred choice. Here, the decision could be based on the case where social sustainability was given the highest weightage. MNA had the highest negative impact at social level as it is associated with the risk of exposing the community as well as the surrounding environment to the contamination for a longer duration of time. Also, the lake is used for recreation purposes which makes the social aspects crucial in the decision making process. Hence, modified capping may be considered the most sustainable remediation option among all other options.

Conclusions

The study presents a sustainability assessment of the four remediation alternatives for the Cedar Lake sediment which was contaminated with PCBs and pesticides. Four remediation alternatives were considered in this study 1) Monitored Natural Attenuation, 2) Dredging and disposal, 3) Conventional capping and 4) Modified capping with Reactive Core Mat. The following conclusions can be derived from the study:

- Sustainability assessment is the congruence of the three pillars of sustainability; environmental, economic and social. Sustainability assessment in the absence of any one of these pillars is considered incomplete.
- Life cycle impact assessment carried out using TRACI and BEES methods showed that conventional capping had the highest negative environmental impacts. MNA appeared to have the least negative impact which is justified as it does not require any dredging or transportation activities. However, it poses a risk to the benthic organisms and the surrounding environment for a longer duration of time.
- The overall sustainability was found to be a function of the preferences given to the three sustainability pillars. The weightages assigned to the three pillars depend upon the relative importance of the pillars for the project based on the preference of stakeholders.
- Based on the overall sustainability assessment, MNA turned out to be the most preferred choice for most of the cases (varying weightages) studied. However, for a case when social pillar was given the highest preference, modified capping turned out to be the most preferred choice.
- Cedar Lake is used for recreational purposes, thus social sustainability is considered crucial for the overall sustainability assessment. Hence, modified capping can be considered as the most sustainable remediation option for the project.

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Author Disclosure Statement

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References

1. U.S. Environmental Protection Agency. Report on the Environment: Contaminated Land. https://www.epa.gov/report-environment/contaminated-land (accessed on November 8, 2018)
2. Sharma, H. D. and Reddy, K. R. "Geoenvironmental engineering: site remediation, waste containment, and emerging waste management technologies." John Wiley & Sons, Inc., Hoboken, New Jersey, 2004.
3. Reddy, K.R., and Kumar, G. Green and sustainable remediation of polluted sites: New concept, assessment tools, and challenges. Keynote Paper, Proceedings of XVI Danube - European Conference on Geotechnical Engineering, Skopje, R. Macedonia, ce/papers, 2018a, 2(2-3), 83-92.
4. USEPA. Superfund: National Priority List (NPL). 2018. https://www.epa.gov/superfund/superfund-national-priorities-list-npl (assessed on August 23, 2018)

5. Gill, R. T., Thornton, S. F., Harbottle, M. J., and Smith, J. W. N. Sustainability assessment of electrokinetic bioremediation compared with alternative remediation options for a petroleum release site. J. Environ. Manage. 2016, 184, 120-131.
6. Reddy, K.R., and Adams, J.A. Sustainable Remediation of Contaminated Sites, Momentum Press, New York, 2015.
7. ITRC (Interstate Technology & Regulatory Council). Green and Sustainable Remediation: A Practical Framework. GSR-2. Washington, D.C.: Interstate Technology & Regulatory Council, Green and Sustainable Remediation Team. www.itrcweb.org.
8. Saaty, T. L. Decision making with the analytic hierarchy process. Int. J. of Services Sciences 2008, 1(1), 83-98.
9. Pons, O., de la Fuente, A., and Aguado, A. The use of MIVES as a sustainability assessment MCDM method for architecture and civil engineering applications. Sustainability 2016, 8(5), 460.
10. Moodley, L., Heip, C. H., and Middelburg, J. J. Benthic activity in sediments of the northwestern Adriatic Sea: sediment oxygen consumption, macro-and meiofauna dynamics. J. Sea Res. 1998, 40(3-4), 263-280.
11. Clarke, D. G., Palermo, M. R., Sturgis, T. C., and Engler, R. M. Subaqueous cap design: Selection of bioturbation profiles, depths, and process rates (No. ERDC-TN-DOER-C21). Engineer Research and Development Center Vicksburg MS Environmental Lab., 2001.
12. CETCO. Reactive core mat with granular activated carbon 2017 http://www.cetco.com/DesktopModules/Bring2mind/DMX/Download.aspx?Command=Core_Download&PortalId=0&EntryId=144 (accessed on August 23, 2019)

13. World Commission on Environment and Development (1987). Our Common Future. Oxford: Oxford University Press. p. 27. ISBN 019282080X
14. Pré (2018): SimaPro 8.5 LCA software. Amersfoort, The Netherlands
15. International Standardization Organization (ISO). Environmental management – life cycle assessment – principles and framework ISO 14040, 2006.
16. Bare, J. C. TRACI. J. Industrial Ecology 2002, 6(3-4): 49-78.
17. Reddy, K. R., Sadasivam, B. Y. and Adams, J. A. Social sustainability evaluation matrix (SSEM) to quantify social aspects of sustainable remediation. In ICSI 2014: Creating Infrastructure for a Sustainable World, ASCE, 2014, pp. 831-841).
18. USEPA. The Social Cost of Carbon, 2017 https://19january2017snapshot.epa.gov/climatechange/social-cost-carbon_.html (accessed on August 23, 2018)
19. Reddy, K. R., and Girish, K. Application of triple bottom line sustainability framework to select remediation method at industrial contaminated site. In Geocongress 2019 (accepted).
20. Reddy, K. R., Adams, J. A., and Richardson, C. Potential technologies for remediation of brownfields. Practice Periodical of Hazardous, Toxic, and Radioactive Waste Management, 1999, 3(2), 61-68.

