Risk Analysis, Vol. 37, No. 7, 2017 DOI: 10.1111/risa.12691

A Bayesian Approach to Integrated Ecological and Human Health Risk Assessment for the South River, Virginia Mercury-Contaminated Site

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We conducted a regional-scale integrated ecological and human health risk assessment by applying the relative risk model with Bayesian networks (BN-RRM) to a case study of the South River, Virginia mercury-contaminated site. Risk to four ecological services of the South River (human health, water quality, recreation, and the recreational fishery) was evaluated using a multiple stressor–multiple endpoint approach. These four ecological services were selected as endpoints based on stakeholder feedback and prioritized management goals for the river. The BN-RRM approach allowed for the calculation of relative risk to 14 biotic, human health, recreation, and water quality endpoints from chemical and ecological stressors in five risk regions of the South River. Results indicated that water quality and the recreational fishery were the ecological services at highest risk in the South River. Human health risk for users of the South River was low relative to the risk to other endpoints. Risk to recreation in the South River was moderate with little spatial variability among the five risk regions. Sensitivity and uncertainty analysis identified stressors and other parameters that influence risk for each endpoint in each risk region. This research demonstrates a probabilistic approach to integrated ecological and human health risk assessment that considers the effects of chemical and ecological stressors across the landscape.

KEY WORDS: Bayesian network relative risk model; ecological risk assessment; ecological services; human health risk assessment; mercury

1. INTRODUCTION

Regional-scale ecological and human health risk assessments (ERA-HHRAs) are used to determine the likelihood of effects from multiple stressors on ecological and/or human endpoints where characteristics of the landscape affect the risk estimate.[1] ERA-HHRAs can inform public health decisions and environmental management.[1] The relative risk model (RRM) framework for risk assessment can incorporate both ecological and human health endpoints in a multiple stressor–multiple endpoint approach. By using an RRM approach with Bayesian networks (BN-RRM), we are able to conduct quantitative, probabilistic, and spatially explicit risk assessments for regional-scale contaminated sites.[1]

In this research, we applied the BN-RRM to an integrated ERA-HHRA using the South River, Virginia as a case study. There were three primary objectives of this research:

(1) To integrate ERA-HHRA into a single framework.
(2) To incorporate ecological services (ES) into an ERA-HHRA as risk assessment endpoints.

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(3) To assess risk to human health and ES for the South River, Virginia.

A total of 14 biotic, human health, recreation, and water quality endpoints were considered in this assessment. The individual endpoints were grouped into four broader ES of the South River (human health, water quality, recreation, and the recreational fishery) and risk was calculated for each ES endpoint and overall ES. In addition, human health risk was calculated for five user scenarios to understand the bounds of human health risk given different hypothetical exposures to sources of dietary mercury. This is the first application of the BN-RRM to human health.

This research was not meant to be a definitive regulatory assessment of human health or ecological risk in the South River. Rather, it was part of a larger effort to synthesize regional scientific research and better understand the effects of mercury contamination in the South River watershed while presenting a new method for integrating ERA and HHRA into a single risk framework.

1.1. Integrating Human Health and Ecological Risk Assessment

Integrated risk assessment has been defined as a "science-based approach that combines the processes of risk estimation for humans, biota, and natural resources in one assessment."[2] Integration occurs at all levels of the risk assessment process, from problem formulation and endpoint determination to risk characterization and communication.

The potential benefits of integrating ERA-HHRA have been outlined in the literature[3–7] but have yet to be demonstrated in a complete risk assessment. Proponents of integration have suggested that it would lead to a more complete understanding of human health and ecological risk by producing coherent and comparable results that could be used by risk managers to understand human and ecological relationships, weigh tradeoffs, and guide management decisions.[3–7] The proposed benefits of integration can be summarized in four key points, which we tested here as hypotheses.

(1) Integration is efficient (both in time and effort).
(2) Integration produces coherent and comparable results.
(3) Integration provides a more complete assessment of risk.
(4) Integration increases transparency in the risk assessment process.

A number of challenges exist that have stalled the integration of ERA and HHRA. First, ERA and HHRA tend to use different language, which makes integration challenging.[4] Second, integration requires communication between human health and ecological risk assessors, which does not always occur.[8] Third, integration requires quantifiable endpoints in both the fields of ERA and HHRA. Many human health and well-being endpoints are qualitative, especially social, cultural, and psychological endpoints.[8] This poses a challenge to ecological risk assessors attempting to integrate human health and well-being into the conceptual models for ERA. While these challenges are certainly real, it has been argued that they are not prohibitive to integrating ERA and HHRA.[3–8]

Through this research, we integrated ERA and HHRA using a multiple stressor–multiple endpoint approach. In doing so, we have provided a concrete example of an ERA-HHRA that supports the hypotheses put forth by Harvey,[3] Bridges,[4] Suter,[5,6] and Vermeire *et al.*[7] regarding the integration of ERA-HHRA.

1.2. Ecological Services

ES and the ecosystem services concept (ESC) were used to frame the integration of ecological and human health endpoints for this assessment. The ESC is an anthropocentric approach to understanding the link between human health and well-being and the ecological systems with which we interact. The ESC frames ES as essential components of natural resource and public health management strategies[10–12] and provides context for assessing risk to human and ecological endpoints for large-scale systems.[13,14] In recent years, the ESC has driven efforts to quantify and valuate services and to include these services in economic, political, social, and natural resource decision making.[10–16]

Regional-scale risk assessments can incorporate ES as endpoints in a multiple stressor–multiple endpoint assessment.[11,13,15] In doing so, it may increase transparency, as vague protection goals are redefined as specific and measurable criteria.[11,13,14] The differences between ES and other more traditional risk assessment endpoints are minimal and can be accommodated with risk assessment frameworks and techniques that are already in practice.[13–16]

1.3. Bayesian Network Relative Risk Model

The RRM provides a framework to assess risk to ecological and human endpoints from multiple stressors over landscape spatial scales.[1] The RRM outlines the exposure pathway from sources of stressors to habitats to endpoints and ranks are used to relate variables in the pathway. The RRM requires evidence of causality from source to endpoint. Stressors that overlap in habitat (both spatially and temporally) with an endpoint pose risk to that endpoint. Relative risk is expressed as a probability distribution across four possible risk states (zero, low, medium, and high) that correspond to specific effects to the endpoint. As reported in Ayer and Landis,[17] the most recent form of the RRM uses BNs to calculate relative risk.

BNs are graphical models used to describe probabilistic cause and effect relationships, making them similar to the conceptual models typically used in risk assessment. A BN is composed of nodes and linkages, which reflect the components and causal pathways of the RRM. In a BN, nodes represent variables. Parent nodes represent input parameters and child nodes receive inputs from one or more parent nodes. Conditional probability tables (CPTs) within the BN describe the interactions between input parameters and the combined effects to the resulting child node. The CPTs describe the probabilities of states in the child node given all possible values of the input variables. BNs are acyclic, meaning that explicit feedback loops are not permitted. More information regarding BNs and their use in environmental management can be found in Woodberry *et al.*,[18] Pollino *et al.*,[19] Marcot *et al.*,[20] McCann *et al.*,[21] Nyberg *et al.*,[22] and Carriger and Barron.[16]

The BN-RRM has been used in a variety of ecological contexts.[17,23–25] The framework has been used to examine the risk of stormwater runoff to Coho salmon[24] and risk of whirling disease to isolated trout populations.[25] This is the first application of the RRM to HHRA and one of few applications of the model to ES risk assessment.[26]

