INTEGRATING RISKS AT CONTAMINATED SITES

Margaret MacDonell, Loren Habegger, Leslie Nieves, and Zachariah Schreiber
Argonne National Laboratory

Curtis Travis
Project Performance Corporation

ABSTRACT

The U.S. Department of Energy is responsible for a number of large sites across the country that were radioactively and chemically contaminated by past nuclear research, development, and production activities. Multiple risk assessments are being conducted for these sites to evaluate current conditions and determine what measures are needed to protect human health and the environment from today through the long term. Integrating the risks associated with multiple contaminants in different environmental media across extensive areas, over time periods that extend beyond 1,000 years, and for a number of different impact categories – from human health and ecological to social and economic – represents a considerable challenge.

A central element of these integrated analyses is the ability to reflect key interrelationships among environmental resources and human communities that may be adversely affected by the actions or inactions being considered for a given site. Complicating the already difficult task of integrating many kinds of risk is the importance of reflecting the diverse values and preferences brought to bear by the multiple parties interested in the risk analysis process and outcome. An initial conceptual framework has been developed to provide an organized structure to this risk integration, with the aim of supporting effective environmental management decisions. This paper highlights key issues associated with comprehensive risk integration and offers suggestions developed from preliminary work at a complex DOE site.

BACKGROUND

Advances in science and technology are increasing our understanding of the complex physical, biological, and social interrelationships in our environment. Combined with enhanced assessment methodologies, these enable us to link evaluations of various health risks and environmental impacts to provide a better foundation for cleanup decisions at complex contaminated sites across the United States.

Integrated assessments consider different types of possible effects – from human and ecological health risks to social, cultural, and economic impacts – that are associated with multiple pollutants in various environmental media over extended locations and time periods. To compare risks and impacts for these sites, we must be able to quantify or otherwise describe them. Sound solutions for managing possible adverse effects of our actions or inactions at these sites depends on our ability to focus the finite resources available on the contaminants, pathways, and resources that matter.

Chemical contaminants found at typical industrial sites are also found at U.S. Department of Energy (DOE) facilities. These include naturally occurring metals, man-made solvents, and some pesticides. Nearly all DOE sites are also radioactively contaminated as a result of past research and development activities. Contaminants range from natural isotopes of uranium, thorium, and radium to fission products such as cesium and strontium and other reactor-produced radionuclides such as plutonium. Hundreds of risk and impact assessments have been conducted for DOE facilities under the Department's environmental management program as part of the process for determining final site disposition. Integrated assessments provide the mechanism for these and other complex sites to fully characterize interrelated impacts, including potential health, ecological, social, and economic effects.

The federal cleanup program is massive and has been criticized for being slow, expensive, and ineffective. To conduct the front-end assessment of health and environmental risks and evaluate remedial alternatives often takes up to five years and more, with much longer schedules for heavily contaminated facilities and controversial projects. Annual costs for the DOE environmental management program alone are on the order of $6 billion, and the total price tag has been estimated to exceed $200 billion [1]. For especially complex DOE facilities such as the Hanford site in Washington, the work is not expected to be completed for another fifty years. While the private sector shoulders the burden for many inactive commercial or industrial sites, taxpayer monies are directly used to pay for the cleanup of federal sites. This leads to considerable scrutiny and ongoing pressure from the public, elected officials, and regulatory agencies for effective and quick solutions.

Unfortunately, site cleanups are far from straightforward as local risk issues often affect the timeliness and practicality of environmental decisions. Because of the additional perception problem associated with radioactive contamination and past closed-door policies that affected public trust in the early years, DOE cleanup projects are even more complicated than most.

Human health is currently being protected at DOE sites through existing controls that include access and use restrictions and waste containment. Although risks to humans have traditionally been the driver for cleanup decisions, many sites contain large tracts of land that served as buffer zones to protect against public exposures during past operational periods, and these areas now support thriving ecosytems due to decades of minimal human disturbance. For example, only about 6% of an estimated total 30,000 mi^2 of land associated with DOE environmental management sites is contaminated, so a considerable amount of land could be made available for other productive uses [1]. As cleanup activities proceed at the individual sites, the Department is working with local communities and state agencies to coordinate the future release of federal land, e.g., to state conservation agencies for wildlife or recreational areas, or to local communities for development. An integrated approach for assessing a variety of potential risks and impacts into the extended future is essential to the effective long-term stewardship of this land.

