Multiple Stressors in Ecological Risk Assessment

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Preface

This white paper is tailored to risk assessors and managers in United States Environmental Protection Agency (EPA) Program Offices and risk practitioners in the private sector who may work with agencies. For these reasons, the white paper must provide a balance of orientation and examples of how to proceed. The paper cannot be so general that it is not informative, and it cannot be a compendium of tools, as that is too much “in the weeds” and the intended audience is apt to be lost in the details.

With this in mind, the paper begins with the context that will be presented in the “Introduction” and in a section entitled “Considering Multiple Stressors.” These sections address the topics that the reader/user will need to think about as they plan and prepare for an ecological risk assessment for multiple stressors.

The rest of the paper is structured around the elements of ecological risk assessment. Here, the “how to” is described in broad terms. These sections include important considerations on how to proceed, as well as examples of useful tools. The intent of the authors is to make the main themes evident throughout the paper, rather than suggest that the document is a cookbook or toolkit. Tried and true approaches are included, as well as reference to some innovative methods. The methods that are in use are in the peer-reviewed literature or government technical reports.
1.0 Introduction

Ecological risk assessments have traditionally focused on chemicals as explained in Suter (1993), a situation that is not so different in the realm of human health environmental risk assessments. Multiple stressor assessments have meant multiple chemicals for many regulatory programs and assessors until fairly recently. As EPA developed formal guidelines for ecological risk assessments, and the National Research Council (NRC) provided input (NRC, 1993), physical and biological stressors became more important in conducting ecological risk assessments. Examples include changes in water flows, temperature and the introduction of invasive species. Part of the process of developing the guidelines included preparation of case studies and issue papers that expanded on or explained concepts or key elements, including those related to multiple stressors.

The present paper follows the generalized form of an ecological risk assessment and explains the important features inherent in risk assessments with multiple stressors. The basic steps as presented in the EPA Framework are followed:

- discussion with management
- problem formulation
- exposure analysis
- response analysis and stressor-response evaluation
- characterization
- final evaluation with management

Multiple stressor ecological risk assessments require some care and planning in order to get the right level of detail and scope and not end up with an assessment that has too many components or is unfocused. The discussion between managers and assessors is an early opportunity to provide the level of focus that informs the assessment process in a way that yields outputs that are most relevant for the management decisions under discussion (see NRC [2009] for lengthy discussion of this point). While this step is true for all ecological risk assessments, in the case of multiple stressors, the circumstances may offer a large and complex array of assessment options.
The complexity and magnitude can choke the assessment design or implementation and inhibit a useful outcome.

During the past 15 years, in the time since the EPA finalized the Guidelines for Ecological Risk Assessment (USEPA, 1998), various research efforts have applied ecological risk assessment methods to different situations. The two most common multiple stressor situations seem to be multiple chemical exposures and watersheds, as discussed below in more detail. An emphasis on methods used in multi-chemical and watershed assessments is practical, indicating the areas where more work has been done on the topic.

2.0 Considering Multiple Stressors

This section includes history and context (e.g., Society of Environmental Toxicology and Chemistry [SETAC], NRC, and previous EPA efforts) that is relevant for multiple stressors in ecological risk assessment. This section discusses when and why it makes sense to proceed with considering multiple stressors risk assessment procedures and methods. The assessment process is linked to stated management goals for the problem at hand.

The authors view this opening portion as the critical orientation piece designed to provide the reader with an understanding that such assessments are appropriate and needed for particular types of problems and can be undertaken. There are challenges and uncertainties that must be recognized with these approaches and it should be noted that a detailed multiple stressor ecological risk assessment is not needed, or not likely to be useful/productive, in all situations.

Risk assessments, both human health and ecological, are inherently practical endeavors intended to inform management decisions and actions, often (but not always) carried out under legal/regulatory frameworks. Ecological risk assessments for multiple stressors present more complicated cases in which the unknowns of ecological systems are coupled with the challenges of stresses that are often quite dissimilar. The special or unique aspects of ecological risks are examined in some detail in Suter (2007), CENR (1999), USEPA (1998), and related documents that present ecological risk assessment practices and processes.
Among the more notable features of ecological risk assessments that are likely to come into play in multiple stressor cases include:

- spatial and temporal aspects of ecosystems
- combinations of various microbes, plants and animals
- more in-depth evaluations of the basic biology of plants and animals
- a focus on populations with attendant extrapolations or modeling
- more in-depth assessment of the interactions among plants, animals and microbes

The term "stressor" is defined in various EPA guidance documents, textbooks and the scientific literature. The EPA Ecological Risk Assessment Guidelines (page A-3) provides the following definition: "any physical, chemical or biological entity that can induce an adverse response" (USEPA, 1998). Suter (1993) notes that a stressor is the proximate cause of an adverse effect, and later Suter (2007) argues that other countries use the term "agent," a more neutral term. Notwithstanding the imperfections, this paper uses the definition in the EPA Guidelines.