Several characteristics of BNs lend themselves to landscape-scale risk assessment. BNs incorporate the deterministic and stochastic aspects of complex systems, explicitly consider uncertainty in the model inputs, and provide probabilistic predictions with measures of the importance of the input variables (sensitivity analysis). Input parameters are represented as probability distributions, which are derived directly from monitoring data. Parent, child, and endpoint nodes are discretized into ranked states, which allows for the evaluation of combined effects from multiple stressors, including those that are categorical or vary in their units of measurement.[19,20] BNs can be updated with new monitoring data as they become available. The BN-RRM can also be used to understand the changes in risk with the implementation of a management action.[17,22,24]

2. METHODS

2.1. Study Area

The South River is located in western Virginia, USA (Fig. 1). The South River Study Area (SRSA) is defined by the boundaries of the South River and Upper Shenandoah River watershed and is divided into six risk regions based on U.S. Geological Survey (USGS) watershed hydrological subbasins and land- use characteristics.[27] Regions are numbered 1 through 6 as the river flows north toward its confluence with the North River and Middle River. The original mercury deposition site is located in Region 2 within the city of Waynesboro, VA. For this assessment, we focused on Risk Regions 2–6, which are predominately downstream of the point source. We excluded Region 1 from the analysis due to the lack of available monitoring data.

The SRSA is composed primarily of forested land, agricultural land, and urban area, the largest of which is the city of Waynesboro.[28] The South River and Upper Shenandoah River are economic and recreational resources for the communities of the SRSA, supporting a recreational fishery and other river- use activities.[29] Local and visiting anglers (i.e., sports fishermen) utilize the recreational fishery, which includes both resident warm water fish (including smallmouth bass and white sucker) as well as stocked trout.[29] Other common recreational activities on the South River include boating, swimming, and wading.[29]

The SRSA was a practical case study for this work as it is a large-scale site that requires a multiple stressor approach to risk assessment.[9] Legacy mercury contamination from a former DuPont manufacturing plant has resulted in widespread mercury contamination of the river and floodplain.[9] Fish consumption advisories are in effect for the South

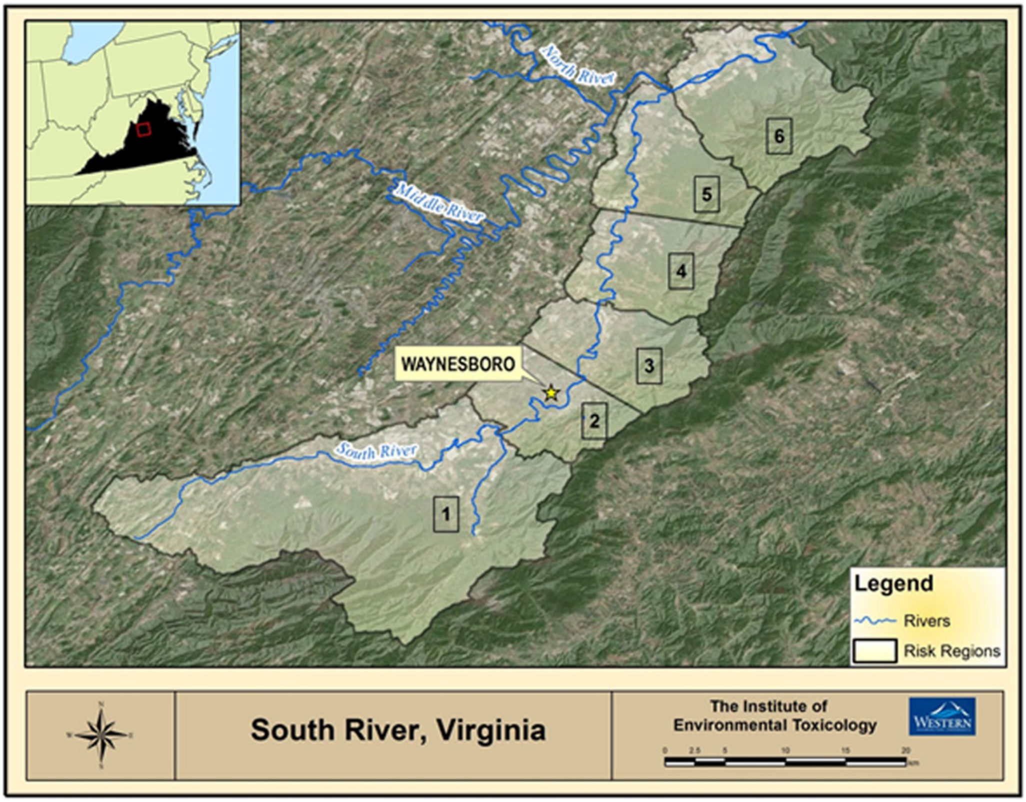

Fig. 1. Map of the South River study area showing the six risk regions for this study.

River through the Virginia Department of Health (VDH) for all fish species excluding stocked trout species, which have tissue mercury concentrations below the VDH criteria for human consumption.[30] As of 2014, both the original plant site and off-site South River floodplains are being managed by the Virginia Department of Environmental Quality (VDEQ) under the Resource Conservation and Recovery Act (RCRA) regulatory framework.[31,32] Since the late 1970s, DuPont has been working with local, state, and federal agencies to address the issue of contamination and monitor the impacts to natural resources at the site.[9] In 2001, the South River Science Team (SRST) was created by the VDEQ to lead collaborative scientific efforts relating to the South River contamination.[9,28] The SRST is also tasked with educating local people on the risk of mercury contamination through angler surveys and community public health programs.[9]

In addition to mercury contamination, agricultural, industrial, and urban land- use patterns in the SRSA introduce chemical stressors to this system, including polyaromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), and organochlorine pesticides. A number of pesticides, including aldrin and dieldrin, have been documented in surface water and groundwater wells within the SRSA.[33,34] The South River is currently listed as an impaired water body under Section 303(d) of the Clean Water Act; Total Maximum Daily Loads (TMDL) have been established for mercury in fish tissue, PCBs in fish tissue, and *Escherichia coli* in the water.[35] Elevated concentrations of phosphorus and suspended solids from point and nonpoint runoff have been identified as ecological stressors to the benthic community of the South River.[36] Other ecological stressors in this system include water temperature fluctuations, fluctuations in river flow, and lack of aquatic habitat.[27]

2.2. Ecological Services of the South River: Endpoint Selection

This research considered four ES of the South River as risk assessment endpoints: human health, water quality, recreation, and the recreational fishery. These services were identified by the SRST

Table I. Four Ecosystem Services Endpoints and Their Associated Management Goals; Each Service Is Defined as an Entity with Attributes that Characterize the Management Goals for Each Service

Ecological Service (Entity)	Management Goals (Attributes)
Human Health	No exceedances of VDH public health standards or VDEQ regulatory criteria for human health.
Recreation	Recreational activities are available throughout the risk region. Activities do not compromise health or well-being of participants.
Water Quality	No exceedances of VDEQ water quality standards for human health or aquatic life.
Recreational Fishery	The fishery is large enough to support a community of local and visiting anglers. Popular fish species are present, including smallmouth bass and stocked trout species.

Table II. Sources of Dietary Mercury by Human User Scenario; the Number of Potential Exposure Pathways Decrease from Top to Bottom; All Exposure Pathways Were Identified by the SRST Human Exposure Team as Potential Dietary Exposures[37]

Human User Scenarios	Sources of Dietary Mercury	Number of Sources
All Pathways of Exposure	Fish (trout and nontrout), waterfowl/game, garden crops, livestock	5
Hunter/Fisher	Fish (trout and nontrout), waterfowl/game	3
Fisher	Fish (trout and nontrout)	2
Farmer	Garden crops, livestock	2
Recreational User	No dietary exposure	0

through communication with local stakeholders[37] and reflect both stakeholder values and management objectives. Each service is measurable and quantifiable as a risk assessment endpoint. Together, risk to these services was combined using Monte Carlo techniques, thereby representing risk to overall ES.