METHODOLOGY FOR INTEGRATED RISK AND IMPACT EVALUATIONS

Basic Assessment Framework

The human environment involves complex interrelationships among: (1) the physical environment – such as air, water, and soil; (2) the biological environment – ranging from watersheds and ecosystems to communities, populations, species, and individuals; and (3) the social and cultural environment – which includes land use, archaeological and cultural resources, economic resources, aesthetics, and spiritual values or quality of life factors. The federal government has established numerous laws that deal with individual components of the environment, and standard guidelines are available for assessing health and ecological risks at contaminated sites. These guidelines are based on the four-step risk assessment process developed by the National Academy of Sciences [2], consisting of: (1) hazard identification, (2) exposure assessment, (3) toxicity assessment, and (4) risk characterization.

Although this framework has served as an overall guide for human and ecological risk assessments, many specific issues for which no prescribed solutions are available must be addressed when implementing the process at complex sites in culturally diverse areas. Moreover, no standard guidance is available for the linked sociocultural and economic impact assessments at these sites, nor has an integrated framework that combines assessments across these technical areas yet been developed for general application. This paper introduces an initial conceptual process that begins to integrate these components, so that site decision makers can base their decisions on a more comprehensive picture of risk/impact information.

Considerable environmental progress has been made over the last three decades in addressing individual contaminants in specific media and implementing environmental management strategies targeted at eliminating or controlling those hazards. While recognizing the value of those successes and the need to continue regulatory programs to reduce risks associated with singe chemicals, recent studies have drawn attention to the need to further consider health and environmental problems in their larger, real-world context. This context involves a complex mix of contaminants, interrelated environmental quality factors, and resource allocation issues [3,4].

An integrated approach calls for considering the overall health of the ecosystem, not just the effect of contaminants on individual species; the overall quality of life, not just primary and secondary effects of contamination on the health of an individual or group; and overall regional economic robustness, not just effects of contamination on individual sectors. To obtain this integrated view, it is important to receive input on values from the entire community, not just from those who could be directly affected by individual contaminant sources. A number of national initiatives are underway to work toward obtaining this broader understanding of overall environmental impacts. For example, the EPA has initiated programs aimed at integrating various risks, which range from comparative risk projects [5] to ongoing assessments of the cumulative risk of toxic air pollutants emitted by a broad range of sources in urban region, with community input to the process.

While these programs have advanced integration across multiple pollutants and pathways, the White House has moved further in the direction of comprehensive assessments across a broad spatial scale, through the call for watershed-based analyses and management of water quality impacts [6]. Particular emphasis is placed on ensuring wide access to information in order to facilitate the participation of community groups and the public. In embracing the White House Clean Water Action Plan, environmental programs of nine federal agencies, including the DOE, are being integrated over a wider context than ever before.

Additional Complications at Large Sites

Certain categories of risks and impacts that may be of minimal concern at smaller sites warrant special consideration at larger sites due to the potential for a significant cumulative or combined effect. Also, multiple occurrences of direct risks and impacts can lead to extensive regional-scale secondary effects such as changes in the dynamics of human or ecological communities that would not occur from smaller isolated risk events. Risks and impacts to be considered for these complex sites frequently involve much more than a simple linear extrapolation of risk/impacts occurring at smaller sites.

With regard to health and ecological risks, combined exposures from multiple contaminants or other stressors can be more prevalent at large, complex sites in relatively undeveloped areas compared to smaller sites in urban areas. For example, larger sites can encompass the full home range of on-site species, and the interrelated community and ecosystem functions and services may be more fully established in relatively isolated areas where a number of DOE sites are located. For ecosystem function, impacts on biological systems from numerous contaminated areas in close proximity may combine to affect community dynamics in ways that are basically different than linear extensions of individual location effects. This nonlinearity is exhibited for example, in landscape fragmentation; after the fragmentation reaches a certain level (e.g., loss of access to water or other resource), new significant effects can result [7]. Analyses conducted at the watershed scale can help ensure that such spatial issues are captured.

For economic impacts, the relationship between “exposure” or trigger mechanism and effect is also nonlinear, and the overlay of stigma effects make the analysis even more complicated for sites whose economic base is substantially dependent on the contaminated site. This is the case for several of the large DOE facilities. Further, sites with extensive buffer zones can encompass unique historic and cultural resources that have considerable non-monetized value to the local community. The presence of such resources, notably those of great importance to indigenous Tribal nations, is more prevalent at certain large sites, and these warrant special considerations that include treaty and trust responsibilities.

