Environmental Management (2008) 42:543–556
DOI 10.1007/s00267-008-9138-y

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A Framework for Fully Integrating Environmental Assessment

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Received: 24 August 2007 / Accepted: 20 April 2008 / Published online: 28 May 2008

Abstract A new framework for environmental assessment is needed because no existing framework explicitly includes all types of environmental assessments. We propose a framework that focuses on resolving environmental problems by integrating different types of assessments. Four general types of assessments are included: (1) condition assessments to detect chemical, physical, and biological impairments; (2) causal pathway assessments to determine causes and identify their sources; (3) predictive assessments to estimate environmental, economic, and societal risks, and benefits associated with different possible management actions; and (4) outcome assessments to evaluate the results of the decisions of an integrative assessment. The four types of assessments can be neatly arrayed in a two-by-two matrix based on the direction of analysis of causal relationships (rows) and whether the assessment identifies problems or solves them (columns). We suggest that all assessments have a common structure of planning, analysis, and synthesis, thus simplifying terminology and facilitating communication between types of assessments and environmental programs. The linkage between assessments is based on intermediate decisions that initiate another assessment or a final decision signaling the resolution of the problem. The framework is applied to three cases: management of a biologically impaired river, remediation of a contaminated site, and reregistration of a pesticide. We believe that this framework clarifies the relationships among the various types of assessment processes and their links to specific decisions.

Keywords Environmental assessment · Environmental management · Causality · Risk assessment · Ecology · Environmental epidemiology · Eco-epidemiology · Environmental outcome

Introduction

No existing framework explicitly includes all types of environmental assessments. Other frameworks have integrated ecological and human health risk assessments, but not risk assessments with other types of environmental assessments (Suter and others 2003; WHO 2001). This lack of integration is a problem, because practitioners of various approaches to environmental assessment may not see how they are conceptually linked. Lack of integration weakens or interrupts the process thus jeopardizing environmental outcomes. For example, assessors of environmental condition based on monitoring often disparage risk assessment as simplistic and unrealistic (Karr and Chu 1999), while some risk assessors complain that monitoring-based assessments do not provide support for risk-based decision making (Suter 2001). And yet, they share an objective: to provide scientific input for decision making. Both issues can be satisfied with an integrated framework that facilitates collaboration among assessors.

The need for multiple types of environmental assessments is not always recognized or accepted. In particular most frameworks for environmental risk assessment treat epidemiological assessments as just "retrospective risk assessments" (Presidential/Congressional Commission 1997; USEPA 1998a). However, it is nonsensical to speak of the risk of an event in the past; either a thing happened or it did not

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(Fairbrother and others 1997). Further, risk assessment frameworks show management decisions coming out of risk assessments without an intervening management assessment to integrate risks with costs, benefits, preferences, or legal constraints. Risk assessors are not the only ones guilty of such hubris. Epidemiology texts present examples of management decisions made from epidemiological results without considering risks or costs from the alternative actions.

A fully integrated framework could create a common set of concepts, tools, and terminology where none currently exists. A more universal, integrated framework may make it easier to perform assessments and for executives, legislators, judiciary, and stakeholders to understand the reasoning of the assessments.

Finally, none of the existing frameworks for environmental risk assessment is focused on making decisions to resolve the problem. For example, the Presidential/Congressional Commission (1997) created a framework that is centered on stakeholder involvement rather than decision making and is in the form of an infinite loop.

In this article, we describe the four types of assessments and explain how they are organized into an integrated environmental assessment framework. We explain a common assessment process that is the basis for all types of assessments. We illustrate the framework with examples of assessment for management of water quality, contaminated sites, and pesticides. Perhaps, this general framework and the common assessment process can make it easier for decision makers and stakeholders to cope with a variety of related environmental programs.

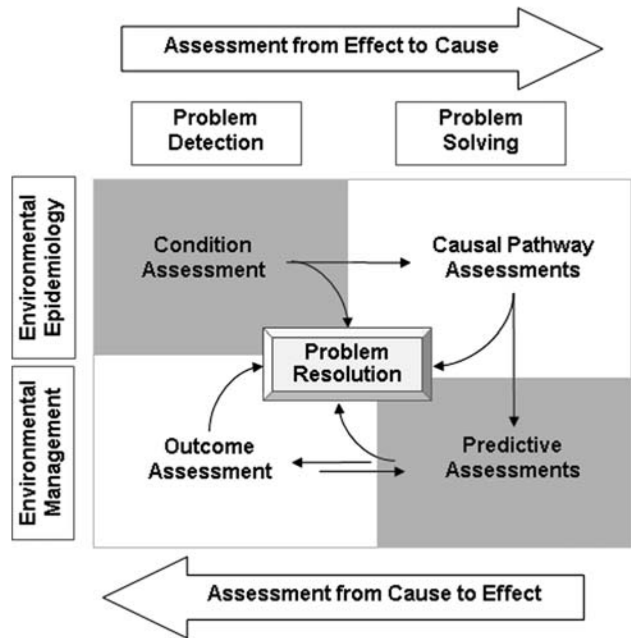

Fig. 1 Environmental assessment framework. The environmental assessment process is depicted as a matrix of assessments that address problem detection (*left column*) and problem solving (*right column*). Problem detection assessments feed into problem solving. Problem solving assessments lead to resolutions. The rows of the matrix are based on the direction of the analysis: eco-epidemiological assessments assess from effect to cause (*top row*) while environmental management assessments assess from cause to effect (*bottom row*). All assessment can potentially lead to a resolution of an environmental problem and an end to an assessment process (*central rectangle*)

Framework for Environmental Assessment

Frameworks for processes typically consist of a flow diagram and text explaining how to perform the process by implementing the diagram. A framework provides guidance on how to implement the process and indicates what tasks need to be performed and in what order. It provides a common terminology and understanding of the process for practitioners and a basis for judging the adequacy of a particular implementation of the process.

Columns

The integrated environmental framework is organized as a two-by-two matrix of assessments (Figs. 1 and 2). The columns consist of processes for detecting or solving problems.