Table 1: Soil and groundwater remediation technologies[2,20]

Remediation Technology	Description
Soil Remediation	
Soil Vapor Extraction	It is used for removal of volatile organic compounds (VOCs) and motor fuels from contaminated soils. It is suitable for relatively homogeneous and highly permeable soils. A soil vapor extraction system consists of three basic components: an extraction system, an air flow system, and an off-gas treatment system. By applying a vacuum to the subsurface within the contaminant zone, the extraction system induces the movement of volatile organics and facilitates their removal and collection. Collected vapors pass through the air flow system and are delivered to the off-gas treatment system, or, if regulatory limits permit, are emitted directly to the atmosphere.
Soil Washing	It is used to treat soils contaminated with a variety of organic and inorganic compounds such as VOCs and metals. It is suitable for coarse-grained soils with high permeability. It is less effective for silt and clay soils. It involves excavation of the contaminated soil and the extraction of contaminants from the soil using water or other aqueous wash solutions. The coarse-grained fraction is cleaned and returned to the excavation.
Electrokinetic Remediation	It is used for treating soils contaminated with heavy metals, radionuclides, and other inorganic species and polar organic contaminants. It is suitable for low permeability soils and heterogeneous soils. It involves a process of applying an electric potential across the contaminated soil through a pair of positive and negative electrodes. The contaminants are transported towards the electrodes. The contaminant loaded liquid collected at the electrodes is then removed by pumping or electroplating or precipitation.
Groundwater Remediation Technology	
Pump and Treat	It is used for cleaning groundwater contaminated with various dissolved chemicals, metals, and oils. It is suitable for high permeability soils and homogenous soils. It involves pumping of contaminated groundwater to the surface, removing the contaminants, and recharging the treated water into the ground or discharging it to surface water or municipal sewage treatment plant.
In-situ flushing	It is used for removing organic and inorganic contaminants from groundwater. It is suitable for low permeability soils, soils with low organic content and low surface area. It involves removing of contaminants from the soil by flushing with water or solution that can enhance desorption or solubilization of the contaminants. The

	flushing solution is pumped into the groundwater with the help of injection wells from where the solution travels downgradient flushing the contaminants from the soil or ground water. After solubilzation of the contaminants present in the soil or groundwater, the solution is pumped out from the downgradient extraction wells.
Permeable Reactive Barriers	It is used for wide range of organic (DCE, TCE, PCBs, PAHs, etc.) and inorganic (heavy metals, radioactive isotopes, etc.) contaminants. It is suitable for permeable soils, contaminants at shallow depth and relatively high groundwater flow. In this method, a permeable wall containing an appropriate reactive material is placed across the path of a contaminant plume. As contaminated water passes through the wall, the contaminants are either removed or degraded.
Monitored Natural Attenuation	It is primarily used for degradation of organic contaminants (chlorinated solvents and BTEX). It can also be used for immobilization of inorganic contaminants, including heavy metals such as lead, chromium and uranium. It is a process of using natural attenuation processes with careful monitoring of the contaminated site within a reasonable time frame. It involves physical, chemical, or biological processes that act without human intervention to reduce the mass, toxicity, mobility, volume, or concentration of contaminants.

Note: DCE = Dichloroethylene; TCE = Trichloroethylene; PCB = Polychlorinated Biphenyl; PAH = Polycyclic Aromatic Hydrocarbon

Table 2. Input material quantities associated with each remediation option used in LCA

Material	MNA	Dredging and disposal	Conventional capping	Modified capping
Dredged sediment (Dummy-material-clay) (ton)	-	38,025	16,520	10,457
Sand (ton)	-	-	6,188	4,950
Gravel (1”-1$^{1/4}$”)(ton)	-	-	3,019	-
Gravel (3”-4”)(ton)	-	-	1,725	1,725
Geotextile fabric	-	-	-	21.2
Granular Activated Carbon (GAC)(Charcoal)(tn)	-	-		1.8
Sampling event (km)	1,600	-	-	-

Table 3. Location of raw material sources and disposal sites

Source/Location	Material	Distance(km)
Covanta Environmental Solutions in Cedar Rapids, IA	Dredged sediment	10.6
Martin Marietta Quarry - Cedar Rapids, Iowa	Sand	16.25
	Gravel- (1”-1 ¼”)	
	Gravel- (3”-4”)	
CETCO, Arlington Heights, IL 60004	Reative Core Mat (RCM)	396
Sediment testing laboratory, Lenexa, Kansas	Contaminated sediment samples	482

Table 4. Social sustainability assessment indicators

Criteria	Indicators
Socio-individual	Overall health and happiness
	Income generating activities
	Contaminant Exposure (Trespasser, worker)
	Accident Risk-Injury
	Recreational activity
Socio-community	Appropriateness of future land use with respect to the community environment
	Enhancement of commercial/income-generating land uses
	Enhancement of recreational facilities
	Degree of "grass-roots" community outreach and involvement
	Time for completion of remediation & opening of park to public
	Degree of improvement in aesthetic value
Socio-economic	Economic impacts of project on community
	Damage to Property
	Effect on Tourism
	Disruption of businesses and local economy during construction / remediation
	Employment opportunities during construction / remediation
	Impact on fishing activities
Socio-environmental	Impact on Aquatic Habitat
	Degree of consumption of natural resources
	Degree to which proposed project will affect other media (i.e., emissions/air pollution resulting from soil or groundwater remediation)
	Effects of anthropogenic contaminants at "chronic" concentrations
	Effects of anthropogenic contaminants at "acute" concentrations

