Improving Tools for Ecological Risk Assessment at Petroleum-contaminated Sites

a report by
Rebecca A Efroymson

Environmental Sciences Division, Oak Ridge National Laboratory, Oak Ridge, TN

Dr Rebecca Efroymson is a Senior Scientist in the Environmental Sciences Division at Oak Ridge National Laboratory, where she has worked since 1994. Her research experience includes the development of frameworks, models and toxicity benchmarks for ecological risk assessment, which are used by the US Environmental Protection Agency, US Department of Energy facilities, US Department of Defense installations, various US states, and international entities. Subjects of these frameworks and models include petroleum exploration and production spills and infrastructure, multimedia air pollutants, military training and testing activities, septic tanks near lakes and estuaries, and land application of biosolids. Dr Efroymson recently developed the first framework for net environmental benefit analysis of contaminated sites. She received her PhD in Environmental Toxicology from Cornell University in 1993 while studying the biodegradation of nonaqueous phase liquids.

Ecological risk assessment is the evaluation of the likelihood that adverse ecological effects result from exposure to one or more chemical or physical agents. Risk assessments are commonly used to support decisions about remediating spills or other contamination on closed or operating exploration and production (E&P) sites and refinery lands, and they may also be employed to site new infrastructure. In addition, risk assessments are a useful way to organise information and disclose effects to the public.[1] Most frameworks for ecological risk assessment include four stages:

- problem formulation;
- characterisation of exposure;
- characterisation of effects; and
- risk characterisation.

The US Environmental Protection Agency (USEPA) framework for ecological risk assessment[2] is depicted in *Figure 1*. The problem formulation is the planning stage of risk assessment, which entails a description of stressors (e.g. chemicals), assessment endpoints (valued ecological entities that are to be protected, e.g. plant production, wildlife population abundance), the spatial and temporal scope of assessment and a conceptual model of exposure pathways. The characterisation of exposure is the stage in which chemical concentrations or areas of disturbed land in the past, present or future are measured or modelled. The characterisation of effects can include dose-response models, toxicity test results, ecological population model results or other exposure-response relationships. The risk characterisation is the stage in which the characterisations of exposure and effects are integrated and summarised, risk is estimated and uncertainties are calculated and discussed. Measurement methods and models for conducting risk assessments at contaminated sites have previously been published,[1] but risk assessment at petroleum-contaminated sites raises issues that necessitate the development of additional tools.

- Measured levels of contamination may not correspond to bioavailable levels, and laboratory toxicity tests conducted with freshly added mixtures or single chemicals may not represent the toxicity of aged (weathered) mixtures of chemicals in the field.
- Population ecology may be more important than toxicology (the traditional basis of ecological risk assessment) in determining risk to wildlife.
- Habitat loss from physical stressors (e.g. brine scars, roads, wells) may be more important than toxicity from chemicals.
- Detailed, definitive ecological risk assessments may not be feasible for large tracts of land that have little contamination.
- Risk management may benefit from the consideration of relative net environmental advantages of ecological restoration and remediation.

Researchers at Oak Ridge National Laboratory (ORNL) and elsewhere have developed new tools for ecological risk assessment that are applicable at E&P sites, as well as many 'downstream' (i.e., refinery and pipeline) sites. Much of this work has been funded by the US Department of Energy National Petroleum Technology Office and has been undertaken in collaboration with the Petroleum Environmental Research Forum (www.perf.org).

In this article, some of the recent advances in ecological risk assessment tools for petroleum-contaminated sites are described, including general notions of bioavailability and plant uptake models for hydrocarbons and metals, wildlife population models that incorporate habitat disturbance and trophic relationships. Also discussed are ecotoxicity benchmarks and critical (habitat) patch size values, and a framework for net environmental benefit analysis.