Problem Detection

The assessments use the results of environmental monitoring to determine whether the environment is impaired

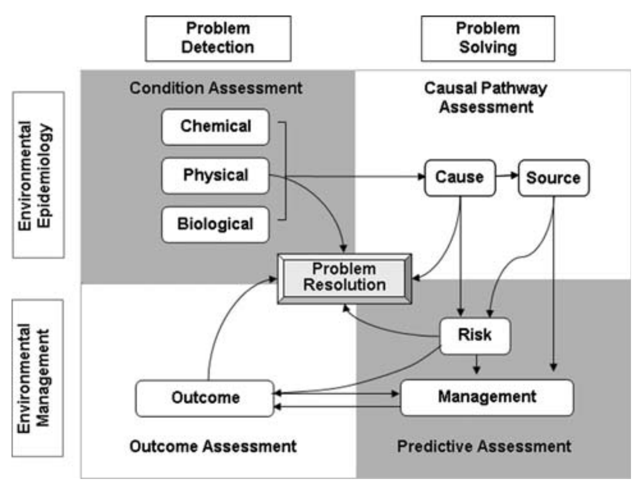

Fig. 2 Elaboration of the framework presented in Fig. 1. Condition assessments may evaluate chemical, physical, or biological conditions. Causal pathway assessments can deal with proximate causes or their sources. Predictive assessments evaluate the risks from alternative actions and the social and economic advantages and disadvantages of management options. Outcome assessments evaluate whether management actions achieve environmental goals

due to any cause (condition assessment) or is impaired due to a failed management action (outcome assessment).

Problem Solving

The assessments determine causes (causal pathway assessments) and evaluate solutions to environmental problems (predictive assessments).

Rows

The rows are formed by the practices of environmental epidemiology and environmental management. They distinguish the two basic activities of explaining what has happened and informing what should happen.

Environmental Epidemiology

The assessments in this row use epidemiological approaches to determine whether an ecosystem or its constituent organisms (including humans) are impaired (condition assessment) and the causes and sources of those impairments (causal pathway assessment). Environmental epidemiology deals with the determination of the incidence, distribution, and causes of injury and disease in human and nonhuman populations and communities. In sum, it characterizes existing environmental conditions and their causes. Hence, the assessor begins with observed effects and makes inferences about causes.

Environmental Management

The predictive assessments in this row estimate the consequences of alternative management actions (risk assessment), and the relative desirability of those actions based on those environmental risks, plus benefits, costs, stakeholder preferences, legal constraints, and other considerations (management assessment). After an action is selected and implemented, outcome assessments determine the performance of the action taken to remediate the cause and its effectiveness in resolving the problem. In sum, this row characterizes possible future environments that may result from alternative management actions and then evaluates the actual outcomes.

Condition Assessment: Problem Detection by Environmental Epidemiology

Condition assessments analyze monitoring data to determine whether environmental goals are being achieved that protect human health and ecosystems. Assessments of physical, chemical, and biological conditions may be performed independently or together. For ecological assessments, this involves comparing attributes of a population, community, or ecosystem to those that would be expected given the ecosystem type and location (Suter and others 2007). For human health, epidemiological statistics are used to determine whether the frequency of diseases or disabilities is higher than expected, given the demographics of a population (Friis and Sellers 2003). If standards exist for a chemical or other agent, a condition assessment may simply determine whether the relevant standard is violated.

Some cases such as mass mortalities of fish are clearly outside the bounds of normality. Such cases require minimal condition assessments. For example, one may simply report the number, size, and species of fish involved and gather samples and data for the causal assessment.

Condition assessments can prompt causal assessments, which lead to risk assessments as shown in the framework (Fig. 2). However, if the impaired condition is identified as contamination (e.g., a standard is exceeded or an oil spill has occurred), a causal assessment may be unnecessary. In addition, condition assessments may provide paired biological, physical, or chemical data for generating risk models (Fig. 2). For site-specific assessments (Example 1) including contaminated sites (Example 2), data from condition assessments can provide a basis for estimating from current conditions the risks that will continue if no remedial action is taken. For assessments such as pesticide reregistration (Example 3), condition assessments can provide exposure-response relationships that contribute to assessments of alternative regulatory decisions.

Causal Pathway Assessments: Beginning Problem Solving by Environmental Epidemiology

Causal pathway assessments determine the probable causes of the environmental impairments revealed by condition assessments. They consider the proximate cause, the source, and the causal pathways that connect them.

It is not always necessary to perform both causal and source assessments. In many cases, identification of the cause also serves to identify the source. If the cause of wildlife mortality is oil and a grounded tanker is spilling oil, the source is self-evident. If impairment is defined by exceedence of a standard, then the cause need not be identified, but the source must be found. Management actions are usually more effective if they remove the source or interrupt events leading to the cause, rather than attempting to remove the proximate cause. Therefore, both the cause and the source of the cause usually must be determined before management actions can be defined.

Causal Assessment

This type of causal pathway assessment identifies the proximate cause, the causal agent that directly induces the biological effect of concern. This is necessary because specific effects often have multiple possible causes. For example, insufficient dissolved oxygen is a proximate cause of fish mortality, but so are chemical contamination and heat stress. Ecologists have adapted and modified epidemiological criteria to consistently evaluate the diverse types of field and laboratory data that are potentially available (Fox 1991; Suter and others 2002, 2007; USEPA 2000).

Source Assessment

These identify and characterize the sources leading to exposure by the causal agents. If there are multiple sources, it apportions exposures among those sources. Some cases are simple; the source of an uncommon aqueous pollutant may be found by examining emission data from permitted upstream sources. More difficult cases involve tracer studies, chemical or biological analyses, or modeling. Examples include isotope analyses to determine the sources of lead (Finkelstein and others 2003; Scheuhammer and Templeton 1998) and nitrogen (deBruyn and others 2003), use of chemical fingerprinting to identify the sources of PAH mixtures (Mahler and others 2005; Menzie and others 2002), and DNA analyses to identify sources of pathogens (Simpson and others 2002). Because source assessments often support decisions of legal liability, the practice is often referred to as environmental forensics (Murphy and Morrison 2002).