Table 5. Direct and indirect costs for remedial options

Remedial Option	MNA	Dredging and Disposal	Conventional Capping	Modified Capping
Direct Cost ($)	545,100	1,447,101	806,404	751,731
Cost of CO_2 ($)	1,498	18,151	6,779	11,156
Total Cost ($)	546,598	1,465,252	813,183	762,887

Table 6. Overall score obtained by the four remediation alternatives in social sustainability assessment

Impact Categories	MNA	Dredging and Disposal	Conventional Capping	Modified Capping
Socio-individual	17	12	13	8
Socio-community	24	14	15	7
Socio-economic	15	18	17	9
Socio-environmental	15	15	12	8
Total score	71	59	57	32

Note: Lowest score = best

Table 7. Requirements, Criteria and Indicators and their respective weightages used in MIVES methodology for overall sustainability assessment

Requirement	W requirement - %	Criteria	W criteria - %	Indicators	W indicator - %
Environmental	**33.33**	**Air**	**33**	Greenhouse gas emissions/Global warming (kg CO_2 eq)	**17**
				Ozone depletion (kg CFC-11 eq)	**17**
				Smog Formation (kg O_3 eq)	**17**
				Human health - Particulate (PM2.5eq)	**17**
				Human health - Cancer (CTUcancer)	**17**
				Human health - Noncancer (CTUnoncancer)	**17**
		Water usage and impacts	**33**	Acidification potential	**50**
				Eutrophication potential	**50**
		Energy	**33**	Non-renewable Energy use (manufacturing/construction, operation, etc.)	**50**
				Non-renewable Energy used for transportation	**50**
Economic	**33.33**	**Direct Costs**	**50**	Materials	**20**
				Labor	**20**
				Transport	**20**
				Equipment	**20**
				Waste treatment and/or disposal	**20**
		Indirect Costs	**50**	Social Cost of CO_2	**100**
Social	**33.33**	**Socio-Individual**	**25**	Overall health and happiness	**20**
				Population demographics (age, income)	**20**
				Contaminant Exposure (Trespasser, worker)	**20**
				Accident Risk-Injury	**20**
				Recreational activity	**20**
		Socio-Community	**25**	Appropriateness of future land use with respect to the community environment	**17**
				Enhancement of commercial/income-generating lan	**17**
				Enhancement of recreational facilities	**17**
				Degree of "grass-roots" community outreach and in	**17**
				Time for completion of remediation & opening of	**17**
				Degree of improvement in aesthetic value	**17**
		Socio-Economic	**25**	Economic impacts of project on community	**17**
				Truck Accidents (Damage to Property)	**17**
				Effect on Tourism	**17**
				Disruption of businesses and local economy during construction / remediation	**17**
				Employment opportunities during construction / re	**17**
				Impact on fishing activities	**17**
		Socio-Environmental	**25**	Impact on Aquatic Habitat	**20**
				Degree of consumption of natural resources	**20**
				Degree to which proposed project will affect other media (i.e., emissions/air pollution resulting from soil or groundwater remediation)	**20**
				Effects of anthropogenic contaminants at "chronic"	**20**
				Effects of anthropogenic contaminants at "acute" co	**20**

Table 8. Different case scenarios for the effect of relative preferences assigned to the three pillars of sustainability

	Weightage (%)		
	Environmental	Economic	Social
Case A	33.3	33.3	33.3
Case B	17	17	67
Case C	17	67	17
Case D	67	17	17

Figure Legends

Figure 1. Site location map

Figure 2. Cedar lake water source

Figure 3. Results of sampling events at Cedar Lake and location of area requiring further remediation

Figure 4. Conceptual design of (a) conventional capping and (b) modified capping

Figure 5. Environmental impact assessment of the four remediation options using TRACI method