Three distinct categories of stressors are recognized in the literature and the Guidelines: chemical, physical, and biological, each of which deserves a brief comment here. Chemical stressors are the most commonly considered in risk assessments, owing to historical and institutional issues. Toxic chemicals, as well as many conventional pollutants, fall into the category of chemical stressors. Several common "pollutants" or conditions that may not be recognized immediately as chemical include acidic or basic waters (change in hydrogen ion concentrations) and hypoxic or hyperoxic waters (low or elevated oxygen partial pressure, respectively). Physical stressors are fewer in number but are quite diverse, ranging from physical impact or contact, water flow, sediment or particulate matter (PM), radiation in any form, sunlight (or its absence), heat (or lack thereof), sound, vibrations, and pressure. Biological stresses are any living organism, of which there are many millions. Many biological stressors are non-native species or species that have become invasive or harmful as a result of some change in the ecosystem.

Multiple stressors are combinations of stresses in either the same or various categories. An emission or discharge that contains several organic chemicals and metals will represent multiple
chemicals. If the emission includes particulate matter, or the discharge includes sediment, or is heated, then the multiple stressors fall into two categories – chemical and physical.

Some common multiple stressor situations include:

- stack emissions: PM (physical), NOx, VOCs (both chemical)
- stormwater discharges: chemicals, sediment (physical) and bacteria (biological)
- construction or agriculture runoff: sediment, chemicals, seeds, bacteria, viruses
- municipal solid waste: contact/impact, chemicals, microbes

The evaluation of multiple stressors is not new and insights can be gained from past experience. A category of multiple stressors that has been considered for a number of years includes chemicals that act via the same toxic mechanism and can therefore be quantitatively assessed at a biochemical level. Dioxins and dioxin-like chemicals are perhaps the best example of this type of multiple stressor (USEPA, 2010a). These chemicals all act via the cellular Ah receptor, but bind with varying effectiveness, thus they exert unequal toxicities. The toxicities can be, and are, quantitatively ranked, according to both chemical congeners and by animal group (mammals, fish and birds). EPA incorporated these toxic equivalency factors (TEFs) and the approach as the most appropriate approach for understanding risks from multiple dioxin-like chemicals (USEPA, 1993; 2008).

Not all situations lend themselves to a multiple stressor approach and, in some cases, such an approach may not be appropriate. For example, statutory or regulatory applications may not lend themselves to, or allow anything other than a single stressor assessment. Evaluation of a new chemical registration under the Toxic Substances Control Act (TSCA) or a pesticide under the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) is defined as a single chemical assessment. Any number of permits may be focused on a single chemical, physical stress, or biological agent. Some contaminated site assessments under the Comprehensive Environmental Responsive, Compensation, and Liability Act (CERCLA) or the Resource Conservation and Recovery Act (RCRA) may have but a single chemical or, as in the case of polychlorinated biphenyl (PCB) contamination, a relatively small group of chemically similar compounds. The
Hudson River cleanup of PCBs is one such site (USEPA, 2012). In many such situations, multiple stressor ecological risk assessments are likely not called for and/or not appropriate.

Some environmental management decisions and associated ecological risk assessments are well suited for complex multiple stressor assessments because several characteristics are met, including:

- a defined geographic area, probably not small and often complex
- stressors are not similar
- more than one ecological receptor is involved
- an ecosystem-level impact is possible or certain
- management can address a multiple stressor situation
- sufficient time is available to perform the assessment

Ecological risk assessments for multiple stressors can involve situations that involve both complex receptors (ecological components and/or ecosystems), as well as combinations of stressors. Risk assessments that have intentionally attempted to address these issues include watershed risk assessments or ecological risk assessments of similar scope. Several such assessments have been completed and are summarized in a text box below. Table 1 also presents more detailed information summarizing the several watershed ecological risk assessments conducted by EPA or independent investigators. In addition, one of the first assessments of ecological risks at a watershed level was carried out for the Upper Fox River in Wisconsin by Harris and Wenger (1998). This assessment was not carried out as part of a regulatory/legal action *per se*, but was conducted as a process for addressing watershed improvement.

The Upper Fox River assessment centered around a panel of experts identifying the major stressors to the ecosystem. The stressors were organized by category and group, rather than as individual chemical, physical, or biological elements. The experts were asked to both organize the stressors and rank them according to severity of risk to the system.

The methodology used in Harris and Wenger (1998) was a matrix consisting of stressor categories as a function of receptor (outcome) values. Interested and knowledgeable people...
### Watershed Level Ecological Risk Assessment Examples

**Sheboygan River and Harbor, Wisconsin** (NOAA and EVS, 1998)
This work analyzed a section of the Sheboygan River that was listed on Superfund in 1986 due primarily to highly elevated levels of PCBs. The published paper analyzes the risks to benthic macro invertebrates, several species of fish, the blue heron, and the mink from exposure to PCBs, PAHs, and heavy metals.

