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A General Risk-Based Adaptive Management Scheme Incorporating the Bayesian Network Relative Risk Model with the South River, Virginia, as Case Study

Wayne G Landis,† April J Markiewicz,† Kim K Ayre,† Annie F Johns,† Meagan J Harris,† Jonah M Stinson,† and Heather M Summers†*

†Institute of Environmental Toxicology, Huxley College of the Environment, Western Washington University, Bellingham, Washington, USA

EDITOR'S NOTE:

This is 1 of 3 companion articles describing the ecological risk assessment for the South River and Upper Shenandoah River in Virginia, USA. The regulatory focus is Hg, and other chemicals and factors such as temperature are included in the analysis. The papers describe the foundations of the Bayesian network-relative risk model methodology and calculated risk across the landscape, evaluate how 2 management alternatives alter the risk distributions, and describe the role of risk assessment in an adaptive management process.

ABSTRACT

Adaptive management has been presented as a method for the remediation, restoration, and protection of ecological systems. Recent reviews have found that the implementation of adaptive management has been unsuccessful in many instances. We present a modification of the model first formulated by Wyant and colleagues that puts ecological risk assessment into a central role in the adaptive management process. This construction has 3 overarching segments. Public engagement and governance determine the goals of society by identifying endpoints and specifying constraints such as costs. The research, engineering, risk assessment, and management section contains the decision loop estimating risk, evaluating options, specifying the monitoring program, and incorporating the data to re-evaluate risk. The 3rd component is the recognition that risk and public engagement can be altered by various externalities such as climate change, economics, technological developments, and population growth. We use the South River, Virginia, USA, study area and our previous research to illustrate each of these components. In our example, we use the Bayesian Network Relative Risk Model to estimate risks, evaluate remediation options, and provide lists of monitoring priorities. The research, engineering, risk assessment, and management loop also provides a structure in which data and the records of what worked and what did not, the learning process, can be stored. The learning process is a central part of adaptive management. We conclude that risk assessment can and should become an integral part of the adaptive management process. *Integr Environ Assess Manag* 2017;13:115–126. © 2016 SETAC.

Keywords: Adaptive management   Ecological risk assessment   Bayesian Network Relative Risk Model   South River, VA

INTRODUCTION

The remediation and restoration of contaminated sites certainly fall into the domain of "wicked problems," where the conditions change over time, as does the cultural context (Stahl 2014). Decisions have to be made regarding appropriate approaches and the importance of the various services provided by that system, and the remediation effort can take decades.

Adaptive management has long been proposed as an approach for the long-term management and restoration of ecological systems (Holling 1978). A key to this approach is the idea that management actions are experiments, and the successes or failures of those actions to meet specific goals are incorporated into the learning process. Walters (1986) provided an extensive review of adaptive management for resource management and introduced a number of innovations in its use. Walters (1986, Chapter 11) addresses the issues when the system has a high number of variables, when stakeholders cannot reach a consensus, and when no single remediation-restoration approach can resolve the conflicts in the interests of the managers. The chapter fore tends many critical factors such as stakeholder engagement and the understanding of uncertainty that are integral to modern formulations of adaptive management.

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* Address correspondence to wayne.landis@wwu.edu

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Lee (1999) evaluated the progress of adaptive management and had 3 conclusions. First, adaptive management had been more influential as an idea than as an applied means of understanding how systems reacted to human influences. Second, adaptive management should be used only after stakeholders and regulators have reached an accord on the kinds of questions to be addressed. Third, social learning as exemplified by adaptive management is likely to be of strategic importance in managing ecosystems. The activities of learning and providing a structure for the learning process have been described in detail by McLoughlin and Thoms (2015).

Williams and Brown (2014) reported that although the idea of adaptive management has evolved, the record of success remains limited. They concluded that although adaptive management does make intuitive sense, a number of roadblocks exist. These roadblocks include:

1) Costs are associated with creating a complex decision-making apparatus and the appropriate technical expertise.
2) Institutional resistance to acknowledging uncertainty exists.
3) Managers often believe that they already know the answer and that follow-up activities are therefore unnecessary.
4) Many involved believe that they already use adaptive management when they do not.
5) Managers and policy makers often have risk aversion for new approaches.
6) Management is often focused on short-term gains, while ignoring long-term benefits and costs.
7) Stakeholders are not engaged in a meaningful fashion.
8) Institutional commitment to continue with the process is lacking.

Other than the first item, the roadblocks appear to be social, cultural, and management issues, not technical limitations. Bias also occurs in other ways.

Iftekhar and Pannell (2015) described the issue of bias in natural resource management and strategies to deal with it as part of an adaptive management process. Examples of such biases that are particularly relevant to contaminated site management are:

- Action bias: the tendency to take action although no action may be a better alternative
- Reference-point bias: the tendency to focus on a predetermined benchmark when estimating the value of that variable
- Planning fallacy: making judgments about an activity that are unreasonably optimistic, underestimating costs and completion time and overestimating efficacy
- Loss aversion: valuing losses more highly than gains of similar magnitude
- Limited reliance on systematic learning: using information from successful management outcomes instead of also using information from cases that failed. One of the suggested mechanisms is the use of a decision support system. Risk assessment is a broad category of such a decision approach.

Ecological risk assessments (ERAs) have been published that incorporate many of the attributes of an adaptive management process. These attributes include stakeholder involvement, dealing with bias and uncertainty, incorporating new information into an assessment, and examining long-term impacts on ecological structures. In addition, risk assessment innately incorporates decision making, the ultimate goal of an adaptive management process.

Wyant et al. (1995) proposed that ERAs be adopted as an organizing principle of the adaptive management process. At that time, ERA was in its early stage of development, with the first United States Environmental Protection Agency (USEPA) framework having just been published (USEPA 1992). In linking ERA results with restoration goals, Wyant et al. (1995) used the nonequilibrium dynamics approach to describe ecological structures. In this approach, the central premise is that ideal or equilibrium states are not possible in nature, and a return to an original status is neither achievable nor desirable. That means that public input and regulatory involvement are necessary to define exactly what is meant by restoration, because some perceptions may be based on an unobtainable or unsustainable condition. Stakeholder consultation and interaction with decision makers have been an innate part of the risk assessment process since the early 1990s (USEPA 1992). Significant advances in the ERA process over the years have only increased its potential to play a key role in adaptive management.