In addition to the importance of addressing these assessment factors that can be unique to large, complex sites, an integrated evaluation of risks and impacts facilitates a more representative view of remediation options. As an example, on-site disposal or treatment of multiple contaminants in a single facility can be better evaluated using an integrated approach, including building on composite analyses that consider multiple sources. Long-term stewardship options should also be integrated across multiple sources, as economies of scale may make certain monitoring options or barriers/access controls more practical for large sites.

Public Involvement

Multi-pronged stakeholder involvement approaches that consider a variety of interaction mechanisms and locations (from libraries to churches) may be required for complex sites with many sources of contamination, given their relatively greater impact on the region and its subgroups. This is particularly true of large Federal sites that are often located in remote areas. For these sites, values of the full affected community may be quite varied and atypical of the "average citizen," and decisions cannot simply be based on standard approaches such as those developed on the basis of regulatory programs alone (such as the community relations component of the Superfund legislation). It is also important to note that stakeholder input at sites that affect a diverse population can be contradictory and difficult to coordinate. Nevertheless, the ultimate aim of a broad consensus process – that a decision not be made until every (group's) voice is heard – makes a rigorous community involvement program essential to effective decision making.

Limited federal resources are available to address contaminated sites, as other matters of national interest – including other programs aimed at protecting and enhancing human health and environmental sustainability – also compete for federal funds. Thus, one of the important aims of a collective and cumulative evaluation is a greater understanding of relative risks, to support these difficult decisions. An integrated impact assessment can help shine a light on the primary contributors to an overall risk picture.

Reducing different component risks to achieve an overall risk reduction, and determining the proper balance to select appropriate control measures from alternate strategies for different risk types, are much more challenging efforts today compared with the relatively straightforward single pollutant-medium decision focus of the past. Technical integration issues are further discussed in a recent report for the DOE Hanford site's groundwater/vadose zone integration project [8] and highlighted in the following section.

INTEGRATED ASSESSMENT ISSUES

Combining Different Types of Risks/Impacts

Risks and impacts can be combined in several ways. Three general assessment categories can be used to guide the answer to the basic question "What is being integrated?"

1. Integration of risks and impacts over *type*, for interdisciplinary combinations across human health, environmental/ecological, sociocultural, and economic effects, as well as intra-disciplinary assessments – e.g., considering within human health, for workers versus the public: acute versus chronic exposures for accident versus routine conditions, and cancer versus noncarcinogenic endpoints.

2. Integration of risks and impacts over *space*, to capture the distribution of effects over multiple contaminant sources and resource/receptor locations, extending to the ecosystem and watershed scales and encompassing the potentially affected economic region; and

3. Integration of risks and impacts over *time*, to address changes that may occur in environmental settings, contaminant conditions, and receptor behaviors and values into the extended future, especially when wastes will remain on-site and require long-term management.

Additional considerations relate to the management and communication elements of the overall remedial action process for a contaminated site. These include the iterative development of management options that reflects new information being gathered through the assessment process, with strong community involvement throughout. This "non-technical assessment" integration is also critically important to the success of a cleanup program.

Key to an effective process is maintaining an emphasis on integration principles while conducting the individual assessments, to ensure that the results will combine to present a consistent, comprehensive environmental story. Cumulative impacts can be critical on a regional scale. In assessing human exposures, contributions from multiple sources must be considered to the extent an individual could come into contact with a wide range of contaminants from scattered locations, e.g., as a result of contaminant migration to surface water or groundwater subsequently used for drinking. Similarly, local land use patterns could result in an individual accessing many contaminated locations and incurring combined exposures over an extended area. Community input is very important to ensuring that the parameter values used to estimate the amount of exposure (time, frequency, and duration) reflect local conditions and behaviors, including those based on unique practices of the area's cultures or subgroups.

An additional issue for integrating across multiple contaminant sources is our limited understanding of how humans respond to low-level environmental exposures to individual chemicals and chemical mixtures. Current risk estimators are primarily based on extrapolation from animal studies with relatively high doses, for individual chemicals. In the near term, flexibility is being incorporated into the cancer risk assessment process to reflect new data that continue to be generated by ongoing research programs [9,10]. Further toxicity research and technological advances in biomarkers and biochips are expected to enhance our ability to evaluate the effects of chemical interactions and risks for sensitive subpopulations whose biological responses may reflect genetic, life stage, or lifestyle factors. Screening assessments and uncertainty analyses are important for focusing on key risk drivers and acknowledging the range of possible conditions and effects that may occur.