**Clinch and Powell Watershed, Virginia** (USEPA, 2002a)
The focus of this EPA white paper is to correlate land usage to species richness, suggesting that coal mining and agricultural usage is negatively affecting the watershed and impacting fish and mussel populations. Forested riparian zones were found to have the highest species diversity in the watershed, while streams adjacent to mining sites and residential and industrial areas had lessened species diversity.

**Middle Snake River, Idaho** (USEPA, 2002b)
Simulation of habitat conditions were used to produce a model that points to increased water temperature, lessened water flow, shallower water depth, and increased nutrification as the major factors controlling macrophyte growth in the Middle Snake River in Idaho. These factors have led to the eutrophication of the river, shifts in species composition, and the loss of diverse species and habitats. Multiple dams, changes to flow, increased pollutants and habitat alterations are thought to have caused the nitrification. The taxa now dominating the river are tolerant of warmer water temperatures, siltation, and pollution.

**Big Darby Creek, Ohio** (Cormier and Smith, 1996)
The purpose of this paper is to demonstrate the responses of Big Darby Creek to threats it has experienced over the course of 30 years. The watershed has remained remarkably healthy and shows great biodiversity. The paper is an analysis of the system and an appraisal of the watershed management practices implemented in the area. The paper applauds the cooperation of county agencies within the area in their combined efforts to protect the watershed, and also notes that farmers formed their own citizen task force to address changes to the watershed and advocacy. Implemented practices lead to significantly reduced sedimentation and significantly increased buffer land (where grasses and trees were planted).

Information for the report came largely from interviews.

**Waquoit Bay, Massachusetts** (USEPA, 2002c)
This report analysis focuses on the effects of nitrogen loading on eelgrass cover and scallop abundance in Waquoit Bay, Massacusetts. A Nitrogen Loading Model (NLM) and an Estuarine Loading Model (ELM) were created to estimate the nitrogen entering the watershed and the nitrogen available to producers respectively. Wastewater nitrogen was found to be the primary source of nitrogen in the bay. Eelgrass cover is shown to diminish with increased nitrogen concentrations, which leads to a decline in the abundance of scallops due to habitat loss.

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served as the review panel to complete the evaluation. The process used 12 stressor categories and 10 valued ecosystem characteristics and the participants ranked each stressor/value combination.

The matrix approach was also the preferred method for a technical expert workshop on multiple stressors convened by SETAC and edited by Foran and Ferenc (1999). In this proceeding, the matrix approach, described by Harris et al. (1994) and applied in the Green Bay/Fox River situation, was recognized as a practical means of combining stressors into categories and
ascribing effect in a relational manner. Thus, rather than a single toxic chemical identified as the stressor, the group "toxic chemicals" could be identified, and an even more general category of "discharges" would include various chemicals, as well as the physical (temperature, flow) and biological (parasites, bacteria, viruses) aspects of the discharge.

3.0 Management-Assessment Decisions

Conventional (i.e., single stressor) ecological risk assessment begins with a discussion between the assessment and management teams (also labeled as “discussion with the manager”). This step becomes more important with multiple stressor ecological risk assessments because of the need to define the management decision and information from the assessment that will inform management options. This discussion is meant to ensure that the nature of the decision is aligned with the complexity and nature of the supporting risk assessment. If management decisions will hinge on a single stressor, then a multi-stressor assessment may not be necessary. On the other hand, when the receptor is a major habitat or ecosystem (i.e., a forest, watershed, prairie, or river), then many stressors likely influence the status of that system or its principal components.

4.0 Problem Formulation

Multiple stressor situations can present difficulties under any circumstances, but the difficulties are compounded by starting off in the wrong direction or using an approach that is incompatible with the assessment. Most ecological risk assessments will have a multiple stressor aspect unless a very narrow set of circumstances is prescribed by the management-assessment team discussion at the outset. The challenge for risk assessors and managers is deciding when to engage in the more complicated multiple stressor assessment.

This section describes how problem formulation needs to be conducted in order to properly frame a multiple stressor problem. This includes main themes and orientation. It will also include examples drawn from EPA experience and programs, as well as the literature. Two types of common multiple-stressor problems are: 1) combinations of similar/related stressors, and 2) combinations of very different stressors. This theme is carried through the rest of the paper. A second set of themes includes prospective and retrospective approaches.

The risks of multiple stressors to ecological receptors can be conceptualized in several ways. In most cases, it will make sense to consider specific groups of animals or plants as has been
traditionally done for ecological risk assessments. These may include species or guilds of fish and wildlife, plants, or other natural resources. Risks might also be considered with respect to ecological functions such as photosynthesis, degradation, nutrient cycling, and carbon flows. A third way to conceptualize ecological risks or multiple stressors is to frame these in terms of risks to ecosystem services. A focus on ecosystem services could provide a means of integrating the combined risks of multiple stressors in a manner that makes sense for decision makers. Some further elaboration of using ecosystem services as the “receptors” and “assessment endpoints” for assessing risks of multiple stressors is provided.