The scheme, as envisioned by Wyant et al. (1995), had at its center the definitions and objectives of the restoration effort. These were defined by context analysis consisting of ecological context and natural disturbance, as well as socioeconomic and cultural context. The objectives defined the assessment endpoints, the scope of the assessment, and any goals for the risk assessment process. The ERA then calculated current risks to the endpoints and predicted changes in risk because of management intervention. Using this scheme, as postmanagement data are collected, the ERA can be updated to provide new risk estimates. A number of additional management options can be considered at this stage. Different management options may have different costs, risks, and efficacy, and this information can be communicated to the decision makers. As envisioned by Wyant et al. (1995), this process is intended to be interactive and iterative.

Apitz (2013) proposed the integration of ecosystem services as risk assessment endpoints. Her formulation was explicit about making trade-offs in decision making, the use of risk assessment, and the valuation of ecosystem services. A key point of this valuable synthesis was the failure of a single decision point or resource decision process to be protective of all services in the managed system. Apitz (2013) reviewed the multiple failures of such approaches by documenting cases in fisheries management, farming policies, and subsidies.

Kapustka et al. (2016) discussed the links among risk assessment, the remediation of contaminated sites, and restoration ecology. Characteristics of the endpoints may be used as measures of restoration success, and the risk assessment should be tied directly to the management goals and restoration targets. As originally described by Wyant et al. (1995), the restoration objectives should also delineate a set of endpoints.

At larger ecological scales and with multiple stressors, Van den Brink et al. (2016) described how an ERA of multiple stressors over landscapes could be applied to the adaptive management process outlined by Wyant et al. (1995). The development of techniques that can estimate risk to multiple endpoints at very large spatial scales makes ERAs even more central to an adaptive management scheme.

There appears to be convergence of adaptive management, the examination of multiple goals and stressors, and the use of ERA. The points made by Apitz (2013) and Kapustka et al. (2016) demand a quantitative approach to the long-term management of ecological resources. Wyant et al. (1995) and Van den Brink et al. (2016) provide the framework. The adoption of Bayesian networks, which are able to incorporate various types of data and provide for the innate inclusion of cause-effect pathways and probability, provide computational tools for the estimation of risk and uncertainty (Marcot et al. 2006; Pollino et al. 2007; Ayre and Landis 2012). The next sections describe how the risk assessment forms a key part of adaptive management and then use a case study to illustrate the framework.

FRAMEWORK FOR A RISK-BASED ADAPTIVE MANAGEMENT PROCESS

Van den Brink et al. (2016) posited that the adaptation of the scheme proposed by Wyant et al. (1995) would allow the inclusion of social, political, and economic factors with scientific information in selecting a course of action. We take this supposition a step further to demonstrate how ERA can be an integral part of the adaptive management process for the remediation and restoration of a site.

Figure 1 is an expansion of the diagram first proposed in Van den Brink et al. (2016). The scheme has 3 components: Part A: Public Engagement and Governance; Part B: Research, Engineering, Risk Assessment and Management; and Part C: Change in Externalities. Part A: Public Engagement and Governance describes the social, cultural, and economic features that influence the endpoints and management options considered in the adaptive management process. These features can include economic goals, the preservation of culturally significant landscapes or species, and human health and well-being components. Many of these goals are written into regulations such as the Clean Water Act, Clean Air Act, Endangered Species Act, natural resource preservation codes, and economic plans. These goals inform 2 critical factors. The first is the endpoints to be considered in the risk assessment, including the attributes that will be measured that reflect these goals, and the criteria for "acceptable" risk. The second is the list of factors that are imposed on the management alternatives. These can include cost, potential economic benefits, compliance with the law, stakeholder preferences, and other factors. Part A provides many of the societal inputs that are necessary for Part B.

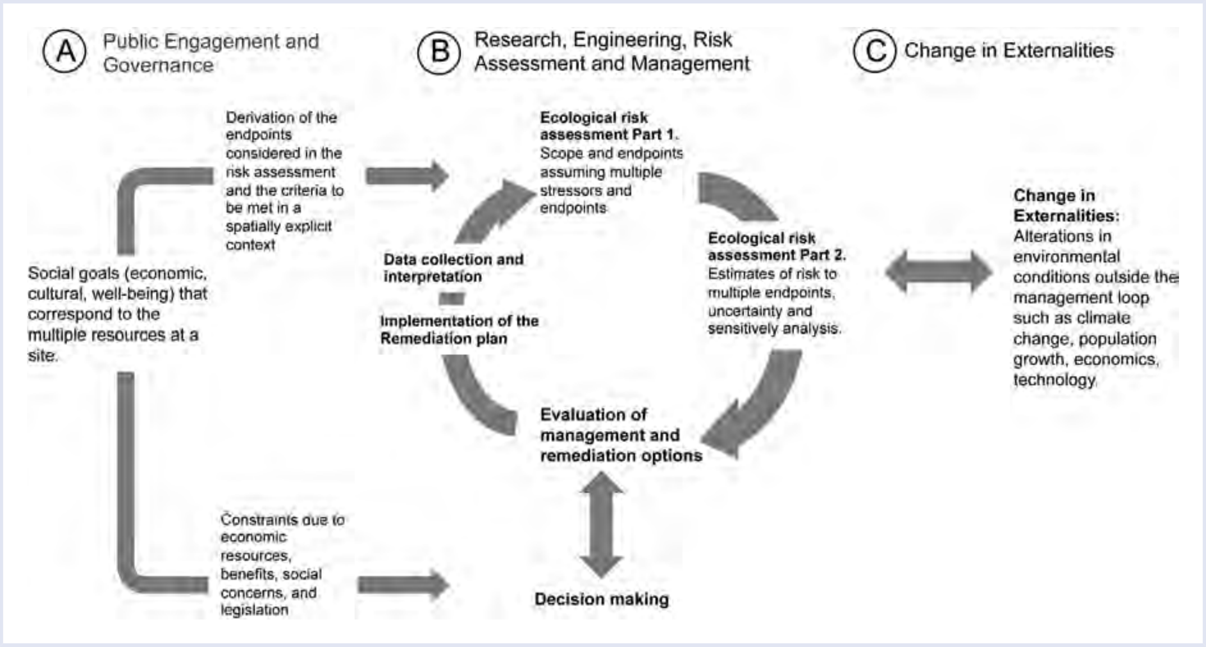

Figure 1. An adaptive management scheme as derived from Wyant et al. (1995) and Van den Brink et al. (2016). Part A describes the public engagement and governance process. Part B focuses on observation, risk analysis, the determination of how management alternatives will alter the risk, follow-up monitoring, and finally further observation and assessment. Part C is the reminder that social values and the ecological context both will change and need to be incorporated into the process.

