CERCLA-Linked Environmental Impact and Benefit Analysis: Evaluating Remedial Alternatives for the Portland Harbor Superfund Site, Portland, Oregon, USA

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EDITOR’S NOTE:
This is 1 of 5 articles generated from the Portland Harbor Superfund Site Sustainability Project (PHSP). The Portland Harbor Superfund Site is one of the “mega-sediment sites” in the United States, comprising about 10 miles of the Lower Willamette River, running through the heart of Portland, Oregon. The primary aim of the PHSP was to conduct a comprehensive sustainability assessment, integrating environmental, economic, and social considerations of a selection of the remedial alternatives laid out by the US Environmental Protection Agency. A range of tools were developed for this project to quantitatively address environmental, economic, and social costs and benefits based upon diverse stakeholder values. In parallel, a probabilistic risk assessment was carried out to evaluate the risk assumptions at the core of the remedial investigation and feasibility study process.

ABSTRACT
This analysis focused on evaluating the environmental consequences of remediation, providing indicators for the environmental quality pillar of 3 “pillars” of the Portland Harbor Sustainability Project (PHSP) framework (the other 2 pillars are economic viability and social equity). The project an environmental impact and benefit analysis (EIBA) and an EIBA-based cost–benefit analysis. Metrics developed in the EIBA were used to quantify and compare remedial alternatives’ environmental benefits and impacts in the human and ecological domains, as a result of remedial actions (relative to no action). The cost–benefit results were used to evaluate whether remediation costs were proportionate or disproportionate to the environmental benefits. Alternatives B and D had the highest overall benefit scores, and Alternative F was disproportionately costly relative to its achieved benefits when compared to the other remedial alternatives. Indeed, the costlier alternatives with larger remedial footprints had lower overall EIBA benefit scores—because of substantially more air emissions, noise, and light impacts, and more disturbance to business, recreational access, and habitat during construction—compared to the less costly and smaller alternatives. Put another way, the adverse effects during construction tended to outweigh the long-term benefits, and the net environmental impacts of the larger remedial alternatives far outweighed their small incremental improvements in risk reduction. Results of this Comprehensive Environmental Response Compensation and Liability Act (CERCLA)-linked environmental analysis were integrated with indicators of economic and social impacts of remediation in a stakeholder values–based sustainability framework. These tools (EIBA, EIBA-based cost–benefit analysis, economic impact assessment, and the stakeholder values–based integration) provide transparent and quantitative evaluations of the benefits and impacts associated with remedial alternatives, and should be applied to complex remediation projects to aid environmental decision making. Integr Environ Assess Manag 2018;14:22–31. © 2017 The Authors. Integrated Environmental Assessment and Management published by Wiley Periodicals, Inc. on behalf of Society of Environmental Toxicology & Chemistry (SETAC).

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INTRODUCTION
The present analysis focused on evaluating the environmental consequences of remediation, providing indicators for the environmental quality pillar of 3 “pillars” of the Portland Harbor Sustainability Project (PHSP) framework (the other 2 pillars are economic viability and social equity). It
included an environmental impact and benefit analysis (EIBA) and an EIBA-based cost–benefit analysis. The PHSP framework was used to quantitatively evaluate indicators of impacts of 6 remedial alternatives A, B, D, E, I, and F, as presented in the 2016 US Environmental Protection Agency (USEPA) Portland Harbor Superfund Site Feasibility Study (herein called the “2016 USEPA FS”) (USEPA 2016) Proposed Plan (PP), summarized in Table 1. The Portland Harbor Superfund Site (PHSS, the “Site”) consists of about 10 miles of the Lower Willamette River immediately downstream of downtown Portland, Oregon, USA, and is managed by USEPA under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA, 1980; USEPA 1988). The remedial alternatives include a combination of remediation technologies—dredging, capping, enhanced natural recovery (ENR), in situ treatment, and monitored natural recovery (MNR). They range in cost from about US $642 million to almost $2.2 billion and may require up to 13 y of construction.

