Results for the Integrated Regional Risk Assessment for the
South River and Upper Shenandoah River, Virginia

Prepared By

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List of Acronyms and Abbreviations

Ag BMP	Agricultural Best Management Practices
AM	Adaptive Management
BST	Bank Stabilization
BK	Biotic Endpoint: Belted Kingfisher
BMP	Best Management Practices
BN	Bayesian Networks or Bayes Nets
BN-RRM	Bayesian Network Relative Risk Model
CI	Confidence Interval
CW	Biotic Endpoint: Carolina Wren
DO	Dissolved Oxygen
EAM	Enhanced Adaptive Management
EPA	Environmental Protection Agency (US EPA)
ERA	Ecological Risk Assessment
GIS	Geographic Information Systems
Hg	Mercury
HH	Human Health
HHRA	Human Health Risk Assessment
HHRA-ERA	Human Health Risk Assessment integrated with Ecological Risk Assessment
HPDP	Hierarchical Patch Dynamics Paradigm
MeHg	Methylmercury
NOAA	National Oceanic and Atmospheric Administration
PAHs	Polycyclic Aromatic Hydrocarbons
PCBs	Polychlorinated Biphenyls
RCRA	Resource Conservation & Recovery Act
RRM	Relative Risk Model
SMB	Biotic Endpoint: Smallmouth Bass
SETAC	Society of Environmental Toxicology and Chemistry
SRSA	South River Study Area
SRST	South River Science Team
THg	Total Mercury
TMDL	Total Maximum Daily Load
USACE	United States Army Corps of Engineers
USGS	United States Geological Survey
USGS NWIS	United States Geological Survey National Water Information System
VDEQ	Virginia Department of Environmental Quality
VDGIF	Virginia Department of Game and Inland Fisheries
WB	Water Quality Endpoint: Boating River Use

Risk Terminology

The risk assessment terminology used in this report is consistent with the U.S. EPA's framework for ecological risk assessment (U.S. EPA, 1992) and the work of Suter (1993). Additional terminology was derived from peer-review scientific literature, with citations provided at the end of the definitions.

Adaptive Management: An iterative process of "learning by doing," where managers learn about current management practices through monitoring data and use the new knowledge to improve the next set of management decisions (Holling 1978, Nyberg et al. 2006).

Assessment Endpoint: An aspect of the natural system that is of value to society or the local community, as well as important to the ecology of the system.

Bayesian Networks: Bayesian networks (Bayes Nets or BNs) are directed acyclic graphs that links sources of stressors, habitats and endpoints through a web of nodes using conditional probability to estimate the likely outcome (McCann et al. 2006).

Bayesian network relative risk model (BN-RRM): A relative risk model where the linkages between the conceptual models are described by using a Bayesian network (also called a Bayes Net). (See Ayre and Landis 2012).

Conceptual Model: Diagrammatic description of the interactions stressors have with ecological components and their associated endpoints.

Effect: A change in the state or dynamics of an organism or other components of the ecological system resulting from exposure to a stressor. An indirect effect occurs when the initial effect results in additional stressors or effects to any component of the system.

Exposure: In the formulation of the relative risk model it is the colocation of a stressor with a receptor in a geographic area or habitat.

Habitat: The type of environment in which the receptors are found. Receptors may live exclusively within a single habitat or may move between and use several habitats.

Measurement Endpoint: An effect that is measured (e.g., toxicity test or field survey) and can be used to link the effects of a stressor to the assessment endpoints.

Stressor: Anything that is physical, chemical, or biological in nature which causes an effect to an organism or system. Initial stressors may result in secondary stressors, as in the case of excess nutrient input (initial stressor) causing mortality due to microbial activity and a decrease in oxygen (secondary stressor).

Receptor: The organism or group of organisms that have the potential to be affected by a stressor.

Relative Risk Model: A cause and effect modeling approach used to calculate risk to endpoints due to multiple stressors entering a number of habitats and having an effect on the endpoint(s) (See Landis and Wiegers 1997 and 2005).

Response: The effect on the receptor as a result of exposure to a stressor.

Risk: The probability, actual or relative, of an unwanted effect on a receptor judged by society to be important (Hines and Landis 2014).

Source: An anthropogenic input or activity that releases or creates a stressor in the environment. The characteristics of a stressor may be influenced by the type of source.

Uncertainty: There are two types of uncertainty we can address in ecological studies: epistemic and linguistic uncertainty (Regan et al. 2002). Uncertainty addressed in this risk assessment is mainly epistemic uncertainty.

> *Epistemic uncertainty* – This includes uncertainty of the knowledge of the state of a system. This could be limitations from measurement devices or uncertainty due to scarce data, extrapolation, and variability in spatial and temporal scales.

> *Linguistic uncertainty* – This is the uncertainty due to the language and vocabulary used in scientific writing. This vocabulary can be very technical and context dependent. At times it can also be ambiguous and vague.

Executive Summary

We have conducted a regional scale risk assessment using the Bayesian Network Relative Risk Model (BN-RRM) to investigate the ecological risk to the South River study area. The goal of this project was to support the decision-making process by determining the current patterns of risk in the study area and then evaluating the effect of proposed management options on that risk. Eight endpoints were chosen to be part of the risk assessment. The four biological endpoints were the smallmouth bass, white sucker, Belted Kingfisher and Carolina Wren. The other four endpoints represented valued ecological and recreational services in the South River watershed, and included compliance with water quality standards. The recreational use endpoints were: fishing river use, swimming river use, and boating river use.

The South River study area (SRSA) was divided into six risk regions based on hydrological sub-basins and land use similarities. Region 1, for which data were lacking is located upstream of the original mercury deposition site. Region 2 is downstream of Region 1 and encompasses the site of the original mercury contamination. Regions 3, 4, and 5 are located in consecutive order further downstream, ending with Region 6 encompassing the area downstream of where the South and North rivers converge to become the South Fork of the Shenandoah River. Although mercury is the original imputes for the site being remediated other chemical and physical stressors were evaluated. In addressing the eight endpoints over five risk regions and with the two proposed management options, we constructed 140 iterations of the BN-RRM models.

There are five specific findings that are presented in the body of this report.

First, it is possible to construct the necessary models to address risk within the South River study area. Patterns of risk can be evaluated with reasonable uncertainty. The importance of the inputs can be evaluated.

Second, risk varies according to location, specifically type and quality of habitat, within the landscape. For example, the risk to smallmouth bass is greater in a portion of the landscape further downstream from the original source of the mercury. The two most important factors in this determination were mercury (legacy contamination) and river temperature as a function of habitat. Conversely, risk to white sucker is greatest in the regions closest to the source of the mercury, however the most important factors were river temperature and stream cover, not mercury. A sensitivity analysis was performed to determine the variables most important in estimating risk to the endpoints. The outcome of the analysis was used to inform the monitoring program about which measurements would be most informative.

Third, it is possible to evaluate different methods and strategies for reducing risk in the South River to each of the endpoints. Two proposed management options were evaluated, agricultural best management practices and bank stabilization. The agricultural best management practices did not appreciably lower or increase risk to any of the endpoints. Bank stabilization, however did reduce risk to several of the endpoints, but only when measures were implemented to prevent destruction of existing habitat used by the endpoints.

Fourth, the risk assessment process can inform the long-term monitoring program for the South River both under current conditions and with the application of management options.

Fifth is the finding that it possible to construct conceptual models to incorporate human health and ecosystem services into a BN-RRM. The models incorporate a variety of exposure scenarios to evaluate the risk to different user groups in the watershed.

1.0 INTRODUCTION

In this report we have summarized the South River risk assessment activities conducted by the Institute of Environmental Toxicology at Western Washington University over the last five years. The goals of this report are to provide an in-depth account of the risk assessment process, to summarize the results with tables and figures to illustrate patterns in the results, and provide conclusions of the risk assessment as of the summer of 2014. The report is organized into several sections.

The **Introduction** (Section 1) provides a background of the site, and the relative risk modeling using the Bayesian Network Relative Risk Model (BN-RRM) used to conduct the risk assessment, as well as provides a synopsis of the results. The **South River Risk Assessment** (Section 2) describes the research site, the development of the risk assessment model, and how Bayesian Networks (Bayes Nets or BNs) were used to estimate risk to eight endpoints across the watershed. The **Evaluating Management Options for the Watershed** (Section 3) describes how two management options were incorporated into the BNs framework and the expected changes in risk with implementation. A summary of **Suggested Parameters for Long-term Monitoring of the South River** (Section 4) describes how this research has been used to evaluate monitoring parameters for the South river and inform future monitoring efforts, in turn contributing to the adaptive management cycle. The **Human Health Risk Assessment** (Section 5) discusses the ongoing project integrating human health risk into the ecological risk assessment of the South River.

1.1 The South River Study Program.

Stahl et al (2014) presents the background for the South River site and a general approach for planning an assessment process. In summary, the South River and its watershed is a legacy site contaminated with Hg that was released to the river from a manufacturing process from the late 1920s to the early 1950s. Legacy sites pose particular assessment and management problems since the data are often collected and retained by different agencies and entities. There are also multiple activities that took place in the watershed over time, leading to a plethora of stressors, affecting a number of endpoints of interest. In 2001, DuPont and the Commonwealth of Virginia established a multi-stakeholder and collaborative program the South River Science Team (SRST) to address the assessment and management of the system.

The potential use of regional scale risk assessment in the planning, problem formulation, assessment and management is summarized in Stahl et al. (2014).The results published in this report are an outcome of the efforts of the SRST to address and manage the South River and its watershed.

1. 2. Regional Risk Assessment and the Relative Risk Model (RRM)

The assessment of the fjord of Port Valdez by our research group led to the development of the relative risk model (RRM) (Landis and Wiegers 1997, 2005, 2007). The impetus for the development of the method was the necessity to incorporate multiple sources with multiple stressors within multiple, diverse habitats that were potentially affecting multiple endpoints within the fjord, as well as in the surrounding watershed. At that time there was not a suitable framework to use on such a complex site at a landscape scale. The basis of the RRM is a conceptual diagram that identifies sources of stressors, stressors, effects of stressors on receptors, and the resulting impacts on endpoints within large spatial scales. Due to the spatially explicit nature of the relative risk model, risk gradients are revealed in the study area. Relative risk models have been completed for a variety of stressors and combinations of stressors including contaminants, disease, environmental parameters, and non-indigenous species (Hayes and Landis 2004, Colnar and Landis 2007, Ayre and Landis 2012, Hines and Landis 2014, Ayre et al. 2014).

Colnar and Landis (2007) introduced the most current version of the relative risk model framework. This version described how the hierarchical patch dynamics paradigm (HPDP) as formulated by Wu and David (2002) could be used to conceptualize how spatial scales, dynamic ecological processes, and habitats interact. Anderson and Landis (2012) provided an extensive demonstration of how this method could be applied with the inclusion of management options for a US Forest Service managed forest system. Although there may be only a primary stressor of interest at the site, it is recognized that at a regional scale other stressors acting upon the endpoints are also considered.

1.3 Bayesian Network Relative Risk Model (BN-RRM)

In order to describe the probabilistic nature of risk, Bayesian networks have recently been applied to the calculation of risk in the RRM (Ayre and Landis 2012, Hines and Landis 2014, Ayre et al. 2014). The BN links cause and effects through a web of nodes using conditional probability to estimate the likely outcome (McCann et al. 2006). Bayesian networks are now used increasingly in risk assessment (Uusitalo et al. 2007, Hart and Pollino 2008) because this tool inherently deals with cause-effect relationships, incorporates uncertainty, and enables the use of combinations of available data and expert knowledge (Uusaitalo et al. 2007). Bayesian belief and decision networks also work well as modeling tools for adaptive management (Nyberg et al. 2006). The causal structure of the RRM can be directly translated into the tiered node structure of a BN (Ayre and Landis 2012, Hines and Landis 2014).