Part B illustrates the interaction among the ERAs, the evaluation of proposed management and remediation alternatives, outcomes from the implementation of those management alternatives, measurement of the factors describing the effects of management, and finally estimates of risk after management. Such a structure provides a learning process to evaluate those methods that work and those that do not, as well as to provide a quantitative evaluation of the results.

Part C serves as a reminder that the cultural values represented by public engagement and governances, the state of the science, and especially external factors (such as climate) will vary over the life span of a remediation and restoration program.

Part B is described in greater detail (Figure 2) to focus on the various interactions of the risk assessment process in an adaptive management framework. The process has 6 steps, although it should be noted that these steps are not necessarily linear.

Step 1 (Ecological Risk Assessment Part 1) defines the scope of and endpoints for the ERA. The regulatory, cultural, and social inputs derived from Part A define the scope of the decision and determine the endpoints, as well as their associated entities. Our assumption is that there will be multiple management goals, sometimes conflicting, associated with multiple stressors across large spatial and temporal scales.

Step 2 (Ecological Risk Assessment Part 2) is the construction of a risk assessment conceptual model, the computational framework built as quantitatively as possible, and the final estimates of risk. Uncertainty is also cataloged and measured. The sensitivity of the result to the inputs is also determined. We use the Bayesian Network Relative Risk Model (BN-RRM) originally described in Ayre and Landis (2012) and further developed in subsequent studies as reported in a number of publications (Ayre et al. 2014; Hines and Landis 2014; Harris 2015; Herring et al. 2015; Johns et al. this issue; Landis et al. this issue). Other techniques that address multiple stressors at landscape scales should also be adaptable. At the end of Step 2 the structure and output of a classic risk assessment are available.

Step 3 is the Evaluation of Management and Remediation Options. One of the outcomes of Step 2 is a list of variables that are the main drivers in the estimates of risk and their environmental interactions. This list of variables can be used in Step 3 to define specific goals of the monitoring program and to design a sampling plan to obtain statistically robust results, including a priori power analysis. The data obtained as a result of the monitoring program are used to reduce uncertainty in the risk estimates or to better describe the variation associated with the variable.

Also, Step 3 receives input from Step 4: Decision Making (see 2nd paragraph that follows). In some instances, the risks calculated in Step 2 may be acceptable and the only required

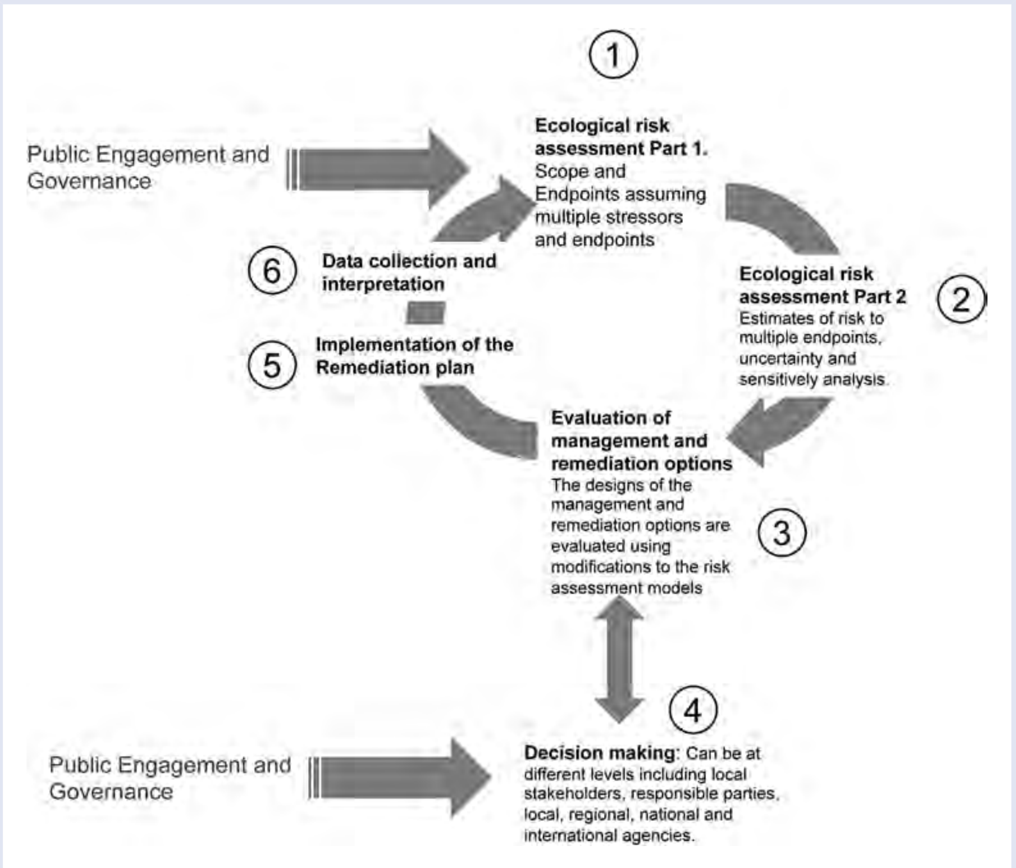

Figure 2. Risk assessment and decision loop. This is the detail of Part B in Figure 1. A detailed description is provided in the text.

management is a monitoring program. However, if the risks are unacceptable, then further management and remediation will be required and acceptable solutions implemented. The search for an acceptable solution is 2-fold. First is the involvement of ecological engineers and remediation specialists to provide candidates for implementation. Second is the evaluation of these candidates for the ability to change risk within the boundary conditions set by Part A: Public Engagement and Governance.