In the context of environmental remediation projects, a key objective of sustainability is to demonstrate that benefits of remediation outweigh impacts (SuRF-UK 2011), thereby enabling sustained future use of limited resources. Furthermore, sustainability should be considered during all phases of a project, including remedy selection (Ellis and Hadley 2009). The 2016 USEPA FS excluded sustainability concepts, although several USEPA documents encourage the implementation of strategic actions to reduce environmental impacts of cleanup actions (USEPA 2009, 2010) and reinforce the value of including sustainability considerations in decision-making processes (NRC 2011, 2014). Although other guidance documents describe frameworks for and approaches to sustainable remediation, including those by the US Navy (NAVFAC 2012), the Sustainable Remediation Forum (SuRF-UK) (Holland et al. 2011; SuRF-UK 2011), the Interstate Technology and Regulatory Council (ITRC 2011a, 2011b), and ASTM International (ASTM 2013a, 2013b), few of these have been implemented for managing contaminated sediments. At the Ninth International Conference on Remediation and Management of Contaminated Sediments in January 2017, however, the incorporation of sustainability, cost-effectiveness, and cost–benefit analyses into sediment remediation decisions was a key theme.

The CERCLA process (USEPA 1988) defines a set of threshold and balancing criteria that must be applied during the selection of remedial alternative. In terms of sediment remediation, these criteria define potentially competing objectives that must be balanced in decision making, but are often only qualitatively addressed (e.g., USEPA 2016), making transparent, systematic decision making problematic. The EIBA provides a framework for quantitatively comparing the performance of alternatives in terms of CERCLA criteria. The EIBA-based cost–benefit analysis highlights the proportionality of the implementation costs to the environmental benefits achieved (DOE 2003; NAVFAC 2012) by each alternative. Implementation costs were considered disproportionate to benefits when the incremental costs of the alternative exceeded the incremental benefits achieved by the alternative, compared to benefits achieved by other lower-cost alternatives. Results can be used to evaluate and optimize environmental trade-offs, in conjunction with human and ecological risk assessment, stakeholder values, and regional economic drivers (see Ruffle et al. this issue, Apitz et al. this issue, and Harrison et al. this issue), for selection of a sustainable remedy.

**METHODS**

The environmental benefits were assessed for each remedial alternative by calculating an overall benefit score aligned with the CERCLA framework through several aggregation steps. The first step was to select metrics to assess alignment of remedial alternatives. Environmental metrics were selected with input or guidance from the USEPA (USEPA 2010), US Navy (NAVFAC 2012), Lower Duwamish Final FS (AECOM 2012) (where a similar framework was

| Remedial alternative nr | USEPA (y) | AECOM (y) | Dredge volume (cy) | Dredge and dredge/cap (acres) | Capping (acres) | ENR (acres) | In-situ treatment (acres) | MNR (acres) | Total costs (US$ millions) |
|------------------------|-----------|-----------|-------------------|-------------------------------|----------------|-------------|-------------------------|-------------|--------------------------|
| A (no action)          | 0 0       | NA        | NA                | NA                            | NA             | NA          | NA                      | NA          | —                        |
| B                      | 4 5       | 576 883   | 72                | 23                            | 100            | 7           | 1966                    | 1051        |
| D                      | 6 8       | 1 108 046 | 132               | 45                            | 87             | 3           | 1900                    | 1355        |
| E                      | 7 13      | 1 928 136 | 204               | 66                            | 60             | 0           | 1838                    | 1758        |
| F                      | 13 26     | 4 462 574 | 387               | 118                           | 28             | 0           | 1634                    | 2969        |
| I                      | 7 11      | 1 649 750 | 167               | 64                            | 60             | 0           | 1876                    | 1644        |

cy = cubic yards; ENR = enhanced natural recovery; MNR = monitored natural recovery; USEPA = US Environmental Protection Agency.

