

Importance of Implementation and Residual Risk Analyses in Sediment Remediation

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ABSTRACT

Management strategies for addressing contaminated sediments can include a wide range of actions, ranging from no action, to the use of engineering controls, to the use of more aggressive, intrusive activities related to removing, containing, or treating sediments because of environmental or navigation considerations. Risk assessment provides a useful foundation for understanding the environmental benefits, residual hazards, and engineering limitations of different remedy alternatives and for identifying or ranking management options. This article, part of a series of panel discussion papers on sediment remediation presented at the Third International Conference on Remediation of Contaminated Sediments held 20–25 January 2005 in New Orleans, Louisiana, USA, reviews 2 types of risk that deserve careful consideration when evaluating remedy alternatives. The evaluation of remedy implementation risks addresses predominantly short-term engineering issues, such as worker and community health and safety, equipment failures, and accident rates. The evaluation of residual risks addresses predominantly longer-term biological and environmental issues, such as ecological recovery, bioaccumulation, and relative changes in exposure and effects to humans, aquatic biota, and wildlife. Understanding the important pathways for contaminant exposure, the human and wildlife populations potentially at risk, and the possible hazards associated with the implementation of different engineering options will contribute to informed decision making with regard to short- and long-term effectiveness, implementability, and potential environmental hazards.

Keywords: Sediment Sediment remediation Risk assessment Residual risk Engineering risk

INTRODUCTION

Whether or not remediation of contaminated sediments is warranted depends on the magnitude of direct or indirect health risks to humans, ecological threats to aquatic biota, and the extent of risk reduction that can be achieved by removal or containment of the contamination. To date, common practice typically consists of a simplistic and conservative determination of baseline risks posed by contaminants in sediments followed by a determination of appropriate cleanup technologies that address unacceptable risks. Typically, the efficacy of different remediation options has been assumed or given only cursory evaluation. In most cases, sediment removal has been presumed by regulatory agencies and most stakeholders to accelerate environmental recovery and assumed necessary to prevent the possibility that an increase in risk would occur following some unforeseen catastrophic event.

There is growing evidence that sediment removal is not always the best approach and that environmental protection based on conservative, worst-case scenarios may not achieve environmental improvement or risk-reduction goals. For example, a sediment dredging project at New Bedford Harbor, Massachusetts, USA, in 1994 and 1995, resulted in the removal of 45% of the in situ polychlorinated biphenyl

(PCB) mass, but did not result in reduced PCB body burdens in caged mussel studies used to monitor biological recovery in the ecosystem (US Environmental Protection Agency [USEPA] 1997). In the Grasse River located in upstate New York, USA, removal of 27% of the PCB mass from sediments in 1995 had little measurable impact on fish tissue levels (Alcoa 1999). Studies conducted at Shipyard Creek, South Carolina, USA; Onondaga Lake, New York, USA; and elsewhere indicate that dredging and other intrusive remedies to address divalent metals, chromium, and mercury may alter geochemical conditions in the sediment, and thereby increase bioavailability and facilitate the formation of more toxic metal species, such as hexavalent chromium and methylmercury (Chapman et al. 2003; Haines et al. 2003).

These and other examples from the United States and elsewhere suggest that, at present, conventional remedy alternatives analysis (often referred to as a feasibility study [FS] in the US Superfund program) does not adequately predict (and generally overpredicts) the short- and long-term risks and benefits of dredging. Furthermore, the FS process does not explicitly account for the envisioned long-term use of a site or adequately consider the ecological threats and human health risks potentially imposed by the implementation of a remediation strategy. Because of the dynamic nature of sediment remediation projects, which may include the use of multiple remedy and treatment technologies, ranking the

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diverse set of environmental risks and identifying the equally diverse set of environmental benefits associated with different sediment remediation strategies is increasingly needed as part of engineering feasibility studies.