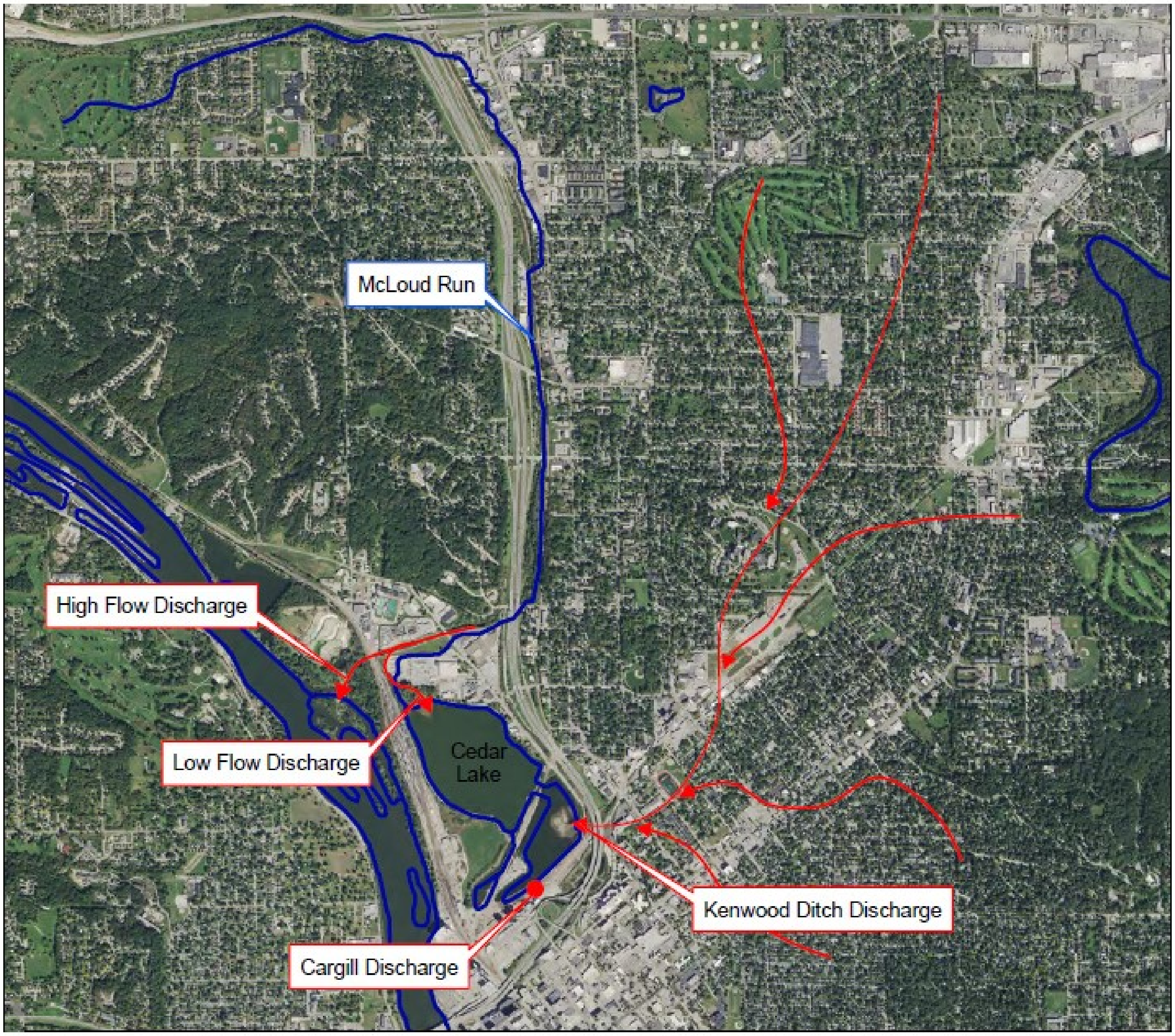
Figure 6. Environmental impact assessment of the four remediation options using BEES method.

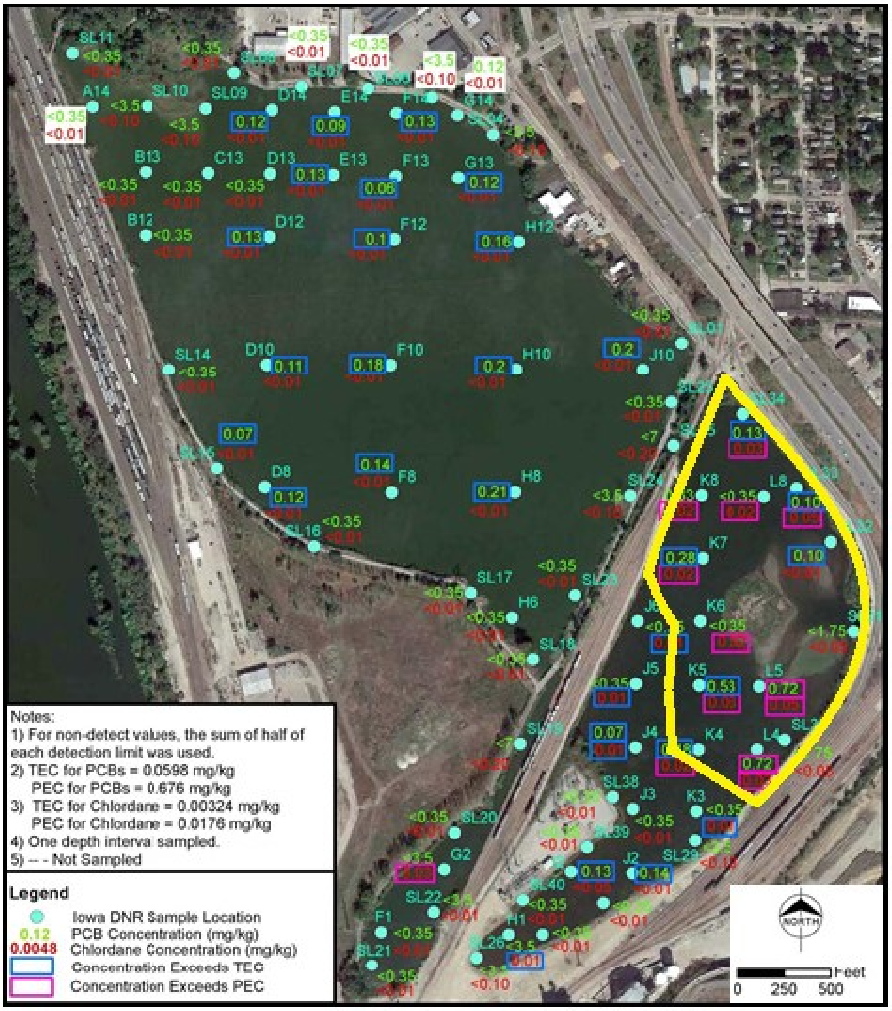
Figure 7. Environmental impact assessment of the four remediation options with 5 km transportation distance using TRACI method.