All data extracted from the 2016 USEPA FS, except construction length estimates and costs, which were developed by AECOM. Total study area is 2167 acres. Total costs are AECOM-adjusted costs (nondiscounted) based on longer estimated construction times from recent local project experience.
developed and accepted by USEPA Region 10), and Portland Harbor stakeholders. Each metric was linked to 1 of 6 CERCLA evaluation criteria:

1) overall protectiveness of human health and the environment (threshold criterion);  
2) reduction of toxicity, volume, or mobility;  
3) long-term effectiveness and permanence;  
4) management of short-term risks;  
5) implementability (balancing criteria); and  
6) consideration of public concerns (modifying criterion) (USEPA 1988).

Cost is the seventh of the USEPA’s 9 CERCLA evaluation criteria; however, this analysis compared the benefits relative to the costs; therefore, costs were not scored. The other 2 USEPA CERCLA criteria, compliance with applicable or relevant and appropriate requirements (ARARs) and state acceptance, although not included in the present analysis, are critical components of the remedy selection process. Compliance with ARARs was not considered a sensitive endpoint for the present analysis. State acceptance is generally evaluated following the publication of the PP; the present study was conducted concurrently with the State of Oregon’s review.

The selected metrics (see Supplemental Data) are measurable “indicator” values that correlate with a parameter of interest (e.g., air emissions as an indicator of short-term risks). Each metric was quantified using available and measurable data (see Data extraction and quantification methods for quantification tools) and given a benefit score from 0 (poor performance) to 10 (optimal performance) so disparate metrics could be aggregated. The benefit scores were scaled in proportion to the quantitative range for a given metric. One endpoint was no action or baseline, and the other endpoint was the largest-scope alternative or, when available and appropriate, a target risk level (e.g., the desired cleanup goal had a benefit score of 10). For example, PCB mass removal ranged from 0 to 289,305 kg PCBs; 0 kg PCB (Alternative A, no action) removal was assigned a score of 0, and 289,305 kg PCB (Alternative F) was assigned a score of 10; the other alternatives were scaled proportionally among them (see Supplemental Data). Depending on the basis for a metric’s scale, the alternatives may not always cover the full range (0 to 10) if they all have less-than-optimal results for that measure. There were no negative scores in the present analysis.

Each environmental metric was weighted according to its relative importance or contribution to the given evaluation criteria, with input from various stakeholders and precedent from other large cleanups; weighting approaches and their consequences were reviewed in a previous application of these tools (AECOM 2012). Then, the weighted averages of the metric scores provided “benefit scores” for each CERCLA evaluation criterion. The threshold criterion was weighted at 25%, balancing criteria were weighted equally at 16.25%, and the modifying criterion was weighted at 10%. Finally, a weighted average of the criteria scores generated a total overall benefit score; this was compared to total cost for each remedial alternative.

Data extraction and quantification methods

Environmental metrics used in the EIBA, listed in Table 2, were quantified for Portland Harbor Remedial Alternatives B, D, E, F, and I by 1) evaluating environmental footprints with SiteWise™ NAVFC 2015; 2) extracting data from the 2016 USEPA FS (when possible) and the 2015 Draft Final USEPA FS (herein called the “2015 USEPA FS”) (USEPA 2015); and 3) quantifying construction disturbances with geographic information system (GIS) mapping.

The environmental footprint included greenhouse gas (GHG) and air pollutant emissions, waste generation, and worker safety risks. These were quantified in SiteWise Version 3.1, a series of publicly available Microsoft Excel spreadsheets used to calculate the environmental footprint of remediation activities (NAVFC 2015), using remedial alternative design characteristics from USEPA (2016) as model inputs.