1. *Suter G W II, Efroymson R A, Sample B E and Jones D S, "Ecological Risk Assessment for Contaminated Sites", (2000), Lewis Publishers, Boca Raton, FL, USA.*
2. *U.S. Environmental Protection Agency, 1998, "Guidelines for Ecological Risk Assessment", EPA/630/R-95/002F, Washington, D.C., USA.*

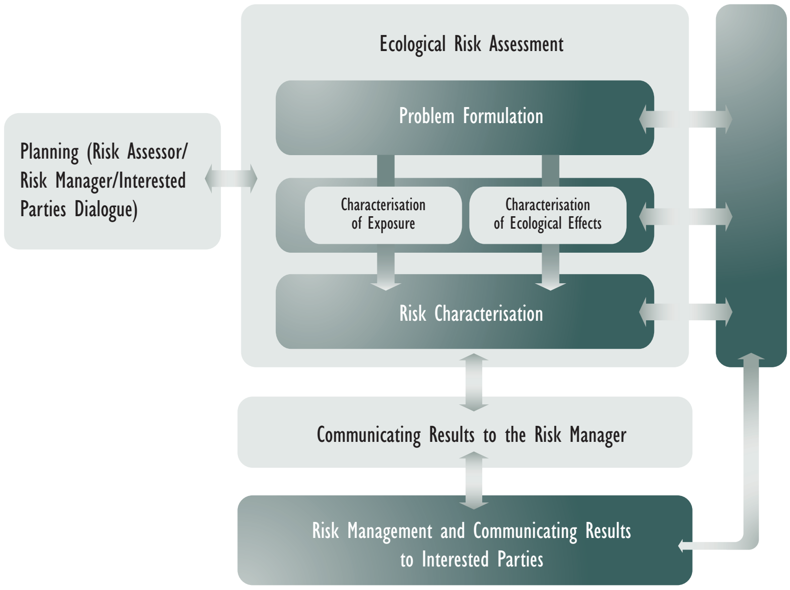
Characterisation of Exposure – Bioavailability

The characterisation of chemical exposure involves the estimation of a chemical dose or concentration in contact with an organism. The assumption is often made that the entire amount of a chemical present in soil is available for uptake and assimilation by potential receptors. Numerous studies in the past two decades have shown that organic compounds and metals in soil are not entirely bioavailable.[3] For example, a large fraction of petroleum material may be irreversibly sorbed to or sequestered in soil. Therefore, studies have been taken to quantify the bioavailability of chemicals at petroleum-contaminated sites. Researchers at Lawrence Berkeley National Laboratory (LBNL) are developing models and using controlled chamber studies to estimate plant uptake of hydrocarbons. Preliminary data suggest that the ratios of plant concentrations to soil concentrations for polycyclic aromatic hydrocarbons and n-alkanes (C-20–C-30) are lower than those for other organic compounds. Regressions for plant uptake of metals from soil have been developed by ORNL, but the predictions are highly uncertain, and assessors would benefit from the incorporation of additional soil characteristics.[4] LBNL has been investigating the gastrointestinal bioavailability of petroleum hydrocarbons to improve human health risk assessment, but methods of investigation are applicable to risk assessments for wildlife as well.[5]