Ecosystem services have become increasingly important for estimating potential impacts to humans from alternative policies or management actions (Munns et al., 2008; Jordan, 2010; Slack, 2010) and the EPA has been actively examining how this goal can be best accomplished. For example, ecosystem services are a central theme for the Office of Research and Development (ORD) research program, Sustainable and Healthy Communities. One planned output from the ORD research program that will contribute to holistic risk assessments is the National Atlas of Ecosystem Services (USEPA, 2010b). This atlas will enable users to view and analyze the geographical distribution of ecosystem services supply, demand, and drivers of change at multiple scales and for communities across the country. The purpose of the atlas is to support evaluations of the relationships between human health and well-being and the provision of ecosystem services. As such, this atlas would serve as an important resource for risk assessments involving multiple stressors. Ecosystem services will vary across habitats and regions and, therefore, explicit consideration of ecosystem services will have an explicit geographic component.

The number and types of receptors chosen for evaluation will depend on the nature of the policy or management decision being examined. The process of selecting ecological receptors is carried out simultaneously with the selection of stressors described later. The following considerations may be helpful for selecting receptors for evaluating risks associated with multiple stressors:

- Geography: exposure assessments for multiple stressors are likely to be most informative if they are place based. Therefore, the definition of spatial boundaries and the ecological resources included within those boundaries are key considerations. If a management
decision covers a broad area, the exposure assessment may need to be carried out for
several areas or regions.

- Relationship to the decisions: the inclusion of particular receptors will sometimes depend,
in part, on knowledge and/or perceptions concerning how receptors may be affected by
the decisions under consideration and how those effects/risks influence the decisions.

- Sensitivity: some ecological receptors may be more sensitive to particular stressors or
interactions among stressors; where knowledge exists on differential sensitivity for
particular receptors, that information may be used to select receptors.

Identifying the Stressors

Conceptual models that link possible stressors with ecological receptors are an essential
component of a multiple stressor ecological risk assessment. Early conceptual models could
begin with a broad list of stressors that may be important and this list could be narrowed later in
the process as information is acquired. The broad list of stressors should be based on:

- The types of environmental attributes and associated stressors that may be influenced by
the policy or management decision;

- Stressors associated with observed ecological effects (i.e., known or suspected initiating
factors); and

- The possible negative influences of those attributes and stressors on ecosystem services.

Conceptual model diagrams should be used to portray how stressors may influence (positively or
negatively) the ecological receptors. These diagrams can be used to reflect direct and indirect
influences, as well as possible interactions among stressors. If risks to ecosystem services are
being evaluated, the conceptual model should reflect how the stressors influence these services.

While conceptual model diagrams can accommodate multiple stressors, the challenge is
balancing detail and clarity as discussed by Menzie et al. (2007) and Suter (1999). A possible
solution for balancing clarity and detail is to utilize nested models that can be viewed using
computers. These models could be three dimensional. At one perspective, they can be shown as
simple two-dimensional representations. However, this surface simplicity can be supported by
more robust underlying detail that can be visualized and operationalized by expanding and
collapsing detail for parts of the conceptual model. There may also be subtle linkages and
feedback systems that can be captured in these “behind the scenes” details. Various forms of visualization will resonate differently among groups of people. Therefore, it can be very helpful for communicators to develop a good understanding of how to best represent conceptual ideas and models to particular communities or groups of people. This will involve learning from the community and group.

5.0 Analysis

Analysis is comprised of exposure and effects assessments. Because these elements are often integrated, the term “analysis” is used for this step of the multiple stressor risk assessment. When assessing the risks associated with multiple stressors, it is important that the analysis properly align exposure with effects. It is also important that the assessment be well defined in terms of specific receptor groups, geographies, and effects endpoints.

Exposure of ecological receptors to a suite of multiple stressors will depend, in part, on the characteristics of receptors. The descriptions of characteristics to be incorporated into the assessment are details associated with the considerations used to select the receptors in the first place. These exposure-related details can be developed around two sets of characteristics:

1. Characteristics influencing direct exposures to stressors - these are characteristics of the receptors that influence their exposures to various stressors. Familiar examples include geography, food, and water sources that may include chemical or biological stressors, and activity patterns.

2. Characteristics influencing susceptibility to effects - these are characteristics that include biological susceptibility, as well as factors that contribute to susceptibility of the ecological receptors to chemical, biological, and/or physical stressors.

A key challenge in assessing exposures for multiple stressors is that the analysis considers a suite of stressors simultaneously and, therefore, the exposure assessment needs to consider how these stressors may combine to affect the receptors. The stressors could act independently, with small combined effects; be additive; synergistic; or antagonistic (offsetting one another). Exposures could result in positive as well as negative (adverse) effects. Therefore, an initial step in the exposure assessment for multiple stressors involves considering how to integrate across the stressors. Menzie et al. (2007) outlined a step-wise approach for identifying and/or evaluating the
combined effects of multiple stressors for effects-based and stressor-based assessments and the
NRC (2009) adopted and modified the approach in Science and Decisions: Advancing Risk
Assessment.