Predictive Assessment: the Bases for Problem Solving by Environmental Management

Predictive assessments estimate changes that will occur under alternative actions to resolve the environmental problem. They include risk assessments and management assessments. Risk assessments estimate effects due to exposures and changes in effects due to management actions that change exposures. Management assessments predict the acceptability of actions by evaluating the risks in light of social, economic, and legal considerations.

Risk Assessment

These are the basis for risk-based management. Risk assessments estimate the potential adverse and beneficial effects of different exposures resulting from alternative management actions, including no action. Management options may include a combination of regulations, economic incentives, engineered controls, social and educational activities, and other approaches that are evaluated for their ability to reduce exposure to acceptable levels. In some contexts, assessments that predict effects of alternative actions are called environmental impact assessments.

Risk assessments may be initiated in various ways. They may be intended to evaluate remedial alternatives for a cause of impairment identified by epidemiological assessments. For agents such as new pesticides, effluents, dams, or exotic organisms, there are no prior environmental assessments; the registration process is the initiator. Risk assessments may also address existing agents for which there is no epidemiological evidence such as most small production volume chemicals or most hazardous waste sites. They may include assessments of risks from proposed activities such as the risk of extirpation of a fish population from alternative fishery management plans or risks of biodiversity loss from alternative conservation plans (Burgman 2005).

The alternative actions are an input to the risk assessment process (SAB 2000). In some cases they are self evident (e.g., permit or prohibit a hydroelectric dam). In other cases a standard set of technologies are the alternatives to be compared (e.g., dispersants, collection or burning for marine oil spills). In still other cases the alternatives must be generated during the risk assessment. In Superfund, the risk assessment is performed in two steps. A baseline risk assessment of the no action alternative is used to develop a remedial goal. That goal is used to design a set of remedial alternatives which are then subject to a comparative risk assessment in the feasibility study. The remedial alternatives with acceptable risks are then evaluated in a management assessment that considers the nine criteria listed in the Lower Fox River case, in Example 2.

Management Assessment

These integrate the environmental risks and benefits of alternative actions with stakeholder preferences, economic costs, regulatory requirements, legal considerations, and any other factors in the decision process. By balancing multiple goals, management assessments may provide a basis for making decisions that are likely to be successfully implemented. However, in many cases, such as new chemicals, the output of the risk assessment is usually sufficient to inform the decision. For example, if a chemical has large risks (e.g., a cancer risk greater than one in ten thousand), it will be prohibited; but if it has very small health and ecological risks, it is likely to be permitted. A formal management assessment is needed when the management decision itself is complex, because the acceptability of risks is unclear, the risks and benefits are numerous or heterogeneous, the decision is controversial, or the success of a management action depends on its political or social acceptance (SAB 2000).

Management assessment implies an integrated analysis and synthesis of decision criteria rather than simply ensuring that the decision maker receives input from all relevant disciplines. Final recommendations may balance risks against costs or utilities. For example, risks from wastes may be balanced against risks from the remedial actions and stakeholder concerns. This may be done qualitatively (e.g., using a checklist of considerations) or by quantitative methods such as net benefit analysis, cost-benefit analysis, and multi-attribute decision analysis (Efroymson and others 2004; Hanley and Spash 1993; Linkov and others 2006). Management assessments may result in a list of actions that are satisfactory, a ranking of alternative actions, or an optimum management action. Formal management assessments are relatively rare, because decision makers often prefer their own subjective processes for integrating input to the decision, but a subjective process is less transparent, less reproducible, and potentially less defensible.

Outcome Assessment: Problem Detection After Environmental Management Actions

Outcome assessments evaluate the success of a management action in achieving environmental goals. Whereas risk and management assessments predict the likely performance of different actions, outcome assessments estimate and measure the actual performance and effectiveness of management actions in the environment. Outcome assessments may be performed in stages. First, performance assessments evaluate if the action reduced or restricted the level of the causative agent as predicted by the risk and management assessments. Second, effectiveness assessments evaluate if the action resulted in an environmental condition that is acceptable and thus resolves the environmental problem. Ideally, both performance and effectiveness assessments are included in an outcome assessment and inform refinements in management actions or indicate that the problem is resolved. However, some effects take decades or centuries to recover, precluding a timely assessment of effectiveness. Other effects, such as most human health effects, are too rare to measure. In these causes, performance alone may be used to decide if the action was sufficient to resolve the problem.

Like a condition assessment, actual measurements must be made in outcome assessments; they cannot be performed by modeling alone. The post-action condition is compared with the prior condition and with reference conditions. For Superfund, the outcome assessment continues for a minimum of five years and evaluates whether the site meets the requirements of the record of decision (ROD). For outcome assessments involving aquatic life, an increase in the presence or abundance of an assemblage or target species may signal that biocriteria have been met. For human health, a decrease in exposure of the population signals that appropriate action was taken. The magnitude of the decrease in exposure or effects compared with the goal determines if the action was sufficient or if additional actions are necessary.

Outcome assessments are recommended for almost all situations, because they evaluate the success or shortcomings of the entire preceding sequence of assessments, decisions, and actions. Even a small relative change is important to note, because it may suggest other options for actions that may ultimately enable full attainment of the environmental goal through an adaptive management process (Holling 1978).

Common Assessment Process

The individual assessments in this framework all share a common process composed of three activities: *planning, analysis, and synthesis* (Fig. 3). In addition, all assessments are initiated by an environmental problem, stakeholder demands, a legal mandate, or a prior assessment and they end with a decision concerning further assessments or management actions. The initiation and decision are not part of the assessment; rather these activities provide the impetus, link different assessments, or resolve the problem. The correspondence of this common process to risk assessment frameworks should be obvious. Therefore, we illustrate the generality of the common process by mapping it onto a causal assessment process that appears in the USEPA CADDIS Website (epa.gov/caddis) (Fig. 4).

All assessments follow the common assessment process, but what is done (Table 1) and the kinds of questions they attempt to answer are very different. Condition assessments ask, “Is there a problem?” Causal pathway assessments ask, “What caused the problem?” Predictive assessments ask, “What will be the consequences of addressing the problem?” Outcome assessments ask, “Did the solution work?”