Ayre and Landis (2012) demonstrated how the version of the RRM used by Anderson and Landis (2012) could be translated into a BN while still retaining the basic framework

of the RRM. Hines and Landis (2014) illustrated how low-impact development adaptive management options can be incorporated into a BN-RRM to estimate pre-spawn mortality of coho salmon in the Pacific Northwest under different management scenarios. The current risk assessment for the South River uses the BN-RRM approach as well.

In the formulation of our BN modeling, the essential structure of the RRM is preserved (**Figure 1-1**). The basic form of the relative risk model (**Figure 1-1a**) is converted into a conceptual model that describes the cause-effect linkages that will be used to estimate risk (**Figure 1-1b**). Then a Bayesian network is built that describes these pathways and incorporates the likelihood distributions for each variable (**Figure 1-1c**).The RRM still retains the source-stressor-habitat/location-effect-impact pathway framework. The result is a conceptual model that describes causality within this same structure, but is specific to the problem under investigation, e.g., the conceptual model-fish endpoint model. This conceptual model to fish endpoint step is specific to the probability of a decline in the fish population. Finally, a Bayesian network is constructed based on the conceptual model and is parameterized for the specific endpoint. The BN resulting from this process specifically describes the pathway for determining risk to smallmouth bass. The outputs of the assessment incorporate both calculated risk and the uncertainty associated with that calculation.

1.4 Risk and Uncertainty

Throughout this document are references to risk and the uncertainty associated with that risk. To clearly evaluate the results presented in the remainder of the document, it is important to understand uncertainty and its use in evaluating risk.

There can be confusion in the difference between risk and uncertainty. This lack of clarity can be exacerbated in the case of Bayesian networks where input and output distributions are explicit and conditional probability tables are used to describe functions. In this paper, risk is defined as the probability, actual or relative, of an unwanted effect on a receptor judged by society to be important. In the case of the BN-RRM, the risk is the likelihood of one of four states or risk ranks (zero, low, medium and high). In the original formulation of the method (Landis and Wiegers 1997) numeric scores were given for each state. Since the introduction of Monte Carlo simulation techniques to the RRM (Hayes and Landis 2004) followed by Bayesian networks (Ayre and Landis 2012) uncertainty has been explicitly represented by distributions.

Our treatment of uncertainty is based on Regan et al (2002) in which there are two types of uncertainty, epistemic and linguistic. Epistemic uncertainty generally addresses the findings under consideration from a study or a model. Classic examples of epistemic uncertainty include the shape of an exposure-effect curve, cause-effect relationships in a conceptual model, and inherent variation in sampling results. Linguistic uncertainty pertains to language as in determining the actual representation of terms like species

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A. Relative Risk Model
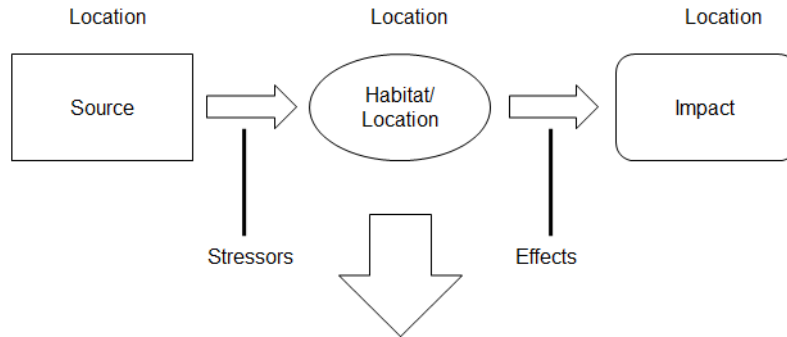
B. Conceptual Model-fish endpoint
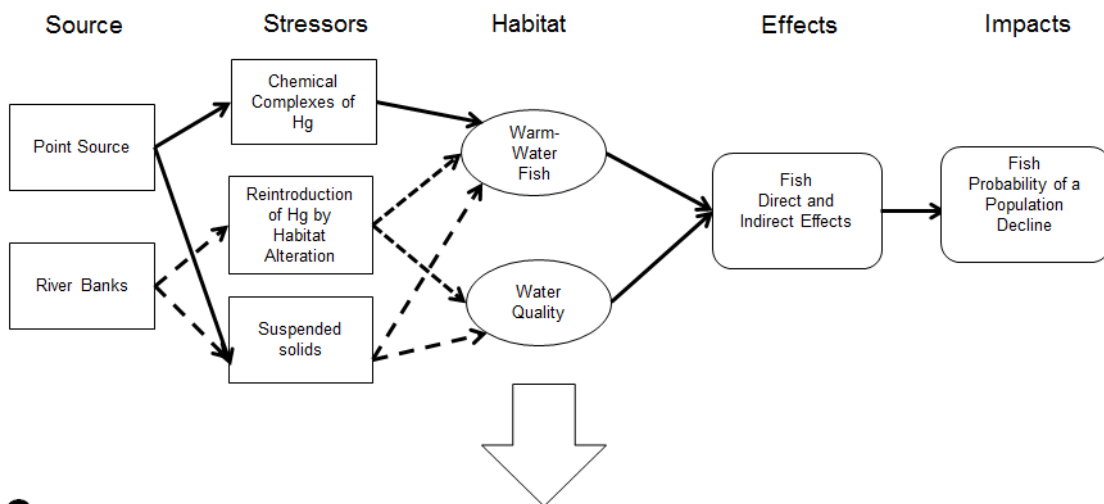
C. BN-RRM-smallmouth bass endpoint
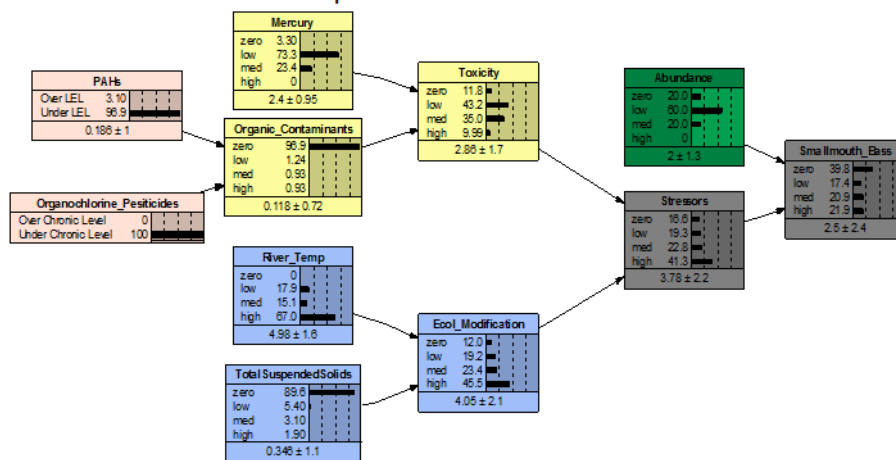
Figure 1-1. The RRM is used to develop a conceptual model which becomes the template for the Bayesian Network. In this example, the conceptual model represents all fish endpoints and the BN is specific to the smallmouth bass endpoint.

diversity, ecosystem health, endpoint or estimated impacts. The use of distributions in this study applies to epistemic uncertainty. Epistemic uncertainty includes measurement error, systematic error, natural variation, inherent randomness, model uncertainty and subjective judgment.

- **Measurement error** is the uncertainty attributed to random variation existing in equipment and other measurement tools and in the operator. This uncertainty can be reduced but not eliminated.
- **Systematic error** is the bias built into the measurement tool and the sampling method. This bias does not represent a random event, but rather a consistent difference between the actual and calculated values as the sample size increases. This type of uncertainty can be reduced.
- **Natural variation** occurs in dynamic systems that change over time and space in a manner that is difficult to predict. As a result of these changes, natural variation is not considered as classic epistemic uncertainty. However, the precise nature of these changes is extraordinarily difficult to measure, and thus the actual value remains unknown. It is important to understand that natural variation is a deterministic process, but measurement and systematic error apply in the estimation of this property.
- **Inherent randomness**, or stochastic uncertainty, is when the system under consideration cannot be reduced to a deterministic equation. Many aspects of ecological systems are best described by distributions that assume stochastic functions (Wu and Loucks 1995). It is unlikely that this source of uncertainty can be eliminated although the probabilities can be better described.
- **Model uncertainty** stems from the inherent simplification that exists in any representation of reality. Regan et al. (2002) focused on computational and mathematical models; however, laboratory tests, microcosms, and field-scale mesocosms are all physical models of reality and extrapolation to a field site can be problematic. Extrapolation of a result from a laboratory experiment, another field site, or even from a portion of the study site is also subject to model uncertainty. The assumption is that the laboratory or study area is an appropriate analog or model for the system under investigation.
- **Subjective judgment** is the source of uncertainty that stems from data evaluation, especially with uncommon data findings and substantial opportunity for measurement error. In these cases, the parameter values often are determined by experts' subjective estimates of the parameter or the probability of an event. A large literature base now exists for issues associated with the extraction of survey information (O'Hagan et al. 2006).

Linguistic uncertainty is more difficult to describe using distributions. However this type of uncertainty can be minimized by using explicit definitions. In this document we have a glossary that defines the terminology as it is used in the BN-RRM and in the remainder of this paper. As often as possible we use the regulatory definitions for water quality parameters.

1.5. Summary of Findings

There are four specific findings that are presented in the body of this report.

1. The BN-RRM methodology enabled us to conduct a spatially explicit ecological risk assessment to determine risk and its associated uncertainty to the four biotic and four abiotic endpoints used in this study.
2. The risk varies according to the location within the landscape. For example the risk to smallmouth bass is greater in an area of the watershed that was miles downstream from the original source of the mercury. The two most important factors in this determination were mercury and river temperature. Conversely, risk to white sucker is greatest in the regions closest to the source of the mercury, however the most important factors were river temperature and stream cover, not mercury. The identification of the variables most important in determining risk can be used to plan future monitoring and remediation programs.
3. It is possible to evaluate different methods and strategies for reducing risk in the South River to each of the endpoints using the BN-RRM. The output from these risk determinations can assist in choosing options and in making predictions that can be applied to an adaptive management program.
4. It is possible to construct conceptual models to incorporate human health and ecosystem services into a BN-RRM that can be used to evaluate risk and alternative management strategies.

The next four sections provide the support for each of these findings.

2.0 SOUTH RIVER RISK ASSESSMENT

2.1 Research Site and Determination of Risk Regions

The South River is located in Augusta County, Virginia in the Shenandoah Valley (**Figure 2-1**). 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. The South Fork of the Shenandoah continues flowing northward to Front Royal, Virginia, where it converges with the North Fork of the Shenandoah to form the Shenandoah River (Eggleston 2009).