Exposures of ecological receptors are considered in terms of common receptors and endpoints. These serve as the needed common denominators for aggregating and evaluating the combination of effects from multiple stressors, as well as for considering how stressors and effects may interact with one another. All positive and negative effects/risks on ecological receptors are expressed in terms of the defined receptors. These are narrowly defined because multiple stressors can vary in the degree of exposure across different types of receptors and because different receptors may have differential sensitivity.

Analytical Approaches

Approaches for assessing risks for multiple stressors have three components: spatial mapping of stressors, integration of exposures across stressors, and incorporation of information on effects. Each of these is described below.

The first component of analysis involves mapping the various stressors onto affected land or water. In some cases, mapping may include a third dimension (depth into the water or land). The spatial distributions of stressors will typically vary from one another and therefore, there will usually be an uneven distribution of stressors and associated overlaps. Mapping of the stressors gives rise to exposure zones that will vary in characteristics depending on the degree of magnitude and overlap of the stressors. These zones can be visualized as aggregates of layers of stressors that vary in thickness as a result of the overlap of layers, and/or the relative magnitudes of the stressors. This part of the analysis can be supported by Geographic Information Systems (GIS) and associated software tools.

GIS and other spatial analysis tools are key elements of the spatial analysis for relating the locations of effects on ecological receptors to the locations and magnitudes of the various stressors. As noted, the potential for combined effects of multiple stressors can be evaluated by examining the overlap of stressors (extent and magnitude) where these are illustrated as layers within a GIS or other spatial framework (Landis and Wiegers, 2005; Zandbergen, 1998). GIS can support the development and application of environmental load profiles (ELPs) as developed in
USEPA Region 2. The ELPs are derived from indices or measures of potential exposure and provide insight into the spatial distribution of combined exposure loads over various communities (USEPA, 2000b) but could also be applied to ecological resources. USEPA Region 6 has also developed a GIS-based approach for aggregating risk factors across landscapes.

Visual depictions of the combined effects of multiple stressors can serve as powerful communication and analytical tools. In particular, response surface modeling can be used to explore the nature of interactions among two or more stressors. These maps have been used for evaluating combinations of factors affecting the effects of stressors on ecosystems. The ability “to see” how two or more stressors influence responses translates the underlying multivariate models into a form that can be understood by individuals with varying mathematical and statistical aptitude.

The second part of the exposure analysis takes into account how stressors interact with one another as they overlay the land or water. There are many ways in which this interaction can be quantified. These range from qualitative and semi-quantitative characterizations of exposure to more detailed analyses that incorporate considerations such as modes of action and information on whether exposures are additive, synergistic, or antagonistic. This part of the analysis may involve the use of statistical and/or mechanistic models along with published literature and knowledge concerning how the stressors may interact.

Statistical models of multiple stressors can be derived to support predictive tools that can be applied for other systems. Multiple and logistic regressions can be used to identify the relative contributions of multiple stressors to observed effects, and the resulting equations can be used to predict combined effects. Diamond and Serveiss (2001) and Potter et al. (2004) have used regression equations to examine the explanatory power of variables in watersheds. Norton et al. (2002) used principal components analysis to evaluate the relative importance of 18 stressors and then used the first six stressor factors (various combinations of the original 18) within a multiple regression model. These regression models are statistical rather than mechanistic, so although they can work well for the system from which they are derived and do provide insight into the potential importance of various stressors under those conditions, their reliability diminishes when they are applied to conditions that fall outside the bounds of that original system. While these
regressions may still provide insight in such cases, the uncertainty associated with the resulting
predictions increases with the degree of departure from the original conditions.

Multivariate statistical methods are the most common and useful tools for exploring associations
between responses and combinations of candidate stressors. They can be used to help design
studies. Results can then be evaluated to determine whether there is a predominant stressor that
explains most of the variance or whether a combination of stressors needs to be considered (Ross
and Davis, 1990; Serveiss, 2002). Statistical tools can also identify possible interactions among
stressors. The utility of the various statistical methods depends primarily on the types of data
they can accommodate and their ability to isolate stressors that are important (e.g., analysis of
covariance) and take into account interactions among stressors (e.g., factorial multiple analysis
of variance).

Process and mechanistic models simulate exposure/response relationships for stressors by
representing the underlying processes and/or physicochemical characteristics, which are
translated into equations. Because these models are built on knowledge of causal relationships,
they can be adapted to new systems and problems. These models have been used to evaluate
processes within organisms, within populations, and within ecosystems. They offer a means of
representing the combined effects of multiple stressors, as illustrated in the discussion of effects-
based assessments.