Initiation

An assessment may be initiated directly by a law, regulation, policy, or other demand by society. Alternatively, it may be initiated by a prior assessment which was itself initiated by a law, regulation, or policy or societal initiative. For example, Section 303b of the Clean Water Act requires that the states, tribes, and territories report to the U.S. Congress the condition of waterbodies and the causes of their impairments. That requirement initiates condition assessments which may initiate causal pathway assessments (see the Middle Cuyahoga River case). The CADDIS stressor identification process is initiated by a detected or suspected biological impairment and the regulatory drivers include the U.S. Clean Water Act,

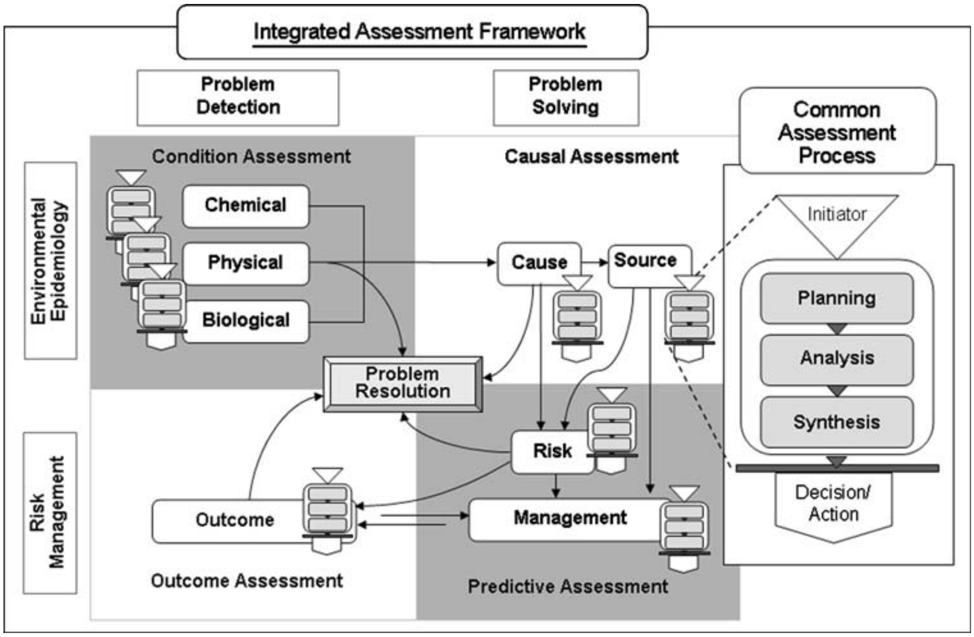

Fig. 3 A common assessment process (bottom right of fig.). Each type of assessment has three stages: planning, analysis, and synthesis (grey oblongs) and may be applied to any of the assessments in the framework. An assessment is initiated by a need or mandate (triangle). An assessment leads to a decision (pentagon). Practitioners of ecological risk assessment may recognize the three stages as problem formulation, risk analysis, and risk characterization, but note that all types of assessments share the same common process

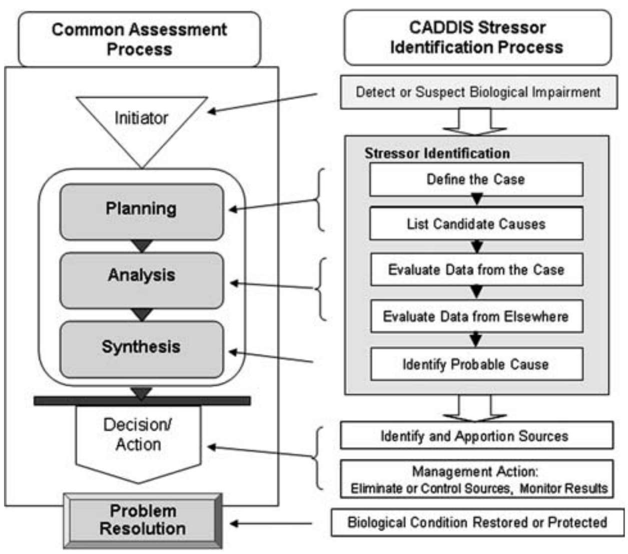

Fig. 4 A cross-mapping between the common assessment process and the CADDIS Stressor Identification process

CERCLA, and others (Fig. 4). Risk assessment of an existing pesticide may be initiated directly by a requirement for periodic reassessment or by results of condition and causal assessments, such as reports of wildlife mortality and pathology assessments (see the carbofuran case).

Planning

Assessors begin an assessment by determining the decision maker's goals and constraints on the assessment. Planning is primarily devoted to ensuring that the data collection and analysis will support the assessment and that the assessment will inform the environmental management decision. However, assessors should also plan for the use of good science and for the integration of environmental assessment with other input to the decision such as societal preferences, engineering feasibility, and other inputs to the decision. The plan for each assessment and for the integration of assessments must be mindful that the entire assessment process will usually consist of multiple assessments that must be linked to resolve an environmental problem.

Also during planning, information about hazardous agents, ecological and human health conditions, and the context of the assessment is assembled. Then measurements to be performed and models to be developed are selected that will allow assessors to estimate what has happened, is happening, or may happen in the environment. The measurements and models are described in an analysis plan. The plan must be capable of generating the cause-effect relationships that will be used to identify causes or forecast and measure outcomes.

Planning narrows the focus to tractable issues and goals and information needed for the assessment. Unnecessarily elaborate assessments waste resources, so fewer problems can be addressed. There must be a balance between acceptable uncertainty and the desire to resolve the problem. Therefore, the assessors should know the bases for the decision and the decision maker's willingness to act under uncertainty. This may be accomplished using a formal process such as the data quality objectives process (USEPA 1994). The decision maker's needs may be modest. It may be sufficient to conclude that the consequences of inaction will be unacceptable, that one plan of action is clearly better than the others, and that a desired improvement is expected to be apparent and measurable within a certain

Table 1 Comparison of the activities performed in different phases of different types of assessments