We defined the South River Study Area (SRSA) as the 607.6 km^2 South River watershed and the South Fork of the Shenandoah River (**Figure 2-1**). We divided the South River watershed into six risk regions based on hydrological sub-basins and land use similarities. **Figure 2-1** shows the South River watershed and division of risk regions starting upstream in Region 1 and progressing downstream to Region 6 where the South River becomes the South Fork of the Shenandoah River. Region 1 is upstream of the original mercury deposition site, and regions 2-6 are downstream with Region 6 downstream of the confluence of the South River and the North River that forms the South Fork of the Shenandoah River. There were insufficient data to parameterize a model for Region 1 and has been identified as a recommended data need for future studies. The primary land uses in Regions 2-6 (**Figure 2-2**) are forested (58%) and agricultural (31%), with the remainder as developed (urbanized) land (8%), mostly comprised of the cities of Waynesboro, Grottoes, and Elkton (Eggleston 2009). The largest population resides in Waynesboro, Virginia (Eggleston 2009).

The source of mercury contamination in the South River came from a textile manufacturing plant owned by DuPont in Waynesboro, VA. Mercury sulfate was used as a catalyst in the textile manufacturing process from 1929 to 1950, and accidental losses resulted in widespread mercury contamination of the river (Bolgiano 1980). Agricultural fungicides, atmospheric wet/dry Hg deposition, and leaking hydraulic seals in industrial equipment are other documented sources of mercury, but are all insignificant compared with the mercury released from the plant (Stahl et al. 2014). According to a study by Bolgiano (1980), the South River and adjacent flood plains contain an estimated 26,000 kg of mercury with an additional 9,000 kg deposited in the South Fork of the Shenandoah River and adjacent flood plains. Concentrations of mercury in sediment, water and biota have not changed appreciably since they were first identified in the 1970s (Bolgiano 1980, Old Dominion University 1996, 1997, 1998, VDEQ 1999, 2008) prompting extensive research over the years into its possible effects on ecological receptors and resources associated with the river.

The South River Science Team (SRST) was formed in 2001 to address the legacy mercury contamination. The SRST is a multi-stakeholder group addressing mercury contamination in the South River (Liberati personal communication 2013; Kain personal communication 2013; Stahl et al. 2014).The group includes members from DuPont, government agencies (local, state, and federal), consulting firms, experts specializing in mercury contamination, and academia (Stahl et al. 2014). The original task of the SRST was to evaluate mercury exposures to humans

through the assessment of previous, as well as current research conducted on the South River. The scope has now broadened to include risk assessments for aquatic and terrestrial endpoints, as well as additional human health endpoints (Stahl et al. 2014). Our research team, the Institute of Environmental Toxicology at Western Washington University started its risk assessment of the South River in the summer of 2011.
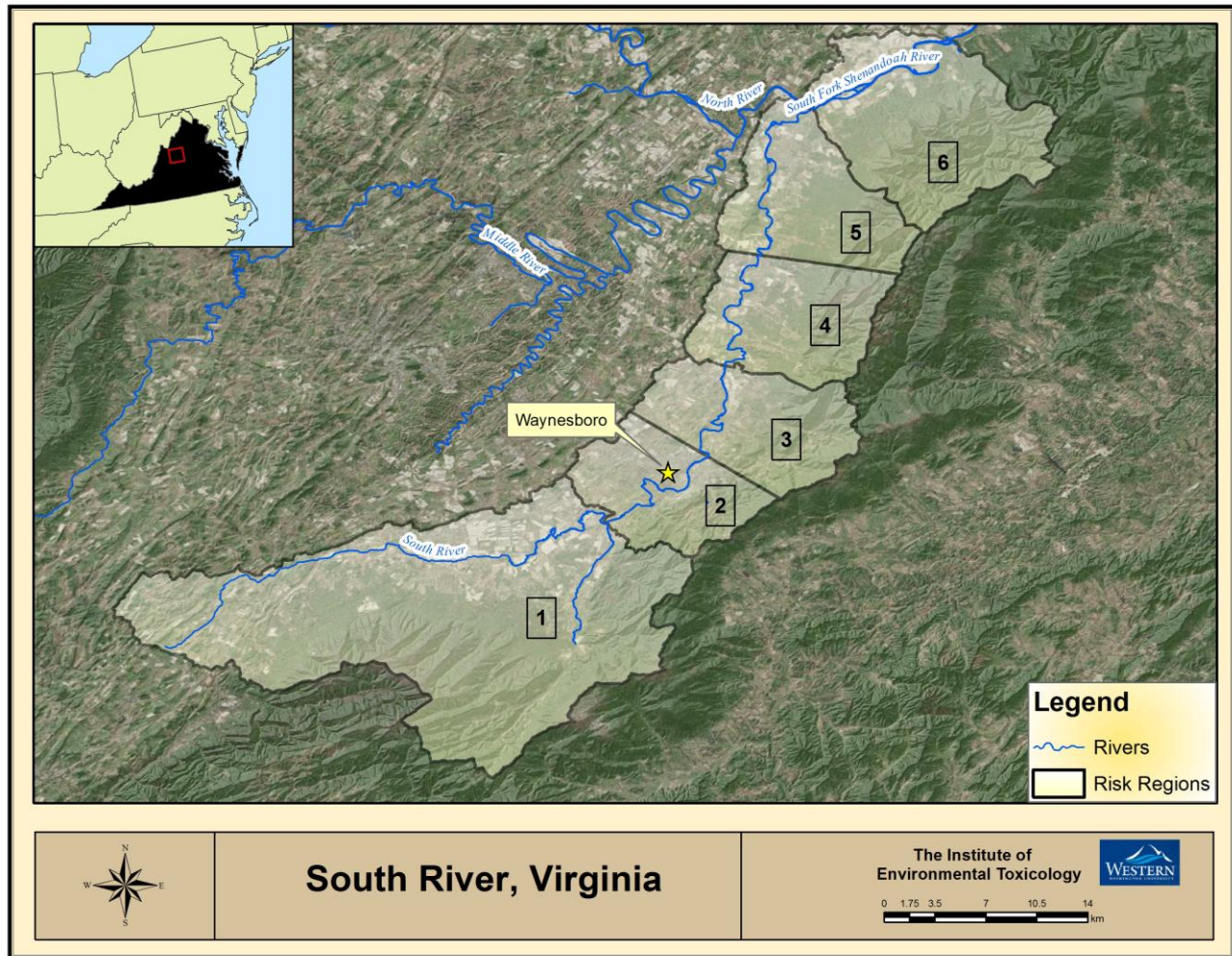
Figure 2-1.   Map of the South River and South River Study Area, Virginia, USA.

2.1.1. Mercury Contamination

Mercury is most often found in its inorganic form bound to sediment in the South River. Mercury also exists in organic forms, most prominently, as methylmercury. Methylation of inorganic mercury can occur in the upper layers of sediment where organic carbon is readily available. Microbiota within the sediment complex the mercury to the organic matter, creating organic methylmercury, the most bioavailable form of mercury. Mercury methylation rates in the South River are dependent on the following factors: soluble inorganic mercury in surface water, sediment, and pore water, methylating bacterial population abundance, temperature, dissolved oxygen, labile organic matter, electron acceptors, and nutrients (Flanders et al. 2010).

The toxicity of mercury varies depending on the form and speciation of mercury. Cells absorb inorganic mercury slowly, making its toxicity less than organic forms of mercury. Methylmercury is considered to be the most toxic form of mercury to mammals, fish, and birds and has proven to be environmentally persistent even after the primary mercury source is eliminated (Scheuhammer et al. 2007, Flanders et al. 2010). This form is more readily absorbed because the methyl group facilitates its transport across cellular membranes, including the blood-brain barrier and nuclear membranes (Wolfe et al. 1998, Boening 2000). The primary route of exposure is dietary for mammals, birds and fish (Scheuhammer et al. 2007). Mercury also bioaccumulates in food webs (Jackson et al. 2011a). Methylmercury can cause a wide range of effects in organisms including reduced hatching success and diminished egg health in avian species, as well as altered growth, survival and embryo viability in fish (Scheuhammer et al. 2007).
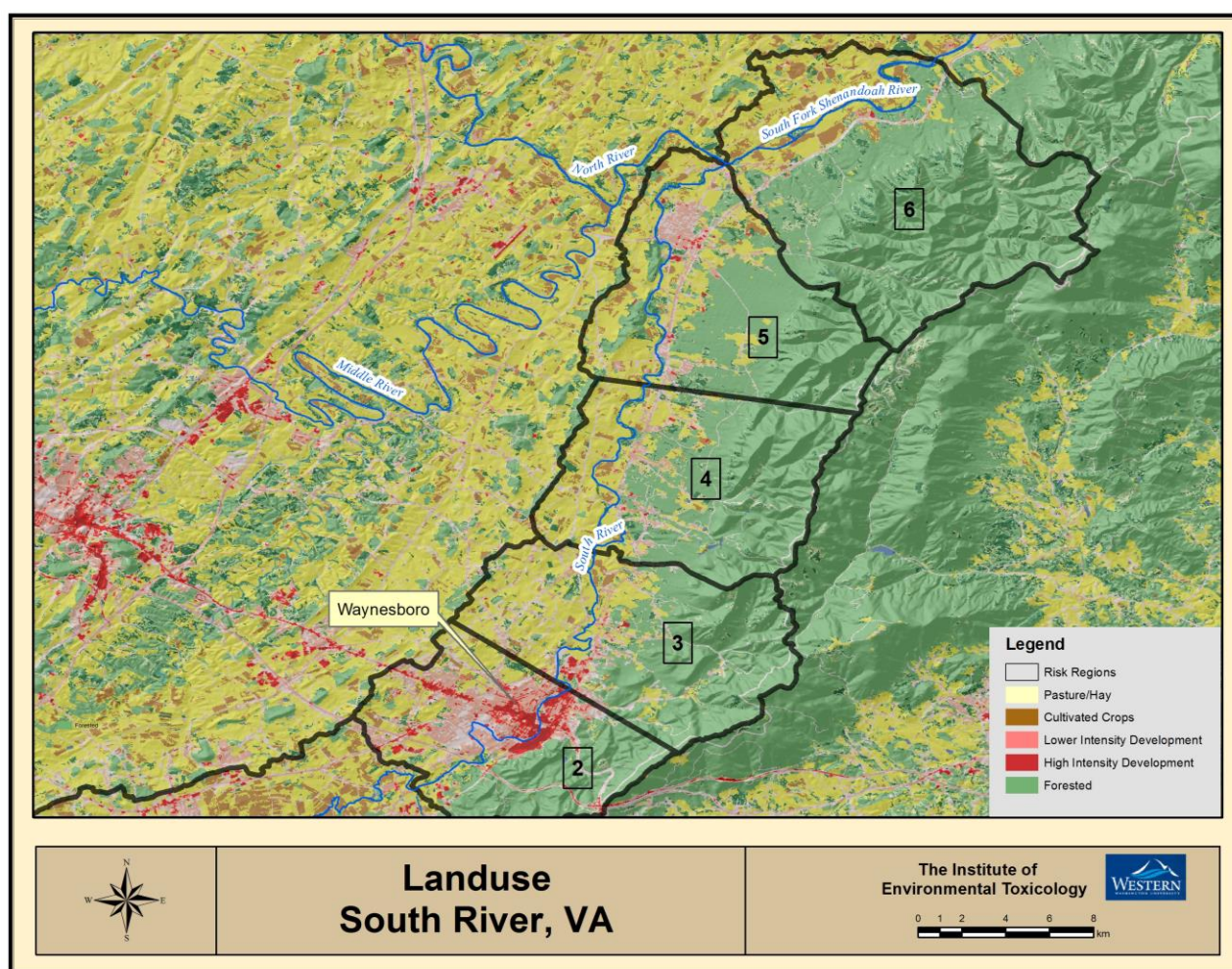
Figure 2-2.   Land use of the South River, Regions 2-6. The town of Waynesboro in Region 2 is the largest developed area in the SRSA.