Characterisation of Effects – Population Ecology

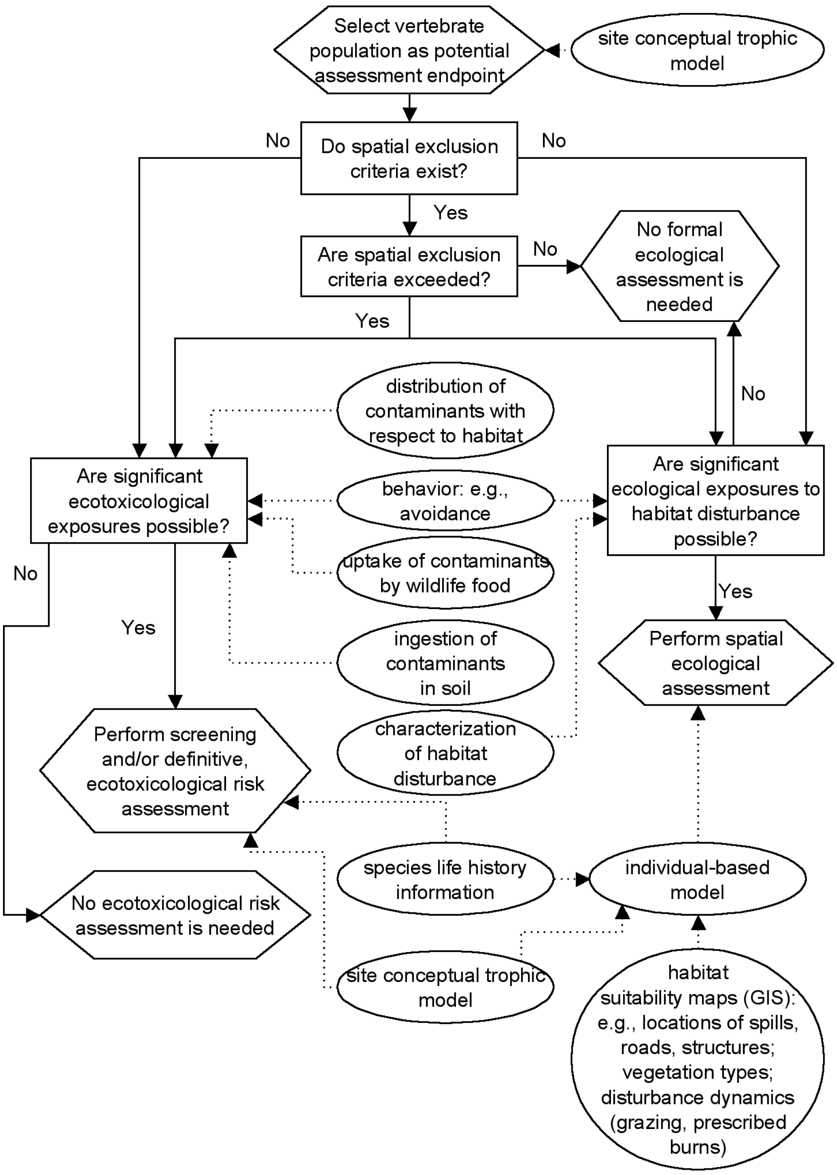
An ecological risk assessment for vertebrates should specify whether the management goal (which may be based on a regulation) is to protect all or a fraction of individuals, or to protect the population. For threatened or endangered species, the protection of the population entails the protection of individuals. However, in most cases, the goal of ecological risk assessment for vertebrates is to protect the population. Brine and petroleum spills may affect terrestrial vertebrates through loss of reproductive habitat or reduced food availability rather than direct toxicity. In risk assessments, spills may sometimes be treated like roads and wells (i.e. as physical stressors), rather than chemicals.[6] An ecological framework for evaluating impacts of spills has been proposed by ORNL in collaboration the Lawrence Livermore National Laboratory (LLNL). The framework recommends the use of individual-based models (IBMs) to assess risk to wildlife populations. IBMs can simulate mechanistic links between the physical environment, as modified by human activities, and biological processes that influence individual animals (e.g. mortality, reproduction, ageing and mate choice). Such models were used to simulate American badger (*Taxidea taxus*) and prairie vole (*Microtus ochrogaster*) populations at the Tallgrass Prairie Preserve E&P site in Osage County, Oklahoma, using both existing and hypothetical spill areas and spatial distributions.[7] The size of simulated populations decreased with increasing brine spill area (see *Figure 2*). The value of this modelling exercise would be increased by additional research aimed at field verification of the

Figure 1: USEPA Ecological Risk Assessment Framework



3. *Lanno R P (ed), "Contaminated Soils: From Soil-Chemical Interactions to Ecosystem Management", 2003, SETAC Press, Pensacola, FL, USA.*
4. *Efroymson R A, Sample B E and Suter II G W, "Bioaccumulation of inorganic chemicals from soil by plants: regressions of field data.",* Environ. Toxicol. Chem. *20: (2001), pp. 2,561–2,571.*
5. *Holman H Y N, Goth-Goldstein R, Aston D, Yun M and Kengsoontra J, "Evaluation of gastrointestinal solubilization of petroleum hydrocarbon residues in soil using an in vitro physiologically based model",* Environ. Sci. Technol. *36: (2001), pp. 1,281–1,286.*
6. *However, roads and wells are typically reclaimed in the long term.*
7. *Efroymson R A, Carlsen T M, Jager H I, Kostova T, Carr E A, Hargrove W W, Kercher J and Ashwood T L, "Toward a Framework for assessing risk to vertebrate populations from brine and petroleum spills at exploration and production sites",* Landscape Ecology and Wildlife Habitat Evaluation: Critical Information for Ecological Risk Assessment*, Land-Use Management Activities, and Biodiversity Enhancement Practices, ASTM STP 1458, in: Kapustka L, Galbraith H, Luxon M and Biddinger G R (eds), (2004), ASTM International, West Conshohocken, PA.*