Each service (endpoint) is defined as an entity and its attributes (Table I), where attributes describe the characteristics or qualities of the service relative to management goals.[27,38] We communicated with the SRST to establish these definitions early in the assessment process in order to clarify the terminology used in the assessment and reduce any perceived ambiguity in the model results. We found that clearly defining each endpoint and its attributes was essential in order to objectively calculate risk and communicate our findings. Within each endpoint definition, the RRM states (zero, low, medium, and high) correspond to the probability of adverse effects to specific attributes of that endpoint.

2.3. Chemical, Ecological, and Habitat Stressors

While mercury is the stressor of regulatory concern for the SRSA,[9,27,29–32] other chemical, ecological, and habitat stressors may pose risk to ES of the South River.[9,27] Evaluation of potential stressors in the South River began with a comprehensive literature search of site-specific stressors, human health criteria, toxicological studies, and regulatory guidelines. This assessment calculates cumulative risk from multiple stressors and evaluates the relative contribution of risk from each stressor. For example, risk to human health may result from exposure to chemical stressors (e.g., mercury, PAHs, organochlorine pesticide) as well as ecological stressors (e.g., *E. coli*, suspended solids) through contact with the river and floodplain (Table SIII). Risk to recreation activities (e.g., boating, swimming, and fishing) may be due to mercury (e.g., fish tissue MeHg, waterfowl, and game THg), ecological parameters of the river (e.g., dissolved oxygen, river temperature, and river discharge), or availability of public access for recreation (Table SIV).

The BN-RRM approach allows for the consideration of many stressors with different sources, units, modes of action, or pathways of exposure. The cumulative risk from all stressors is calculated, and the relative contribution of each stressor to the endpoint risk is determined by a sensitivity analysis of the BNs. A complete list of stressors considered in these models is included as Table SII.

2.4. Human Health User Scenarios

The human health risk was further broken down to evaluate relative health risk to hypothetical or theoretical users of the South River. Risk to human health was assessed for five user scenarios: (1) All Pathways of Exposure, (2) Hunter/Fisher, (3) Fisher, (4) Farmer, and (5) Recreational User (Table II). The number of potential exposure pathways decreased in each successive user scenario. All potential dietary exposure pathways were identified by the SRST Human Exposure Team.[37] Dietary exposure to mercury differed among user scenarios,

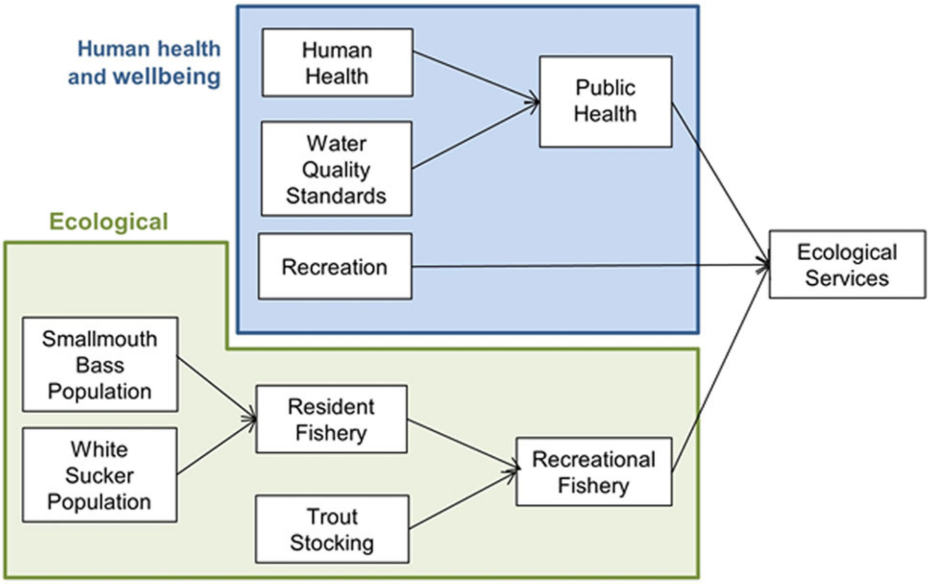

Fig. 2. Ecological services conceptual model. Colored boxes denote the human health and ecological portions of the model. Direct effects to human health and well-being are in blue; ecological effects are green (colors visible in on-line version).

based on hypothetical or potential future uses of the floodplain for garden crops, livestock rearing, and hunting. Direct exposure to river water, sediments, and floodplain soils was considered in every user scenario. Risk was calculated for each user scenario and each region (Regions 2–6). The All Pathways scenario considers all potential sources of dietary mercury exposure. For this reason, results from the All Pathways scenario were used as the human health inputs for the overall ES model.

2.5. Model Construction and the BN-RRM Process

The overall conceptual model for ES is shown in Fig. 2. Submodels exist for human health and recreation (Figures S1 and S2), which feed into the overall ES model. Conceptual models were constructed to link sources of stressors to endpoints through known causal pathways.[1,39] The conceptual models were then used to develop the BNs for each endpoint using the BN software Netica™.[41] Fig. 3 presents the BN for the overall ES model. Throughout the process of BN development, we followed the recommendations for BN structure outlined by Hosack *et al.*[40] and Marcot *et al.*[20]

Once the structure of the BN is established, the model parameters (nodes) are defined and the relationships between parameters are quantified. This process can be broken down into four steps. First, each node is defined and assigned a unit of measurement based on the data available. Second, each node is discretized into ranked states that are assigned numerical vales (scores). Third, the relationships between nodes are quantified using CPTs. Finally, the values for each input parameter are populated using site-specific data to derive a probability distribution for each state of the input node. These four steps are outlined in detail in the following sections, and further rationale is documented and available to the reader in the Supplemental Information.

2.5.1. Node Definitions and Data Sources

Each model parameter or node was defined using an entity-attribute approach (see Section 2.2 and Table I).[38] Additional information on the biotic and water quality endpoints has been published previously.[27] Based on the node definition, an appropriate unit of measurement was identified and a data source was selected. For example, to represent mercury exposure of smallmouth bass, monitoring data for fish tissue methylmercury concentrations were used. The data were available from approximately 30 years of monitoring by the SRST.[9,27]

Each node in the models described in this research was defined through communication with the SRST and represents either site monitoring data or a specific management goal. Intermediate nodes were