The candidates proposed by these specialists are now built into the initial risk assessment to reflect factors or conditions that would change with the implementation of different management strategies or remediation options. The risks are then recalculated. Three important factors are calculated in this process. First is the reduction in risk to the endpoints due to the reduction in chemical concentrations, habitat loss, or the presence of nonindigenous species or other stressor in the environment. Second is the change in risk due to the construction of and implementation of the alternative management action in the affected environment. Implementation of a remediation or restoration plan may incur short-term risks; for example, if habitat is lost due to bank stabilization, it may increase risk to a species nesting in that specific location. Third is the determination from the uncertainty and sensitivity analysis of the variables influencing the estimates of risk and the identification of a monitoring strategy. The goal of these steps is to identify the risks, explore the changes in risk caused by the implementation of various management and remediation options, and then point to the variables determining the success of each strategy. The output from Step 3 is then transmitted to Step 4.

Step 4 is Decision Making. This step is the iterative decision-making process for the remediation or restoration action, taking into account the results of the initial risk assessment and the predicted changes in risk after a management option or options have been implemented. This is a step where information from Part A (Public Engagement and Governance) is applied. The limits on cost, the values of certain endpoints, how values are influenced by location in the study area, and trade-offs are determined by stakeholders and decision makers. Costs of monitoring to measure the success of the strategy and maintenance of structures can be included. We suggest that multicriteria decision analysis (MCDA) would be a useful tool as described by Foran et al. (2015).

Step 4 now transmits the decisions regarding the remediation action to Step 3, and the risk assessment outputs are calculated for the final restoration plan. The information derived from this assessment process serves as testable hypotheses regarding the outcome of the management activities. These hypotheses will provide specific information on which variables are critical to be measured to track the progress of the restoration activity, as well as reduce uncertainty in the estimation of risk.

Step 5 (Implementation of the Remediation Plan) is the implementation of the program where the remediation step is conducted in concert with an active monitoring program. The changes in the sources, the stressors, the distribution of habitats, and the effects to endpoints, patterns, and probabilities of effects are observed and can be used to refine further risk assessments.

The implementation of a set of remediation strategies serves as the experiment treatment segment of an adaptive management process. In the case of a contaminated site, we foresee restrictions on the size and extent of these trial treatments to not put the system at an increased risk. Laboratory or contained field trials could also add information useful in evaluating a methodology or the ability of a monitoring technique to measure change. This type of information can be input to the BN-RRM to calculate the resultant alteration in risk.

Step 6 is Data Collection and Interpretation. Because measurements are being taken before and after the implementation of remediation or restoration options, this is considered a before and after control impact (BACI) design. USEPA (2002) describes in detail BACI sample design and statistical evaluation. Conquest (2000), Clements et al. (2002), and Clements and Rohr (2009) presented a number of tools to evaluate changes in community structure and ecological responses after a control impact has been implemented.

The information obtained in Step 6 is then used to update the cause-effect portion of the BN-RRM, the conditional probability tables, and the probability distributions of the inputs. In some instances, the additional information can cause an evaluation of the suitability of a measure or endpoint as part of the decision-making process.

The process returns to Step 1, on to Step 2, and so on. It is important that the entire loop be followed because the uncertainties in the original models may be reduced, relationships between variables may have changed, or the conceptual model may have to be altered.

Inputs from Part C: Change in Externalities are now input to the process. If changes have occurred because of changes in cultural norms, regulations, or other factors, the specifications describing the endpoints can be revisited. If the environment has been modified because of climate change, alterations to the intended use of the landscape, or improvements in control technology, those can be introduced into the risk-based adaptive management assessment process.

The process of recording the changes in risk in subsequent interactions of the loop also documents societal goals, scientific understanding, and the performance of the restoration activities during the remediation process. One of the most challenging aspects of the adaptive management process is learning what worked, what did not, where we are now, and what is expected in the future. This information is recorded in the risk assessment models in each stage of the loop and the subsequent iterations.

Now we have proposed a process for incorporating ERA into adaptive management, as derived from Wyant et al. (1995) and Van den Brink et al. (2016). The next step is to examine how this process can be applied to a case study. The case study is the South River, Virginia, USA, study area (SRSA).

APPLICATION OF THE RISK-BASED ADAPTIVE MANAGEMENT PROCESS TO THE SOUTH RIVER STUDY AREA

We are using the South River to illustrate the risk-based adaptive management process, employing as an example a well-established, ongoing, and long-term management activity. First, we will summarize the context of this site and its long history. Then we will describe how the process corresponds to the 3 basic parts of the risk-based adaptive management cycle.

South River study area

The South River is located in Augusta County, Virginia, in the Shenandoah Valley (Figure 3). The headwaters of the South River form southwest of Waynesboro, Virginia, and flow northward for 84.7 km until merging with the Middle River and North River in Port Republic, Virginia, to form the South Fork of the Shenandoah River (Eggleston 2009).

Stahl et al. (2014) provide the background history of the South River region and the impacts to it from long-term discharges of mercury (Hg) into the river, as well as provide a general approach for conducting an ERA of it as a Resource Conservation and Recovery Act site. In summary, the South River and its watershed is a legacy contaminated site as a result of Hg being released into the river as a waste product during a manufacturing process from the late 1920s to the early 1950s. In 2001, DuPont and the Commonwealth of Virginia established a multistakeholder and collaborative group, the South River Science Team (SRST), to address the contamination and future management of the South River.

This research study was started in 2009 to support the efforts of the SRST. Based on their engagement and direction, the SRSA was delineated. It encompasses the approximately 600-km^2 South River watershed, as well as a portion of the South Fork Shenandoah River watershed. We divided the SRSA into 6 risk regions based on hydrological subbasins and land-use similarities (Figure 3). Risk region 1 encompasses the headwaters of the South River. Risk region 2 includes the town of Waynesboro and the former E. I. du Pont de Nemours and Company (DuPont) facility. The origin of the Hg contamination is in this part of the watershed. Regions 3 through 5 are downstream of Waynesboro, and risk region 6 begins where the South River merges with the North River to form the South Fork of the Shenandoah River. Risk was assessed in regions 2 through 6; risk was not assessed in region 1 because of lack of site-specific monitoring data.