In addition to mercury, other stressors were identified to biotic receptors and water quality parameters (Summers 2012, Ayre et al. Report 2013-1) due to the substantial amount of agricultural land use practices within the SRSA. Because of these varied land uses, we included two of the most common chemical classes of contaminants associated with them: polycyclic aromatic hydrocarbons (PAHs) and organochlorine pesticides as measures of potential exposure. We also included environmental stressors and habitat factors, such as river temperature, total suspended solids, avian nest predation, available habitat, submerged aquatic vegetation, dissolved oxygen, bacteria indicators, total phosphorus and discharge regime (Summers 2012, Ayre et al. 2013).

2.2 Endpoint Selection

As part of the initial conceptual model formation, we developed a list of receptors for evaluation based on the values of stakeholders in the South River and the South River Science Team. For the initial biotic risk assessment, we chose four biotic endpoints from this list: two species of fish, the smallmouth bass (*Micropterus dolomieu*) and white sucker (*Catostomus commersoni*), and two species of birds, the Belted Kingfisher (*Megaceryle alcyon*) and Carolina Wren (*Thryothorus ludovicianus*). These species also represent different mercury exposure pathways within the SRSA. We created conceptual models and BNs to model the risks to these endpoints.

- **Smallmouth bass (SMB)** are an important recreational fishery in this watershed and are valued by both harvest and catch-and-release anglers (DelVecchio et al. 2010). Smallmouth bass are high in the aquatic food web in the South River and therefore contain some of the highest mercury body burdens of all fish species sampled by the SRST (VDEQ 2003).
- **White sucker (WS)** are not valued as a game species, but represent fish species at a lower trophic level than smallmouth bass (Murphy et al. 2005). They represent a slightly different mercury exposure pathway as they are in more contact with bottom sediments, which contain sediment-bound inorganic mercury and are near the source of methylated mercury when released by biological and chemical cycles.

The two bird species, Belted Kingfisher and Carolina Wren, were chosen as endpoints for their value to recreational bird watchers and outdoor enthusiasts rather than for economic services and purposes.

- **Belted Kingfishers (BK)** are piscivorous and acquire mercury primarily from their food source (fish). Contaminated fish contain body burdens of methylmercury that bioaccumulate and cause toxic effects to higher trophic predators, such as the Belted Kingfisher that reside along the river year-round.
- **Carolina Wrens (CW)** represent a different pathway of mercury exposure because they are insectivores and likely obtain mercury by eating ground insects and spiders (Cristol et al. 2008, Rimmer et al. 2005). Members of the SRST have demonstrated that mercury has adversely affected the nesting success of Carolina Wren along the South River

(Jackson et al. 2011a). In addition, studies have shown that mercury body burdens in the Wrens are elevated far downstream of the mercury source (Jackson et al. 2011b).

These two species of birds also represent varied life histories, specifically in their habitat preferences. Kingfishers burrow in the banks of lakes and rivers; potentially exposing them to higher concentrations of soil bound contaminants such as inorganic mercury. Wrens chose to nest on the ground, in trees, and even in barns or abandoned buildings.

In addition to the four biotic endpoints, we also modeled four endpoints representing valued ecological and recreational services in the South River watershed. Three endpoints related to popular recreational activities, whereas the fourth addressed compliance with water quality standards. The recreational use endpoints were fishing river use, swimming river use, and boating river use since most recreational uses of the South River involve fishing, boating (kayaking, canoeing and tubing) or swimming although it is also enjoyed for wildlife watching (Bugas 2005). Three main factors affecting participation in these activities are weather and water conditions (temperature and stream flow) (Wilke 1992), and fecal coliform levels. Regardless of source, whether from humans, pets, waterfowl, and/or wildlife, exposure to fecal coliform bacteria has been shown to cause health impacts to swimmers and boaters, and to alter the public's perception about these activities in impaired streams (Prüss 1998).

The Clean Water Act authorizes the US EPA to assess the conditions of all surface waters, and those that do not meet its mandated water quality standards are listed as Impaired Waters for the water quality criterion not met. The US EPA delegates its authority to assess, protect, and restore surface waters to state agencies in which the surface waters are located. In Virginia the state agency is the Virginia Department of Environmental Quality (VDEQ). The VDEQ has listed the South River as impaired for recreation, fish consumption, and aquatic life based on levels of fecal coliform bacteria, mercury, and impaired benthic macroinvertebrate communities (USEPA 2009a, b).

Other factors that may exacerbate these conditions and impact stream biota are: legacy organic contaminants in the sediment that can become resuspended in the water column, increased nutrient loading causing algal blooms and hypoxia triggered by high phosphorus levels, and alteration of stream temperature and flow regimes. Restoring water quality to meet compliance standards, i.e., water quality achievement, was selected as the fourth assessment endpoint due to the amount of the public resources involved in monitoring, assessment and cleanup of the South River to comply with federal mandates, and because of the river's importance to the surrounding communities.

2.3 Model Construction: South River Conceptual Models

The first step in constructing the conceptual model (which will later be used as the framework for the BNs) is determining the sources of stressors to the target species or endpoints. Development of the conceptual model requires identifying causal pathways between stressors and the species or resource they potentially impact.

Evaluation of potential stressors to the biotic endpoints (smallmouth bass (SB), white sucker (WS), Belted Kingfisher (BK), and Carolina Wren (CW)) began with an extensive literature search for each target species, listing all potential chemical contaminants, habitat considerations and ecological stressors based on life-history profiles and current research. The process resulted in a unique set of stressors for each target species (**Table 2-1)**.

Next, we investigated the spatial relationships between sources of stressors and the receptors to assess causal pathways in each region of the South River study area. Consideration of the geospatial relationships is an important step in the RRM risk assessment process. Using the cause and effect pathways identified in the conceptual model, we then grouped stressors into three categories of inputs based on similar cause and effect pathways: 1) chemical stressors, such as mercury, PAHs, and organochlorine pesticides; 2) habitat preference and stressors, such as potential habitat and territory size; and 3) ecological stressors, such as river temperature, turbidity and total suspended solids, submerged aquatic vegetation, predation, fish length and air temperature. We used this basic structure for all target species, but with a slightly modified one for fish whose habitat is restricted to the river. For smallmouth bass and white sucker, we used abundance to represent potential exposure to the stressors within risk regions. Examples of cause and effect conceptual models for each species can be found in **Appendix 1**. Not all pathways were present or present to the same degree in each risk region; therefore the input parameters for habitat varied based on amount of geographic overlap between stressor sources and species habitat and abundance.

Regulation and management of river water quality is often based on measurements of physical, chemical, and biological characteristics because these metrics can be easily monitored and compared to established benchmarks for protecting human health. Not all of these metrics have the same influence on valued ecological resources, with some having a more direct influence than others. An extensive literature review was conducted to determine which metrics, or stream attributes, had causal pathways connecting them to one or more of the assessment endpoints. These attributes were considered stressors in the conceptual model (**Appendix 1**)

Risk to the water quality achievement endpoint is affected by total phosphorus loading, bacteria indicators, i.e., fecal coliform concentrations, summer dissolved oxygen levels, mercury fish body burden, deviation from summer and winter temperature 30-year averages, deviation from summer and winter discharge 30-year averages, and fish stocking. These parameters are discussed in more detail in the model parameterization section. The conceptual model for water quality and recreational river uses is presented in **Appendix 1**.

2.4 Development of the BN-RRM

The conceptual models were constructed to form a framework for the BNs. Each box in the conceptual model represents a node in the BN. The links represent causal relationships between a set of nodes. The BNs maintain the tiered nature and linear flow of the conceptual models. The development of the BN-RRM process starts with identifying the available data for each parameter and then completing the model parameterization. We separated model

parameterization into two categories, 1) defining the input parameter states, and 2) completing the conditional probability tables for the "child" nodes. The child nodes are those having a causal dependency on another "parent" node in the conceptual model.

Table 2-1. Summary of chemical, ecological and habitat stressors for smallmouth bass, white sucker, Belted Kingfisher, and Carolina Wren endpoints. *Italicized* stressors were considered, but not used in this risk assessment due to lack of available site-specific data.

Smallmouth Bass	White Sucker	Belted Kingfisher	Carolina Wren
Chemical Stressors			
Mercury	Mercury	Mercury	Mercury
PAHs - Sediment Exposure	PAHs - Sediment Exposure	PAHs - Sediment Exposure	PAHs - Sediment Exposure
Organochlorine Pesticides - Water Exposure	Organochlorine Pesticides - Water Exposure	Organochlorine Pesticides - Water Exposure	Organochlorine Pesticides - Water Exposure
Ecological Stressors			
River Temperature	River Temperature	Turbidity	Winter Air Temperature
Total Suspended Solids	Stream cover	Submerged Aquatic Vegetation	Nest Predation
Predation Rate	*Streamflow*	Fish Length	
	Predation rate	Nest Predation	
Habitat Stressors			
		Territory Size	Potential Habitat
		Potential Habitat	*Territory Size*
		Bank Height	
		Stream Bank % Clay, Sand and Silt	

Each node has two or more possible states. States labeled zero, low, medium, or high represent values of a parameter that, when all the interactions between the nodes are considered, pose zero, low, medium, or high risk to the endpoint. The parameter values for each state were determined through literature review, exposure-response data, and expert elicitation (Summers 2012, Ayre et al. 2013). In some cases, states were defined by specific regulatory criteria. For example, "Organochlorine Pesticide" states were defined as "Under Chronic Level" or "Over Chronic Level" according to the NOAA Screening Quick Reference Tables (Buchman 2008). Bayesian networks excel at using different forms of information to describe complex systems, especially when scientific justifications supporting cause and effect relationships are not

available, but expert opinion suggests a causal connection. The uncertainty involved in each type of data source can be incorporated implicitly in the network as probability distributions, allowing data-rich causal pathways to be used with pathways based on expert opinion only.

Each parent node represents a stressor (or source of that stressor) and receives no input from other nodes. Parent nodes are also referred to as input nodes. These nodes were defined by the conceptual model and parameterized using site data, exposure-response data, published studies, and expert elicitation. An input node with uncertainty was assigned a uniform probability distribution (Marcot et al. 2006a, Summers 2012, Ayre et al. 2013). Child nodes receive input from two or more nodes in the previous tier. Each child node is based on a conditional probability table (CPT) that contains all the possible state combinations of the parent nodes and specifies the probability distributions of the child node states for each combination.

This ranking system is derived from the ranking scheme used in the RRM (Landis and Wiegers 1997, 2005, 2007). A node with four states has values of 0, 2, 4, and 6 respectively. A node with two states is given values of 0 and 6 (Summers 2012, Hines and Landis 2014). The derivation of the breakpoints for the nodes is determined by the relative amounts of habitat, the amount of stressor, the exposure-response relationship, and by natural breaks in the data for some characteristics of the environment. The schemes used are dependent upon the variable and the breakpoints listed for each.

2.5 Data and Sources

Most of the data used in this risk assessment were provided by URS Corporation via the SRST from site-specific studies. Additional data were obtained from USGS gauges (USGS a, b, c, d) and NOAA. When site-specific species data were not available, species-specific sources with similar watershed characteristics from the scientific literature were used. We have compiled a metadata table (**Appendix 2**) that lists the input parameters, the measurement variables for each of the input parameters and the source of where we obtained the data. The models and findings presented in this report are the most up-to-date data we had available to us as of January 2014. A description of the initial model parameterization of the BN nodes can be found in **Appendices 3 and 4**.