Table 2. CERCLA-linked environmental metrics used in this analysisa

| 1. Overall protectiveness | 1a. Exposure at the end of construction | 1b. Risks from implementation |
|---------------------------|---------------------------------------|-----------------------------|
| 2. Reduction of toxicity, mobility, or volume | 2a. Contaminated surface sediment left on site | 2b. Reduction in mobility of hazardous substances |
| 3. Long-term effectiveness and permanence | 3a. Human health risks | 3b. Ecological risks |
| 3c. Remedy success certainty | 3d. Reliability of institutional and engineering controls |
| 4. Short-term risks | 4a. Community risks | 4b. Disturbances during construction |
| 4c. Worker accident risk | 5. Implementability | 5a. Ability to construct and operate |
| 5b. Ability to monitor effectiveness | 5c. Availability of specialists, equipment, and materials |
| 6. Consideration of public concerns | 6a. Stakeholder/community values and public acceptance |
| 7. Cost | Total cost (used in cost/benefit ratio) |

*aMany of these metrics have multiple measurements.
Most data used to quantify metrics, such as the spatial extent of technology assignments, site-wide surface weighted average concentrations (SWAC), and human and ecological risk immediately postconstruction were directly extracted from the 2016 USEPA FS. The estimated costs and construction times used in the present analysis were based on those in the 2016 USEPA FS but were adjusted by AECOM based on field-validated inputs from other Pacific Northwest projects. Key adjustments included longer construction time, lower production rates, and increased oversight and management costs.

Construction-related disturbances were quantified using GIS based on the area of overlap between active (defined as the sum of dredging, capping, treatment, and ENR) remedial footprints and areas of water-related infrastructure, business, recreational, and habitat areas or shorelines. Footprints for Alternatives B, D, E, and F were extracted from the 2015 USEPA FS; the footprint for Alternative I was extracted from the 2016 USEPA FS. Shoreline marine and rail infrastructure necessary for business operations and access were obtained from City of Portland Planning Department maps (City of Portland 2007). Water-dependent businesses were represented by overwater structures such as docks, piling, marinas, and piers (Anchor QEA 2012). Recreational access included beach areas for human health direct contact scenarios, shoreline public parks, and boat launch areas (Kennedy/Jenks 2013; City of Portland 2014). Nearshore high-value habitat, defined by National Oceanic and Atmospheric Administration (NOAA 2017), extends from the top of the bank (+13 feet North American Vertical Datum of 1988 [NAVD88]) to the bottom of the main channel shallow water zone (–15 feet NAVD88).

Environmental impact and benefit analysis evaluation criteria and metrics

The following evaluations provide the basis for the numerical scoring and weighting of each metric in the EIBA. As listed in Table 2, each metric was mapped to 1 of the 9 CERCLA criteria.

- **Exposure at the end of construction** (Metric 1a, 4/5 weighting): The average reduction in site-wide SWACs for the focused contaminants of concern (COCs) immediately after construction. The focused COCs include total polychlorinated biphenyls (PCBs), total polycyclic aromatic hydrocarbons (PAHs), total dioxins/furans, and sum (DDx) of dichlorodiphenyldichloroethane (DDT), dichlorodiphenyldichloroethylene (DDE), dichlorodiphenyldichloroethane (DDD). Natural recovery was not factored into the ranking (USEPA has not considered natural recovery in its FS due to uncertainties in models).

- **Risks from implementation** (Metric 1b, 1/5 weighting): Construction time was used as a surrogate for short-term risks to the community, construction workers, and the environment.

- **Reduction in the mass of contamination** (Metric 2a, 1/3 weighting): The magnitude of subsurface contamination remaining in place was inversely related to the mass of PCB contamination removed.

- **Reduction in mobility of hazardous substances** (Metric 2b, 2/3 weighting): Reduction was based on the weighted average of the acreage for each active technology used in the cleanup area.

- **Human carcinogenic and noncancer risks** (Metric 3a, weighting 1/3): The sediment-related human health risk predicted to remain on site immediately after construction. Time-0 postconstruction risks, defined as the risks present immediately following completion of active remedial construction, were calculated in the human health risk assessment (Kennedy/Jenks 2013). Human health risks included direct contact for the tribal fisher and consumption of contaminated fish and shellfish by the subsistence adult, subsistence child, and nursing infant for the following risk-driver chemicals: PCBs, dioxins and furans, As, PAHs, and DDX. Because each remedial alternative has a different construction length, Time-0 referred to a different date for each alternative. In contrast, residual risk was defined as the risk that will remain on site after the remediation goals have been achieved (e.g., 30 y after remediation); residual risks over time were not evaluated in the 2016 USEPA FS, so the EIBA incorporated data from the 2012 Draft FS.