This article reviews the importance of linking risk assessment to cost/benefit analysis and discusses 2 types of risk—engineering and biological—that deserve careful consideration when evaluating sediment remedy alternatives. The evaluation of remedy implementation risks addresses predominantly short-term engineering issues associated with applying the remedy such as worker and community health and safety, equipment failures, and accident rates. The evaluation of residual risks addresses predominantly longer-term changes in exposure and effects to humans, aquatic biota, and wildlife after the remedy has been implemented. Understanding the important pathways for contaminant exposure, the human and wildlife populations at risk, and the risks associated with different engineering options can contribute to informed decision making with regard to short- and long-term effectiveness, implementability, and potential environmental hazards.

CURRENT REGULATORY CONSIDERATIONS

The importance of considering implementation risks and residual risks is emphasized in USEPA regulations and guidance. In particular, the National Contingency Plan (NCP) requires, as part of a feasibility assessment process, an evaluation of overall protectiveness, long-term effectiveness and permanence, reduction of toxicity, mobility, and volume through treatment, short-term effectiveness, and implementability (USEPA 1990). Consideration of the short-term impacts and effectiveness of an environmental remedy, as well as the prospects for long-term effectiveness and performance, are part of the evaluation criteria for detailed analyses of remedy alternatives in the federal Superfund program (USEPA 1988) and in several US state programs, such as the New York State Department of Environmental Conservation (NYSDEC) Technical and Administrative Guidance Memorandum (TAGM) 4030 (NYSDEC 1990) and California's Voluntary Cleanup Program (California Environmental Protection Agency [CalEPA] 1995).

According to the NCP, the general preference to reduce mobility, toxicity, or volume through treatment must be weighed along with other factors, including remedy implementation risk (short-term effectiveness), overall risk reduction (long-term effectiveness), and cost (USEPA 1990). This balancing of benefits (or risks) and costs is exemplified in USEPA's *Contaminated Sediment Management Strategy*, which states that, in certain circumstances, the best remedy strategy may not be intrusive, but instead involve the implementation of pollution-prevention measures and both point and non-point source controls to allow natural recovery processes such as biodegradation, chemical degradation, and the deposition of clean sediments to diminish risks associated with a sediment site (USEPA 1998a). Where predictive models and bench-scale testing support conclusions that the implementation of a remedy will cause more environmental benefit than harm, recent USEPA guidance on sediment remediation at contaminated sites indicates that so-called active monitoring or in situ remediation may be the preferred approach (USEPA 2005).

The need to evaluate potential human health and ecological risk in the remedy selection process is explicit in nearly all remedial action objectives (RAOs) established for cleanup of contaminated soil and sediment sites in the United States, as well as in several other countries. In the United States, USEPA ecological risk-assessment guidance emphasizes that ecological risk reductions associated with a remedy must be balanced against the potential impacts of the remedy itself (USEPA 1998b). Guidance from Australia/New Zealand, Canada, and The Netherlands also specify the need for baseline and postremediation risk analyses to ascertain the potential for unintended environmental consequences and adverse biological effects (ANZECC/NHMRC 1992; MHSPE 1994; CCME 1997).

In the context of human health, a failure to adequately evaluate implementation risks during the remedy selection process can result in unanticipated injuries (or even fatalities) to workers and nearby residents during cleanup. The consequences may also include costly delays associated with substantial remedy modifications or abandonment of an incomplete remedy (Church 2001). In the context of ecosystem restoration, the US Army Corps of Engineers (USACE 2003) increasingly includes nonmonetary metrics to evaluate the accomplishments or results of environmental projects, judge cost effectiveness, as well as to identify both short- and long-term success. Thus, short-term implementation risks, such as those posed by extensive dredging activities and the transportation of waste materials and both capping and backfill materials, must be carefully evaluated and weighed against any long-term risk reduction that may be achieved.

APPROACHES TO RISK OF REMEDY EVALUATION

Several paradigms have been used that incorporate risk analysis or environmental benefits analysis into environmental management. For example, Hauger et al. (2002) and Knapp et al. (2003) have developed risk/cost/benefit models to evaluate wastewater treatment systems and water transfers from agricultural to urban and environmental uses. Similar models have been proposed to evaluate different agricultural practices (Osei et al. 2003), forest management practices (Brown 2002), remediation of contaminated lands (Tam and Byer 2002), perform environmental impact assessments (Bojorquez-Tapia et al. 2005), and public health management programs (Axelrad et al. 2005; Denman et al. 2005). Taylor et al. (2004) have addressed the uncertainties associated with environmental measurements taken for the purpose of characterizing contaminated lands and supporting remedy decision making and have shown how measurement errors contribute to decision errors, which can have significant financial and public-health consequences.