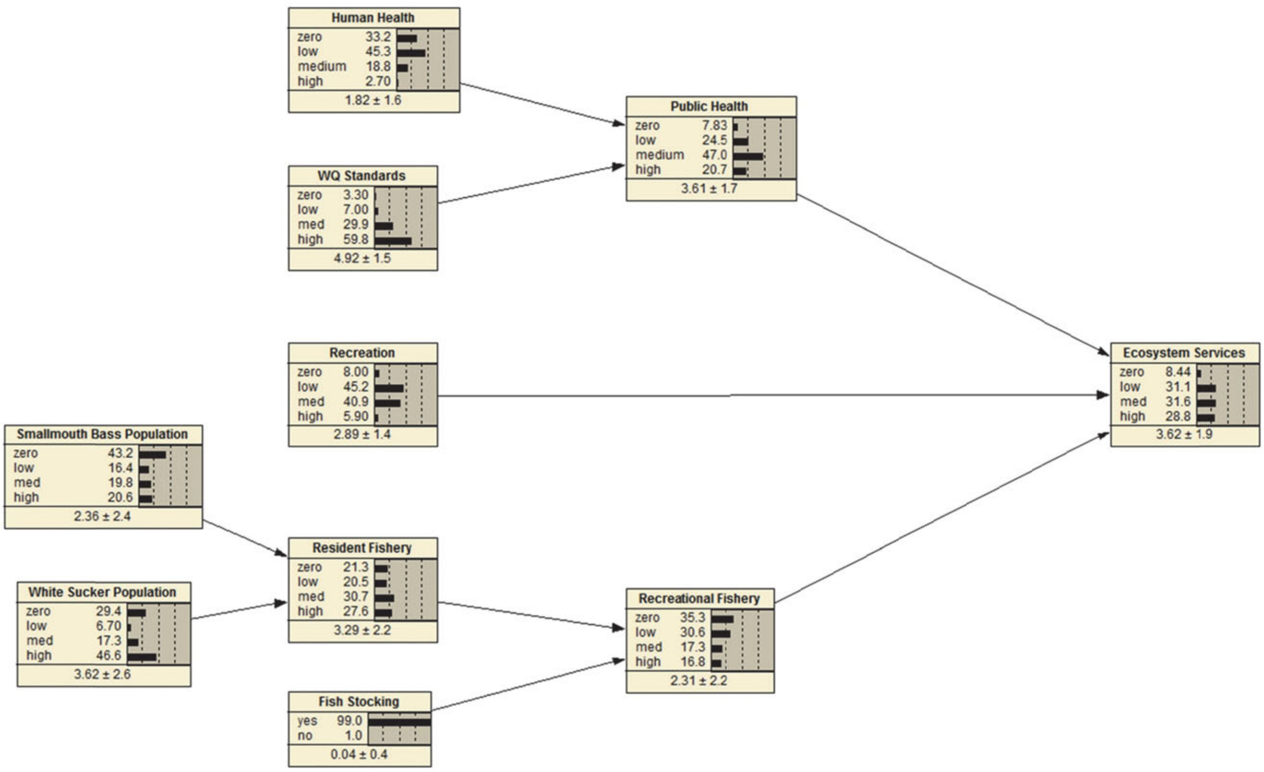

Fig. 3. Bayesian network for ecological services, Region 2. Refer to supplemetal file es_r2.neta to view this BN in netica.

used to summarize input parameters that shared similar sources, pathways of exposure, or mechanisms of action; these nodes were also defined to reduce ambiguity in the model.

2.5.2. Discrete Node States

Following the methodology of the RRM, every node in the BN was discretized into ranked states, enabling us to compare the relative contributions of varied stressors and the interactions between these stressors.[17] In most cases, we followed the four-state ranking schemes used previously in the RRM, in which states are represented as a category of effect (zero, low, medium, and high) and associated with an effect score from 0 to 6 (e.g., zero = 0, low = 2, medium = 4, and high = 6).[17,24,27] For some nodes, two or three states were used to more accurately reflect natural breaks in the data or regulatory criteria and scores for each state were adjusted accordingly. In Netica, the distribution of the effect score is entered as the node state value, which is required to calculate a probability distribution for the final (endpoint) node.[41]

When setting the node states, we considered ecological and toxicological data, regulatory criteria, and management objectives. For example, the node states for the input parameter River Phosphorus were set based on ecological threshold values of phosphorus as a contributor to algal blooms, while the River Mercury and Bacteria Indicator nodes were assigned states corresponding to VADEQ water quality criteria for human health and aquatic life (Table SVI). In the case of Fish Tissue Mercury, we set the node states according to dose-response data for mercury in smallmouth bass, where the states correspond directly to ECx values.[27] We evaluated the effects of different node states on the results through multiple beta models until we felt confident that the ranking scheme was representative of the data, was useful to the risk managers, and would not introduce bias into the results.

Endpoints were also discretized following the four-state ranking scheme (zero, low, medium, and high) of the RRM. For every endpoint node, the four risk states were defined as the probability of adverse effects to specific attributes of the endpoint (Table SI).

Discretizing model parameters is one of the challenges of using BNs in ecological modeling and decision making because statistical accuracy can be lost in the process.[19,42] Additionally, the values of the node states can alter the risk results, introducing bias or uncertainty into the models.[19,42] However, through discretizing, we gain the ability to calculate the relative contributions of risk from a diverse set of stressors to both human and ecological endpoints. By evaluating the BNs throughout the model development process, we aim to eliminate bias or subjectivity that may result from the discretization process.

In addition, we have found that model discretization (using node states defined as either numerical ranges of values or qualitative conditions) facilitates risk communication and decision making by establishing agreed upon terminology, increasing transparency, and defining risks as a set of conditions that are directly related to site conditions and regulatory criteria.

2.5.3. Conditional Probability Tables

The relationship between nodes is represented by a link or arrow in the BN and quantified in a CPT. The values of the CPT are used to calculate the probability distribution of the resulting intermediate node.[41] CPTs can be completed using a variety of methods depending on the information available. These methods can be broken down into four categories: expert judgment, empirical evidence, mathematical or biological equations, and case file learning.[19,20,42] In a single model, CPTs for different nodes may be completed using different methods or a combination of methods may be used within a single CPT.[19,42]

The CPTs in these models were completed based on empirical data from peer-reviewed studies and government reports, expert judgment from SRST scientists and mangers, and site-specific monitoring data or spatial data. For example, to complete the CPTs for cumulative dietary mercury exposure from multiple food sources, we reviewed estimated fish consumption rates from local angler surveys[43,44] as well as data from the USEPA *Exposure Factors Handbook* for human health risk assessment.[45]

CPTs were evaluated in a process similar to that described for node states (Section 2.5.2). Multiple beta versions of the CPTs were created to assess the effect of the CPT on the risk calculation. For node combinations that were less certain (e.g., less available data to support the relationship or greater natural variability in the response itself), the beta versions reflected different scenarios for the relationship. This beta testing of CPTs and BNs has been described in further detail by Marcot *et al.* and Pollino *et al.*[19,20]

2.5.4. Site-Specific Data

Site-specific data were used to set the probability distributions of the input nodes for each risk region. Data came from many sources including the National Oceanic and Atmospheric Administration, USGS, VDH, VDEQ, Virginia Department of Game and Inland Fisheries, City of Waynesboro, and the SRST. The frequency of data points in each state determined the probability distribution of the states for the input node. Uncertainty was expressed explicitly in the input frequencies. For parameters with no available data, we assigned the node a uniform distribution, or an equal probability of any risk state. This was to show that any state was equally likely to occur in the risk region, given our knowledge. The use of site-specific monitoring data as input frequencies ensured that the risk results were relevant and applicable to site management.[20,42]

2.6. Risk Calculation

Netica uses probabilistic inference to compute a probability distribution for each intermediate and endpoint node given the values of the input distributions and the CPTs.[41] For each endpoint node, Netica displays a risk distribution (the calculated probability that any given risk state will occur) and a relative risk score. The risk score is calculated from the node state scores (0–6); it is the mean of state scores weighted by the probability of occurrences and the standard deviation. Risk scores are continuous; in these models, risk scores range from 0 (low risk) to 6 (high risk).

While risk scores facilitate the communication of general trends, risk distributions are useful for conveying specific information about patterns of risk and comparing differences by endpoint or by region. There is no assumption of normal distributions; rather, the distributions reflect the actual frequencies resulting from the model calculations.