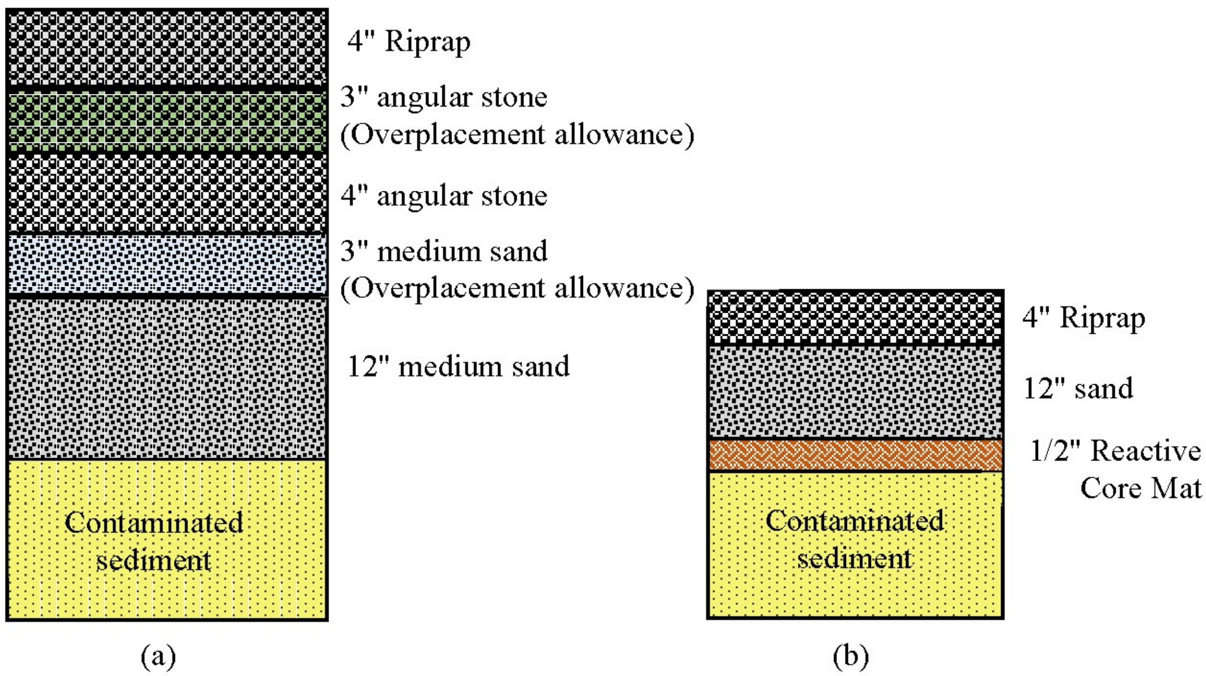
Figure 8. Schematic of MIVES methodology for evaluating sustainability index

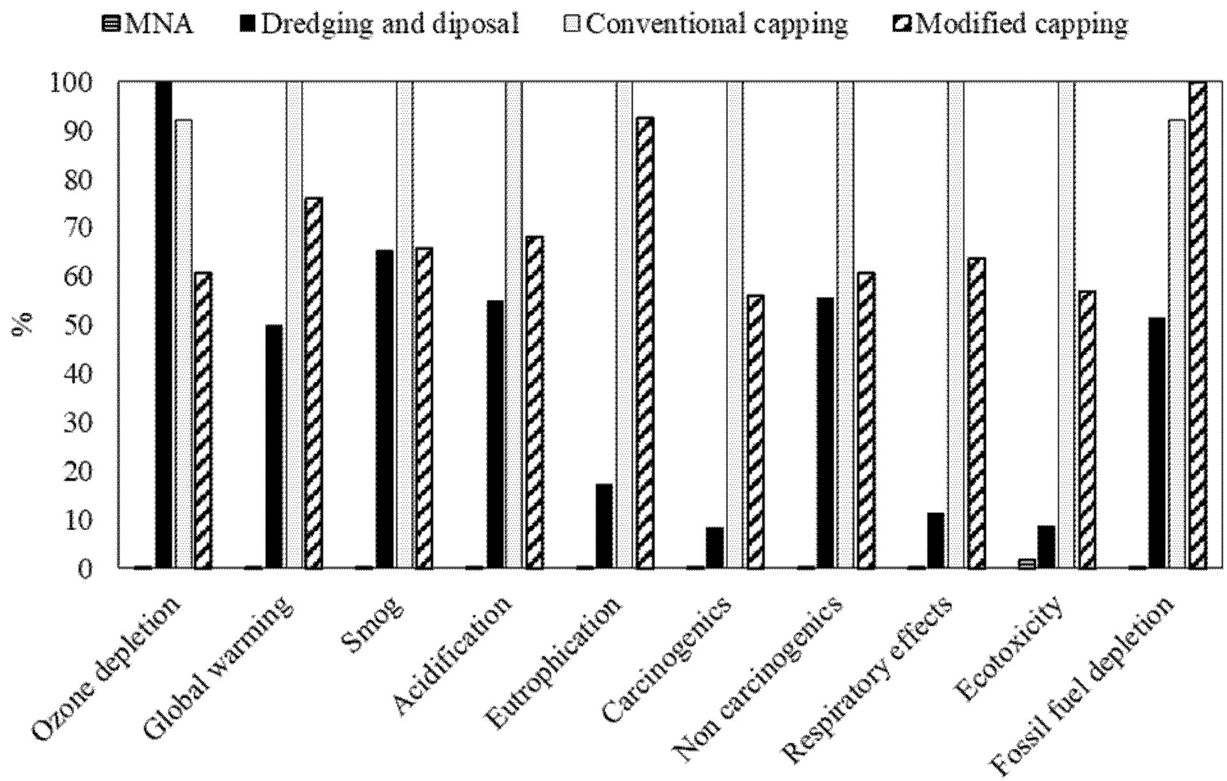
Figure 9. Overall sustainability assessment results a) Case A; b) Case B; c) Case C; and d) Case D