At present, 2 different risk-assessment paradigms offer the clearest direction on how best to merge quantitative risk assessment with economic analysis and societal valuation of potentially affected natural resources. Both cases (Suter et al. 1995; Efrogmson et al. 2003) demonstrate that the extent to which environmental risks and benefits can be quantitatively included in economic analysis is largely dependent on the use of detailed risk-assessment methods (Dockins et al. 2004).

Suter et al. (1995) have proposed a model for organizing the results of a risk assessment for evaluation of health and ecological risks before and after remediation, as well as evaluation of the impacts posed by different remedy options.

Table 1. Four key considerations in the assessment of implementation risks

1. Protection of the community during remedial actions. This aspect of short-term effectiveness addresses risks that result from remedy implementation, such as dust from excavation or air-quality impacts from the operation of an incinerator.
2. Environmental impacts. This factor addresses the potential adverse environmental impacts that may result from remedy implementation and evaluates how effectively available mitigation measures would prevent or reduce these impacts.
3. Time until remedial action objectives (RAOs) are achieved. This factor includes an estimate of the time required to achieve protection for either the entire site or individual components associated with the site.
4. Protection of workers and the local community during remedial actions. This factor assesses threats that may be posed to workers and local communities and the effectiveness and reliability of protective measures.

Suter et al. (1995) proposed 3 categories of human and ecological risk. The 1st category is *de manifestis* risks, which are those risks that require remediation, unless the remedial action conflicts with the protection of human health. *De manifestis* ecological risks often include risks imposed on threatened or endangered species, wetlands, and ecological components with extraordinary local or ecological value. *De manifestis* human-health risks are defined by an excess cancer risk greater than or equal to 10^{-4} or a hazard quotient (HQ) or hazard index greater than or equal to a value of 1 for any individual contaminant or for combined exposures across contaminants of similar toxicological effects.

The 2nd category is *de minimis* risks. *De minimis* ecological risks do not normally require remediation because the risks are considered trivial. Suter et al. (1995) defined *de minimis* ecological risk, based on regulatory precedents, as a less than 20% reduction in the abundance or production of a population within suitable habitat, the loss of less than 20% of the species in a community, or the loss of less than 20% of the habitat area. Suter et al (1995) defines *de minimis* human-health risk as excess cancer risk less than or equal to 10^{-6} or an HQ less than a value of 1 for any individual contaminant or for combined exposures across contaminants of similar toxicological effects. The 3rd category of risk is intermediate health and ecological risks, which fall between *de manifestis* and *de minimis* risks and generally require further evaluation and cost-benefit analyses to determine the need for remediation.

The approach by Suter et al. (1995), however, does not

account for the ecological recovery of a site, the different recovery rates for different species, or the relative abundance of the species in the larger ecosystem, each of which can be critical decision-making components. Although Suter et al. (1995) argue there is legal precedent for using the 20% criterion when evaluating a remediation project and acute impacts, this appears to be a generalization with considerable uncertainty. The appropriate benchmark for pass-fail (either below or above 20%) should be evaluated on a site-specific basis.

A different approach has been proposed by Efrogmson et al. (2003), who describe a net environmental benefits (NEB) framework to quantify the gains in environmental services or other ecological properties attained by remediation or ecological restoration and to account for the environmental injuries caused by those same actions. The approach relies on the use of reference sites to establish baseline conditions before and after remediation. It also provides a framework to include ecological improvement activities that do not necessarily focus directly on contaminant isolation or removal, such as wetland construction, reef construction, or other types of habitat mitigation measures that can be quantified either economically or based on some index of value to society.