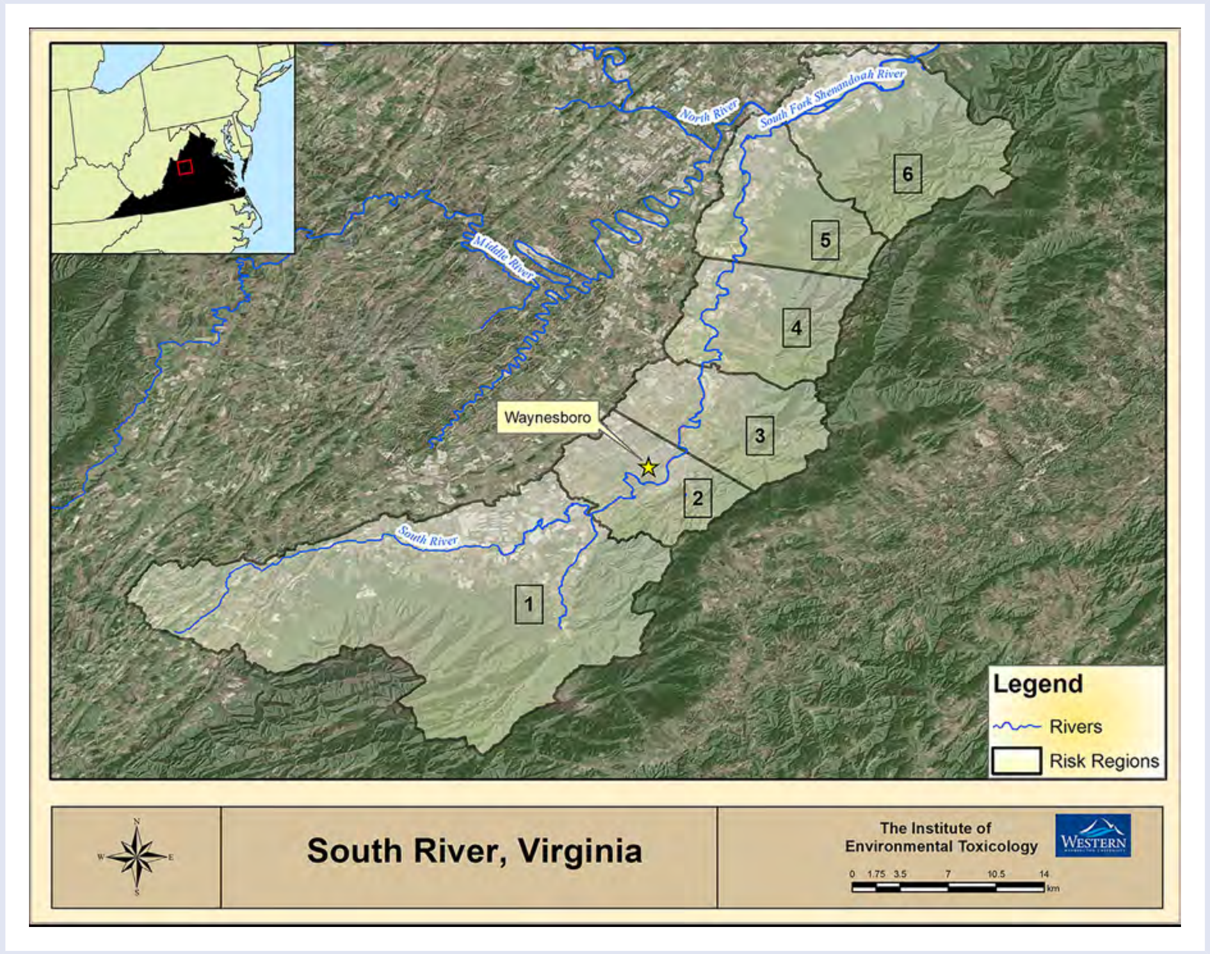

Figure 3. South River study area. The area was broken into 6 regions for the analysis. Risk was calculated for each endpoint for regions 2 through 6. Insufficient data were available for region 1 to perform a risk calculation.

The primary land uses in the SRSA are forestry (58%), agricultural (31%), and urban (8%) (Eggleston 2009). The eastern portion of the watershed is forested, and the western portion is composed of zoned urban and agricultural land (Figure 3). The city of Waynesboro, in region 2, accounts for most of the urban area and is the location of the DuPont facility from which Hg was released into the South River.

Application of the risk-based adaptive management process to the SRSA

Part A: Public Engagement and Governance. The SRST provided the public engagement and governance function as outlined in Part A of Figure 1. The SRST coordinates research and management activities to address the legacy Hg contamination in the South River and South Fork Shenandoah. The membership originally was composed of scientists from Virginia State's regulatory agencies and DuPont, but now its membership has been expanded to include scientists from federal agencies and other stakeholders including elected officials, decision makers, and representatives of local environmental groups (Stahl et al. 2014).

The diverse makeup of the SRST has been a key to its success. One of the lessons learned from stakeholder participation and public outreach efforts is the recognition that changing demographics in the region may influence Hg exposure estimates and ultimately human health risk. For example, there is a growing Hispanic population in the region, and studies have indicated that Latinos are disproportionately exposed to Hg because of their fishing habits—that is, fishing in local waterways for personal consumption. These fishing practices and fish consumption behaviors, as well as primary and secondary contact with the contaminated river through swimming and other river-use activities, are affecting individuals' exposure to Hg in the region (Stahl et al. 2014).

The SRST implemented a watershed-level, risk-based assessment process starting in 2001 to evaluate the potential impacts of Hg to the South River caused by the DuPont facility's historical operations. Stahl et al. (2014) described the initial problem formulation conducted by the SRST for the watershed-level ERA. The initial problem formulation focused on Hg, because it is the primary regulatory driver. However, in consultation with the SRST, Landis et al. (this issue) conducted a more comprehensive ERA and added other stressors to describe the breadth of multiple stressors occurring in the study area. The endpoints evaluated in this ERA, as well as the management alternatives to include in the risk calculations (Landis et al. 2016), were made in consultation with the SRST.