2.6 Model Parameterization: Biotic Models

Parameterization of the model began with selecting a dataset for each input parameter in the model. We limited most chemical exposure datasets we used to data collected from 2005 to the present due to bank stabilization (BST) management strategies implemented in 2005 near the former DuPont site to reduce deposition of mercury laden sediment into the river during flood events (Flanders et al. 2010). For some chemical data, however, there were not enough data collected during that time frame to adequately parameterize the model. So input parameters for PAHs were expanded to included data collected from 2003-2010, and for organochlorine

pesticides from 2003-2007 for all target species. Input parameters for mercury body burden in Belted Kingfishers and Carolina Wrens included all available data collected from 2003 onward.

The SRST data characteristics dictated the sources of information we selected from the scientific literature to help us identify risks from the chemical stressors. For example, body burden data were available for mercury in fish and birds, so we used articles that reported mercury residue concentrations and their associated effects in fish species and blood mercury concentrations in birds. It was important to select sources that reported dose-response curves to identify zero, low, medium, and high effect concentrations in categorizing the input parameters. Studies that only reported no-effect concentrations and low-effect concentrations were used to provide data for the zero and low rankings. As a result of the literature search to identify cause and effect relationships between stressors and target species, we identified a sub-set of articles describing dose-response relationships between the stressor and target species specifically for chemical and ecological stressors.

Following data and literature source selection, the next step in model parameterization was to define the risk rankings of each input and calculate the probability of each risk outcome. Tables in **Appendix 3** describe model parameterization for the biotic endpoints. We have included the input parameters, the definitions of parameter states from which we calculated the input node frequencies of the BNs, the justification, and also provided references for these parameters. We classified the effects based on risk categories of zero, low, medium and high. For some parameters (PAHs and organochlorine pesticides), we used fewer risk ranking categories due to the uncertainty associated with that parameter. We determined the delineations between risk categories either by using regulatory criteria, suggested impact described by the author, or natural breaks in the dose-response curve data. When none of these were available, the following general rule was used: Zero Risk = ≤5% effect, Low Risk = 5 – 20% effect, Medium Risk = 20-50% effect and High Risk = ≥50% effect.

Next we determined the probability distribution for each input parameter based on the site-specific data. The following is an example of the process used for the Hg body burden input parameter for smallmouth bass that was used for the other input parameters. The mercury dose-response curve data for fish came from Dillon et al. (2010).

Rank	Tissue Concentration	Effect
Zero	≤ 0.2 mg Hg/kg fish tissue	<5 percent effect
Low	0.21 -1.1 mg Hg/kg fish tissue	5-24 percent effect
Medium	1.2 - 2.8 mg Hg/kg fish tissue	24-50 percent effect
High	>2.9 mg Hg/kg fish tissue	>50 percent effect

Using these levels, we sorted the South River smallmouth bass data by risk region and determined the risk rank for each fish. We then calculated the frequency distribution of mercury

residue concentrations in the fish for each risk level and divided these frequencies by the total number of samples in each region to determine the probability of effects in each risk level.

A similar method was used to define the input parameter probabilities for all stressors with the exception of species abundance. A few of these processes are described for the fish endpoints below. The descriptions for remainder of the input parameters for each endpoint can be found in the model parameterization tables in **Appendix 3**.

Species Abundance. To express the potential exposure of an organism to a contaminant in a spatially explicit manner, we compared the abundance of each species within each risk region to the total abundance in the SRSA to define risk levels for the abundance input parameter. This parameter represents the relative species abundances in each region and is used in the models to represent a measure of potential exposure. The abundance parameter scales the risk output by weighting regions with high abundance to reflect an increase in exposure.

Smallmouth Bass Temperature Tolerance. A literature search analyzing the effects of temperature on smallmouth bass was completed to address questions concerning temperature rankings presented in the original BNs and report (Summers 2012). Four articles (Casselman et al. 2002, Smith et al. 2005, Sharma et al. 2007, Sharma and Jackson 2008) were used as a starting point in the search for temperature data. These articles cited smallmouth bass temperature data from earlier studies that we were then able to obtain and use the original experimental data.

In ranking the temperature as a stressor, we accounted for each life stage of smallmouth bass (spawning, eggs/fry, juveniles, adults, etc.). We also considered the timeline associated with each life stage. Two life stages we found to be important to the survival of smallmouth bass were the eggs (time from the initiation of spawning to the hatching of eggs) and the first winter for the fish (Shuter et al. 1980, Armour 1993). Smallmouth bass spawning and hatching occurs in waters between 15-27°C (Shuter et al. 1980), however, when exposed to temperatures of 30°C, eggs did not hatch or larvae died shortly after hatching (**Figure 2-3**) (Kerr 1966). The likelihood of water temperature reaching and maintaining temperatures of 30°C in the spring (when spawning and hatching is occurring) is unlikely. For instance, only one region, Region 6, had temperatures that were >27°C during the end of hatch season. Region 6 had ten samples between 27°C and 28.1°C in the later part of the month of June. All other regions were within the 15-27°C preferred spawning and hatching temperature range. If water temperatures start to warm earlier in the year, spawning and therefore hatching may occur earlier (Wrenn 1984). Wrenn (1984) observed spawning events when water reached 17-22°C, regardless of the month.

Growth of the young of the year (YOY) smallmouth bass is important because larger fish have a better chance of surviving the first winter (Shuter et al. 1980, Armour 1993). When temperatures drop below 7-10°C, the fish depend on stored fats for energy and nourishment during the winter months (Armour 1993). Survival is therefore strongly correlated to the size (length and weight) of the fish. Fish that had higher growth rates had a higher survival rate (Shuter et al. 1980, Armour 1993). The optimum growth rates for juvenile smallmouth bass ranged from 23-29°C, with greatest growth occurring at 26°C (Horning and Pearson 1973, Armour 1993).

Based on the results from these studies, we altered our lower temperature risk rankings to encompass the preferred spawning and hatching temperatures (Shuter et al. 1980, Wrenn 1984) and the preferred temperatures of adult smallmouth bass (Zweifel et al. 1999)., Two additional scenarios were created for the lower temperature bounds. In these scenarios, the lower thermal limits were expanded to include spawning and hatching temperatures (Shuter et al. 1980, Wrenn 1984) and preferred temperatures of juvenile (20.2-30.9°C) and adult (18-21°C) smallmouth bass (Zweifel et al. 1999). The more moderate temperature scenario (scenario 2) was selected as the 'best' lower temperature ranges (see **Table 2-2** for temperature ranges and justification). No change was required for the upper temperature risk rankings because those temperatures reflected the optimal growth rates, as well as the preferred, avoidance, and lethal temperatures of the juvenile and adult smallmouth bass. Note that there are upper and lower limits to the temperature tolerances and our goal was to encompass these limits for as many life stages as possible in the risk ranks.

After applying the alternative temperature ranking schemes to the BNs, very little change was observed to the smallmouth bass risk scores in any risk region. Overall, risk slightly decreased, with a 1.8% decline in the probability of high risk and a 4% increase in probability of no risk. The low and medium risk distributions were relatively unchanged and remained similar to the original BN model values. The second scenario was then applied to the current BN models. This scenario encompassed temperature preferences and avoidances of juvenile and adult smallmouth bass. This scenario also uses data closest to site-specific data we could find.

Mercury Exposure-response for Fish. The original risk assessment used the log transformed dose-response curve from Dillon et al. (2010) to estimate total mercury concentrations associated with different levels of adult/juvenile fish injury. For the re-evaluation, we used the raw data in the model rather than the log of total mercury concentrations **(Figure 2-4)**. We only included data for fish that had total mercury concentrations of less than 6 mg/kg wet weight. This allowed the model to have an improved fit of the dose-response data at lower total mercury concentrations. Decision-makers are most interested in the lower portion of the curve because the target total mercury concentration for fish in the South River is 0.3 mg/kg wet weight (USEPA 2010). After censoring the data as described, we fit a three parameter log-logistic model using the dose-response curve (drc) function in the dose-response modeling (drm) package in R statistical software. We included 95% confidence intervals.

The total mercury concentration ranges were obtained by calculating the concentration associated with the injury effect level percentage, obtained from the dose-response curve that represents the break between the four possible Mercury node states. A Mercury node state of zero is defined as less than 5% injury; low represents 5-24% injury; medium represents 24-50% injury; and high represents greater than 50% injury (Summers 2012). To examine the change in results from using the upper confidence limit, the regression line, or the lower confidence limit to set the breakpoint concentrations risk estimates were calculated using each scenario.

The model prediction scenario changed the probability of a state by only a few percent in each risk region, and there was no consistent increase or decrease in a specific state probability with the application of this scenario.
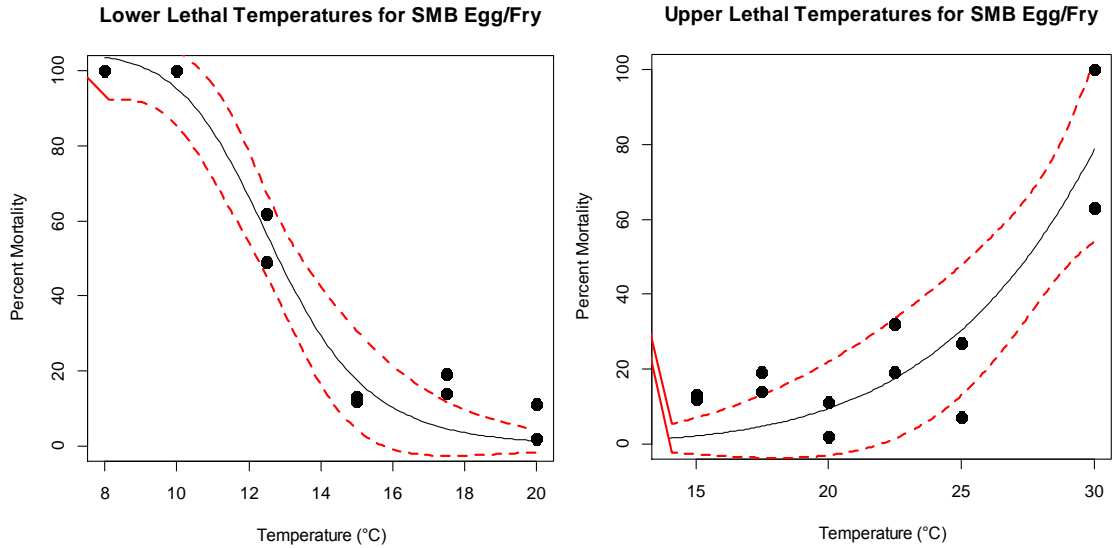
Figure 2-3. Temperature exposure-response curve for smallmouth bass. Temperature and percent mortality data for smallmouth bass egg and larval stages. This is a log-logistic model; dashed lines indicate 95% confidence intervals (CI). The 63% mortality point at 30°C represents eggs that hatched, but larvae died soon after hatching. *Data source: Kerr 1966, also see Shuter et al. 1980.*
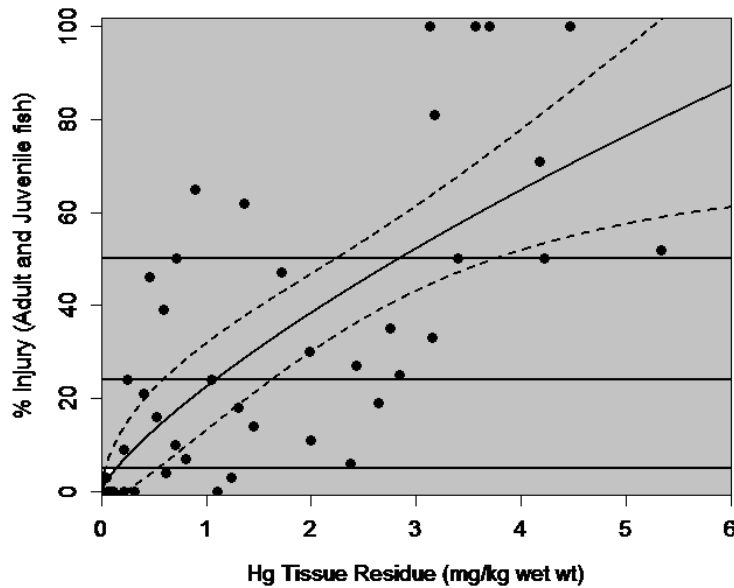
Figure 2-4. Mercury exposure-response curve. A three parameter log-logistic model with 95% confidence intervals (dashed lines) fit to untransformed adult and juvenile injury data from Dillon et al. (2010). The horizontal lines represent the percent injury ranges associated with each effect level for smallmouth bass and white sucker.