According to Efrogmson et al. (2003), a remedy may provide no net benefit or may cause more harm than good if it is ineffective and does not substantially reduce risk or if the action causes environmental injuries greater than the damage associated with baseline conditions. The underlying challenge to the NEB approach is the appropriate framework for

Table 2. Common remedy implementation risks that should be included in the evaluation of remedy options at a sediment site

1. On-site worker accidents that may occur during construction and remediation operations
2. Accidents and spills that may occur during transport of large quantities of site-related materials, such as dredged material, clean backfill material, and capping material
3. Impact on water quality of resuspension of sediments during dredging
4. Impact of resuspension of sediments during dredging on the natural recovery of the sediments
5. Air-quality impacts during dredging and materials handling in the sediment consolidation area
6. Impact of discharge of effluent from sediment dewatering operations back into the environment
7. Temporary loss of habitat due to the physical removal of benthic macroinvertebrate communities and/or their habitat during dredging or burial of organisms under clean cap/backfill materials
8. Quality-of-life impacts, including potential restricted use of areas in the vicinity of the cleanup site and increased local truck traffic transporting site-related materials during remedy implementation

Table 3. A review of implementation risks conducted in the United States at several contaminated land and sediment project sites

Project name	Implementation risks evaluated	Conclusions/status
Hardage Superfund Site (USEPA Region VI)	<ul style="list-style-type: none"> • Off-site human health risks • Emissions during remediation • Chemical fire, explosion, and personal injury 	Intrusive remedy was rejected prior to implementation due to consideration of potential worker and community risks. The theoretical cancer risks posed by the intrusive remedy were over 1000× higher than for the alternative nonintrusive remedy. The risk of worker accidents and heat stress was greater than the alternative nonintrusive remedy. US District Court found in favor of the alternative remedy.
McColl Superfund Site (USEPA Region IX)	<ul style="list-style-type: none"> • Chemical vapor emissions during remediation • Worker personal protective equipment (PPE) requirements 	Uncertainties associated with undertaking full-scale excavation in close proximity to residences were determined to be high. The risks of injury to workers and the off-site community also were high and were not offset by risk reduction that might be achieved by the proposed remedy. USEPA reversed its position and selected a nonintrusive partial solidification remedy.
PetroProcessors Superfund Site (USEPA Region VI)	<ul style="list-style-type: none"> • Chemical vapor emissions 	The proposed intrusive remedy was halted by USEPA when vapor emissions were found to be consistently unacceptable. The vapor emissions resulted in exceedances of occupational exposure standards at the site boundary and threatened off-site community health. An alternative nonintrusive remedy was selected and implemented after 2 y of re-evaluation.
Brio Refining Superfund Site (USEPA Region VI)	<ul style="list-style-type: none"> • Emission problems during excavation • Exceedances of short-term air standards • Engineering controls needed to abate emissions 	USEPA issued an amended cleanup decision for the Site, which replaced the excavation and on-site incineration remedy with a containment remedy after the agency considered potential worker- and community-health risks associated with the implementation of the initially proposed remedy.
Tyson's Lagoon Superfund Site (USEPA Region III)	<ul style="list-style-type: none"> • Release of vapors to community 	The disadvantages associated with the proposed excavation remedy included greater potential release of volatile organic vapors to the community as compared with an alternative remedy that included soil vacuum extraction. USEPA issued a revised cleanup decision shortly after decision making that replaced excavation and off-site disposal with a remedy based on soil vacuum extraction.