The integration process for ecological risk assessment is much more complicated than for humans because of the large numbers of potential species, hazards or stressors, and endpoints of interest – many of which may be determined by the needs and values of local communities. Screening assessments are especially crucial in this area, with initial assessments often being qualitative so key ecological conditions and contaminant combinations that affect exposures across a large spatial scale can be identified. More quantitative assessments can then be conducted for specific contaminants, receptor systems, and effects at key locations. In considering the link to other disciplines as part of the more focused evaluation, the human health component (e.g., via the food chain), and sociocultural, and economic factors are also important. For example, even though they may be screened from significance on an ecological basis, species of societal and cultural or economic importance, such as white deer or salmon, should be included in the assessments to ensure that key cross-discipline information is developed for the decision maker.

With regard to sociocultural impacts, general social science approaches are available for assessing social structures and cultural values and the potential for change and attendant effects. Information can be gathered from historic records and from individual interviews and focus group discussions, from which rankings of relative value may be developed. To be effective, it is essential that these assessments be developed in close partnership with the communities or groups being studied. This participation is important throughout the process, from selecting indicators through data interpretation.

Approaches for estimating economic impacts are closely tied to the types of change in resource quality or use being considered. For contaminated sites, the assessment is directly related to the health and ecological risk assessment results and public perceptions of change in the availability and quality of resources. Economic market effects and changes in resource or activity values can be directly generated by adverse health or ecological risks, or by perceptions of those risks triggered by information about them and how it is presented. Indirect regional economic impacts can result from direct impacts through "ripple effects." Thus, it is important to identify key links among the four general discipline areas (human, environmental/ecological, sociocultural, and economic) early in the sitewide evaluation process.

Armed with input from the community, existing economic impact assessment tools can be adapted and refined for application at a specific complex site. These include: econometric models to assess direct changes in resource or product prices or quantities, with subsidy corrections in subsidized markets; econometric or input/output models to assess secondary regional impacts; cost estimates for alternative sources or decontamination, for loss of marketed resources; and non-monetary valuation methods for loss of nonmarket resources. As a caution, it is important to recognize our limitations in predicting future conditions and effects beyond the near term [11]. For example, economic predictions beyond 20 years would be weak at best [8].

Another key temporal consideration is that active remedial measures taken to protect possible future individuals from residual contamination, such as excavating contaminated soil or pumping groundwater, could cause considerable adverse effects to existing environmental, cultural, and economic resources, as well as to workers conducting these activities. There is no assurance that losses incurred in the near term will be offset by any potential future benefits.

Linking Conceptual Models

Commonalities and overlaps exist among the discipline-specific methods, but no standard approach yet exists for a fully integrated process. This status reflects the evolving formalization of a multi-faceted approach, but it also reflects the fact that widely different situations are being addressed and no single process is appropriate for all. The general planning approach for initiating an assessment of risks and impacts at relatively straightforward sites is also useful for complex sites. This standard approach involves identifying a set of discipline-specific conceptual models that characterize the individual sources of contamination or other stressors, the means by which an exposure can occur or an impact event can be triggered, and the related risks or effects. These separate models can then be linked to forge a summary concept that relates parallel components of the individual processes [8], as illustrated in Figure 1.