We calculated cumulative risk by region and by endpoint using a Monte Carlo approach (Crystal Ball Oracle version 11.1.2.3.000). The risk distributions from each of the endpoint nodes in the BNs were used as input data for the Monte Carlo simulation

(10,000 iterations, Latin Hypercube). The cumulative risk results that resulted from the Monte Carlo simulation were used to compare total risk by endpoint and by risk region. Risk to all services can be compared and summed because they are measured in the same units (relative risk), which is a benefit of the BN-RRM approach when integrating human health and ES endpoints into an ERA framework.

2.7. Model Evaluation

2.7.1. *Sensitivity Analysis*

Sensitivity analysis explains the extent to which the endpoint node is influenced by the values of the input nodes.[19,46] The sensitivity analysis is used to understand which variables contribute risk to the endpoint.[24,27] It can also be used to identify variables that are important for future monitoring efforts or risk management actions.[24,27] If data are unavailable for a variable and a uniform distribution is assigned to the node, the uncertainty will likely be reflected in the sensitivity analysis.

A sensitivity analysis was performed for each endpoint in each risk region, looking at the influence of the input parameters on the endpoint node (sensitivity to findings).[41] Because the states are discrete ranks, sensitivity was measured as mutual information, or reduction in entropy.[18,19,41]

We limited the sensitivity analysis to include only the input nodes and endpoints (excluding the intermediate nodes), thereby eliminating the effect of the BN structure on the sensitivity analysis[18,19] and focusing on parameters that are likely to change with management. The top three stressors identified by the sensitivity analysis were compared across endpoints and among risk regions. For the ES BN (Fig. 3), we performed an additional sensitivity analysis that included the intermediate nodes in order to better understand how groupings of inputs affect the endpoint. For example, all fishery-related input nodes were grouped together in a sensitivity analysis to quantify the effects of this portion of the BN on risk to ES.

2.7.2. *Influence Analysis*

Influence analysis can be used to describe minimum or maximum risk scenarios that bracket the possible range of risk.[46] We performed influence analysis of the ES BN (Fig. 3) to understand how changes to the input parameters affected the risk distribution for ES. For this analysis, we set input parameters to either the zero state (minimum) or high state (maximum) and compared the results to the risk distributions that we had calculated under the initial model conditions following the methods of Marcot.[46]

3. RESULTS: PATTERNS OF RISK

3.1. Ecological Services

Risk to the ES of the South River varied more by service than by region. Human health risk in the South River was lower than risk to all other services in all regions. Risk to recreation was moderate across all regions with little variability among regions. Risk results for human health and recreation are described in further detail in the following sections.

Water quality was the service at highest risk in all risk regions (Fig. 4). There was a 77.9% to 89.7% probability of risk in the medium or high state for water quality, depending on the risk region (Table SVII). Risk to the recreational fishery varied spatially more than risk to other services (Fig. 4a). Risk to the recreational fishery was low in Regions 2 and 5, with 65.9% and 67.4% in the zero or low-risk state for these regions, respectively. Risk in Regions 3 and 6 was moderate, with 66.7% and 59.7% in the medium or high risk state, respectively. Risk to the fishery was the highest in Region 4, with a 76.1% likelihood of medium or high risk.

The Monte Carlo simulation provided cumulative risk distributions for the comparison of risk to the ES over all of the risk regions combined (Fig. 4b). The cumulative risk distributions exhibit the same patterns described above (highest risk to water quality, lowest risk to human health). The shape of the cumulative distribution provides additional information about the spatial variability of risk and the uncertainty associated with the risk estimates for each region. For example, the variability in risk between regions for the recreational fishery endpoint is represented by the wide tails of the cumulative distribution for this endpoint.

3.2. Human Health

Human health risk was assessed for five hypothetical user scenarios: All Pathways of Exposure, Hunter/Fisher, Fisher, Farmer, and Recreational

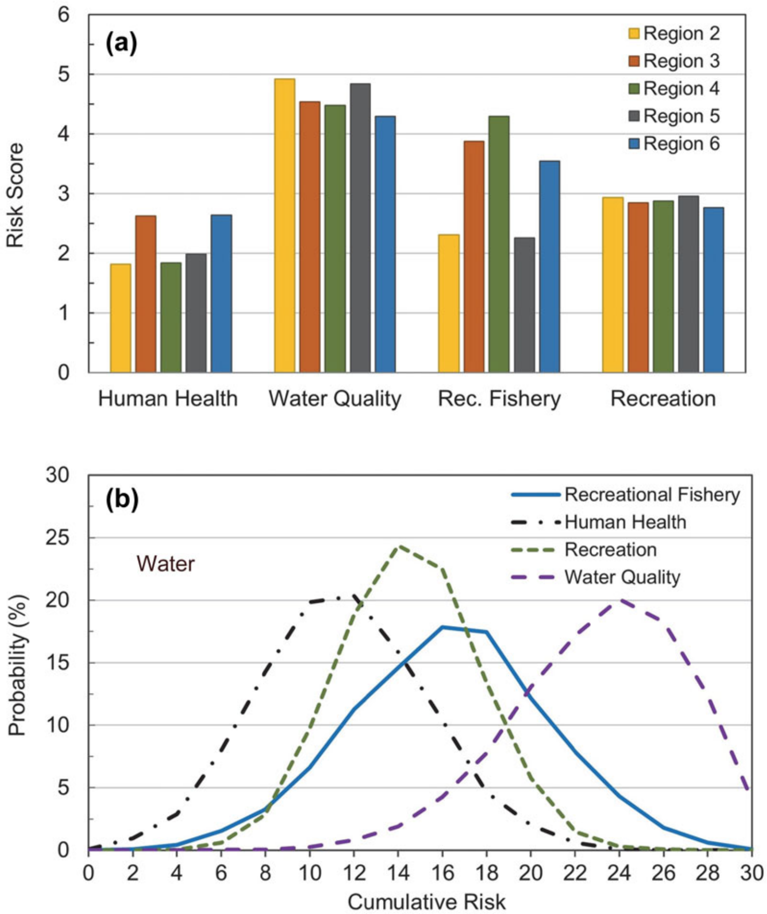

Fig. 4. Risk results for four ecological services displayed as risk scores (a) and cumulative risk distributions (b). Water quality is the service at the highest risk; human health is the service at the lowest risk. (a) Risk to the recreational fishery has the greatest spatial variability of the services; risk to recreation varies the least between risk regions. Risk scores range from 0 to 6. (b) Risk scores are summed across all risk regions (Monte Carlo) to derive the cumulative risk distribution for each ecological service. Cumulative risk scores range from 0 to 30. Though cumulative risk is displayed as a curve, the x values are discrete.

User (Table II). The All Pathways scenario, which considers all potential sources of dietary mercury, was used as the human health component of the overall ES model.

Human health risk was highest in Regions 3 and 6 and lowest in Regions 2 and 4 for all user scenarios (Fig. 5). The elevated risk in Regions 3 and 6 was most pronounced in the All Pathways, Hunter/Fisher, and Fisher scenarios, all of which included fish consumption as a dietary exposure pathway. There was little regional variability in risk for the Farmer and Recreational User, which exclude fish consumption.

The All Pathways scenario is the "worst-case" scenario for human health risk. Still, risk was low for all regions, with risk scores ranging from 1.82 to 2.64 (Fig. 5) and a high-risk outcome was unlikely (2–11% probability of high risk, depending on the region; Table SVIII). Risk calculations for the user scenarios showed that risk decreased with fewer dietary exposure pathways, but did not disappear completely. In all regions, risk decreased from All Pathways to Hunter/ Fisher, Fisher, Farmer, and Recreational User (Fig. 5).