Part B: Research, Engineering, Risk Assessment and Management. Three risk assessments of the South River have been conducted that used the BN-RRM (Harris 2015; Johns et al. this issue; Landis et al. this issue). Detailed descriptions of the BN-RRM methodology and its use with management alternatives are included in those studies.

Step 1 (Ecological Risk Assessment Part 1). The initial ERA included 4 biotic and 4 abiotic endpoints, including Hg and multiple other stressors (Landis et al. this issue). This risk assessment described current conditions and predicted the patterns of risk from the stressors to the biotic endpoints in the study area.

The 2nd ERA (Johns et al. this issue) had the same number of endpoints but incorporated 2 management alternatives selected by the SRST into the structure of the initial ERA. The management options were: 1) agricultural best management practices (AgBMPs) to reduce nutrient loading, and 2) bank stabilization in specific areas of the watershed to prevent further inputs of Hg to the river from floodplain soils and bank erosion. The assessment examined how each management alternative altered the distribution of risk in the study area.

The 3rd risk assessment adapted the Resource Conservation and Recovery Act–style human health risk assessment to the BN-RRM framework so that human health and ecosystem services could be analyzed (Harris 2015). The ecosystem services and human health assessment focused on current conditions and used a different set of endpoints than the initial assessment for biotic and abiotic endpoints described in Landis et al. (2016). The effects of the management alternatives were not investigated in the present study.

The endpoints used in each ERA are listed in Table 1. In each ERA, risk was calculated for each of the regions, and patterns in risk, the sources of the risk, and uncertainty were compared. Table 2 presents a summary of each of the 3 risk assessment efforts, the types of models that were used, and the number of endpoints that were assessed.

Step 2 (Ecological Risk Assessment Part 2). In the initial ERA (Landis et al. this issue), the risk calculations led us to develop 3 conclusions. First, risk to the biotic endpoints varied according to location, type, and quality of habitat, as well as type and duration of exposure to stressors within the landscape. For example, the highest risk to smallmouth bass and Carolina wren occurred in regions 4 and 5, far downstream of the original source of Hg in region 2. The risk scores for white sucker and belted kingfisher, however, were highest in region 2. Moreover, risks to the abiotic endpoints were more consistent from region to region compared with the biotic endpoints. An evaluation of the uncertainty and the sensitivity analysis indicated that the patterns of risk were evaluated with reasonable certitude. Second, overall risk scores for abiotic (service-based) endpoints were greater than overall risk scores for biotic endpoints. Third, although Hg reduction is the regulatory priority for the South River, Hg was not the only stressor driving risk to the endpoints. For smallmouth bass, water temperature was a more important determinant of risk than tissue methylmercury (MeHg) concentrations. Blood MeHg concentrations and nest predation were the 2 most important factors determining risk to the Carolina wren. For the abiotic endpoints, river temperature, river discharge, dissolved oxygen, and bacterial counts were the key variables.

Table 1. Endpoints used in the Bayesian Network Relative Risk Model risk assessments for the South River study area

Bayesian network risk model	Endpoint
Initial biotic model	Belted kingfisher (*Megaceryle alcyon*)
	Carolina wren (*Thryothorus ludovicianus*)
	Smallmouth bass (*Micropterus dolomieu*)
	White sucker (*Catostomus commersoni*)
Initial abiotic model	Water-quality standards (VDEQ standards for protection of aquatic life)
	Fishing river use
	Swimming river use
	Boating river use
Ecosystem services and human health model	Human health[a]
	Recreation[b]
	Water quality (VDEQ water-quality standards for human health and aquatic life)
	Recreational fishery

[a] Human health assessment was completed for 5 human user scenarios or pathways, and results were compared between them.

[b] Recreation assessment included 5 individual recreation activities, and results were compared between them.

VDEQ = Virginia Department of Environmental Quality.

Table 2. Risk models, scenarios, and number of endpoints for each of the 3 risk assessment studies summarized for the South River study area

Ecological risk assessment	BN risk models	Endpoints
Initial ecological risk assessment (Landis et al. this issue)	Initial biotic + initial abiotic models	8
Ecological risk assessment with AgBMP and BST (Johns et al. this issue)	Initial biotic + initial abiotic models + ecenarios: BMPs and BST	8
Human health and ecosystems services (Harris 2015)	Ecosystem services and human health model	
	Human health scenarios 1) All Pathways of exposure, 2) Hunter or fisher, 3) Fisher, 4) Farmer, and 5) Recreational user	
	Recreation scenarios 1) Boating, 2) Swimming, 3) Fishing, 4) Floodplain, 5) River	4

AgBMP = agricultural best management practices; BST = bank stabilization.

The 2nd study evaluated the 2 management alternatives, AgBMPs and bank stabilization, for reducing risk in the region from Hg (Johns et al. this issue). Adjustments were made to the BN-RRM models in the initial ERA to account for the anticipated changes caused by the implementation of AgBMPs and bank stabilization throughout the South River. Uncertainty was evaluated and sensitivity estimated. The AgBMPs only slightly lowered the level of risk to the endpoints. Bank stabilization had a more variable range of effects. According to these models, implementation of bank stabilization would reduce the risk from Hg to smallmouth bass and belted kingfisher, but it would increase the risk from water quality to these and other biotic endpoints. Furthermore, if care is not taken to prevent loss of belted kingfisher nesting habitat during bank stabilization efforts, risk would increase to this endpoint.

The 3rd risk assessment focused on human health and parameters that described ecosystem services provided by the South River (Harris 2015). It was found that risk to the human health endpoint was lower than risks to the water quality, recreational fishery, and recreation endpoints. The water quality endpoint was at highest risk in all of the risk regions. Risk to the recreational fishery varied more than the other endpoints, with the highest risk in regions 2 and 5. Risk to human health was evaluated over 5 different scenarios—recreational, farmer, fisher, fisher and farmer, and all pathways of exposure—and was found to be highest in regions 3 and 6. The present study demonstrated that it was possible to estimate risk to human health and ecosystem services using the same BN-RRM approach used in the 2 ERA studies. Because of the similarities in approach, the risks were easily compared and the importance of key variables could be evaluated between the endpoints.