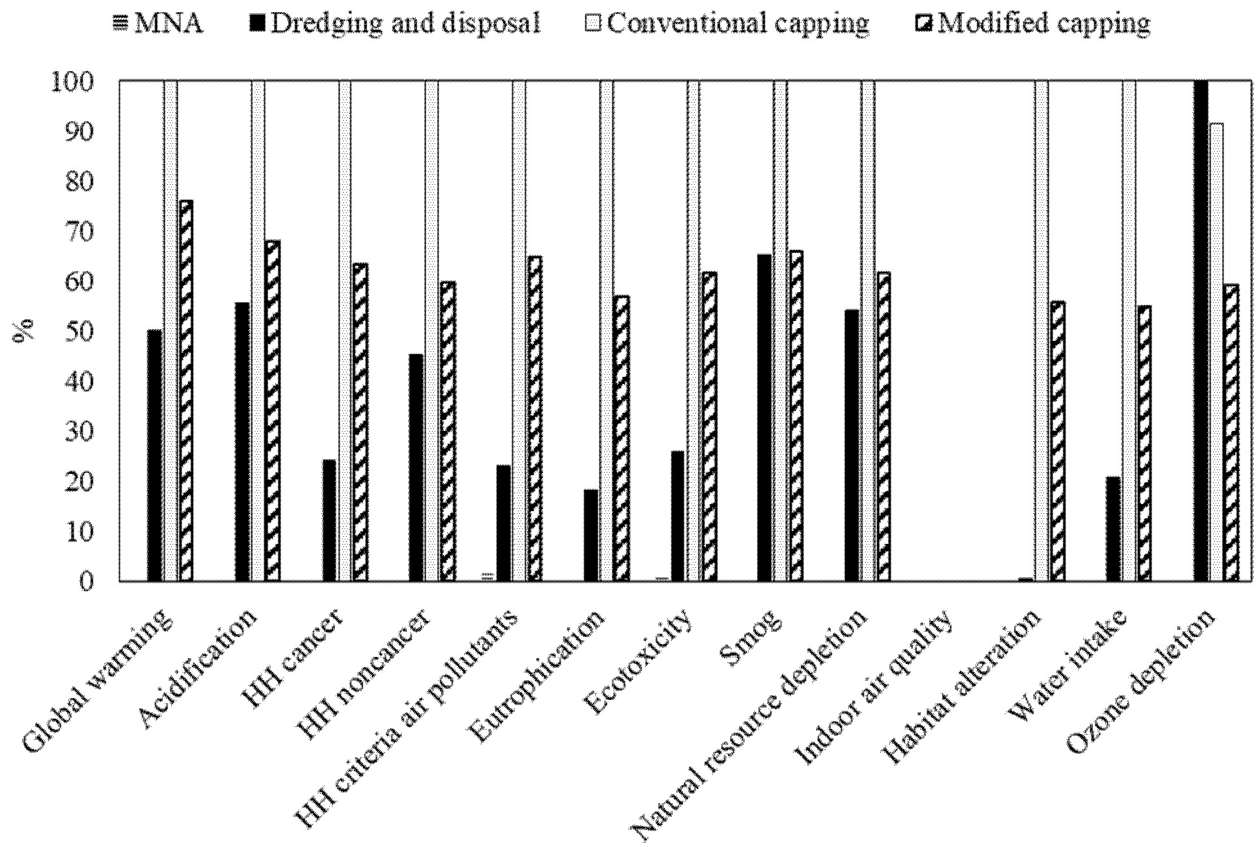
Imagery ©2018 Google, Map data ©2018 Google 1000 ft