	Planning	Analysis	Synthesis	Decisions
Condition	Defines the scope of the assessment (what potential effects will be monitored, where, and when) and plans the analysis	Characterizes the conditions in the case being assessed and the acceptable or natural range of possible conditions	Compares the condition observed in the study to standards, reference, or background levels and determines whether impairment is occurring	• Declare the system unimpaired and end the process • Identify an impairment • Continue monitoring
Causal pathway				
Causal	Develops a list of candidate causes and plans the analysis to determine the probable causes	Develops the evidence to evaluate each possible cause, primarily by defining associations between the effects and the possible causes	Compares evidence among possible causes and identifies probable causes	• Identify a probable cause for further assessment • Determine that the cause is not appropriate for further assessment (e.g., the impairment is due to a drought) • Gather more data and repeat the causal analysis because evidence was unclear or insufficient
Source	Identifies potential sources and their distributions and then plans the analysis	Develops the evidence by sampling, analysis and characterization of materials, statistical analyses, geographical analysis, and transport and fate modeling	Brings together the modeling and analytical results to identify sources and estimate source contributions	• Allocate the contribution of sources to the exposure • Determine that the source is not appropriate for further assessment (e.g., the source is a natural hot spring) • Gather more data and repeat the source assessment because evidence was unclear or insufficient
Predictive				
Risk	Identifies management goals, constraints, endpoints, and management options and then plans the analysis	Estimates the probable exposure and response given different scenarios and different types of evidence	Compares the risks estimated by the analysis and presents the risk estimates and uncertainties, recommends protective levels or restoration targets, or presents the relative risks of alternative actions	• Take action because of severe risks • End the process because of minimal risks • Gather more data and repeat the assessment due to uncertainty • Proceed to a formal management assessment that balances risks against other considerations
Management	Focuses the assessment on societal values that may be affected by the suggested management options for reducing environmental risks	Qualitatively or quantitatively evaluates relevant decision criteria such as costs, risks, benefits, cultural and societal values, and regulatory compliance for each alternative action	Determines the relative advantages of the alternative actions based on their net benefits, cost-benefit ratios, net utilities, or other decision criteria	• Attempt to resolve the environmental problem by some form of environmental intervention • Take no action • Request more information • Determine whether and how to assess the success of the outcome
Outcome	Plans the monitoring programs and the statistical analyses to be applied to the resulting data	Analyzes monitoring data to characterize changes in environmental conditions associated with the management actions	Compares the condition prior to and after actions to determine if the management goals are attained and the environmental problem is resolved	• End the assessment process because goals have been achieved • Return to either a risk or management assessment because goals are not being achieved • Continue monitoring because the results are not clear

time frame. Planning during causal assessment includes two steps in the CADDIS stressor identification process: define the case and list candidate causes (Fig. 4).

Analysis

Analysis is defined here as a process by which data and other information are organized and evaluated and computations are performed to provide more useful information. At the core of analysis are one or more causal relationships. General and case specific empirical and mechanistic models are used to infer what has happened in the past, whether conditions and change are natural or anthropogenic, or what may happen in the future. The analysis may include summary statistics, quantitative models, and logical arguments. Among the most useful analyses are those that demonstrate that the intensity or specific mechanism of a causal agent can or cannot cause the effect or accurately predicts the effect. In the CADDIS stressor identification process, analysis is broken down into two steps, evaluating evidence from the case and from elsewhere (Fig. 4) (www.epa.gov/caddis).

Synthesis

Synthesis brings together the results from the analysis to generate the findings of the assessment in a useful form for the decision. Synthesis is devoted to producing a coherent output that integrates all evidence and endpoints to inform the decision. This includes deriving endpoint estimates and associated uncertainties from the results of the analysis, integrating multiple forms of evidence, comparing the management alternatives, and deriving overall results. The methods and criteria for syntheses vary with the type of assessment, but they share similar processes of estimation, integration, comparison, and characterization (USEPA 2007). In the CADDIS stressor identification process, synthesis is the identification of a probable cause by weighing the evidence (Fig. 4).

Decisions and Actions

At the end of each assessment, a decision is made. The decision can be (1) to stop the assessment process because there is no further problem; (2) to perform an assessment-informed management action; (3) to initiate the next assessment in the sequence; or (4) to by-pass the next assessment and proceed to a another type of assessment. Alternatively, although not a preferred option, a decision can be made without using the information offered by the assessment (e.g., if the assessment results suggest a politically or economically unacceptable conclusion—NRC 2005). At the end of the CADDIS stressor identification process, three typical types of decisions are possible (Fig. 4): (1) the cause is identified and a source assessment is initiated; (2) the identified cause is not within the jurisdiction of the manager and the problem is referred to an appropriate management body or the assessment process is terminated; and (3) the cause is not identified and new data are collected to refine the assessment.

Abbreviating the Framework

Depending on the mandate, a full assessment can be initiated at any point in the integrated framework and need not include all of the potential assessments (Fig. 2). In particular, an expediency or emergency by-pass circumvents causal and source assessments, because causes and sources are known. Further, in an imminent or on-going environmental disaster, appropriate actions may be obvious and do not require a case-specific assessment. In such cases, containment is paramount and rapid evaluation of risks from different remedial options is needed. Ideally, a risk-based remedial action plan would already be available to the emergency response team. The flexibility to begin or return to any step in the process allows for iteration, self-checks, and adaptive management.

Applying the Framework

The integrated framework is implicit in some existing environmental assessment and management processes. We have chosen three cases illustrating different regulatory programs and that have led to environmental outcomes. Because the framework is applied after the fact, the organization of the cases is illustrative rather than descriptive of how the assessment process was organized.

Example 1: Middle Cuyahoga River Assessments—TMDL Program

To illustrate how our framework relates to the U.S. Clean Water Act's cycle of assessments and management decisions, we have selected the Middle Cuyahoga River as a case study.

Initiator

Each year a report is filed with the U.S. Congress that lists all bodies of water identified by the states as impaired, the "303d List of Impaired Waters." The Clean Water Act requires that steps be taken to restore 303d-listed bodies of water to acceptable, useful conditions. To that end, the U.S. Environmental Protection Agency (USEPA) mandates that states determine the Total Maximum Daily Load (TMDL) of the pollutant that can be safely discharged while maintaining acceptable use of the body of water. The TMDL rule further requires states to develop a restoration implementation plan. The figure eight diagram (Fig. 5) depicts the sequence of assessments involved with the 303(d) listing and the TMDL processes (USEPA 2002). Although its form is different, the diagram contains all the components of our environmental assessment framework in roughly the same sequence (Fig. 2).