Unlike statistical models, process and mechanistic models incorporate mathematical
representations of underlying processes. They can be applied to effects-based assessments of
multiple stressors to help explain observed conditions and they can be used in stressor-based
assessments to make predictions. Process and mechanistic models could involve any level of
organization from effects at the population level (Barnthouse et al., 2000) to the combined
effects of chemicals in the body (Andersen et al., 1987; Andersen, 1991; Dennison et al., 2003;
Dennison et al., 2004; Krishnan et al., 2002; Yang et al., 1995). Because mechanistic elements
are included, these models can be used to examine the combined effects of multiple stressors that
act on the same targets or affect the same endpoints. Process and mechanistic models require a
fundamental understanding of the nature of causes and causal interactions. As such, the
development and application of these models provide a valuable framework for investigating the
combined effects of multiple stressors.
Screening of candidate stressors serves to highlight which ones should become the focus of more in-depth analysis. Other stressors and pathways can be carried on a watch list for the analysis to assure they are tracked at some level, so they can be incorporated if new information becomes available. But it is usually not necessary or appropriate to devote the same level of analysis to each stressor–pathway combination. Screening of the stressors can be accomplished by applying statistical tools (Norton et al., 2002) and strength of evidence approaches such those as outlined in the site investigation process.

In other cases, candidate stressors can be screened if their magnitudes fall below de minimis levels such as ecological benchmarks, which are commonly anchored to concentrations or doses but can also correspond to overall target risks. Note that benchmarks should be used carefully as they are often derived on a stressor-specific basis. Therefore, the stressor could fall below its individual threshold, but still combine with other stressors to contribute to an effect. Examples include mixtures of chemicals such as certain dioxin-like compounds, divalent metals, and polycyclic aromatic hydrocarbons (PAHs) that are known to act on common endpoints and by similar toxic mechanisms. Because of the possibility of such joint effects, screening benchmarks are sometimes set below the thresholds at which potential individual effects might occur.

Matrix and ranking methods appear to be particularly useful for organizing stressor-based assessments of combined effects. These methods can make use of disparate qualitative and/or quantitative information that often typifies what is available for the various stressors (Bryce et al., 1999; Foran and Ferenc, 1999; Landis and Wiegers, 1997; Zandbergen, 1998). Matrix methods offer a systematic way for organizing available information. Professional judgment is used to guide the analyses, commonly involving small groups of experts and discussions with stakeholders. The goal is to identify stressors or combinations of stressors that are most likely to affect or are affecting environmental conditions. Matrix methods can also be used to examine potential interactions among stressors. Matrix and ranking approaches can be readily applied to various scales of biological organization from populations to ecosystems.

The Relative Risk Model (RRM) is an example of a matrix and ranking method that has been broadly applied (Landis et al., 2004; Landis and Wiegers, 2005; Luxon and Landis, 2005; Moraes et al., 2002). The method offers promise as a way to structure analysis of combined effects for stressor-based evaluations. RRM relies on ordinal ranks for classifying the relative
importance or magnitude of sources of stressors, effects, and the estimate of impacts. The use of
ranks makes it possible to combine measures that are in very different units. For example, a
chemical and a physical stressor (e.g., temperature) can be combined with respect to how they
might alter habitat. The results can be presented graphically to portray the accumulated stressor
load with respect to an assessment endpoint.

GIS-based approaches have been used to forecast the combined effects of multiple stressors
(USEPA, 2004; Zandbergen, 1998). One such approach – Alternative Futures Analyses – relies
on GIS-based tools to examine how landscape changes translate into changes in the conditions of
watersheds (Kepner et al., 2004; USEPA, 2000a). The landscape changes are converted to
changes in physical and chemical stressors that can act together to alter conditions. This analysis
is accomplished by underlying process models and through the use of professional judgment.
The stressors are then related to spatially-explicit outcomes in overall condition. Because the
results are presented as maps that show the net changes in conditions, they are accessible by a
wide audience. Other examples of spatially-explicit approaches that include multiple stressors
include Land Use Evolution and Assessment Modeling (LEAM), which has recently been
adapted to evaluate land use and environmental and economic impacts at military installations,
and cumulative habitat and watershed impact approaches (Dale et al., 1998; Wickwire et al.,
2004).

6.0 Risk Characterization

Because of their complexity, multiple stressor risk assessments can best be approached using a
tiered or phased approach. The approach is designed to narrow the focus of the assessment such
that the most important stressors and risks are identified and characterized. Phased approaches
are commonly used in risk assessments as a means to balance resources against the desire to
reduce uncertainty in the assessments. Evaluating the combined effects of multiple stressors can
be daunting, especially as additional stressors are included in the evaluation with an interest in
examining a wide range of effects and interactions. The problem is viewed by the authors from
the perspective of the value of information added for decision making. Therefore, the suggested
approach begins as simply as possible, but is as comprehensive as appropriate for the problem.
In-depth, more detailed analysis is added, only as necessary, to characterize risks at a level
appropriate for the management decision.
A critical aspect of a phased approach is recognizing the core elements that should be considered in the evaluation from the onset. That suggests an inclusive conceptual approach, along with an initial effort to prioritize the relative importance of the various stressors. The conceptual model helps track various exposure pathways and inter-relationships, and it can be used to indicate the relative importance of stressor and pathway combinations. In this way, it is possible to simultaneously capture the breadth of the problem as well as focus on its key aspects. This phased approach has the following elements:

- Develop a conceptual model sufficient to bound the problem; include all relevant stressors and describe how they might act in combination.