Table 2-2. Rankings and justification for the smallmouth bass river temperature parameters. Fry and fingerlings life stages were adversely affected by warmer temperatures. In adult life stages, temperature affected growth rates and avoidance behavior.

Ranking	Justification	References
Zero 20 - 26°C	Ideal temperatures for spawning and growth; Temperature optimum for juvenile growth and fry survival; Preferred adult temperature range	Horning and Pearson 1973, Shuter et al. 1980, Armour 1993
Low 17 - 19.9°C or 26.1-29°C	Spawning occurring at lower temp range, however we have reached upper temp. limit for spawning (27°C); Positive growth rates for juvenile and fry (upper temps)	Kerr 1966, Horning and Pearson 1973, Shuter et al. 1980
Medium 15 - 16.9°C or 29.1 - 31.9°C	Reaching minimum spawning temps, survival rates of egg/fry start to decrease; Nearing the upper avoidance temperatures by SMB (31°C); 100% mortality of egg/fry at upper temperatures (>30°C)	Kerr 1966, Cherry et al. 1975, Stauffer et al. 1976, Shuter et al. 1980
High ≤14.9°C or ≥32°C	Below 15°C spawning likely won't occur; Egg survival decreases; Nest abandonment by male fish leads to increased predation; Colder waters (10-12°C) are associated with a fungus that causes egg/fry mortality; Avoidance temperatures for adults and juvenile fish; Upper thermal limits for fry and fingerlings ~33°C	Kerr 1966, Horning and Pearson 1973, Cherry et al. 1975 and 1977, Shuter et al. 1980, Armour 1993

2.7 Model Parameterization: WQ Models

Regulation and management of river water quality is often based on measurements of physical, chemical and biological characteristics because these metrics can easily be monitored, and compared to established benchmarks for protecting human health. Such comparisons provide information about the site-specific conditions, but do not allow risk managers to assess the likelihood of impacts from those conditions. We used some of these metrics to determine the effects of water quality parameters on ecological services using a slightly different approach. We constructed a BN to assess the potential impacts of current conditions in the South River towards achievement of water quality standards and sustaining recreational use, specifically fishing, boating and swimming. We incorporated parameters into the model that cause direct or indirect effects on fish or other biota, as well as stream conditions related to the assessment of water quality, other stream biota, such as fish mercury body burden, dissolved oxygen, and phosphorus levels. Hydrologic parameters included in the model were: the magnitude of deviations in recent stream temperature, discharge and dissolved oxygen levels relative to long-term, seasonal averages. The other principle input parameters were total phosphorus and *Escherichia coli (E. coli)* concentrations in the river, as well as methylmercury levels in fish based on their causal relationships to the ecological services of concern for communities surrounding the South River.

Stream Temperature and Discharge. The model included the potential effects of stream temperature, discharge and dissolved oxygen conditions in the South River on water quality and recreational use by evaluating how conditions in 2010-2011 compared to thirty-year averages (1975-2005). The use of long-term averages as a metric for comparing stream conditions is recommended to incorporate extreme events, and facilitate the evaluation of potential impacts of deviations from "normal" conditions (World Meteorological Association 2006; Pollino et al. 2007). We delineated monthly average temperature (^{o}C), discharge (ft^{3}s^{-1}), and dissolved oxygen (mg/L^{-1}) by season with Fall/Winter corresponding to the period of October 1 through March 30 and Spring/Summer from April 1 through September 30.

Although conditions have been monitored in the South River for an extensive amount of time, it was difficult to find hydrologic stations that had consistent records for at least thirty years. Historical temperature data were obtained from the US Geological Survey's (USGS) National Water Information System website (http://nwis.waterdata.usgs.gov) by accessing data from hydrologic stations operated by the Virginia Department of Environmental Quality (VDEQ). These stations, however, did not record stream flow using the same methods and metrics used today. Long-term stream discharge records, as well as data from 2010-2011, were accessed from the USGS National Hydrography Dataset (http://nhd.usgs.gov). Hydrologic data were available from stations within all risk regions except for Region 1 and Region 4. Seasonal averages were calculated from the long-term data and compared to measurements from 2010-2011 to determine the magnitude of deviations from historic conditions.

Dissolved Oxygen. The most recent dissolved oxygen data available for the South River at the time of this study have been collected between 2006 and 2008. Our primary sources for dissolved oxygen data were hydrologic stations operated by the VDEQ obtained from the USGS National Water Information System website (http://nwis.waterdata.usgs.gov). These data were pooled with data collected by the SRST to ensure that all risk regions had a similar seasonal record. Dissolved oxygen levels between 5 and 9 mg/L^{-1} were assigned to the "normal" categorical state, which was defined relative to the Virginia water quality standard of 5 mg/L^{-1} and the dissolved oxygen 100 percent saturation level of 9 mg/L^{-1} at 21 ^{o}C.

Total Phosphorus. Phosphorus is the nutrient that most often limits the growth of algae and cyanobacteria in freshwater. Excessive amounts trigger rapid algal growth and proliferation, blocking the penetration of light and increasing the amount of detritus in the water column, causing hypoxia in summer months. Total phosphorus concentrations measured by VDEQ water stations and the SRST between 2006-2013 were used to evaluate levels of phosphorus in the South River. Criteria for evaluating phosphorus concentrations were based on regulatory standards and the potential to stimulate algal blooms. The US Environmental Protection Agency (U.S. EPA) has designated 0.1 mg/L^{-1} as the desired background and regulatory goal for total phosphorus in surface waters. Concentrations at or below this level were categorized as "zero" because they are below this regulatory benchmark. Rivers with phosphorus levels of 0.1-0.3 mg/L typically do not develop surface algal blooms; however, above 0.3 mg/L algae and diatoms begin to flourish (Black et al. 2010). Thus, concentrations between 0.1-0.3 mg/L fall into the "low" phosphorus state and concentrations between 0.3 and 0.5 mg/L are considered

"medium" phosphorus state. Concentrations greater than 0.5mg/L were categorized as a "high" state based on the potential for adversely affecting water quality (Black et al. 2010).

Fecal Bacteria. Escherichia coli, is the primary fecal bacteria indicator used to screen for unhealthy levels of fecal matter in surface waters. The regulatory standard for *E. coli* bacterial counts is 235 cfu/100 mL for a single water sample (9 VAC 25-260-170). Above this level bacteria may pose a risk to human health through exposure during recreational activities. A comprehensive review of the relationship between recreational activities in surface waters and *E. coli* found that the incidence of illness increased linearly with exposure to waters with bacteria concentrations above 100 cfu/100 mL (Prüss 1998). Therefore in the model, bacterial concentrations measured in the South River that were below 200 cfu/100 mL were assigned zero risk and concentrations above 1000 cfu/100 mL were categorized as high risk.

Fish Mercury Concentrations. Fish tissue methylmercury concentrations were assessed using data for all fish species and following the same methodology as was used for the smallmouth bass model.

Fish Stocking. One of the assessment endpoints in the water quality risk assessment model was recreational fishing, which is influenced by the abundance of fish in reaches of the South River. We included an input parameter in the model that impacts fish abundance directly, i.e., the presence or absence of fish stocking within a risk region. Locations for fish stocking in the South River were identified and mapped to determine which risk regions were routinely stocked with fish. This parameter is unique in that the data were qualitative and there was a direct causality between the parameter and one of the assessment endpoints.

Appendix 4 describes the model parameterization for the water quality input parameters. This includes the parameters, data sources, ranks, justification and references for the input parameters in the water quality model.

2.8 Conditional Probability Tables

Conditional probability tables (CPTs) describe the relationship between two or more input nodes in the BNs. The conditional probability tables also describe the exposure potential geospatially, for example when the geographic distribution of a chemical contaminant intersects with a species preferred habitat.

The conditional node has the same four states (zero, low, medium and high) as the input nodes. In some cases, the input node may be less well defined and contain three or even two states, making the resulting conditional probability table smaller. If data are available to describe the relationship of two stressors, then the conditional probability tables are filled in from those data. In many cases, however, the combined impact of stressors is not quantitatively defined or well understood. For conditional nodes where no quantitative description of the interaction of two or more stressors is given, we used a quantitative meta-analysis approach from an extensive literature search to define the conditional probability tables. This was the primary method for defining the conditional nodes in this research as few studies were completed that contained full

dose-response relationships. The quality of information needed to fully describe stressor-response interactions is often lacking when dealing with just chemical contaminants. It is even more difficult to obtain when combining chemicals with habitats or with ecological stressors. For this reason, the combination of input nodes was limited to three inputs only.

2.9 Model Evaluation and Calculation of Risk

The frequencies (distributions) for the input nodes for each model were derived from data specific to each of the risk regions. For each of the risk regions except Region 1, there are four biotic endpoint models. As such, a total of 20 models were constructed to provide an overall pattern of risk for biotic endpoints in the study area. The water quality BN incorporated all four endpoints and a model was constructed for each risk region, resulting in a total of 25 models being constructed.

We used Netica™ by Norsys Software Corp (http://www.norsys.com/) to create and evaluate the BNs. A sensitivity analysis was completed within the same software package to determine the parameters with the most influence on endpoint risk. Examples of the models can be found in **Appendices 5 and 6** and are available online or by CD. Viewing the models is easy and only requires downloading and installing the free version of Netica™ from their website. Once installed, you will be able to view the models, CPTs, and frequency tables, as well as see how different inputs alter the risk results. We strongly recommend taking the online introduction to Bayesian networks before investigating the models (available at http://www.norsys.com/tutorials/netica/nt_toc_A.htm).

Monte Carlo Simulation: Additive Risk Curves. In addition to the risk output from the BNs, we summed the risk from all of the endpoints in each risk region, thus calculating a total risk curve for each region. The endpoint probability distributions from the BNs were used as input data for the Monte Carlo computation of final combined risk. The Monte Carlo computation was completed using Oracle® Crystal Ball, Fusion Edition software (version 11.1.2.3.000) (http://www.oracle.com/technetwork/middleware/crystalball/overview/index.html) as a macro in Microsoft® Excel 2013. We used the Latin hypercube sampling and ran the simulation for 10,000 iterations. By summing the risk for each region, we could compare risk between the regions, and as discussed later, between the management options.