Condition Assessment

The Ohio EPA monitors waters of the state on a five year cycle and characterizes streams from exceptional to very poor condition based on bioassessments of fish and benthic invertebrate assemblages (Ohio EPA 1988). In 1996, the Ohio EPA found that the Middle Cuyahoga River, near the cities of Kent and Munroe Falls, was only partially attaining State standards for warm water habitats (Table 2).

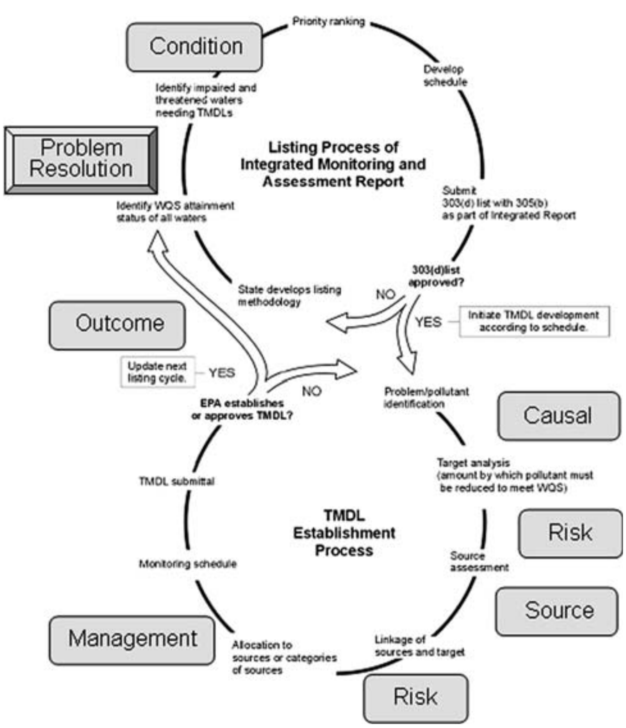

Fig. 5 A diagram of the assessments and decisions involved in the listing of waters as impaired and the determination of total maximum daily loads (USEPA 2002). The corresponding components of the assessment and management framework are indicated in grey oblongs: condition assessment (listing process), causal assessment (problem/pollutant identification), risk assessment of effects from exposure (target analysis), source assessment, risk assessment of sources (Linkage of sources and target), management assessment (allocation to sources), and outcome assessment (update next listing cycle) (from USEPA 2002)

Causal Pathway Assessment

In 2000, that section of the river was placed on the State's 303(d) list of impaired waters and a TMDL was completed (Ohio EPA 2000). A causal assessment identified low dissolved oxygen as the preeminent cause for low diversity and low numbers of fish in the river upstream from the Kent Dam. Low dissolved oxygen (average 4 mg/L, 24-hour average, and a range of minima over several days from <0.01 to 3.0 mg/l) was associated with eutrophication from nutrient loading by municipal point sources, the upstream Akron Reservoir, combined sewer overflows, septic systems, and urban runoff (source assessment).

Risk Assessment

The TMDL risk assessment determined that reductions in nutrients alone were unlikely to improve aquatic life due to contributing factors from two dams which altered flow, aeration, and benthic habitat. Furthermore, the dams were physical barriers to fish migration. The TMDL recommended increasing natural river characteristics by modification of dams and flow releases, and decreasing loading of pollutants that lead to low dissolved oxygen. Options included minimum release requirements for the Akron Reservoir, removal of dams in Kent and Munroe Falls, or significant upgrades to point source discharges to drastically reduce nutrient loadings.

Management Assessment

For the Kent locale, there were technical and social challenges due to the historic value of the dam and nearby area as well as costs for upgrading waste water treatment facilities. Ultimately a management alternative was negotiated and implemented that preserved the historic character of the area while providing a free-flowing river that aerated the water.

Management Action

In Kent, the old canal lock east of the dam was removed, the historically significant arched dam structure was preserved and modified into a fountain, and the area of the former dam pool, now above water, was developed into a heritage park (Fig. 6). Upstream, extensive natural stream channel and stream-bank restoration further increased the likelihood of improvements to aquatic life. The natural waterfall was rediscovered under the Monroe Dam and its esthetic form was restored by removing the dam.

Outcome Assessment

Monitoring before and after remediation demonstrated that dissolved oxygen was increased, species that had been

Table 2 Ohio EPA Kent Dam pool bioassessment

	Pre-remediation	Post-remediation
Fish index (IBI)	28.0	44.0
Habitat index (QHEI)	51.0	79.5
Warm water criteria: IBI $\geq$ 40; QHEI $\geq$ 60		

Source: USEPA (2005)

excluded by the dams were found in the area, and a wider diversity and abundance of fish were observed (USEPA 2005).

Resolution

The full assessment cycle was successful because each assessment was integrated with the next assessment, clear objectives were developed for each assessment and the overall integrated assessment, and different assessors were responsible for assessments within their area of expertise and authority. Compelling scientific information was succinctly provided to resource managers and stakeholders who were involved at appropriate stages of the assessments. Multiple regulatory authorities were invoked to maintain momentum and financial incentives, and resources were obtained to implement management actions (USEPA 2005).

Example 2: Lower Fox River/Green Bay Superfund Assessments

Initiator

The Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA or Superfund), was created to clean up hazardous wastes that posed potential threats to human health or the environment. After the law was passed, U.S. governmental agencies developed two assessment and management processes to address different provisions of the Act:

(1) Agencies that are trustees of natural resources perform a Natural Resource Damage Assessment (NRDA). It includes a condition assessment to determine whether resources at the site are injured and a *causal assessment* to determine whether the wastes are the cause.
(2) The USEPA and state regulatory agencies perform a condition assessment to determine if the site is sufficiently contaminated to be on the National Priority List. They then perform a set of *risk assessments*, the remedial investigation/feasibility study (RI/FS), to estimate risks from no action and from alternative remedial actions (USEPA 1998b). The Record of Decision (ROD) is a management assessment that selects the remedial action.