Cumulative risk scores for each user scenario combined risk over every risk region (Fig. 5b). Cumulative risk ranged from 0 to 30 from summing risk scores (0–6) across five risk regions. The cumulative risk pattern for human health was similar to the patterns observed in individual risk regions. Cumulative risk distributions for all user groups who ate fish (All Pathways, Hunter/Fisher, and Fisher) were similarly shaped and skewed toward the low state. Risk distributions for the Farmer and Recreational User were skewed farther toward the zero risk state, though risk was still possible (Fig. 5b).

3.3. Recreation

Risk was assessed for five recreational activities and overall recreation. Risk to overall recreation in the South River was skewed toward the low and

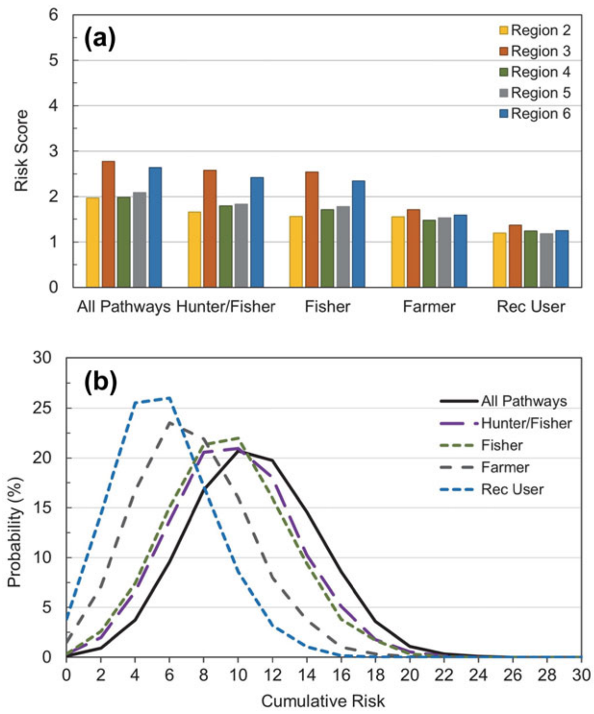

Fig. 5. Risk results for human health user scenarios displayed as risk scores and cumulative risk distributions. (a) Fish consumption contributes to the differences in risk among regions, increasing the spatial variability of health risk. Risk scores range from 0 to 6. (b) Risk is summed across all risk regions (Monte Carlo) to derive the cumulative risk distribution for each ecological service. Cumulative risk scores range from 0 to 30. Though cumulative risk is displayed as a curve, the *x* values are discrete.

medium states for all risk regions. The likelihood of high risk in any region was approximately 5% (Table SVII). Risk to individual recreational activities depended on both the activity and the risk region, though differences between regions were minimal (Table SIX). Risk was higher for swimming and boating than for other recreational uses. Risk to fishing and hunting was low for all regions, and the recreational activity with the lowest risk was birding/sightseeing.

4. MODEL EVALUATION

4.1. Sensitivity Analysis for Ecological Services

Sensitivity analysis indicated that the recreational fishery and recreation contributed the greatest risk to the overall ES endpoint. Human health did not contribute considerable risk to ES because risk to human health was low in all regions. The smallmouth bass population influenced risk to the recreational fishery and ES in all regions. White sucker population was a top contributor of risk to the recreational fishery in Regions 2 and 3. In Region 4, where risk was highest to the recreational fishery, risk was also highest to ES.

Sensitivity analysis for the water quality BN indicated that Dissolved Oxygen, Discharge, and River Temperature were parameters that contributed risk to water quality (Fig. 6a). Water quality was most sensitive to *E. coli* concentrations in Region 3, where *E. coli* has been measured at concentrations exceeding the TMDL. Phosphorus concentrations were not a primary driver of risk to water quality.

4.2. Sensitivity Analysis for Human Health

Sensitivity analysis of the human health BNs indicated that floodplain soil mercury, river mercury, and bacteria were the largest factors influencing risk to human health, though not always for the same reasons (Fig. 6b). Low garden crop mercury concentrations resulted in low risk to human health for the Farmer and All Pathways users in all regions. In contrast, elevated soil mercury concentrations and *E. coli* bacteria increased risk to human health. Bacteria Indicators increased risk in Regions 3 and 5, where measured concentrations of *E. coli* bacteria were the highest (Fig. 6b).

Resident fish species (nontrout) were the primary source of dietary mercury exposure for All Pathways, Hunter/Fisher, and Fisher. Mercury in nontrout species was the main risk driver in Regions 2, 4, and 5, where measured fish tissue mercury concentrations are elevated for nontrout species and low for trout species. In Regions 3 and 6, where data were unavailable for mercury in trout, the sensitivity analysis indicates a greater contribution of risk from trout species. However, these results are a function of the uncertainty in the fish tissue mercury rather than a measured increase in mercury concentration. Additional monitoring data for trout species in these regions would increase the certainty in the risk estimates and the sensitivity results.

4.3. Sensitivity Analysis for Recreation

Public access and mercury in waterfowl/game influenced risk to floodplain recreation in all regions (Fig. 6c). Mercury in waterfowl and wildlife, which was low in all regions, resulted in low risk to the