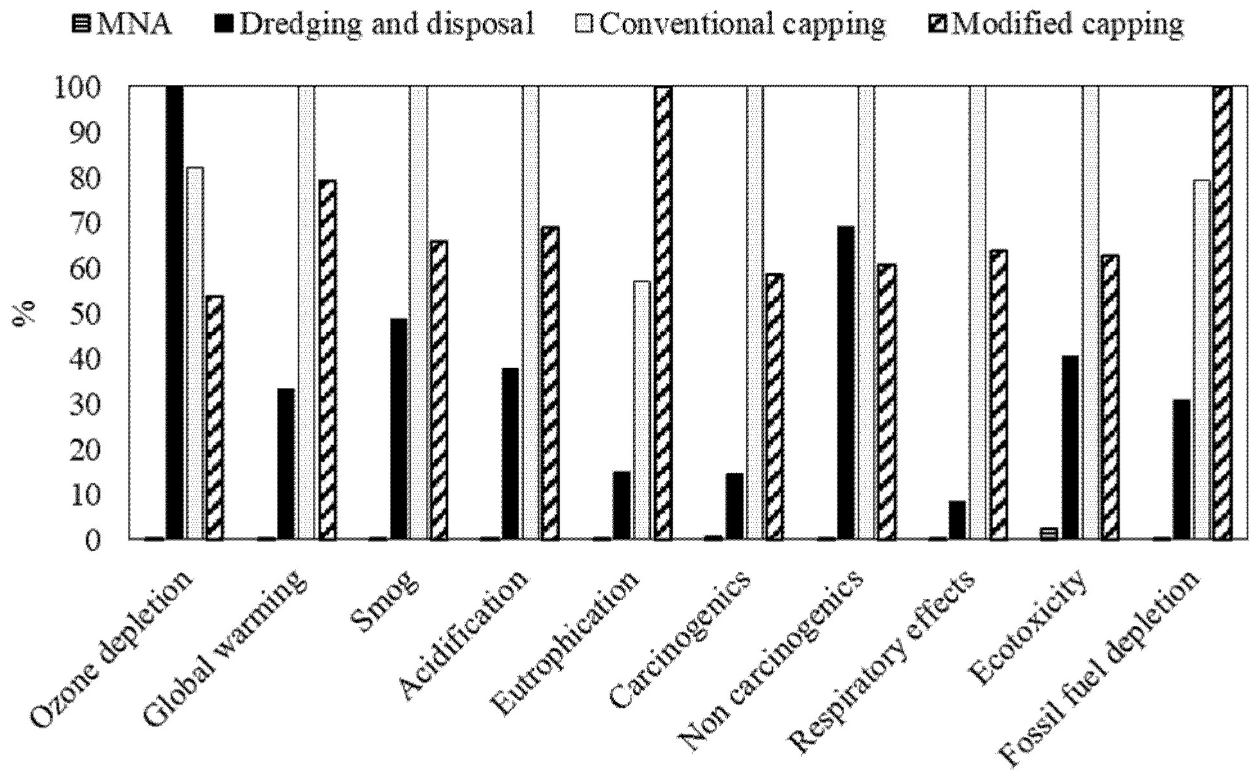

McLoud Run
High Flow Discharge
Low Flow Discharge
Cedar
Lake
Kenwood Ditch Discharge
Cargill Discharge


Notes:
1) For non-detect values, the sum of half of each detection limit was used.
2) TEC for PCBs = 0.0598 mg/kg
PEC for PCBs = 0.676 mg/kg
3) TEC for Chlordane = 0.00324 mg/kg
PEC for Chlordane = 0.0176 mg/kg
4) One depth interval sampled.
5) --- Not Sampled
Legend
Iowa DNR Sample Location
0.12 PCB Concentration (mg/kg)
0.0048 Chlordane Concentration (mg/kg)
Concentration Exceeds TEC
Concentration Exceeds PEC
NORTH
0 250 500 Feet

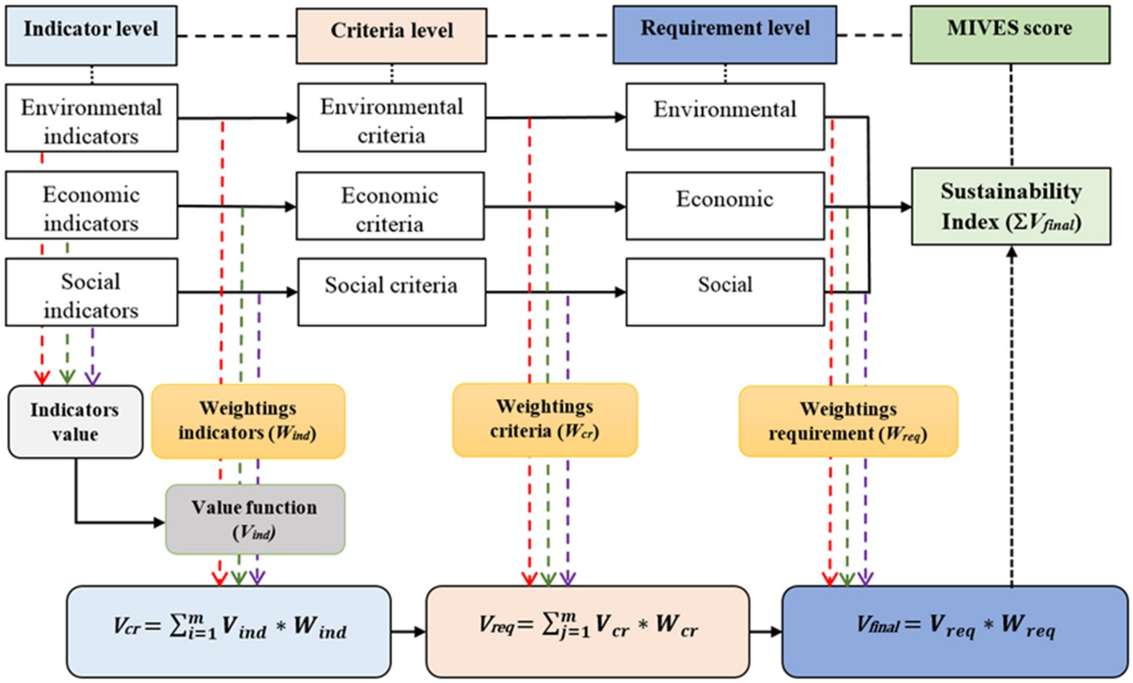

4" Riprap
3" angular stone
(Overplacement allowance)
4" angular stone
3" medium sand
(Overplacement allowance)
12" medium sand
Contaminated sediment
(a)
4" Riprap
12" sand
1/2" Reactive Core Mat
Contaminated sediment
(b)