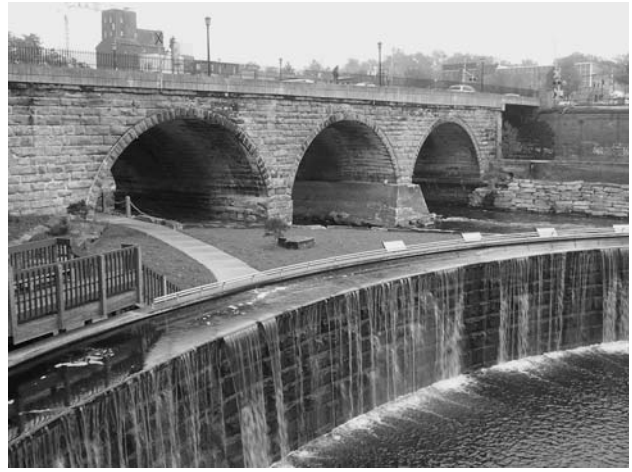

Fig. 6 After completion of the Kent Dam project, the river flows freely through the old lock structure (right) and the original arched stone dam was retained and converted to a fountain (left) (photo courtesy of Ohio EPA)

Superfund Natural Resource Damage Assessment: Biological Condition and Causal Pathway Assessments

Before the Fox River became a Superfund site in 1999, extensive condition and causal assessments were done by the Wisconsin Department of Natural Resources (WDNR). The Department of the Interior (DoI) and participating Native American Trustees for the NRDA on the lower Fox River and Green Bay, Wisconsin, site filed the official Natural Resources Damage Assessment reporting injuries to migratory birds resulting from hazardous substances within the Fox River and Green Bay system (Stratus Consulting, Inc. 1999a; WDNR and USEPA 2006; USFWS 1999). WDNR and USEPA also documented pathways from known releases of PCBs in the Fox River to known injuries in the Fox River, Green Bay, and Lake Michigan (Stratus Consulting, Inc. 1999c; USEPA 1992).

The condition assessment revealed numerous effects on fish and wildlife including endangered species and loss on natural resources to humans. PCB exposure, uptake, and injury were described for Forster's terns (*Sterna forsteri*), double-crested cormorants (*Phalacrocorax auritus*), red-breasted mergansers (*Mergus serrator*), black-crowned night-herons (*Nycticorax nycticorax*), tree swallows (*Tachycineta bicolor*), bald eagles (*Haliaetus leucocephalus*), and other species. In addition, liver tumors were found in 34% of Walleye and PCB concentrations in multiple fish species were sufficient to impose human consumption advisories (Stratus Consulting, Inc. 1999b).

Causal assessments established that PCBs were the cause of observed effects on wildlife. A source assessment traced the PCBs to their manufacture by Monsanto and then use by paper mills on the Fox River that manufactured carbon-free copy paper (WDNR and USEPA 2006; US-FWS 1999).

Superfund Site Remediation

Figure 7 depicts the rather complicated site remediation process from listing a Superfund site to post-remedial monitoring.

Condition Assessment (Chemical)

The Wisconsin Department of Natural Resources (WDNR) and the USEPA listed this site based on a waste-focused condition assessment (versus the resource-focused condition assessment of the NRDA) that revealed approximately 36 metric tons of PCBs in the lower Fox River and Green Bay (USEPA 1989). Sediments of the lower 30 miles (48 km) of the Fox River contain PCBs concentrations as high as 100 parts per million (ppm) (WDNR 1988).

Risk Assessment

Based on a risk assessment (RI/FS) for 63 km of the Lower Fox River and Green Bay (RETEC Group 2002), the regulators filed two records of decision in 2002 and 2003 that set PCB clean up levels at 1 ppm (WDNR 2003; WDNR and USEPA 2006).

Management Assessment

The Superfund remedial decision process compares the options using nine criteria: protection of human health and the environment; compliance with Applicable or Relevant and Appropriate Requirements (ARARS) (regulatory standards); long-term effectiveness; reduction of toxicity, mobility, or volume; short-term effectiveness; implementability; cost; agency acceptance; and community acceptance. This provides consistency and transparency in decision making and affords a clear target for the assessment process. In 2005 and 2006, some of the necessary consent decrees were completed that allocated the clean up costs among polluters of the river. In 2006, a remediation implementation plan was accepted that recommended a combination of dredging, capping, and other procedures and included monitoring before and after remediation to support an outcome assessment (WDNR and USEPA 2006).

Outcome Assessment

Remediation began in 2007 and will be followed by 40 years of monitoring and outcome assessments.

Example 3: Pesticide Registration—Carbofuran

Initiator

In the United States, pesticides must be registered by the USEPA and periodically reregistered. The registration of new products is based on conventional health and ecological risk assessments using modeled exposures and laboratory tests of toxic effects. However, reregistrations may take advantage of monitoring data or incident reports to assess conditions resulting from prior uses and incorporate the results of those epidemiological assessments into the risk assessment.

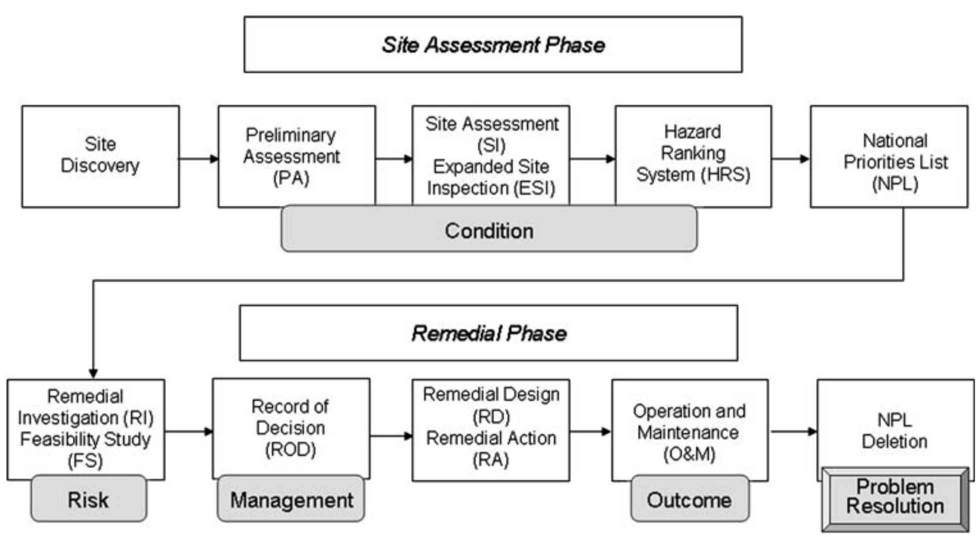

Fig. 7 Superfund process: The site assessment phase is a condition assessment that determines whether the site is sufficiently contaminated to be listed. The remedial phase includes the risk assessment of the RI/FS and the management assessment of the ROD. The outcome assessment is a component of the operation and maintenance plan that may lead to the deletion of the site from the National Priority List (NPL) (original diagram no longer on website, similar found in USEPA 1998b)