Uncertainty Evaluation. We quantitatively and qualitatively assessed the uncertainty in the network and model outputs through several methods. Uncertainty in the model structure was assessed qualitatively through a discussion of input parameters and pathways both included and excluded in the model. In some cases, literature searches identified important stressors where site-specific data or regional equivalent data were not available, which will be discussed later. We described uncertainty in input parameters explicitly in the probability distributions. We applied identical distributions for the risk states when there were no data available for a particular parameter in the risk region.

Uncertainty in the cause and effect pathways resulted in more similar conditional probability distributions in the CPTs. Since there was little site-specific information describing the interactions of parameters, all conditional probability tables were constructed based on information obtained from scientific literature.

Sensitivity Analysis. Model sensitivity is calculated as the reduction in variance in the case of continuous variables, or in this case where categorical variables are used, entropy reduction. (Marcot 2012). The analysis compared each input parameter to the endpoint node and determined to what degree the parameter influenced the endpoint. The sensitivity analysis was conducted within the Netica™ modeling framework and the Sensitivity to Findings tool. The result was a list of parameters ranked from most influential to least influential (Norsys Netica™ 2014, Pollino et al. 2007).

Low Mercury Scenario. In addition to the sensitivity analysis, there are additional benefits to using BNs. We can use the model as an interactive tool to examine alternative input states. One of those states was the assumption that Hg risk was low so the Hg node was set to the low rank for all cases. The output from the revised model was then compared to the original model outputs and the percent change in risk scores was calculated.

2.10 Results: Patterns of Risk to the South River

This section summarizes the risk estimates for our biotic and water quality endpoints in five of the six risk regions for which there was adequate data, i.e., Regions 2-6.The results are the risk distributions for each endpoint in each of the five risk regions as generated from the BN output. These are not sample distributions from sampling a larger population, but represent the frequency of outputs generated by the model. In each instance the Netica software calculates a mean and a standard deviation for each distribution, but note that the distributions are usually non-normal. Thus very different distributions may have similar mean values. It is more important to compare the distributions rather than focus on the mean.

Table 2-3. Risk Scores for the endpoints by risk region. The labels are as follows: SMB-smallmouth bass, WS-white sucker, BK-Belted Kingfisher, CW-Carolina Wren, WQ-water quality standards, WF-Fishing River Use, WS2-Swimming River Use, WB-Boating River Use.

Region	Biotic Endpoints				Water Quality				Totals		
	SMB	WS	BK	CW	WQ	WF	WS2	WB	Biotic	Water	Overall
2	2.4	3.6	2.5	1.1	4.9	1.6	4.5	4.4	9.6	15.4	25.0
3	2.7	3.1	1.5	1.9	4.5	1.5	4.6	4.6	9.2	15.2	24.4
4	4.3	2.4	2.1	3.0	4.5	2.1	4.3	4.2	11.8	15.1	26.9
5	4.5	1.3	2.2	2.9	4.8	1.9	4.8	4.7	10.9	16.2	27.1
6	3.3	1.7	1.5	2.5	4.3	1.2	4.6	4.5	9.0	14.6	23.6
Totals	17.2	12.1	9.8	11.4	23.0	8.3	22.8	22.4	50.5	76.5	127.0

One of the challenges in large-scale risk assessment is summarizing the patterns of risk in the landscape. **Table 2-3** summarizes all of the relative risk scores derived by the BNs for each endpoint in each region. **Appendices 5 and 6** contain figures of all of the BNs for the biotic and water quality endpoints respectively using Region 2 as an example. The BN figures show the probability distributions of input nodes, intermediate nodes, and endpoint nodes (risk).

Risk to Biotic Endpoints. The smallmouth bass had the highest risk scores of all of the biotic endpoints. Regions 4 and 5 were the areas of highest risk (risk scores of 4.3 and 4.5 respectively) for the smallmouth bass. Carolina Wren had a similar pattern as the smallmouth bass (highest risks in Regions 4 and 5), but with lower risk scores. White sucker and Belted Kingfisher had the highest scores in Region 2. All biotic endpoints except white sucker had lower risk in Region 6 compared to Region 5. This was most likely due to the fact that Region 6 included the South River and the South Fork of the Shenandoah River where they converge. When we analyzed the total risk scores for each of the biotic endpoints, we find a higher risk associated with the fish species (smallmouth bass and white sucker) compared to the bird species (Belted Kingfisher and Carolina Wren). If we examine the risk scores by region for the biotic endpoints, we see that Region 4 had the greatest risk (11.8) and Region 5 the second greatest risk (10.9). To provide perspective for the total risk scores, the maximum risk score that a region could have would be 48 (a maximum risk score of 6 times the 8 endpoints = 48). Endpoint totals are out of 30 (a maximum score of 6 for the 5 regions = 30). These findings are summarized in **Table 2-3**.

The distributions of risk for each of the biotic endpoint are presented in **Figures 2-5** through **2-8.** and are represented by four discrete risk states and characterize the percent probability of risk given the available evidence (data). These figures display the risk to each endpoint for all of the risk regions (excluding Region 1) to enable the comparison of risk in a spatial context. In analyzing the distributions of risk to the biotic endpoints, the smallmouth bass was at greatest risk with 74-77% of the probability in the medium and high risk states for Regions 4 and 5 respectively (**Figure 2-5**). The white sucker had the second highest risk with a probability of 54-64% in the medium and high risk states (**Figure 2-6**). In all regions, a fish endpoint was always at greater risk than either of the bird endpoints. No region was at greater risk to all biotic endpoints than another region. Results varied by endpoints; risk varied most (in the combined medium and high risk states) for the white sucker (**Figure 2-6**) and Carolina Wren (**Figure 2-8**) between the five risk regions.