- **Ecological risks** (Metric 3b, weighting 1/3): The postconstruction ecological risk was based on direct contact with COCs in sediment (the area with unacceptable benthic surface sediment risk remaining after construction) and ingestion through the food chain (maximum hazard quotient of the focused COCs) (Windward Environmental 2013). Risk-driver chemicals for ecological receptors via direct contact and fish and shellfish ingestion included PCBs, total PAHs, DDX, and dioxins.

- **Degree of certainty that the remedial alternatives will be successful** (Metric 3c, weighting 1/6): This metric was based on the total capping and dredging acres, assuming that the remedial technologies depending only on isolation or removal (i.e., capping and dredging) have a higher degree of certainty of success than remedial technologies that depend on natural recovery (i.e., ENR and MNR). The larger alternatives have more certainty that the technologies applied will be successful.

- **Reliability of institutional controls (ICs) and engineering controls** (Metric 3d, weighting 1/6): Because all remedial alternatives will rely on ICs to manage residual risk, reliability was scored on the basis of engineering controls (scores were inversely proportional to the surface area for which buried contamination remains on site).

- **Community risks** (Metric 4a, weighting 1/4): Risks related to construction were based on the volume of material removed, handled, and placed at the site and the total air emissions (i.e., GHGs, nitrogen oxides, sulfur oxides, and particulate matter).

- **Disturbance during construction** (Metric 4b, weighting 1/4): Calculated as the active remedial footprint overlap with shoreline area that would disrupt infrastructure
access, water-dependent business, recreational access, and habitat.

- Worker accident risks during construction (Metric 4c, weighting 1/4): Related to the accident (injury and fatality) risks from construction (quantified in SiteWise, based on accident statistics for representative job sectors).
- Effectiveness of the protective measures (Metric 4d, weighting 1/4): The effectiveness of protective measures such as ICs and best management practices that would be used to mitigate construction risks was assumed to be inversely proportional to the construction time.
- Ability to construct and operate (Metric 5a, weighting 1/3): The ability to construct and operate was related to the materials handling volume because larger alternatives are more logistically difficult.
- Ability to monitor effectiveness (Metric 5b, weighting 1/3): The amount of long-term monitoring that will be required for each alternative was proportional to the total area with contamination remaining on site (the sum of the cap, in situ treatment, ENR, and MNR acreage).
- Availability of specialists, equipment, and materials (Metric 5c, weighting 1/3): Availability was assumed to be proportional to the size and complexity of the remedy, which was directly related to the number of barge and rail loads necessary for delivery and removal.
- Community acceptance (Metric 6): The social equity score of community values from the stakeholder values–based assessment (Apitz et al. this issue) was used in the EIBA for scoring the “consideration of public concerns” criterion. Community values included stakeholder involvement, communication of uncertainty, archaeological site disturbance, and economic, recreational, Native American, and in-water reuse potential.
- Costs: Nondiscounted total remedy costs, ranging from $1.1 billion (Alternative B) to $3.0 billion (Alternative F), estimated by AECOM using remedial alternative design parameters from USEPA (2016) and in-house costing tools, were used in the EIBA analysis.

RESULTS AND DISCUSSION

The aggregation of environmental impact metrics into CERCLA-linked EIBA scores was used to evaluate the net CERCLA-linked benefits of each alternative and to determine whether the remedy costs were disproportionate to the benefits achieved by the alternative. These are important aspects of remedial decision making on their own; these metrics are then further integrated with indicators of impact to economic and social stakeholder values to generate an assessment of stakeholder value–linked sustainability of remedial alternatives (Apitz et al. this issue).