- Screen stressors to arrive at an appropriate and manageable number for the problem. This is a focusing exercise; other stressors and pathways can be represented in the conceptual model, but resources are directed to understanding the stressor and pathway combinations considered to have the greatest potential effects. Retain screened stressors on a watch list for subsequent checks after more information is developed.

- Evaluate the individual effects of individual stressors to determine if any are predominantly contributing to, or could contribute to the effect(s) of interest.

- Evaluate the collective effects of stressors without yet considering the potential for interactions (e.g., synergism or antagonism), and identify the potential for stressor or effect overlap, (e.g., based on common properties or temporal and spatial links).

- Evaluate the combined effects of stressors taking into account potential interactions, and considering qualitative to quantitative methods depending on the information available.

The key to the phased process is revisiting these steps at intermediate stages throughout the assessment to assure that contributing stressors, influencing factors, and effect endpoints are integrated so that combined effects and primary risk contributors can be well characterized to the level existing knowledge allows.

Multiple stressor ecological risk assessments can rely upon measures of relative risk, the use of absolute risk estimates or metrics, or a combination of both types of risk estimates. A combination of relative risk measures and risk benchmark metrics may be the most effective way
of conveying risk-related information because it gives a simultaneous sense for tradeoffs, as well as providing a basis for comparison to external risk-based criteria. The relative risk measures provide insights on the examination of the relative magnitudes of tradeoffs (increases and decreases) under various policy and management decisions. The relative risk approach also serves to identify which stressors are most important. Bayesian statistical analyses can be employed to translate various types of information into visual depictions of the relative magnitudes of risk, as well as the relative degrees of uncertainty around these magnitudes. Risk benchmark metrics can be used to provide insight regarding whether conditions or changes in conditions result in shifts across thresholds commonly used to judge risks. Examples of the latter include demarcations among ecological benchmarks or indices.

While helpful insights can be drawn from relative risk assessments, many risk managers find it helpful to consider risks with respect to “acceptability” as a basis for taking specific actions. Thus, bringing together relative and absolute risk metrics can provide broader insights into current conditions and how they may change under alternatives. This combined relative and absolute risk approach shows the direction and magnitudes of influences as well as whether the results have resulted in shifts in risks or conditions from “unacceptable” to “acceptable.” Relative and absolute risk measures can both be designed to account for the combined effects of multiple stressors (Menzie et al., 2007).

7.0 Risk Management Consideration

As presented earlier in this paper, management considerations are key to the design of any risk assessment (NRC, 2009) in order to ensure that the outcomes and outputs from the assessment are practical for informing management decisions and actions. One key aspect of multiple stressor ecological risk assessments is an understanding between the assessment team and manager(s) about the nature, scope, logistics and possible results of the assessment.

The first step in this part of the process is to check the outcome of the discussion between the assessment and management teams. This discussion, as noted above, must develop a decision typology or matrix to indicate the information required for management decisions. Under a perfect and unaltered situation, which is rare, the assessment produces the type of information that fits into one of the anticipated groups and relates to an identified management decision.
More commonly, either the information is not exactly what was expected, or the decision frame has changed as the assessment was underway.

Assessors and managers need to have a clear understanding of the information that a multiple stressor ecological risk assessment can yield, and what results are not possible. The understanding is best if written and distributed to all involved. Another key element is the level and extent of review of the assessment product (i.e., is outside peer review appropriate? or should internal reviewers be used?). Multiple stressor ecological risk assessments will likely always have some level of peer review, adding a step in the overall process.

Assessment team members will need to identify a mechanism by which management is kept informed of progress, challenges, gaps, etc., especially developments that may alter or impede the assessment. Routine updates are necessary to confirm the original assumptions remain valid and to confirm that the management issues (schedule, budget, significance) have not changed.

The final step in management-assessment coordination is consultation between the two over the final risk assessment product. Part of this consultation needs to be a discussion about communication, audiences, and participants, as well as the review.
8.0  Literature Cited


Multiple Stressors in Ecological Risk Assessment

October 2012

USEPA. 2004. Air Screening Assessment for Cook County, Illinois, and Lake County, Indiana. Argonne, IL: Argonne National Laboratory, Environmental, Assessment Division and Decision and Information Sciences Division (Nieves LA, Butler JP, Hartmann H, Thimmapuram P, authors) for U.S. Environmental Protection Agency Office of Pollution Prevention and Toxics and U.S. EPA Region V.