Table 3. Continued

Project name	Implementation risks evaluated	Conclusions/status
Lone Pine Landfill Superfund Site (USEPA Region II)	<ul style="list-style-type: none"> • Potential fire and explosion • Potential hazardous vapors during excavation • Potential worker direct contact to hazardous materials • Potential for traffic accidents 	Site cleanup review found that the potential long-term benefits of soil excavation did not outweigh potential short-term threats; i.e., soil excavation could create environmental impacts and threaten public health where none existed previously. The remedy selected by USEPA specified a containment alternative that included the installation of a soil cap and slurry wall.
American Chemical Service Superfund Site (USEPA Region V)	<ul style="list-style-type: none"> • Safety measures needed to protect workers from volatile organic chemical levels • Explosion hazards 	The USEPA revised the site-cleanup decision due to concerns regarding the health and safety of workers and the surrounding public in the event that widespread waste excavation released high levels of volatile organic chemicals to air.
Hastings on the Hudson (NYSDEC)	<ul style="list-style-type: none"> • Potential for on-site worker fatalities • Potential for off-site transportation fatalities • Geotechnical feasibility of deep excavation 	The site cleanup feasibility analysis concluded that off-site fatal transportation accident risks for soil excavation were 75× greater than for a containment remedy. Similarly, on-site fatal transportation accident risks for the excavation remedy were 100× higher than for the containment remedy. Outcome is still pending.
Allied Paper, Inc. Portage Creek Kalamazoo River Superfund Site (USEPA Region V)	<ul style="list-style-type: none"> • Accidents during on-site materials handling • Accidents during off-site transportation • Destruction of riverine habitat 	The site cleanup feasibility analysis concluded that the risk of at least 1 fatality was less for bank stabilization and river-wide capping than for river-wide dredging with upland confined disposal. The expected frequency of collision-related fatalities and injuries were calculated to be significantly higher for river-wide dredging than for other remedies. Outcome still pending.

comparing baseline and postremediation conditions. Comparisons made solely on the basis of chemical contamination or societal values could bias decision making toward remediation, whereas comparisons made solely on a cost basis could bias decision making toward inaction.

Perhaps the next stage in the evolution of both the Suter et al. (1995) and Efrogmson et al. (2003) approaches is to incorporate both risk-assessment paradigms with multicriteria decision analysis (MCDA) and comparative risk analysis (CRA). MCDA and CRA are emerging as integral components of both risk evaluation and environmental decision making (Kiker et al. 2005), and have been applied successfully to environmental impact assessment. Both approaches provide a framework for combining information developed from environmental modeling and risk assessment, cost and benefit analyses, opinion polls, and other data-generating methods,

and ranking the value of different remedy actions, as well as the probabilities for successful mitigation of environmental risks. MCDA and CRA also have the additional advantage of visualizing tradeoffs among multiple, conflicting criteria and quantifying the uncertainties necessary for comparison of multiple remedy options.

CONSIDERATION OF IMPLEMENTATION RISKS

Table 1 lists 4 key considerations adopted from NYSDEC (1990) that, in general, should be addressed in the evaluation of the short-term effectiveness of a sediment remedy. Table 2 presents a list of the most common set of remedy-implementation risk considerations that should be included in the evaluation of different remedy options at a sediment site. In some instances, risk surrogates, such as contaminant concentrations or qualitative measures of impact on habitat,

must be used because of the difficulties of quantifying direct measures of risk. This is consistent with recommendations from the US National Research Council (NRC 2001) regarding assessment and management of sites contaminated by PCBs. Further, in some cases, risk elements associated with certain remedy alternatives may not be considered or quantitatively evaluated because the risks are determined to be de minimis on the basis of preliminary or screening risk analysis (USEPA 2005).

In the United States, guidelines for evaluating remedy-implementation risks are found in several US guidance documents (USEPA 1991, 2001b). According to USEPA (1991), the risks posed to workers and the community during remedy implementation can be evaluated either qualitatively or quantitatively, depending on conditions at the site. For example, intrusive remedies expose workers to an increased risk of physical injury and, in some cases, heat stress and heat stroke, or fires and explosions. Similarly, transportation of excavated materials and capping/backfill materials may generate high traffic volumes that can result in spills or traffic accidents. Specifically, when short-term risks are not expected to be a problem for a site, a more qualitative evaluation generally is appropriate. In these cases, a qualitative evaluation of the magnitude, duration, and/or likelihood of the exposures and risks should be conducted, and assessors could describe short-term risks in a qualitative manner relative to the results of the baseline risk assessment. A quantitative evaluation of short-term risks is most likely to be useful when the types, levels, and/or availability of hazardous substances are expected to change significantly as a result of remediation (USEPA 1991).