Predictive Assessment

Carbofuran is an N-methyl carbamate insecticide which acts by inhibiting the neurotransmitter acetylcholine. Because of its extreme toxicity to birds and the many reported incidents of bird kills, the granular form was restricted to a few uses in 1994. Both forms were reassessed in 2006 under the requirements of the Food Quality Protection Act (USEPA 2006b). The risk assessment used both deterministic and probabilistic risk modeling to estimate that risks of mortality were severe for birds and mammals. In addition, it used condition assessments and causal assessments in the form of 31 bird-kill incident reports and kill investigations that determined carbofuran to be the cause. These eco-epidemiological reports provide another source of exposure-response information that confirmed the reasonableness of the risk models. The human health risk assessment also found significant risks based on both risk models and human poisoning incidents.

Resolution

As a result of these findings, the Agency reached an interim decision that "products containing carbofuran will not be eligible for reregistration" (USEPA 2006a). If this decision stands, there will be no outcome assessment because there will be no carbofuran applications to monitor and assess. So, although monitoring requirements are common in pesticide registration decisions, monitoring would not be necessary if carbofuran is banned.

Current Practice Compared with Ideal

Most assessments are not as well integrated as these selected examples. And, even these three were integrated in a somewhat ad hoc fashion. This is due in part to the lack of integration among environmental programs. For example, the USEPA's Environmental Monitoring and Assessment Program (EMAP) was designed for evaluating status and trends. EMAP data have been used to evaluate impairment of aquatic communities, but it is not connected to the TMDL program which requires determination of causes of impairments. Similarly, the TMDL regulation requires that causes, sources and pollutant loads be calculated and that implementation plans be prepared, but it does not specifically require implementation or an outcome assessment. The Superfund's RI/FS and NRDA programs are not linked, leading to inefficiencies. In some cases, lack of integration of risk assessment and management has resulted in inaction (NRC 2005). Furthermore, the language that is used in different programs masks their commonalities, making these processes seem more complicated than they really are. Using a common framework could make integration more common and more effective.

Discussion and Conclusions

We believe that this matrix framework for environmental assessment and management provides significant advantages because it is based on sound principles for scientifically informed multi-dimensional decision making (Suter and Cormier 2008). First and foremost, it keeps assessors focused on supporting decisions that lead to resolution of an environmental problem. These include the decisions that result from the individual assessments (how to proceed) and the ultimate environmental management decisions (what to do) and (are we done?). It makes it clear that both the assessors and the other environmental scientists who generate the data must serve the interests and needs of environmental managers. Without such an inclusive and decision-focused framework, it will not be clear to scientists how to generate a useful synthesis of information. For example, many condition assessments do not provide the needed information for assessing causation and do not generate condition measures that can address stakeholder concerns or support management decisions. Further, the figurative and literal centrality of the end of the assessment process, the "problem resolution" (Fig. 1), emphasizes the desire of decision makers to expeditiously and successfully complete the process and move on to the next issue or problem.

Second, the framework emphasizes the need to fully use available science throughout the process. For example, risk assessors should, whenever possible, look to condition and causal assessments rather than relying solely on standard assumptions, models, and laboratory data. This is obvious in risk assessments of ongoing problems like contaminated sites. However, even with cases such as evaluation of risks posed by new chemicals, condition assessments of locations exposed to analogous chemicals can provide important evidence. Similarly, risk assessments that do not follow through with outcome assessments miss the opportunity to assure success and improve the scientific bases for future assessments and management decisions.

Third, the generality of the framework encourages the performance of integrated assessments that provide a consistent input to management decisions that benefit the environment, human health, and human welfare at all relevant scales and levels of organization. The World Health Organization developed a framework for integrated health and ecological risk assessment (Suter and others 2003; WHO 2001), but the framework presented here integrates the entire assessment and management process so that the decision maker receives consistent and coherent scientific support.

Finally, the common framework may unify diverse assessment frameworks and practices. Environmental assessments are done for many reasons in different places based on approaches developed at different times under different policies, so the underlying commonality is obscured. As a result, the components of the assessment process have been reinvented many times. Yet, examination reveals that they all fit within a pattern of discovery and resolution that can be explained by this common process and general framework.

The basic frameworks for human health and ecological risk assessment (NRC 1983; USEPA 1992, 1998a) have been so successful in improving risk assessment practices that they have been adopted and applied in numerous countries and contexts (Dale and others 2008; Power and McCarty 1998, 2002). Similarly, we hope that a fully integrated framework for environmental assessment will provide a more uniform and, therefore, a clearer and more accessible process. We hope that a common language among assessors will increase cooperation and the likelihood that integrative environmental assessment will occur. By improving the relevance of the scientific input and increasing the transparency of the integrated assessment, we hope to increase rationality of the environmental management processes and lead to informed decision making.

Acknowledgments We appreciate the constructive criticisms from Jay Messer, Michael Kravitz, Larry Barnthouse, Rick Linthurst, and Michael Troyer, who may still disagree with some portions of the framework, but who share our commitment to ensuring that scientific knowledge influences and guides environmental decision making. We thank Steve Tuckerman of Ohio EPA for providing the photograph of the Kent Dam removal project. The ideas in this article are our own and do not represent policy or recommendations of the U.S. Environmental Protection Agency and our work was not financially supported by any group and was done on our own time.

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