Environmental metrics results

For Time-0 postconstruction risks immediately after construction (Note: USEPA did not estimate residual risk over time in the 2016 USEPA FS), the increased costs of the larger alternatives did not correspond proportionally to increases in human health benefit and risk reduction. Alternative B had the largest risk reduction for the cost (Figure 2). However, none of the alternatives would achieve background risk of (8 × 10⁻⁶) immediately postconstruction, one of the remedial action objectives identified in the 2016 USEPA FS. To further evaluate the postconstruction risks at the Site calculated by the deterministic baseline human health risk assessment (Kennedy/Jenks 2013), a separate probabilistic risk analysis was completed and is summarized in a companion article (Ruffle et al. this issue). The findings of the Ruffle et al. analysis indicate that the earlier deterministic approach overstated the current baseline risks and hazards for most anglers.

The environmental footprints of remedial alternatives (Figures 1a and 1b) were proportional to the size of the active remedial footprints. As expected, larger dredge volumes and longer construction periods generated greater quantities of waste requiring transportation, which led to larger environmental impacts. In terms of waste generation, each of the alternatives (except no action) generates the same quantity of hazardous waste. The higher waste quantities for larger alternatives were attributed to nonhazardous material—Alternative F generated more than 10 × the quantity of nonhazardous waste as did Alternative B (see Supplemental Data).

Up to 54% of water-dependent shoreline infrastructure, 22% of overwater business operations, 40% of recreational shoreline, and 39% of the potential habitat area would be impacted by the remedies. Alternative F would have greater than 2 × more impact and disturbance compared to Alternative B.

Figure 3 shows that although SWAC reduction (total return) achieved by each remedial alternative increased as more money was spent, the amount of SWAC reduction achieved for each dollar spent (average return) decreased; this indicated that Alternative B provided the most SWAC reduction per dollar spent and the larger-scale alternatives did not achieve SWAC reductions proportional to the amount of money spent. Figures 2 and 3 illustrate that there was also a point of diminishing returns in the risk–benefit of the larger remedial alternatives.

Environmental impact and benefit analysis cost–benefit results

The total benefit scores for Alternatives B through F, tabulated in Table 3, ranged from 1.5 to 5.3. These aggregate scores (scaled from 0 to 10) provided a quantitative approach to evaluating remedial alternatives in terms of the CERCLA-linked environmental benefits of the cleanup, addressing both the desirable and undesirable impacts of each alternative. Alternatives B (5.3 score) and D (4.1 score) had the highest environmental benefit scores among the alternatives evaluated. Alternative B provided the highest benefit per dollar spent, and more expensive alternatives did not show proportional increases in overall benefit (Figure 4a). Figure 4b illustrates that Alternative B “dominates” the other alternatives; it achieved the most benefit compared to the alternative.
larger alternatives (D, E, F, and I) at a lower cost. The overall benefit scores were lower for larger alternatives, indicating that more dredging had substantial adverse effects during construction that tended to outweigh the long-term benefits.

Collectively, Figures 2 through 4b illustrate various approaches to identifying where costs may be disproportionate to benefits. The results indicate that Alternative B would be the most cost-effective remedy and that Alternative F is

Figure 1a. Environmental footprint normalized impacts. Environmental footprint metrics were quantified in SiteWise™ and normalized to the largest alternative footprint evaluated (Alternative F). GHG = greenhouse gas; NOx = nitrogen oxide; PM = particulate matter; SOx = sulfur oxide.

Figure 1b. Greenhouse gas emissions by construction activity. The total GHG, expressed in tons of CO2e for each remedial alternative, are presented with contributions from materials production, waste and equipment transportation, equipment use, and residual handling (dewatering and disposal). CO2e = carbon dioxide equivalents; GHG = greenhouse gas.
disproportionately costly compared to its benefits in relation to the other remedial alternatives. The net environmental impacts of the more aggressive alternatives far outweighed their small incremental improvements in risk reduction.