Figure 2: A Preliminary Ecological Framework for Evaluating Terrestrial Vertebrate Populations at E&P Sites



results. Future population modelling to investigate habitat fragmentation from spills and E&P infrastructure such as roads is planned on an E&P site in Utah with funding from the US Bureau of Land Management. Similarly, large spills and roads may interrupt ecological corridors. A tool called 'pathway analysis through habitat' has been developed to predict the location of favoured corridors of animal movement between patches of habitat within any map.[8] Virtual 'walkers' with habitat preferences of particular species are simulated using a parallel supercomputer. This tool requires a map of habitat suitability categories, a map of spatially contiguous patches of each habitat suitability category, and the habitat category or categories between which corridors are to be identified. In addition, species-specific data are needed – habitat preferences, as well as energy costs of movement, the likelihood of finding food and likelihood of mortality in each habitat type. Corridor results between meadows in Yellowstone National Park are depicted in *Figure 3*. Through the use of this tool, habitat corridors may be avoided during the siting of infrastructure, and spill restoration priorities can be identified.

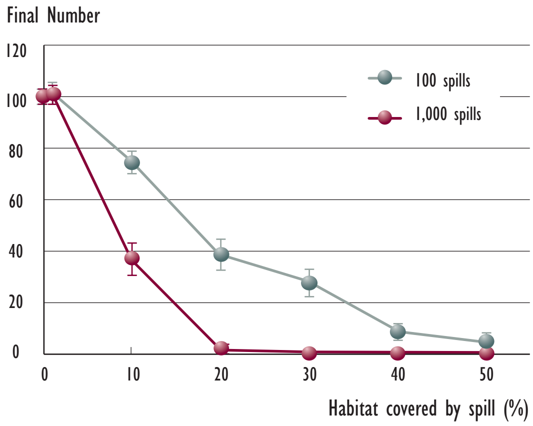
Risk Assessments – Adding Focus

Often it is not economically feasible to conduct a detailed, definitive ecological risk assessment on all chemicals in all contaminated areas and with respect to all potential receptors. Screening-level ecological risk assessments are conducted to focus ecological risk assessments on the chemicals or other stressors, locations and receptors with the most potential for ecological risk. Traditionally, ecotoxicity 'benchmarks', also termed 'reference values', 'screening values' or 'criteria', have been used to limit definitive risk assessments to the most important exposure pathways. These values are concentrations of chemicals in environmental media that signify the boundary between potential and no potential risk. At least three recent reviews were conducted to attempt to identify these reference values or supporting data.[10] Unfortunately, the ecotoxicity data available on total petroleum hydrocarbons and total polycyclic aromatic hydrocarbons are not sufficient to establish general benchmark or reference values for effects of these chemicals on plants, invertebrates or vertebrates in multiple soils in the field with confidence. However, with additional research,

8. *Hargrove W W and Hoffman F M, http://research.esd.ornl.gov/~hnw/walkers/presentation3/ 19th Annual Symposium of the United States Regional Association of the International Association for Landscape Ecology, Las Vegas, 30 March-3 April 2004.*
9. *This figure is reproduced from the article "Toward an Ecological Framework for Assessing Risk to VertebratePopulations from Brine and Petroleum Spills at Exploration and Production Sites", which will be published in STP 1458 – Landscape Ecology and Wildlife Habitat Evaluation: Critical Information for Ecological Risk Assessment, Land Use, copyright ASTM International, 100 Barr Harbor Drive, West Conshohocken, PA 19,428.*
10. *Efroymson R A, Sample B E and Peterson M J, "Ecotoxicity test data for total petroleum hydrocarbons in soil: plants and soil-dwelling invertebrates",* Hum. Ecol. Risk Assess. *(2004), 10: pp. 207–231; Kapustka L A, "Establishing Eco-SSLs for PAHs: Lessons revealed from a review of literature on exposure and effects to terrestrial receptors",* Hum. Ecol. Risk Assess. *10: (2004), 185–205; Jensen J and Sverdrup L E, "Polycyclic aromatic hydrocarbon ecosotoxicity data for developing soil quality criteria",* Rev. Environ. Contam. Toxicol. *179: (2003), pp. 73–97.*

toxic concentrations of mixtures of chemicals with similar modes of action (e.g. narcotics) may be estimated using mechanistic approaches.[11] The potentially large number of small brine and oil spills on E&P sites of high habitat value prompts the question of whether simple field criteria (e.g. threshold total area) may be used to exclude the spills from formal ecological risk assessment. Some US states have developed contaminant area limits that may be termed 'exclusion criteria' and are analogous to the 'benchmarks' described previously.[12] For example, the Pennsylvania Department of Environmental Protection (PADEP) assumes that two acres of surface soil contamination does not pose risk to vertebrate populations.[13] However, these values are policy decisions which are not based on population biology or landscape ecology considerations.