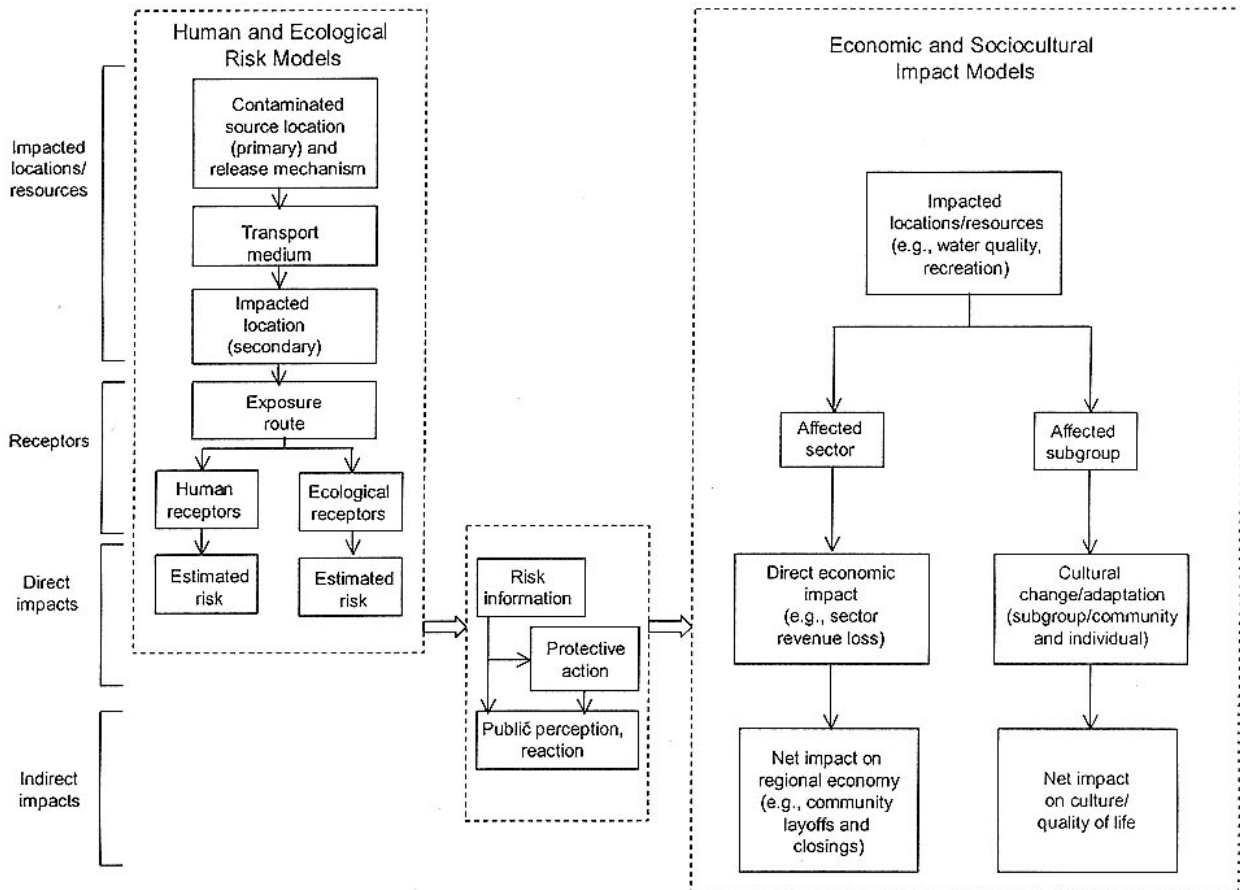

Fig. 1. Illustration of integrated conceptual models.

The conceptual models used to assess integrated risks and impacts at complex sites need to address prescribed requirements per environmental regulations. However, as has been acknowledged in the emerging integrated risk literature, additional considerations come into play for complex sites that may warrant going beyond the regulatory approach alone, to ensure that appropriate information is developed to support sound environmental decisions that will remain effective and protective for the long term.

Enhancements to prescribed regulatory approaches can take several forms, depending on the conditions at a given site and in the local community. In many cases, simplified screening models that use measured data can be much more effective, at least at the initial assessment stage, than multi-element, multi-dimensional models that use predicted values as inputs. The integrated evaluation of interactions among widespread contamination problems and environmental resources can be addressed most cost-effectively by employing a phased approach. While some exploration of methods and issues related to follow-on stages of the analysis is warranted, the outcomes of initial stages can be used to define the need for and focus of later stages. Using a phased approach with increasing quantification or complexity allows assessors to iteratively hone in on the important contaminants, locations, resources, receptors, and potential effects that warrant detailed study. The iterative process suggested by the EPA Science Advisory Board is illustrated in Figure 2.