<table>
<thead>
<tr>
<th>Name of Watershed</th>
<th>Location</th>
<th>Type of Ecosystem</th>
<th>Sources of Anthropogenic Input</th>
<th>Receptors</th>
<th>Stressors</th>
<th>Response of Receptor to Stressor</th>
<th>Method of Analysis</th>
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</thead>
<tbody>
<tr>
<td>Sheboygan River and Harbor</td>
<td>Wisconsin</td>
<td>Superfund site, covering 14 miles of Sheboygan River with adjacent lands used for agricultural, residential, and industrial purposes</td>
<td>PCBs, PAHs and metals from industrial sources, a landfill and a coal gasification plant</td>
<td>benthic invertebrates</td>
<td>metals, PCBs, and PAHs</td>
<td>0-97% range of survivorship at 18 testing stations with PCBs, PAH and metals detected</td>
<td>contaminated sediment exposure, abundance, survivorship, species richness</td>
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<td>white sucker</td>
<td>PCBs and PAHs</td>
<td>hematological, biochemical, and histological alterations, adverse reproductive response</td>
<td>tissue and egg concentrations are evaluated using existing studies and THQs, comparison of sediment sample concentrations with literature</td>
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<td>smallmouth bass</td>
<td>fish</td>
<td>adverse reproductive effects</td>
<td>tissued samples from small mammals, crayfish and fish collected; consumption estimated; compared to literature</td>
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<td>longnose dace</td>
<td>fish</td>
<td>mortality, reduced growth and reproduction</td>
<td>compared mining, agricultural, and residential sites for species richness, abundance</td>
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<td>Clinch and Powell Valley, Watershed</td>
<td>Virginia</td>
<td>mainly forested and agricultural land</td>
<td>coal mining, urbanization, and industrial and agricultural sources, increased drought conditions</td>
<td>fish</td>
<td>increased sediment loads, agricultural and residential nutrient input, and toxic input due to mining, low flow, habitat loss</td>
<td>decline in abundance of wild trout, loss of spawning and overwintering habitat, dams hinder migration, temperatures are not conducive to reproduction, scarcity of prey due to low dissolved oxygen (DO) concentrations, unsuccessful reproduction</td>
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<td>rainbow trout</td>
<td>fish</td>
<td>model simulation of macrophyte growth shows the effects of temperature, water flow, nutrification, and water depth</td>
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<td>white sturgeon</td>
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<td>Bliss Rapids snail</td>
<td>mollusks</td>
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<td>Banbury Springs lanx</td>
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<tr>
<td>Middle Snake River</td>
<td>Idaho</td>
<td>100 km stretch (Milner Dam to King Hill) of the 1,667 km long Snake River Plain of southern Idaho</td>
<td>impoundments, flow diversions, and increased chemical and microbiological pollutant loadings.</td>
<td>fish</td>
<td>increased sediment loads, agricultural and residential nutrient input, and toxic input due to mining, low flow, habitat loss</td>
<td>decline in abundance of wild trout, loss of spawning and overwintering habitat, dams hinder migration, temperatures are not conducive to reproduction, scarcity of prey due to low dissolved oxygen (DO) concentrations, unsuccessful reproduction</td>
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Table 1 – Summary of Ecological Risk Assessments
Multiple Stressors in Ecological Risk Assessment
September 2012
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<th>Name of Watershed</th>
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<th>Method of Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Big Darby Creek Watershed</td>
<td>Ohio</td>
<td>560 sq. miles, 100 fish species and 40 mussel species</td>
<td>mainly agricultural, residential, and some industrial</td>
<td>Big Darby Watershed's habitats and ecosystem</td>
<td>agricultural: transport of nutrients, pesticides and sediments, habitat reduction, increased water temperature, threats to aquatic life, reduced species diversity</td>
<td>potentially: increased nutrification, sedimentation, eutrophication, hydraulic modification, habitat alteration, pollution, increased water temperature, threats to aquatic life, reduced species diversity</td>
<td>interviews and review of documents</td>
</tr>
<tr>
<td>Waquoit Bay Watershed</td>
<td>Massachusetts</td>
<td>53 km² of freshwater streams and ponds, salt ponds and marshes, pine and oak forests, barrier beaches, and open estuarine waters</td>
<td>pollution from agricultural, industrial, and residential sources, as well as construction sites and atmospheric deposition; habitat degradation from boating and dredging; overfishing</td>
<td>estuarine percent eelgrass cover</td>
<td>nutrient enrichment due to nitrogen</td>
<td>increased nitrogen leads to decreased eelgrass cover</td>
<td>nitrogen and estuarine loading models were created</td>
</tr>
</tbody>
</table>

Table 1 – Summary of Ecological Risk Assessments

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Multiple Stressors in Ecological Risk Assessment
September 2012