Figure 3: Simulated Habitat Loss from Hypothetical Brine Scars Decreased Final Number of Badgers at the Tallgrass Prairie Preserve in Oklahoma, USA



Model and figure provided by H I Jager, Oak Ridge National Laboratory, Tennessee, US

Where habitat area is a concern, remaining patches of suitable habitat may be compared with 'critical patch size' i.e. the contiguous habitat area needed to maintain a population.[14] Estimates of critical patch sizes are available for 33 species of small mammals, 36 species of large mammals, 77 species of birds and 44 species of herptiles. In general, critical patch size is largest for large omnivorous and carnivorous mammals, followed by small mammals, herptiles and birds, but the variance is largest for birds. If contiguous habitat patches at an E&P site have areas below the species-specific critical patch size, a wildlife population may not persist. It is anticipated that the results of the population models described above will also aid in future development of 'exclusion criteria' for leaving unrestored (but adequate) habitat at E&P sites.

Risk Assessments – Adding Benefits

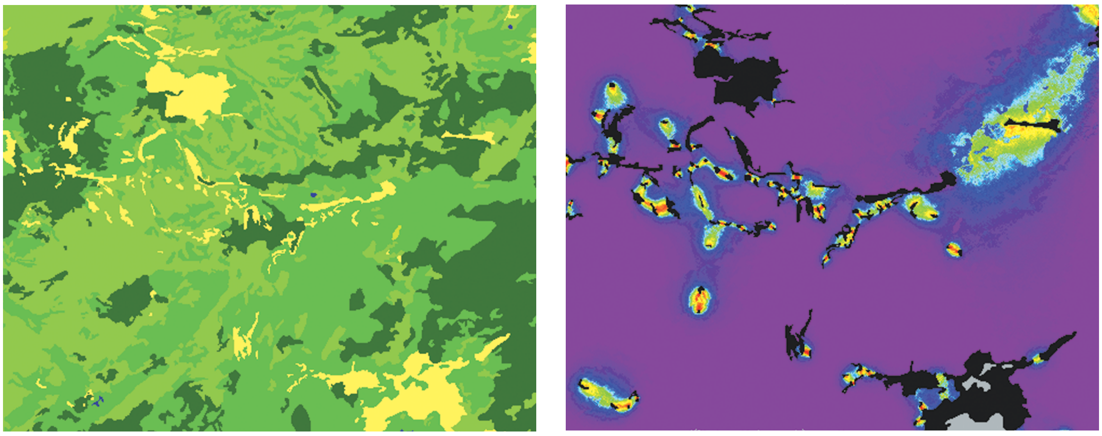
Ecological risk assessment methodology may not be adequate for supporting some decisions at petroleum-contaminated sites. Although human health risk and economic cost are also considered, additional environmental information may be needed as well. For example, comparisons of remediation alternatives and ecological restoration options may require the estimation and comparison of net environmental benefits of each. A framework has been developed for net environmental benefit analysis (NEBA) of petroleum-contaminated sites that builds on principles of ecological risk assessment.[15] A NEBA for chemically contaminated sites typically involves comparison of several management alternatives:

- leaving contamination in place;
- physically, chemically or biologically remediating the site through traditional means;
- improving ecological value through onsite and offsite restoration alternatives that do not directly focus on removal of chemical contamination; or
- a combination of these alternatives.

Changes in ecological services[16] or populations through time are assessed for each alternative (see *Figure 4*). Principles of NEBA were first used to assess the impacts of marine oil spill dispersants.[17] NEBA has the potential to help land managers avoid the possibility that the selected remedial or ecological restoration alternative will provide no net environmental benefit over natural attenuation of contaminants and ecological recovery. Additional tools are needed to support NEBA – non-monetary environmental valuation methods, exposure-response models for chemicals and physical stressors such as roads and wells and associated habitat fragmentation, models of ecological recovery, and optimal strategies for ecological restoration.