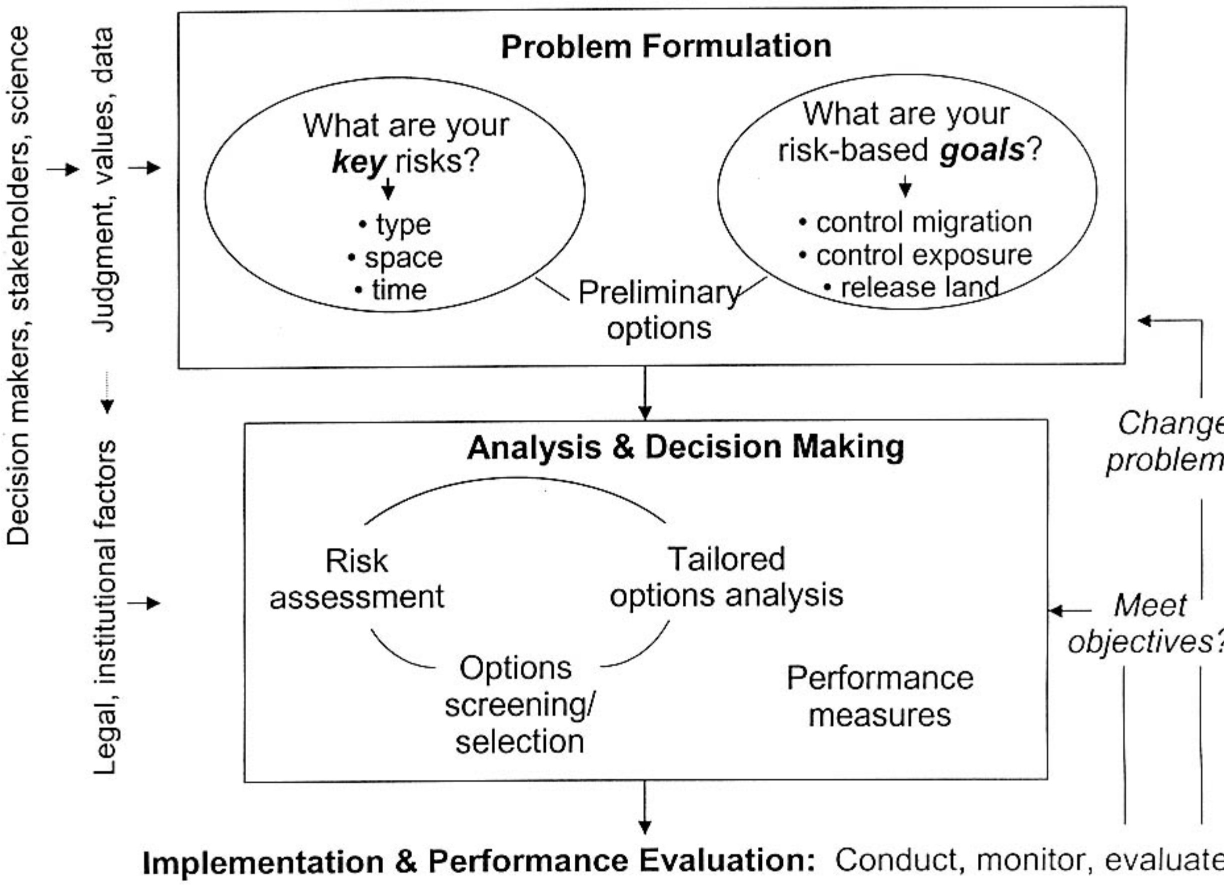

Fig. 2. Implementation & Performance evaluation: conduct, monitor, evaluate.

Addressing Uncertainty

Integration assessors should be especially mindful of evaluating uncertainty, as the pursuit of comprehensive knowledge about the breadth of all factors at play across each scientific discipline would break the bank for a project on the assessment phase alone, leaving no money for the actual cleanup work. Thus, it is important to limit the extent of data collection in pursuit of the "holy grail" of complete site characterization. Just as it is impossible to predict exactly what environmental conditions or human behaviors will be in the future, it is impossible to know precisely where all contaminants will be, at what levels, and how they are behaving at any given time. One approach for addressing uncertainties and unknowns is to conduct reasonably bounding assessments, e.g., based on mass balances combined with historic knowledge about site operations and available characterization and monitoring data. The bounding approach can also be applied to expected model outcomes using methods such as Monte Carlo statistical techniques.