MNA
Dredging and diposal
Conventional capping
Modified capping
%
100
90
80
70
60
50
40
30
20
10
0
Ozone depletion
Global warming
Smog
Acidification
Eutrophication
Carcinogenics
Non carcinogenics
Respiratory effects
Ecotoxicity
Fossil fuel depletion

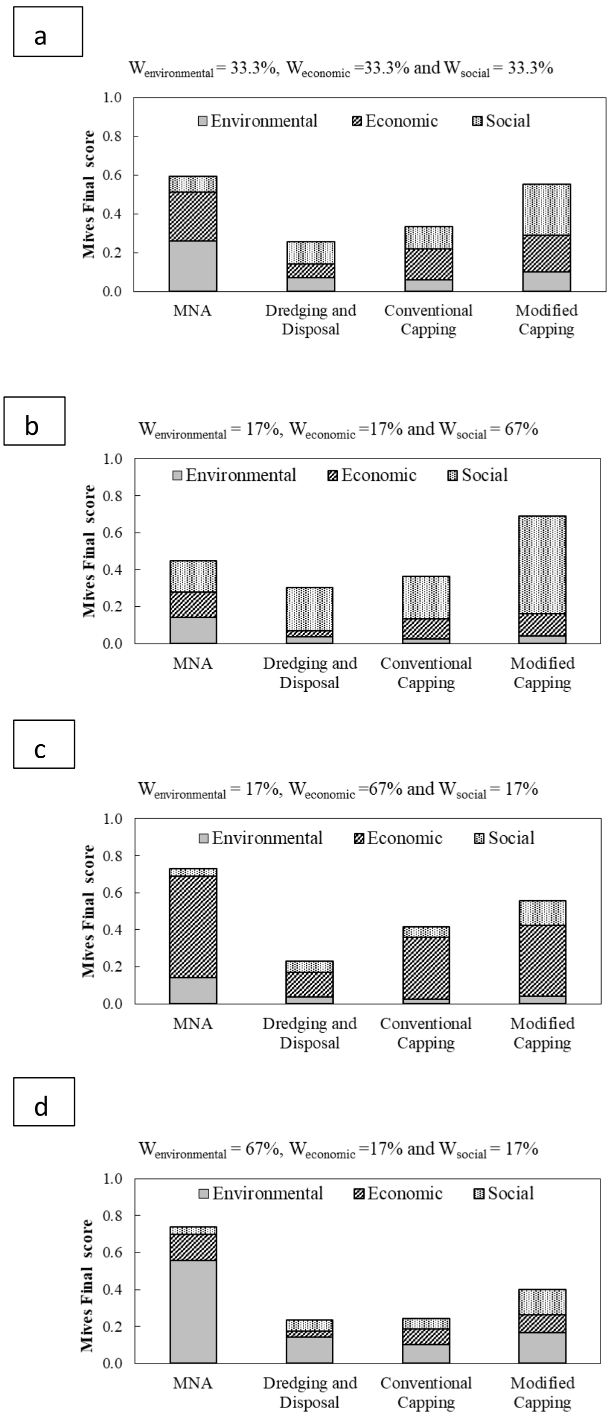

MNA
Dredging and disposal
Conventional capping
Modified capping
100
90
80
70
60
50
40
30
20
10
0
%
Global warming
Acidification
HH cancer
HH noncancer
HH criteria air pollutants
Eutrophication
Ecotoxicity
Smog
Natural resource depletion
Indoor air quality
Habitat alteration
Water intake
Ozone depletion



MNA
Dredging and disposal
Conventional capping
Modified capping
%
100
90
80
70
60
50
40
30
20
10
0
Ozone depletion
Global warming
Smog
Acidification
Eutrophication
Carcinogenics
Non carcinogenics
Respiratory effects
Ecotoxicity
Fossil fuel depletion



Indicator level
Criteria level
Requirement level
MIVES score
Environmental indicators
Environmental criteria
Environmental
Economic indicators
Economic criteria
Economic
Sustainability Index (ΣV_{final})
Social indicators
Social criteria
Social
Indicators value
Weightings indicators (W_{ind})
Weightings criteria (W_{cr})
Weightings requirement (W_{req})
Value function (V_{ind})
$V_{cr} = \sum_{i=1}^{m} V_{ind} * W_{ind}$
$V_{req} = \sum_{j=1}^{m} V_{cr} * W_{cr}$
$V_{final} = V_{req} * W_{req}$


a
$W_{environmental}$ = 33.3%, $W_{economic}$ =33.3% and W_{social} = 33.3%
Environmental
Economic
Social
Mives Final score
1.0
0.8
0.6
0.4
0.2
0.0
MNA
Dredging and Disposal
Conventional Capping
Modified Capping
b
$W_{environmental}$ = 17%, $W_{economic}$ =17% and W_{social} = 67%
Environmental
Economic
Social
Mives Final score
1.0
0.8
0.6
0.4
0.2
0.0
MNA
Dredging and Disposal
Conventional Capping
Modified Capping
c
$W_{environmental}$ = 17%, $W_{economic}$ =67% and W_{social} = 17%
Environmental
Economic
Social
Mives Final score
1.0
0.8
0.6
0.4
0.2
0.0
MNA
Dredging and Disposal
Conventional Capping
Modified Capping
d
$W_{environmental}$ = 67%, $W_{economic}$ =17% and W_{social} = 17%
Environmental
Economic
Social
Mives Final score
1.0
0.8
0.6
0.4
0.2
0.0
MNA
Dredging and Disposal
Conventional Capping
Modified Capping