While excavation and treatment remedies have been successfully implemented at many sites, the costs and implementation times for such remedies are often higher than originally anticipated. At several notable Superfund sites in the United States (Table 3), intrusive remedies offered little, if any, additional long-term risk reduction compared with containment-based remedies. Evaluations at several Superfund sites, including the Hardage (Oklahoma, USA), Lone Pine Landfill (New Jersey, USA), Tyson's Lagoon (Pennsylvania, USA), and American Chemical Service Superfund (Indiana, USA) sites, demonstrated that the short-term remedy implementation risks posed by excavation were significant and outweighed any long-term risk reduction afforded by intrusive remedies (Table 3). At each of these sites, in situ remedies based on containment, with limited or no removal, were ultimately selected. While these examples represent upland remediation projects, similar considerations likely apply in the context of large-scale sediment-remediation projects.

CONSIDERATION OF POSTREMEDIAL RESIDUAL RISKS

The magnitude of residual risk is considered when evaluating remedial alternatives, particularly as part of the evaluation of overall protectiveness of human health and the environment and the long-term effectiveness of the remedy option, which represent 2 of the 9 NCP remedy-evaluation criteria. According to USEPA (1991, 2001a), residual risks should be calculated using the same exposure assumptions and toxicity values used in the site baseline assessment.

For sediment sites, the scope of residual risk analysis that should be considered prospectively as part of the final remedy

decision-making process includes focus on the potential risks to benthic macroinvertebrates, wildlife, and humans resulting from exposure to chemicals in sediment, fish tissue, and surface water as identified in a baseline ecological or human-health risk assessment completed during the site-investigation process. The effects of remedial alternatives on both chemical and physical stressors should be quantified to the extent practicable by the state of the science and available site-specific information. By doing so, the overall significance of the risk assessment is elevated significantly by tying the residual-risk analysis performed during the remedy FS back to risk assessments performed as part of the site-investigation process.

The time frame to evaluate different remedy alternatives (e.g., the required time to meet remediation goals for the site) is another important consideration (USEPA 2005). USEPA guidance generally requires remediation efforts to meet cleanup goals within a reasonable time frame, leaving a large degree of subjectivity when defining what is reasonable for remediation (USEPA 2001a, 2005). If monitored natural recovery (MNR) is included among the remedy options (and it generally should in nearly every situation), then the time for MNR to achieve a risk-based RAO could be a reasonable time frame. Thus, one can determine whether the reduced time to achieve an RAO for dredging and capping relative to MNR is associated with lower or higher risks as compared with the implementation of an MNR remedy approach. If risks are less for MNR, one can also address whether the reduced risks are of sufficient magnitude to outweigh the increased investment of resources to actively remove or isolate the sediment.

Comparisons of baseline risks with risk-reduction measures and evaluation of the time to achieve risk-based RAOs require relatively accurate ecological and human health risk projections for each remedy alternative. These projections have to be modeled using site-specific hydrology, hydrodynamic and hydrogeology data, sediment geophysical and contaminant properties, fate and transport mechanisms, and ecological inputs. The models or assessment tools used will depend on the type of risk evaluated. For example, prediction of the risk of exceeding species-specific critical body residues might involve the prediction of surface water concentrations and the use of a food-chain model.

In some cases, current available modeling tools may not be sophisticated enough to make the necessary calculations to forecast risk into the future, particularly with respect to integrating contaminant fate and transport with risk. Research is needed to develop models capable of making long-term predictions of sediment-contaminant concentrations, in situ or technology-related risks, ecological recovery and costs to permit comparisons of remediation alternatives based on short-term and long-term risk reduction and risk management.

SUMMARY AND CONCLUSION

The 2 primary goals of sediment remediation are to (1) reduce the risks of sediment contaminants such that protection of human health and the environment is achieved and (2) restore an ecosystem damaged by existing or historically released contaminants. However, in some cases, remediation activities provide little or no measurable risk reduction and can impact waterways and sediment sites more significantly than the existing contamination, particularly if the remedial action affects sensitive ecological species or environments. Further-

more, the cleanup of areas in which contaminants do not pose significant ecological or human health risks may involve imposition of ecological or human health risks that exceed the desired ecological benefits. These risks can result from habitat destruction, the redistribution of contamination, increased bioaccumulation, or from new or exacerbated contaminant exposure pathways during the remediation. In such cases, the better course of action may be to encourage in situ attenuation and MNR of the sediment rather than implement intrusive activities. By careful evaluation of both implementation risks and residual risks, the opportunity for causing more environmental harm than good can be avoided, and human safety and environmental precautions can be implemented to minimize unanticipated injuries.