An additional uncertainty consideration for assessments applies when not all areas of a site can achieve residual contaminant levels compatible with unrestricted use, meaning that to ensure protection some barrier or other control measure will be needed to block potential future receptors from contacting remaining hazards. Since such measures have finite life spans, risk assessors can work with risk managers to craft an iterative monitoring program aimed at detecting deviations from the controlled conditions over time, combined with a contingency response plan. This approach manages potential deviations throughout the stewardship process rather than striving to eliminate all uncertainties prior to beginning the protective long-term maintenance phase. Testing predictions with evolving monitoring data allows the models to be refined to increasingly reflect the site-specific conditions.

One practical approach to managing uncertainty over time is to scope assessments and controls for 50-year intervals – to bound uncertainties in a relatively manageable time frame rather than attempting to control them into the distant future at the outset – and iteratively transfer responsibility to the next generation. This sustains an institutional link and recognizes that scientific and technological advances will likely alter our understanding of conditions and ability to control hazards and releases within successive 50-year intervals.

Evaluating integrated risks and impacts at complex sites goes well beyond a summation of impacts across scattered sources. Standard methods used to assess risks and impacts within individual disciplines provide useful insights for the integration process. As currently formulated, classical approaches can be extended through linked models and screening tools that provide an overall framework for defining principal risks and impacts and interrelationships among hazards, resources and receptors, trigger events, and effects. Key objectives and considerations for an integrated risk/impact assessment at a complex site are noted in Table I, along with some conceptual and practical limitations that could be considered

Three general recommendations for addressing common risk questions at complex sites follow. First, address the source term issue – *how much contaminated material is there?* – by developing reasonable bounding estimates using historical knowledge combined with characterization data and other available measurements. Second, address the transport issue – *where is it going?* – by predicting the future hazard trajectory using environmental transport models of intermediate-level complexity to generate best estimates, designed to capture the time when significant contamination reaches key release points. Third, address the technical credibility issue – *how reasonable are the predictions?* – by developing reality checks using conceptual and descriptive information to validate the model estimates, e.g., for the breakthrough times to release points.

SUMMARY AND CONCLUSIONS

Environmental managers and the interested public are increasingly recognizing the value of addressing health and environmental impacts associated with contaminated sites through an integrated assessment process. Such a process can account for different sensitivities of unique environmental settings, interrelationships of complex mixtures of contaminants, the broad spatial and temporal range of impacts that include indirect effects on human welfare, and overall resource allocation issues. The advantages of applying an integrated approach are in particular being recognized at complex sites being evaluated by the DOE under its extensive environmental management program. These sites contain a wide range of chemical and radioactive contamination problems, and many are located in isolated regions where the relative impact of site disposition is more pronounced than for facilities in more populated areas with a much broader economic base.

Given the important role of these sites in the structures of their communities, potential risks to human and ecological health, either real or perceived, can lead to significant secondary impacts on the local economic, social and cultural resources. While protecting public and worker health and safety under existing regulatory guidelines remains a priority, longer-term objectives that include determining appropriate future uses for these sites is helping to refocus the foundation of environmental management onto a more integrated, comprehensive process.

In designing an assessment approach, it is useful to consider the importance of integration in three domains: temporal, spatial, and across impact types. In integrating across a range of time frames (similar to a life-cycle analysis approach), the effect of current risk management strategies can be weighed against the potential for long-term future impacts. In this way, resources and control measures required to prevent unacceptable impacts over extended areas and time periods can be identified and iteratively evaluated. Spatial integration considers not only the locational aspects of multiple source-receptor relationships but also the nature of regional dynamics associated with potential health and welfare effects. It is critically important to the success of cleanup projects to include the affected community in the risk assessment and decision-making process, to ensure that their values and concerns are reflected in the analyses.

Finally, it should be recognized that there currently exists no fixed or uniform approach for conducting fully integrated risk and impact assessment for complex sites. Implementing the necessary integration requires both an understanding of the characteristics and diversity of the region and an ability to creatively extend more traditional risk and impact assessment procedures to address unique site and community conditions.

A number of conclusions can be drawn from this conceptual overview of integrated risk and impact assessments for complex contaminated sites. First, going beyond limited discipline-specific analyses to take a broader view and working with the community and other interested parties from the outset can lead to a comprehensive consideration of major issues for a given site. Second, conceptual models can be developed individually for human health, environmental, sociocultural, and economic impacts – using a common general framework – and then linked to facilitate an integrated assessment. Third, conducting a phased approach that begins with screening analyses and includes a combination of qualitative and semiquantitative evaluations can provide effective coverage of the key issues. Together, these elements can identify the primary drivers of risks and impacts so resources can be allocated where they achieve the best overall benefit – from the near term through the long term – as well as highlighting areas for further science and technology research. The value of integrated assessments lies in their ability to provide a much better representation of real-world conditions and thus a stronger basis for practical, effective environmental decisions.