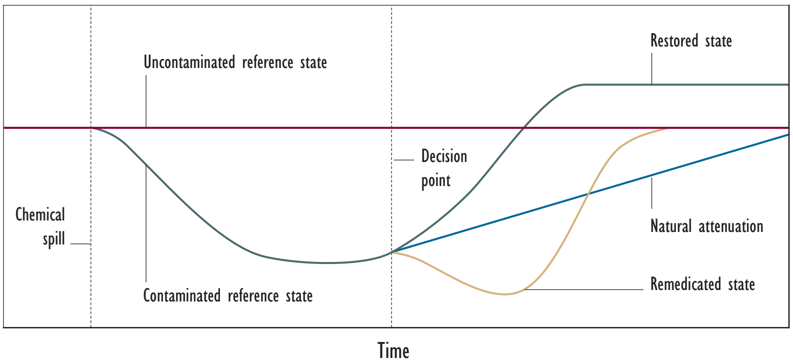
11. *DiToro D M, McGrath J A and Hansen D J, "Technical basis for narcotic chemicals and polycyclic aromatic hydrocarbon criteria",* I. Water and tissue, Environ. Toxicol. Chem. *19: (2000), pp. 1,951–1,970.*
12. *Sorensen M and Margolin J A, "Evaluating Potential Ecological Impacts At Exploration & Production Sites",* A Compilation of Screening Criteria, Topical Report, *(2002), GRI-02/0006, GRI, Des Plains, IL.*
13. *PADEP, "Ecological Screening Process. Pennsylvania Department of Environmental Protection", November 10 1998, www.dep.state.pa.us/dep/subject/advcoun/cleanup/attachmentve3.doc*

Figure 4: Distribution of Corridors Between Meadow Habitats for a Hypothetical Meadow-loving Species at Yellowstone National Park, USA



Patches of meadow (yellow) amid patches of various successional stages of lodgepole pine (left) and wildlife corridors between meadow patches (now shown in black), where most intense corridors are depicted in red and yellow (right).

Figure 5: Hypothetical trajectory of environmental service or other ecological entity with time, following a petroleum spill (contaminated reference state); conditions that would have been expected to prevail in the absence of the spill (uncontaminated reference state); expected trajectory of the remediated state; and expected trajectory of the restored state. A net environmental benefit analysis would compare these curves.



Conclusion

Ecological risk assessments are benefiting from new tools that provide scientific credibility, focus the assessment on the exposure routes with the likeliest effects, consider impacts on wildlife from the population perspective, and examine the big picture, including benefits of proposed remedial actions. Risk assessment methods, in general, need to promote rigorous, relevant and recent science. Future research would enhance the value of these tools for the petroleum industry, including studies of all aspects of bioavailability of hydrocarbons and other chemical contaminants, field validation of population models and case studies of net environmental benefit analysis. ■

Acknowledgements

This research was sponsored by the National Petroleum Technology Office, US Department of Energy, and performed at Oak Ridge National Laboratory (ORNL). ORNL is managed by UT-Battelle, LLC, for the US Department of Energy under contract DE-AC05-00OR22725. The manuscript was improved by the review comments of several anonymous petroleum industry reviewers and Jim Loar of Oak Ridge National Laboratory.

14. *Carlsen T M, Cody J D and Kercher J R, "The spatial extent of contaminants and the landscape scale: An analysis of the wildlife, conservation biology, and population modeling literature"*, Environ. Toxicol. Chem. *23: (2004), pp. 798–811.*
15. *Efroymson R A, Nicolette J P and Suter G W II, "A Framework for Net Environmental Benefit Analysis for Remediation or Restoration of Petroleum-Contaminated Sites", ORNL/TM-2003/17, Oak Ridge National Laboratory, Oak Ridge, TN, http://www.esd.ornl.gov/programs/ecorisk/documents/NEBA-petrol-s-report-RE.pdf; (2003), Efroymson R A, Nicolette J P and Suter G W II, in: "A framework for Net Environmental Benefit Analysis for remediation or restoration of contaminated sites"*, Environ. Manage.
16. *Ecological services are functions of ecosystems that may serve humans or other components of ecosystems, NEBA often focuses on ecological services because they are often more easily valued than other aspects of ecosystems; such as populations.*
17. *NOAA Hazardous Materials Response Branch, "Excavation and rock washing treatment technology: Net environmental benefit analysis"*, National Oceanic and Atmospheric Administration, *(1990), Seattle, WA, USA.*