Each of these studies generated a list of variables that were the most important in each model for determining risk (Table 3). Uncertainty analysis of the models in each of these studies provided a list of variables that, with additional data, would decrease the uncertainty in the risk estimations (Table 4). These lists specify the types of measurements that would both indicate a change in risk and improve the accuracy of the risk estimate.

Step 3 (Evaluation of Management and Remediation Options). One of the questions in designing a monitoring plan for the long-term management of a resource is what to measure. In each of the risk assessments described earlier, a sensitivity analysis was used to identify the variables that are most important in determining the risk to each endpoint. In a Bayesian network, entropy reduction is used to quantify model sensitivity. The methods and detailed results of the entropy analysis for each risk assessment are given in Landis et al. (this issue), Johns et al. (this issue), and Harris (2015). In the following sections, we describe how the results of those analyses can be used to design a monitoring program.

Table 3. Parameters identified as the most important in each model for determining risk and recommended for inclusion in the monitoring program that will support the South River risk assessment

Part 1. Risk assessment	
Endpoint	**Input parameter**
Belted kingfisher	Hg[a] (5)—blood samples
	Fish length[a] (5)
	Potential habitat[a] (2)—land-use type (%)
	Territory[a] (3)—nests per length of river section (m)
Carolina wren	Hg[a] (4)—blood samples
	Nest predation (5)
	Potential habitat[a] (2)—land-use type (%)
	Winter air temperature (4)
Smallmouth bass	River Temperature[a] (5)
	Hg[a] (5)—fish fillet Hg concentrations (MeHg and tHg)
White sucker	River temperature[a] (5)
	Stream cover[a] (5)—submerged aquatic vegetation cover (%)
	Hg[a] (4)—fish fillet Hg concentrations (MeHg and tHg)
	PAHs[a] (1)
Water-quality standards	Dissolved oxygen[a] (5)—summer dissolved O_2
	Bacteria[a] (4)—bacteria indicators (*Escherichia coli*)
	River temperature[a] (3)—winter temperature
	River discharge[a] (3)—summer and winter discharge
Fishing river use	Dissolved oxygen[a] (5)—summer dissolved O_2
	MeHg[a] (4)—fish fillet MeHg concentrations
	River temperature[a] (5)—summer and winter temperature
Swimming river use	Bacteria[a] (4)—bacteria indicators (*E. coli*)
	River temperature[a] (5)—summer and winter temperature
	River discharge[a] (1)—summer discharge
Boating river use	River temperature[a] (5)—summer and winter temperature
	Bacteria[a] (4)—bacteria indicators (*E. coli*)
	River discharge[a] (1)—winter discharge
Part 2. Risk assessment of management alternatives	
Management type	**Input parameter**
Agricultural best management practices	Total suspended solids
	Total P
	E. coli levels
Bank stabilization	Total suspended solids
	Fish fillet Hg concentrations
	Bird blood Hg concentrations
	Stream cover
	Habitat alteration (habitat loss for the belted kingfisher)
	Dissolved oxygen
	Discharge

These parameters had the greatest influence specifically on risk to the fish, birds, and water-quality endpoints. Parameters are listed from top priority down for each endpoint; the numbers in parentheses indicate the number of risk regions in which the parameter was important.

[a] We recommended continued monitoring or, in some cases, adding this parameter to the monitoring plan. Part 1 delineates the recommendations for reducing uncertainty in the initial risk estimates. Part 2 provides recommendations if management alternatives are implemented.

Hg = mercury; MeHg = methylmercury; tHg = total mercury.

Parameters from the ERAs. The recommended monitoring parameters for each endpoint (Table 3) are based on the input parameters that have the greatest influence on that endpoint. The parameters are listed in descending order of priority, and the numbers in parentheses indicate in how many regions the parameter was important in determining risk. Although not every parameter is important to each risk region, it is still important to sample for it in each region. Such data provide information on spatial gradients and temporal changes in the watershed.

It is not yet clear what management alternative will be implemented in the SRSA. The sensitivity analysis for each, however, indicates which variables should be monitored as the alternative is implemented. Those variables are listed in Table 3, part 2. Note that the lists for the management options are very different. The recommended monitoring parameters for AgBMPs include 3 water-quality parameters: total suspended solids, total phosphorus, and *Escherichia coli* concentrations. Bank stabilization has a much broader list of parameters because the option is expected to impact the availability of the Hg and alter habitat during and after construction.

Identifying sources of uncertainty and data limitations. By examining the available data and identifying sources of uncertainty and data limitations, we have been able to recommend parameters for future monitoring to reduce the uncertainty in the risk estimates. These suggestions are presented in Table 4 and are organized by risk region. A brief description follows.

Risk region 1 has not been sampled, so uncertainty regarding all endpoints is large compared with the other risk regions. As a result, a set of risk assessment models could not be constructed and, therefore, reliable comparisons could not be made with the other risk regions. Region 1 is upstream of the source of Hg; however, agricultural, residential, and small manufacturing sites have the potential to influence downstream sites through the release of contaminants, nutrients, bacteria, and warm-water inputs. Especially after implementation of the management options, data from region 1 may provide additional information regarding confounding factors influencing both the risk to the endpoints and the efficacy of the management actions.

Region 2 encompasses Waynesboro, the source of the Hg contamination. Consequently, it has been sampled for Hg and the biota extensively studied so the sensitivity analysis did not reveal critical sampling or measurement uncertainties similar to the other risk regions. However, in the analysis of the bank stabilization management option in each of the risk regions, the location and amount of belted kingfisher habitat in relation to where bank modifications were conducted was found to be important. Although not a model uncertainty, such consideration is necessary depending on the type of bank modification and its extent.