TABLE I. Objectives and Considerations for an Integrated Assessment at a Complex Site

Objectives	Considerations
Consider a full range of possible effects, across health, environmental, sociocultural, and economic disciplines.	Combining all effects into a single metric is probably not possible.
Apply a standard approach that reconciles different methodologies, assumptions, and data used previously and anticipated to be used in the future.	Tailor the assessment process to site conditions; no single approach is appropriate for all applications.
Reflect existing environmental, sociocultural, and economic conditions.	Focus on potential changes in levels rather than on attempting to establish absolute risk/impact levels of existing conditions.
Employ a consistent approach for evaluating the same types of risks/impacts for different population groups.	Do not assume common values for all affected groups; rather, solicit their input.
Consider cumulative effects of multiple sources and interactive effects of multiple contaminants.	Conduct screening analyses and establish cut-off points to exclude minor sources from the full assessment, and incorporate emerging toxicity data.
Evaluate risks/impacts at several geographic scales: local through regional.	Develop different conceptual models to capture local and regional effects.
Evaluate risks/impacts in the near-, intermediate-, and long-term time frames.	Address the near term quantitatively, while addressing the longer term for some risks/impacts qualitatively (at least for now).
Consider the individual and cumulative effects of uncertainties.	Focus on major uncertainties, as determined by sensitivity analyses.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the considerable contributions of the U.S. Department of Energy Center for Risk Excellence team who provided input to the Risk/Impact Technical Report for the Hanford site; the leadership and encouragement of Dr. Alvin Young, Director of the Center; and the contributions of Douglas Hildebrand, U.S. Department of Energy Richland Operations Office. Work supported by the U.S. Department of Energy Office of Environmental Management under Contract No. W-31-109-ENG-38.

REFERENCES

[1] U.S. Department of Energy (1996): The 1996 Baseline Environmental Management Report, Office of Environmental Management, Washington, D.C., June.

[2] Stallones, R.A., Chair (1983): Risk Assessment in the Federal Government: Managing the Process, Final Report, National Academy of Sciences Committee on the Institutional Means for Assessment of Risks to Public Health, Washington, D.C.

[3] Omenn, G.S., Chair (1997): Framework for Environmental Health Risk Management, Final Report, Presidential/Congressional Commission on Risk Assessment and Risk Management, Washington, D.C.

[4] U.S. Environmental Protection Agency (1999): Integrated Environmental Decision-making in the Twenty-first Century, Review Draft (EPA-SAB-EC-98-xxx), available at http://www.epa.gov/science1/intenv.htm, May 3.

[5] U.S. Environmental Protection Agency (1993): A Guidebook to Comparative Risks and Setting Environmental Priorities, EPA 230-B-93-003, Office of Policy, Planning and Evaluation, Washington, D.C.

[6] U.S. Environmental Protection Agency (1999): The Clean Water Action Plan: Restoring and Protecting America's Waters, http://www.cleanwater.gov/new/fact_sheet.html, revised June 16.

[7] Pimm, S.L., M.E. Gilpin (1989): "Theoretical Issues in Conservation Biology," pp. 287-305, Perspectives in Ecological Theory, J. Roughgarden, R.M. May, S.A. Levin (Eds.), Princeton University Press, Princeton, NJ.

[8] Argonne National Laboratory (1999): Risk/Impact Technical Report for the Hanford Groundwater/ Vadose Zone Integration Project, prepared for the DOE Center for Risk Excellence, available at http://www.riskcenter.doe.gov, December.

[9] U.S. Environmental Protection Agency (1996): Proposed Guidelines for Carcinogen Risk Assessment; Notice, *Federal Register* 61(79):1790-18011, April.

[10] U.S. Environmental Protection Agency (1999): Revisions to the Proposed Guidelines for Carcinogen Risk Assessment. Submitted for Review by the Science Advisory Board's Cancer Guidelines Subcommittee, *Federal Register* 64(167), January 20-21.

[11] Casman, E.A., M.G. Morgan, H. Dowlatabadi (1999): Mixed Levels of Uncertainty in Complex Policy Models, *Risk Analysis* 19(1):33-42.