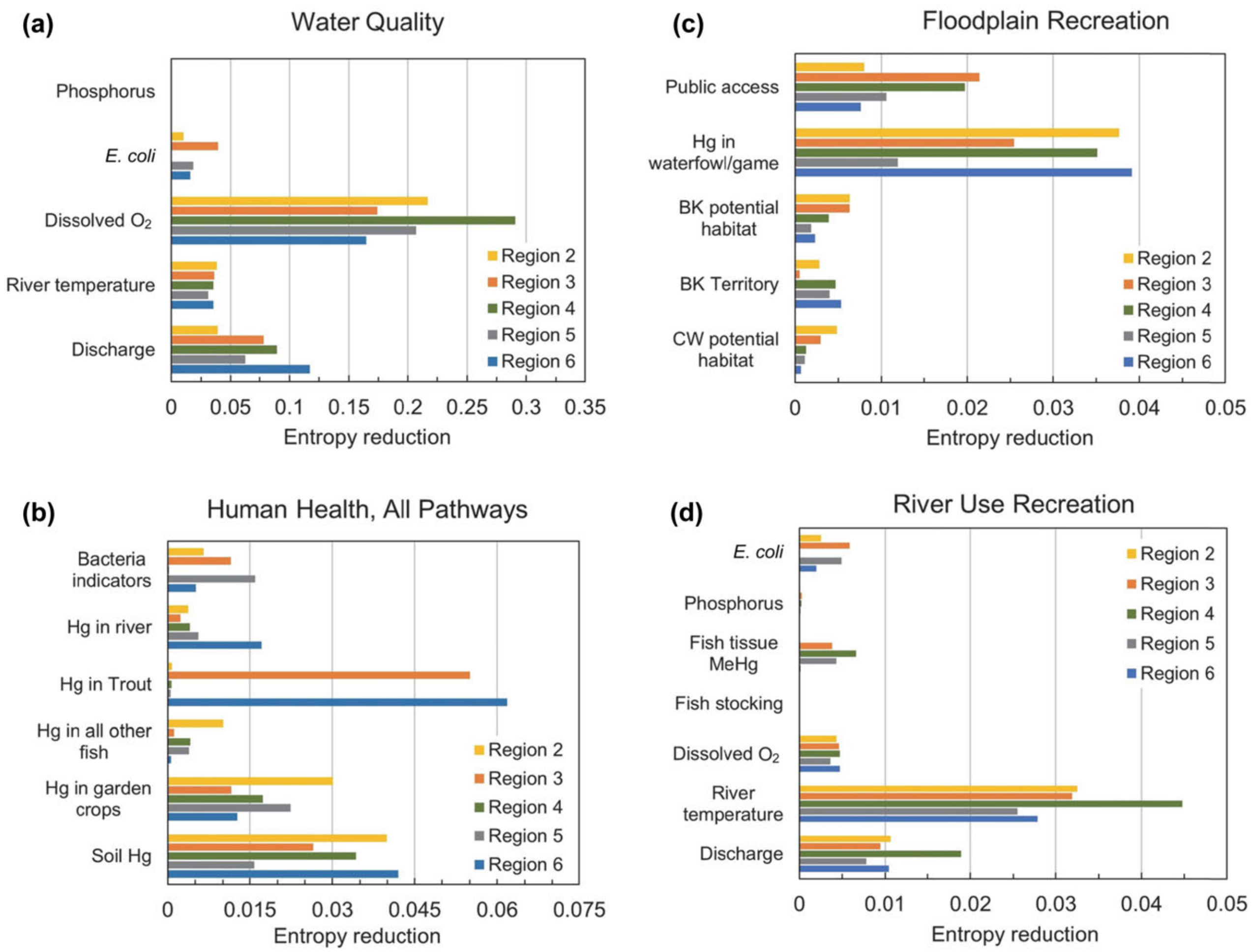

Fig. 6. Sensitivity analysis results for (a) water quality, (b) human health, All Pathways, (c) floodplain recreation, and (d) river-use recreation. Recreation is subdivided into floodplain and river uses because the recreational activities of the floodplain and river are influenced by different variables. Sensitivity analysis results for the recreational fishery are not shown.

hunting endpoint. Availability of Carolina Wren and Belted Kingfisher habitat influenced risk to the birding endpoint. River temperature and discharge were key drivers of risk to river-use recreation (Fig. 6d). Risk to fishing was driven by dissolved oxygen levels and fish tissue methylmercury.

4.4. Influence Analysis for Ecological Services

An influence analysis of the ES BN showed that all parameters had an effect on the endpoint (Fig. 7). When human health was set to high (the least likely state), risk to ES was skewed toward medium and high (Fig. 7b). Similarly, when water quality was set to zero (again, the least likely state), risk to ES was skewed toward low and medium (Fig. 7c). This analysis was used to understand how hypothetical changes in risk to human health and water quality would influence risk to ES.[46]

5. DISCUSSION

5.1. Site-Specific Patterns of Risk

5.1.1. Ecological Services

Stressors in the South River impact the ES of the river and its floodplain. While direct human health risks are low, risks to ecosystem services are likely to impact residents and river users. Risk to ES is driven by risk to water quality, recreation, and the recreational fishery. Spatial differences in risk can be attributed to water quality and fishery-related input parameters, including dissolved oxygen and

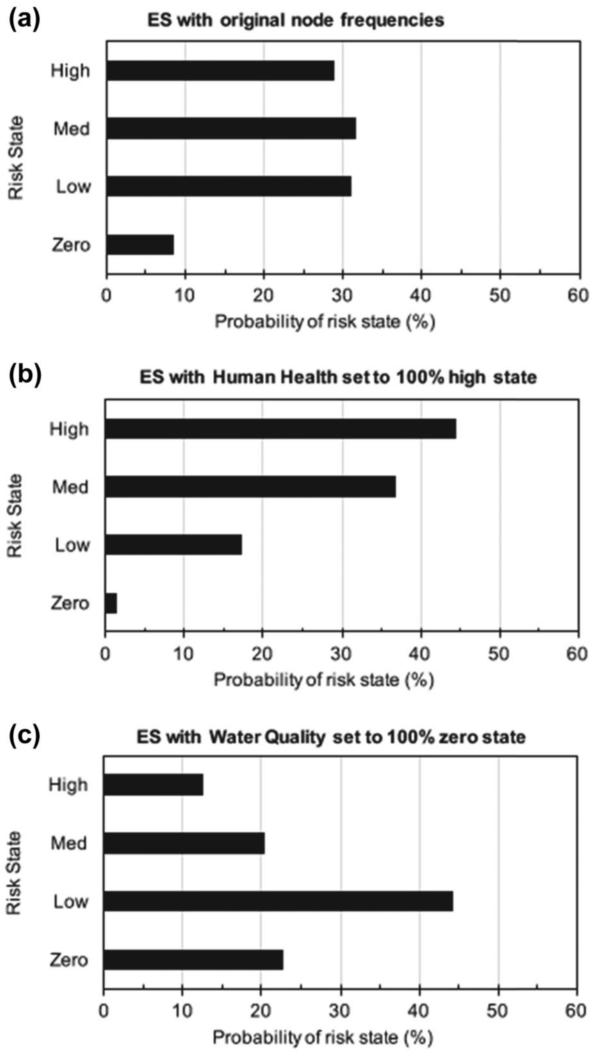

Fig. 7. Influence analysis of the ES model (Region 2). The analysis compares risk to ES given original input node frequencies (a) to two hypothetical scenarios: 100% probability of high to human health risk (b) and 100% probability of low water quality risk (c).

fecal bacteria levels (water quality inputs) and smallmouth bass population and fish stocking (fishery inputs). Fish stocking in Regions 2 and 5 lowers risk to the recreational fishery and ES in these regions because the stocked fishes support the demands of the recreational fishery without increasing the risk of mercury exposure from fish consumption.

5.1.2. *Human Health*

Sensitivity analysis of the human health BN shows that soil mercury and river mercury consistently contribute risk to human health for all regions and user scenarios. Dietary mercury from resident fish species (nontrout) increases risk to human health. Low mercury in garden crops resulted in lower risk to human health. Fecal bacteria increased human health risk in regions where bacterial counts are elevated. While human health risk is low in all regions, it is slightly elevated in Regions 3 and 6. The differences in risk among regions can be attributed to two factors: 1) fish tissue mercury and 2) fecal bacteria. Elevated concentrations of mercury in fish tissue in samples from Region 3 are a likely contributor to higher risk in this region. Fecal bacteria concentrations are also elevated in Region 3 compared to concentrations in other regions. Region 6 is underrepresented in current monitoring efforts, and data are unavailable for the soil mercury and surface water (river) mercury. Without data, these nodes are assigned an equal probability of being in any of the four risk states. This uncertainty is expressed in the risk distribution and risk score. With additional monitoring data to parameterize Region 6, it is likely that the risk distribution would become more certain.

Risk to the individual user scenarios exhibits spatial patterns of risk similar to the All Pathways scenario described previously. Scenarios that included a greater number of exposure media (Hunter/Fisher, for example) exhibited higher risk. Fish consumption appears to be driving the differences in risk among scenarios and increases spatial variability of health risk.

The results of this assessment are consistent with the findings of the SRST Human Exposure Team,[31,37] yet they provide additional information about the interactions between human health and other ES. This information can be used to guide future monitoring efforts and inform management decisions for the SRSA.

5.1.3. *Recreation*

Risk to recreation is low to medium, with less spatial variability among risk regions than is seen for other endpoints. Small spatial differences in risk can be attributed to the input node frequencies for a given region. Slightly elevated risk in Region 5 is likely due to higher risk to swimming and boating, which are primarily driven by water temperature and river discharge. Belted Kingfisher territory may also contribute to elevated risk in Regions 2 and 5, with the probability of unacceptable Kingfisher territory at 40% and 52%, respectively. Interestingly, there is no single input that stands out as a contributor of risk in Region 2; rather, it is a cumulative effect of small increases in risk for multiple input parameters. River temperature contributes risk to recreation more than other input parameters. Boating, swimming, and fishing are sensitive to changes in river temperature.[27] River temperature and discharge are indicators of water conditions that are likely to affect the public's participation in and satisfaction from river-based recreational activities. Fluctuations in river temperature and river discharge could also lead to unsafe conditions for river users. Public access determines the availability of recreation in a region. Where public access is limited or does not exist, recreation is not available and risk to recreation is forced to the medium- or high-risk states.