In regions 3 and 6, the lack of data for trout Hg tissue concentrations increased the uncertainty in the human health risk estimates. Although it is likely that trout Hg tissue

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Table 4. Data needs for reduction in model uncertainty for each of the risk regions

Region	Monitoring data
Region 1	Sampling of parameters listed in Table 3
Region 2	Map of **belted kingfisher** habitat in the area of bank stabilization
Region 3	**MeHg in trout from the human health model**
Region 4	River temperature, discharge, and dissolved O_2 data
Region 5	PAH and pesticide data (more data samples)
Region 6	**Belted kingfisher:** fish length, turbidity
	Carolina wren: Hg blood
	Smallmouth bass and white sucker: Hg tissue
	Water quality: total phosphorus, MeHg for all fish
	Fish stocking
	MeHg in trout
All regions	**Belted kingfisher:** mercury, pesticides, turbidity, submerged aquatic vegetation, territory, potential habitat, nest predation
	Carolina wren: mercury, pesticides, abundance, potential habitat, nest predation
	Smallmouth bass: pesticides, abundance
	White sucker: mercury, pesticides, stream cover, abundance
	Water quality: summer dissolved O_2, winter dissolved O_2, *Escherichia coli* (limited samples across all regions)

Boldface type indicates endpoints.

concentrations in regions 3 and 6 reflected the same trends as found in nearby regions, additional monitoring data are needed to update the models for these regions.

In region 4, water quality data were important to several of the endpoints and as such, more data, comparable with those collected by a US Geological Survey gauge station, would reduce uncertainty. In region 5, relatively few samples reported PAH and pesticide concentrations. More data would help quantify their concentrations more accurately and identify whether these substances are posing a risk, as well as determine whether their presence is due to isolated pulses or chronic releases to the river.

Region 6 that includes the South Fork of the Shenandoah River had relatively few monitoring data. This risk region is approximately 24 river miles downstream from the headwaters of the South River, and its importance was understood only later in the risk assessment process. Still, further monitoring in region 6 would provide data that could be used to update the risk estimates. As with region 3, additional trout tissue Hg concentrations would reduce uncertainty in the human health risk estimates for this region.

In the current database, the majority of the data were from samples collected more than 5 years ago. For example, river temperature was one of the parameters with the greatest influence on the endpoints, yet the last available data were from 2011. Updating these data would enable us to update 6 of the 8 endpoints in the models.

Step 4 (Decision Making). Kiker et al. (2008) discussed the integration of risk assessment with the MCDA approach for contaminated sites. In turn, Foran et al. (2015) developed an enhanced adaptive management approach based on the MCDA framework. This framework focused on the remediation of Hg from the site with smallmouth bass as the biotic endpoint. The study is an important contribution because it serves as a mathematical expression of the priorities for at least 1 stressor–endpoint pair within the South River. Now that the MCDA framework has been developed, it can serve as a foundation for incorporating other stressors and endpoints.

It should be possible to construct a similar framework using Bayesian networks as the computational background. Nyberg et al. (2006) discussed the use of Bayesian networks in adaptive management. In a classic study, Carriger and Barron (2011) explored the use of influence diagrams, that is, Bayesian networks that explicitly represent decisions related to an issue and the influence of those decisions on desired or undesired outcomes. They applied this tool to evaluate and propose response options to minimize risks to ecosystem services from an oil spill. Based on these studies, we do not see any fundamental barrier to applying the MCDA approach as used in Foran et al. (2015), using Bayesian networks.

Steps 5 (Implementation of the Remediation Plan) and 6 (Data Collection and Interpretation). Both Steps 5 and 6 are now under way in the SRSA. A stabilization of the bank at the site of the original outfall has already been done and the reduction in Hg assessed. A design process is under way for the stabilization of 10 miles of banks in risk region 1.

Learning. An important part of the risk-based adaptive management process is the formal learning process. The risk assessment process allows for the calculation of risk under the initial conditions and predictions of risk given the implementation of management options. By monitoring the site during and after implementation, the new data can be used to calculate actual changes in risk, or realized risk. These new risk estimates are then used to evaluate the implementation strategy and consider new management strategies or research questions. Without this process, true adaptive management has not occurred. The BN-RRM approach used in the present study is convenient for this type of formal learning because the Bayesian networks are easily updated with additional monitoring data or new information.

Part C: Change in Externalities. This part of the process is the recognition that the context of the adaptive management process will change over time. The regulatory environment of the 1920s to1950s when Hg was used as part of the manufacturing process by DuPont and released untreated to the adjacent South River is very different from today. Similarly, the tools used to perform risk assessments have evolved over time, as have the technologies to collect, measure, and analyze environmental variables over larger spatial and temporal scales.

The demographics of the region have also changed with an increase in the local Hispanic population. These demographic changes have implications for Hg exposure because of fish consumption patterns by different ethnic groups, ultimately affecting human health risks to the local communities and users of the South River. Uses in and on the river have also changed over time, for example, jet skis, sailboards, and standup paddleboards that will change human exposure routes and duration.

More recently, climate has become a factor to consider as well. Climate in the South River region is predicted to see an increase in temperature with a change in the patterns of precipitation (Sun et al. 2015). Such changes may alter risks to biotic and abiotic endpoints by altering environmental conditions and ecological structure and functions, impacting the effectiveness of management options, or changing the transport and fate of Hg and MeHg in the SRSA. Altered temperature and precipitation regimes will likely impact the design of bank stabilization structures and change management strategies to mitigate the formation of MeHg. New species and diseases may also appear in the region. Fortunately, downscaled climate models provide a picture of future climate conditions that can be bracketed into probable ranges, making planning possible. True adaptive management will require managers and decision makers to account for these and other long-term changes in the SRSA.

SUMMARY AND CONCLUSIONS

The SRSA case study provides an example of how to apply the risk-based adaptive management process. The methods described in the present study are quantitative and transparent, and explicitly incorporate probability and uncertainty. The learning process is recorded in the estimation of input parameters, the risk calculations, and in the comparison of predicted versus realized risk. Other sites and situations can be managed using such an approach.

Contaminated sites, such as the SRSA, often require making decisions regarding management strategies that have to balance cost, human and ecological risks, and the interests of multiple governance and engagement stakeholder groups. The challenges of dealing with the varying sets of remediation and restoration goals are described in a recent series of papers (Hooper et al. 2016; Kapustka et al. 2016; Rohr et al. 2016). The risk-based adaptive management process can aid communication and cooperation between stakeholders by presenting the scheme in a quantitative and iterative manner. It should be a straightforward process to apply our outlined approach to other sites and circumstances for which these challenges exist.

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Data availability—The data are available from the first two papers now in press that are part of this 3-paper series. Each has extensive supplemental files including the models discussed in this paper.

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