Sensitivity analysis

A sensitivity analysis was conducted for 5 different variables including weighting of 6 CERCLA criteria, USEPA versus AECOM cost estimates, rail versus barge transport to

Figure 2. Fish and shellfish consumption risk versus cost for remedial alternatives. The subsistence angler cumulative carcinogenic postconstruction risks as a result of consuming fish and shellfish (RAO 2) are plotted versus estimated remedy costs (0% discount) for remedial alternatives (A through F). The increased cost of the larger alternatives does not show large proportional increases in human health benefit. EPA = US Environmental Protection Agency.

Figure 3. Total cost versus cumulative SWAC reduction. Cost-effectiveness calculated using remedial costs (0% net present value; adjusted by AECOM) and postconstruction Time-0 SWACs. Alternative B is the point of departure after which costs continue to increase, but additional return, measured in terms of reduction in SWAC, is not achieved for larger alternatives. SWAC = surface weighted average concentrations.
the landfill, use of an on-site landfill, and dredge production rates. The results of the EIBA were calculated with various weighting schemes—unweighted (equal), exclusion of overall protectiveness (because it is a threshold criterion), and an alternate weighting scheme accepted previously by USEPA Region 10 (AECOM 2012). Based upon these sensitivity findings, the conclusions presented are robust. Of note, transporting waste to a landfill via rail (vs barge and truck) for Alternative I would reduce GHG emissions by 20,228 metric tons (32% reduction for waste transportation) and worker accident risk by at least 11 recordable injuries. However, the ranking of the alternatives did not change when the metrics were adjusted for the alternate waste transportation scenarios.

Limitations and uncertainty

The PHSP was conducted following the issuance of the FS and PP, prior to the signing of the Record of Decision (ROD) (USEPA 2017) for the Site. As such, the PHSP did not address state acceptance information (which was not available at the time of the project) and did not include the data provided in the responsiveness summary following the PP public comment period. The timing of the PHSP also limited the team’s ability to incorporate stakeholder comments into the development of more sustainable remedial alternatives. Approaches to addressing stakeholder priorities are discussed in Apitz et al. (this issue). Additionally, the effects of MNR processes on the Time-0 SWACs and estimates for residual risk over time were not characterized in the 2016 USEPA FS. Such uncertainties can result in highly overconservative risk assessments (e.g., von Stockelberg et al. 2008).

Some of these uncertainties are addressed in Ruffle et al. (this issue). Despite these limitations, the risk assumptions within USEPA (2016) were applied in the metric development for the present project, and thus these broader issues could not be addressed in the present analysis, though the resolution of this uncertainty would likely have a meaningful effect on the long-term effectiveness criteria, and thus on the results of the EIBA.

CONCLUSIONS

The EIBA utilized cost-effectiveness (SWAC and risk reduction curves) and cost–benefit tools (based on EIBA scores) to evaluate whether CERCLA criteria-linked benefits of Portland Harbor remedial alternatives were proportional to their costs. Alternatives B and D had the highest overall benefit scores, and Alternative F was disproportionately costly compared to the benefits relative to the other remedial alternatives. The net environmental impacts of the larger remedies far outweighed their small incremental improvements in risk reduction. Additionally, without a calibrated fate and transport model (USEPA 2016) to estimate residual risks over time, there is limited basis for selection of a larger alternative over Alternative B or D.

Results of this CERCLA-linked environmental analysis were integrated with indicators of economic and social impacts of the PHSP remediation in a stakeholder values–based sustainability framework for evaluating trade-offs when making remedy decisions (Apitz et al. this issue). The CERCLA-linked framework applied in the PHSP should be applied to sediment remediation projects to aid environmental decision making. The present analysis is