5.2. Summary of Findings

Through this research, we applied the BN-RRM approach to calculate site-specific relative risk for four ES endpoints. This research provides the first concrete example of an integrated ERA-HHRA in the peer-reviewed literature. We have used the South River as a case study to demonstrate the BN-RRM approach for assessing risk to human and ecological endpoints.

Findings of this risk assessment can be grouped into two categories: 1) site-specific results for the South River and 2) conclusions regarding the integration of ERA and HHRA and the use of ES as risk assessment endpoints. Four key findings of this study are:

(1) Human health risk is low in the South River and less spatially variable than risk to other ES.
(2) Mercury and other stressors in the South River increase the risk of exceeding water quality standards and limiting recreational activities.
(3) Integrating ERA and HHRA is both possible and practical; the BN-RRM is an effective tool for integrated risk assessment.
(4) Risk can be assessed to ES that are clearly defined and measurable.

5.3. South River: Informing Future Monitoring and Management

The BN-RRM can be used to identify the variables that should be included for measurement and to guide future monitoring efforts on the South River.[27,47] Variables that are shown in the sensitivity analysis to influence risk to the endpoint may be useful parameters to measure over time. Changes to these parameters, for example, reduction in mercury or change in temperature, may lead to change in risk to the endpoints.

For the South River, we recommend continued monitoring of fish tissue mercury and surface water mercury as well as river temperature, dissolved oxygen, and discharge. Fecal bacteria concentrations (specifically *E. coli*) should be measured regularly to inform management actions for water quality and human health. The lack of fish tissue mercury data for trout species in Regions 3 and 6 introduced uncertainty into our models. While methylmercury in trout has been documented to comply with the human consumption criteria in the SRSA,[30] continued monitoring of trout species would be useful for informing the ERA-HHRA and reducing the uncertainty in the human health risk estimates.

This research can also be used in the adaptive management process to assess changes in risk due to two proposed management options: agriculture BMPs and bank stabilization.[47,48] Inclusion of the BN-RRM in the adaptive management cycle allows for a quantitative analysis of management options and a better understanding of possible management tradeoffs.[47–49]

5.4. Integrating Human and Ecological Risk

An integrated approach to ERA and HHRA using the BN-RRM framework is both possible and practical. The BN-RRM provided a consistent framework for the integration of 14 biotic, human health, recreation, and water quality endpoints in a single ERA-HHRA. Conceptual models were constructed as to remain compatible and feed into one another. Assumptions, initial conditions, and spatial and temporal scales remained consistent for human, biotic, and water quality endpoints. Common methods for evaluating evidence, expressing uncertainty, and conveying risk led to results that were comparable for ecological and human health endpoints. The results of this assessment can be used to inform management decisions for the SRSA, and the methods can be applied to other sites for which there are sufficient data.

While many authors have proposed that an integrated approach to ERA-HHRA would be useful,[3–7] this research provides the first concrete example for testing the proposed benefits of such an approach. We have come to the following conclusions that support the hypotheses of Harvey,[3] Bridges,[4] Suter,[5,6] and Vermeire *et al.*[7]

Integration was efficient (both in time and effort). A single framework was used to describe sources, stressors, habitats, and exposure pathways for human and ecological endpoints. Three conceptual models were constructed for 14 endpoints. Site-specific data were used to calculate risk to four ES endpoints simultaneously.

Integration produced coherent and comparable results. An integrated ERA-HHRA required consistent methods, scale, and assumptions, which ensured that risk calculations remained relative among endpoints. A quantitative approach (the BN-RRM) further ensured that results were comparable across endpoints.

*Integration provided a more complete assessment of ris*k, whereas separate risk assessments would have addressed only parts of the larger pattern of risk. This ERA-HHRA can be used to understand patterns of risk and to determine the extent to which sources and stressors contribute risk to both human and ecological endpoints.

Integration increased transparency in the risk assessment process. The BN-RRM methods of this risk assessment allowed for transparency in the process, including the construction of the conceptual models, risk calculations, and model evaluation (sensitivity analysis, for example). It is not clear whether integration itself contributed to the transparency of this risk assessment.

5.5. Risk Assessment of Ecological Services

In addition to integration of an ERA-HHRA, this research demonstrates that ES endpoints are compatible with probabilistic risk assessment using the BN-RRM framework. Using the BN-RRM framework, risk can be calculated for any ecological service endpoint that (1) is measurable and changes to which are observable and/or testable and (2) causal pathways exist and can be used to assess risk from sources and stressors to endpoints. Even traditionally qualitative ES, such as esthetics or cultural values, can be defined and measured for inclusion in risk assessment, site management, or regulatory decision making.

Communication among stakeholders, managers, and the risk assessor is an essential component of an ES assessment. During the initial phases of the risk assessment, stakeholders and managers should agree on a conceptual model and definitions for each endpoint (both the entity and the attributes). These definitions can be based directly on values of the stakeholders or on preestablished regulatory criteria. Services chosen as risk assessment endpoints should be relevant to stakeholder values and present within the scope of the risk assessment—both spatially and temporally.

5.6. Spatially Explicit Risk Assessment

We found that spatial data and analyses could be easily integrated into the BN-RRM process. We used GIS to organize and display site-specific monitoring results, which gave us a better understanding of the spatial and temporal coverage of data. Through spatial analysis and mapping, we were able to identify key monitoring parameters and gaps in monitoring data, information that is currently being used by the SRST to inform future monitoring in the region.

As a spatially explicit probabilistic model, the BN-RRM benefits from the inclusion of site-specific data. The capacity of GIS to organize, analyze, and display spatial data enhances the BN-RRM model and allows for greater transparency in the risk assessment process. Given these benefits, GIS should be utilized in ERA and HHRA more frequently, especially for landscape-scale risk assessments.

ACKNOWLEDGMENTS

The SRST supplied the majority of the data for this research. Numerous members of the SRST shared with me their technical expertise and knowledge of the South River. Annie Johns, Carlie Herring, and Kim Kolb Ayre provided guidance on the BN-RRM process. Jonah Stinson contributed valuable GIS experience and assistance. Annette Guiseppi-Ellie provided valuable insight into the terminology and process that are parts of the human health risk assessment field. Funding for this research was provided by E. I. du Pont de Nemours and Company to the Institute of Environmental Toxicology at Huxley College at Western Washington University through contract agreement number CW195474.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article at the publisher's website:

Figure S1. Human health conceptual model, All Pathways of Exposure scenario.
Figure S2. Recreation conceptual model.
Figure S3. Bayesian network for human health, Region 2. Refer to *HH˙R2.neta.*
Figure S4. Bayesian network for recreation, Region 2. Refer to *recreation˙R2.neta.*
Table SI. Description of Risk States for Ecological Services Endpoints
Table SII. Input Variable Data Sources; Some Input Variables Are Shared by Multiple Ecological Services (e.g., Fish Tissue MeHg, Bacteria Indicators); the Complete SRST Monitoring Data Set Was Received Directly from the SRST (Personal Communications 3 Jan 2014)
Table SIII. Model Inputs for Four Ecological Services
Table SIV. Model Inputs for Five Hypothetical Human User Scenarios
Table SV. Model Inputs for Five Recreational Activities
Table SVI. Definition of Input Variables
Table SVII. Risk Distributions for Four Ecological Services and the Overall Ecological Services Endpoint
Table SVIII. Risk Distributions for Human Health User Scenarios
Table SIX. Risk Distributions for Recreational Activities