The success of environmental benefit–cost analysis for environmental remediation will require greater reliance on human health and ecological-risk assessment in conjunction with the evolution of multivariate decision-making methods such as MCDA and CRA. The extent to which benefits can be quantitatively included in an economic analysis is largely determined by the choice of risk-assessment methods (Dockins et al. 2004). Interdisciplinary collaboration between engineers, economists, regulatory specialists, community stakeholders, and experts in risk-assessment-related disciplines will be critical to further development of objective, quantitative remedy-alternatives analysis.

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REFERENCES

- Alcoa Corporation. 1999. Comprehensive characterization of the Lower Grasse River. Report submitted to USEPA Region 2. New York (NY): Alcoa.
- [ANZECC/NHMRC] Australian and New Zealand Environment and Conservation Council / National Health and Medical Research Council. 1992. Australian and New Zealand Guidelines for the Assessment and Management of Contaminated Sites.
- Axelrad DA, Baetcke K, Dockins C, Griffiths CW, Hill RN, Murphy PA, Owens N, Simon NB, Teuschler LK. 2005. Risk assessment for benefits analysis: Framework for analysis of a thyroid-disrupting chemical. *J Toxicol Environ Health A* 68:837–855.
- Bojorquez-Tapia LA, Sanchez-Colon S, Florez A. 2005. Building consensus in environmental impact assessment through multicriteria modeling and sensitivity analysis. *Environ Manage* 11(Epub 11 August).
- Brown S. 2002. Measuring, monitoring, and verification of carbon benefits for forest-based projects. *Philos Transact A Math Phys Eng Sci* 360:1669–1683.
- [CalEPA] California Environmental Protection Agency. 1995. The voluntary cleanup program. Department of Toxic Substances Control, Sacramento. EO-95-006-PP. <http://www.dtsc.ca.gov/PolicyAndProcedures/SiteCleanup/eo-95-006-pp.pdf>. Accessed 22 March 2005.
- [CCME] Canadian Council of Ministers of the Environment. 1997. Guidance document on the management of contaminated sites in Canada. PN1279. Winnipeg (MB): Environment Canada.
- Chapman PM, Wang F, Janssen CR, Goulet RR, Kamunde CN. 2003. Conducting ecological risk assessment of inorganic metals and metalloids: Current status. *Human Ecol Risk Assess* 9:641–697.
- Church BW. 2001. Remedial actions: The unacknowledged transfer of risk. *Environ Sci Pollution Res Special* 1:9–24.
- Denman A, Groves-Kirkby C, Coskeran T, Parkinson S, Phillips P, Tornberg R. 2005. Evaluating the health benefits and cost-effectiveness of the radon remediation programme in domestic properties in Northhamptonshire, UK. *Health Policy* 73:139–150.
- Dockins C, Griffiths CW, Owens N, Simon NB, Axelrad DA. 2004. Linking economics and risk assessment. *J Toxicol Environ Health A* 67:611–620.
- Efroymson RA, Nicolette JP, Suter III GW. 2003. A framework for net environmental benefit analysis for remediation or restoration of petroleum-contaminated sites. Oak Ridge National Laboratories, Environmental Sciences Division. ORNL/TM-2003/17.
- Haines TA, May TW, Finlayson RT, Mierzykowski SE. 2003. Factors affecting food chain transfer of mercury in the vicinity of the Nyanza Site, Sudbury River, Massachusetts. *Environ Monitor Assess* 86:211–232.
- Hauger MB, Rauch W, Linde JJ, Mikkelsen PS. 2002. Cost benefit risk—A concept for management of integrated urban wastewater systems. *Water Sci Technol* 45:185–193.
- Kiker GA, Bridges TS, Linkov I, Varghese A, Seager T. 2005. Application of multi-criteria decision analysis in environmental decision-making. *Integr Environ Assess Manag* 1:1–14.