| Evaluation criteria                                      | Weighting factor | Remedial alternatives and benefit scores |
|---------------------------------------------------------|------------------|----------------------------------------|
| Overall protectiveness of human health and the environment | 25%              | A 2.0 B 7.5 C 8.0 D 8.2 E 8.0 F 8.0 |
| Reduction of toxicity, mobility, or volume               | 16%              | A 0.0 B 1.9 C 2.5 D 3.3 E 5.2 F 3.0 |
| Long-term effectiveness and permanence                   | 16%              | A 0.0 B 5.0 C 5.8 D 6.2 E 6.9 F 6.0 |
| Management of short-term risks                           | 16%              | A 10.0 B 7.4 C 6.2 D 4.5 E 0.0 F 5.0 |
| Implementability                                         | 16%              | A 10.0 B 5.5 C 4.8 D 3.7 E 0.5 F 3.7 |
| Consideration of public concerns                         | 10%              | A 5.1 B 5.1 C 5.1 D 5.1 E 5.0 F 5.1 |
| Total weighted environmental benefit score               | 10%              | A 4.3 B 5.6 C 5.6 D 5.4 E 4.5 F 5.4 |
| Total costs (US$ millions nondiscounted)                 | NA               | A 1051 B 1355 C 1758 D 2969 E 1644 |
| Benefit/cost (benefit points per US$ billion)            | NA               | A 5.3 B 4.1 C 3.1 D 1.5 E 3.3 F 3.3 |

ARARs = applicable or relevant and appropriate requirements; CERCLA = Comprehensive Environmental Response Compensation and Liability Act; EIBA = environmental impact and benefit analysis.

aThe remedial alternatives are scored on linear scale of 0 to 10 based on quantitative, aggregated, weighted, metric scores. Metric scores are aggregated into CERCLA criteria scores, then summed into a total overall score based on the criteria weighting factor. A score of 0 represents the lowest benefit or a poor performing alternative. A score of 10 represents the highest benefit or an excellent performing alternative, then normalized into a bang-for-the-buck (benefit/cost) score. Alternative B provides the most benefit per dollar spent. Two CERCLA criteria are not included in the ranking: 1) “Compliance with ARARs” is not included because it was an insensitive metric; 2) “State Acceptance” is not evaluated. “Cost” is not ranked but used in denominator of benefit/cost ratio. Total costs are nondiscounted and adjusted by AECOM on longer estimated construction times from recent local project experience.
intended to support the required CERCLA analysis, but represents a paradigm shift toward more quantitative and transparent stakeholder value–focused evaluation that incorporates metrics of importance to a broad base of community stakeholders. These tools described here, including EIBA, EIBA-based cost–benefit analysis, economic impact assessment, and the stakeholder values–based integration, are consistent with established sustainability frameworks and guidance; they support balanced and transparent decision making and should be applied on a project-specific basis, considering stakeholder priorities at a given site.

![Figure 4a](image)

**Figure 4a.** Benefits and costs for remedial alternatives. The net environmental benefit scores range between 4 and 6 (scaled 0 to 10), but total remedy costs and construction time increase with successively larger alternatives. More expensive alternatives did not show proportional increases in benefits. Costs adjusted by AECOM are based on longer estimated construction times from recent local project experience. EPA = US Environmental Protection Agency.

![Figure 4b](image)

**Figure 4b.** Benefit scores versus costs for remedial alternatives. Cost–benefit shown as a weighted environmental benefit score plotted against remedy costs. Alternative B provides the most benefit for the cost and is the point of diminishing return compared to the larger alternatives (D, E, F, and I). Costs adjusted by AECOM are based on longer estimated construction times from recent local project experience.
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Data Accessibility—Data and associated metadata and calculation tools for this research are available upon request from the corresponding author Amanda McNally at amcnally@geosyntec.com. A PDF of the full report submitted to USEPA Region 10 is available online as part of the public comment submittal package for USEPA’s Proposed Plan in 2016. The data calculations and tools used to calculate the results are described to a level that can be replicated.

SUPPLEMENTAL DATA

Supplemental Data Table 1. Detailed cost–benefit EIBA table

Supplemental Data Table 2. SiteWise™ environmental footprint results

Supplemental Data Table 3. Sensitivity analysis results

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