- Knapp KC, Weinberg M, Howitt R, Posnikoff JF. 2003. Water transfers, agriculture, and groundwater management: A dynamic economic analysis. *J Environ Manage* 67:291–301.
- [MHSPE] Ministry of Housing, Spatial Planning and the Environment. 1994. Environmental quality objectives in The Netherlands: A review of environmental quality objectives and their policy framework in The Netherlands. Bilthoven (The Netherlands): Risk Assessment & Environmental Quality Division, Directorate for Chemicals, External Safety & Radiation Protection.
- [NRC] National Research Council. 2001. A risk-management strategy for PCB-contaminated sediments. Washington DC: National Academy.
- [NYSDEC] New York State Department of Environmental Conservation. 1990. Technical and administrative memorandum 4030: Selection of remedial actions at inactive hazardous waste sites.
- Osei E, Gassman PW, Hauck LM, Jones R, Beran L, Dyke PT, Goss DW, Flowers JD, McFarland AM, Saleh A. 2003. Environmental benefits and economic costs of manure incorporation on dairy waste application fields. *J Environ Manage* 68:1–11.
- Suter GW II, Cornaby BW, Hadden CT, Hull RN, Stack M, Safran FA. 1995. An approach for balancing health and ecological risks at hazardous waste sites. *Risk Anal* 15:221–231.
- Tam EK, Byer PH. 2002. Remediation of contaminated lands: A decision methodology for site owners. *J Environ Manage* 64:387–400.
- Taylor PD, Ramsey MH, Potts PJ. 2004. Balancing measurement uncertainty against financial benefits: Comparison of in situ and ex situ analysis of contaminated land. *Environ Sci Technol* 38:6824–6831.
- [USACE] US Army Corps of Engineers. 2003. Improving environmental benefits analysis in ecosystem restoration planning. Alexandria (VA): Institute for Water Resources IWR Report 03-PS-3. <http://www.iwr.usace.army.mil/iwr/ecosystem/envirobenefits.htm>. Accessed 22 March 2005.
- [USEPA] US Environmental Protection Agency. 1988. Guidance for conducting remedial investigations and feasibility studies under CERCLA-interim final. EPA: 540 G-89-004; NTIS: PB89-184626.
- [USEPA] US Environmental Protection Agency. 1990. National oil and hazardous substances pollution contingency plan (NCP). *Fed Reg* 55:8666–8812.
- [USEPA] US Environmental Protection Agency. 1991. Risk assessment guidance for Superfund. Vol 1, human health evaluation manual. Part C, risk evaluation of remedial alternatives, interim. PB90-15581, EPA 540/1-89/002. Human Health Education Manual.
- [USEPA] US Environmental Protection Agency. 1997. Report on the effects of hot spot dredging operations New Bedford Harbor Superfund site New Bedford, Massachusetts. Narragansett (RI): US Environmental Protection Agency.
- [USEPA] US Environmental Protection Agency. 1998a. Contaminated sediment management strategy. Washington DC: Office of Water. EPA/823/R-98/001.
- [USEPA] US Environmental Protection Agency. 1998b. Guidelines for ecological risk assessment. EPA/630/R-95/002F. *Fed Reg* 63:26846–26924.
- [USEPA] US Environmental Protection Agency. 2001a. Principles for managing contaminated sediment risks at hazardous waste sites. Washington DC: Office of Solid Waste and Emergency Response (OSWER). OSWER Directive 9285.6-08.
- [USEPA] US Environmental Protection Agency. 2001b. Risk assessment guidance for Superfund. Vol 1, Human health evaluation manual, Part D, standardized planning, reporting and review of Superfund risk assessments, final.
- [USEPA] US Environmental Protection Agency. 2005. Contaminated sediment remediation guidance for hazardous waste sites. Washington DC: Office of Solid Waste and Emergency Response (OSWER). OSWER Directive 9355.0-85.