Risk to Water Quality Endpoints. The risks to water quality endpoints did not span the range of values found for the biotic endpoints (**Table 2-3**). Water Quality Standards, Swimming River Use, and Boating River Use all had similar risk scores and patterns of risk probability distributions relative to each other in all regions of the study area. The Water Quality Standards endpoint had the highest risk scores, with the Swimming and Boating River Use slightly lower. Region 5 had the greatest total risk associated with the water quality endpoints, whereas Region 6 had the least risk (**Table 2-3**).
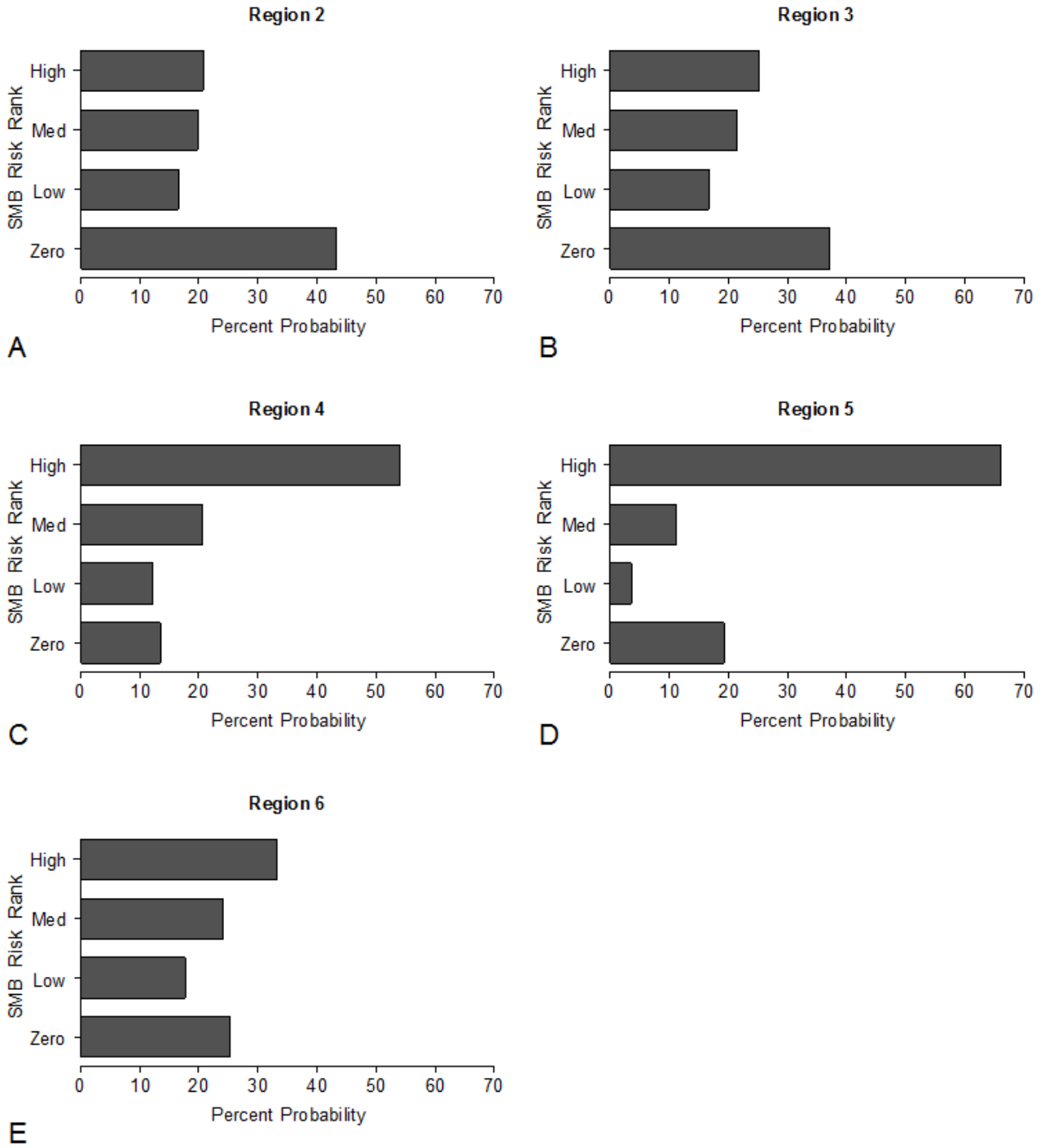
Figure 2-5. Probability distribution of risk to the smallmouth bass endpoint. Risk was greatest in Regions 4 and 5; Regions 2 and 3 had a similar risk pattern.
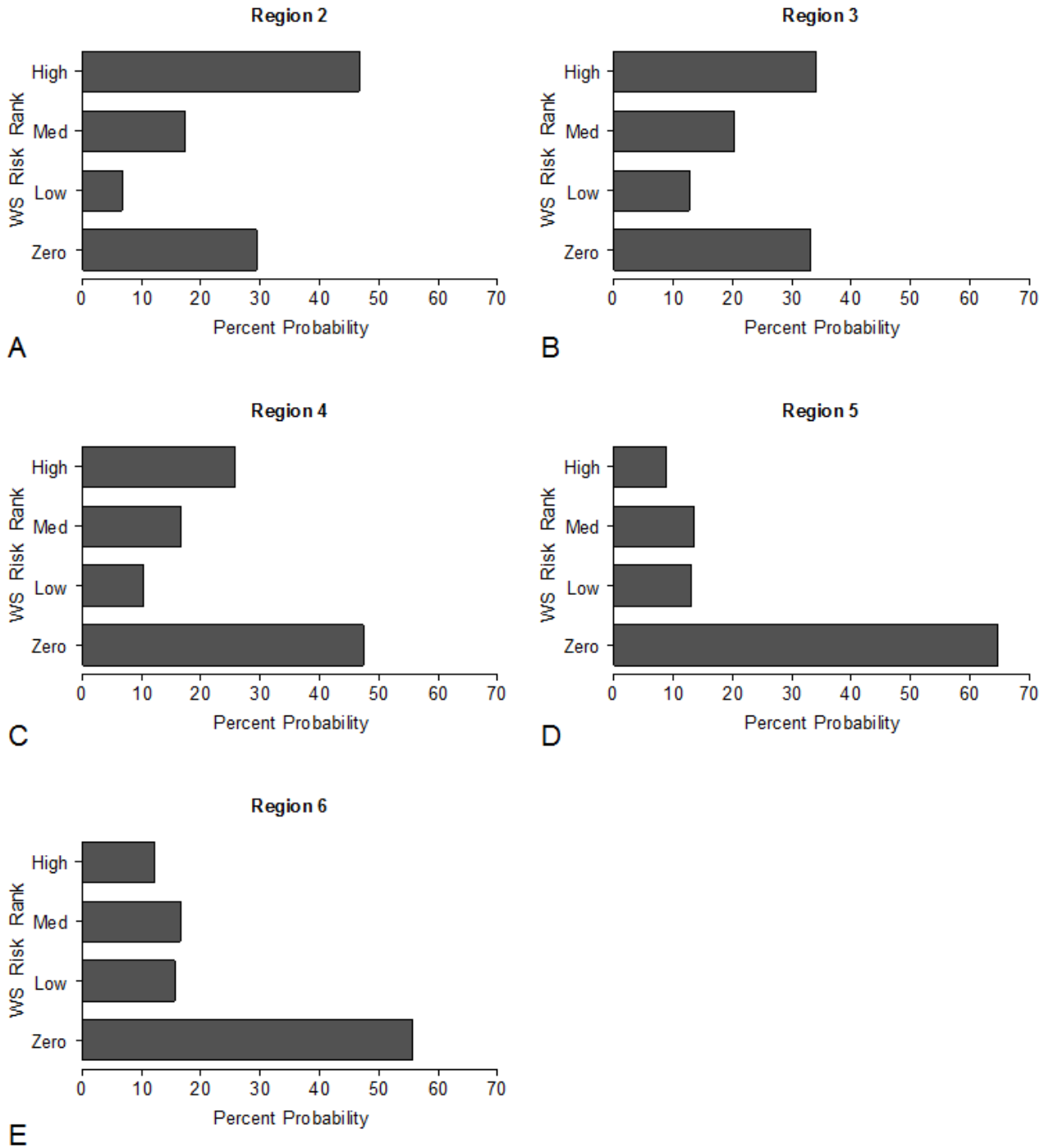
Figure 2-6. Probability distribution of risk to the white sucker (WS) endpoint. Regions 5 and 6 had a similar risk pattern, both of which were skewed towards the zero risk state.
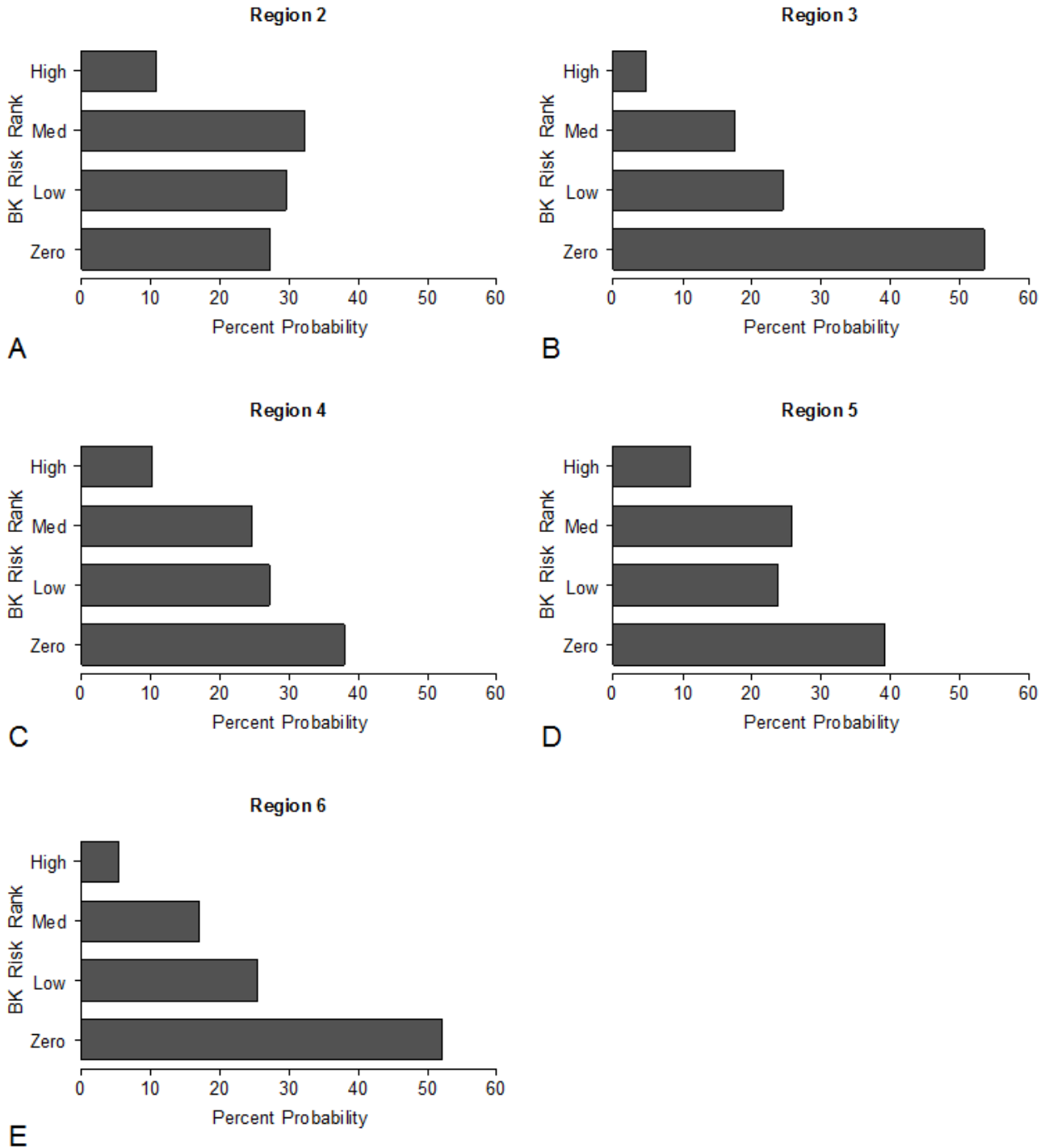
Figure 2-7. Probability distribution of risk to the Belted Kingfisher (BK) endpoint. Regions 3 and 6 had similar risk patterns, skewed towards the zero and low risk states.
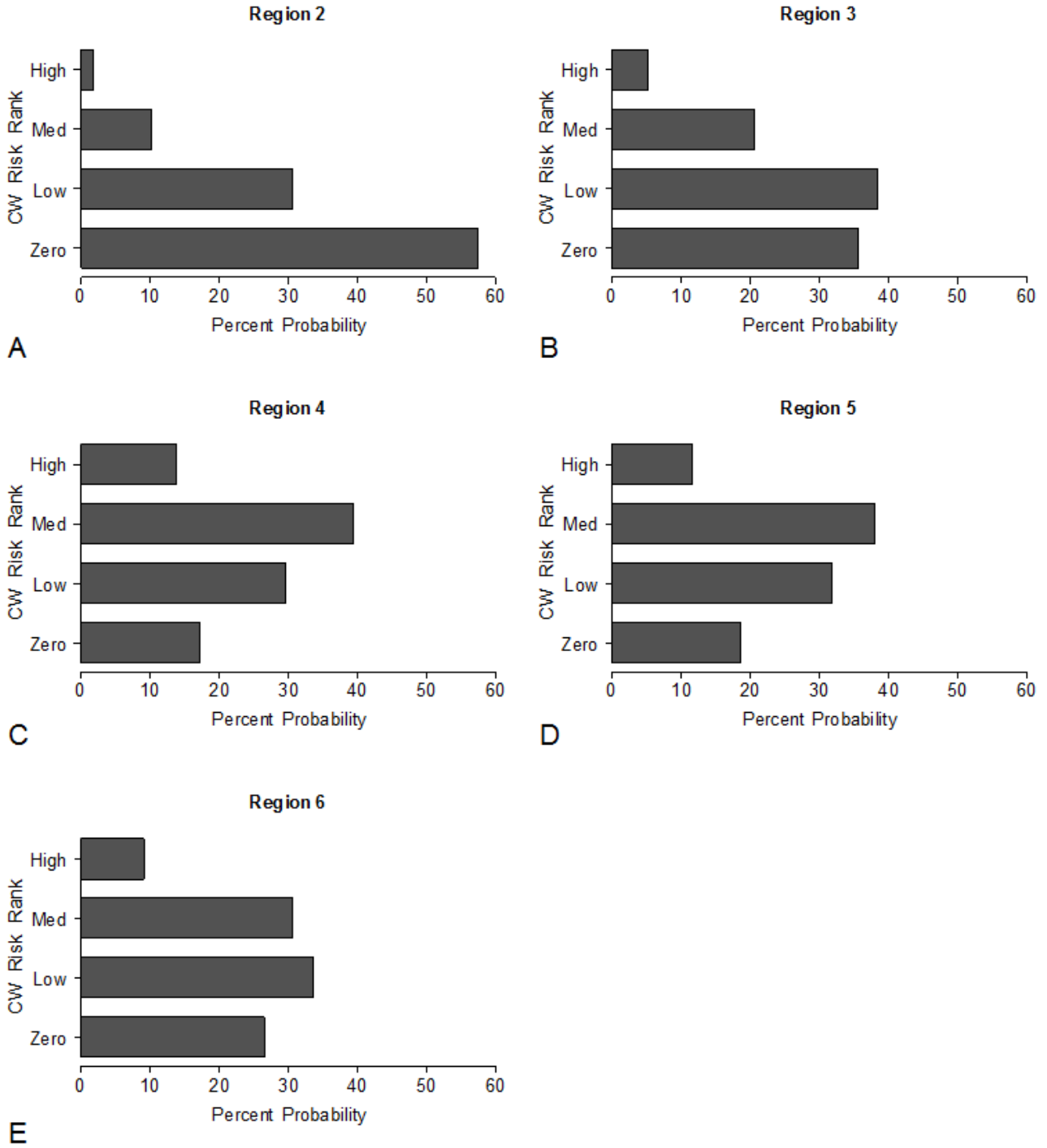
Figure 2-8. Probability distribution of risk to the Carolina Wren endpoint. Regions 4 and 5 had a similar risk pattern.

The probability distributions for the Water Quality Standards, and Swimming and Boating River Use, were skewed towards the medium and high-risk states. For instance, the Water Quality Standards had 77.9 - 89.7% probability of risk in the medium and high states for the various regions (**Figure 2-9**). The Swimming River Use had 80 - 90% probability in the medium and high states (**Figures 2-10)**, and Boating River Use had 78 - 88% probability of risk in the medium and high states (**Figure 2-11**). When evaluated on a risk region scale, the Water Quality Standards had a similar risk pattern in all of the risk regions. When compared to Boating and Swimming River Use endpoints, all three had similar risk patterns in Regions 3 and 5. When we compared just the Swimming and Boating River Use endpoints, risk patterns were similar in Regions 3-6.

Fishing River Use was at a lower risk throughout the SRSA compared to the other endpoints. Regions 2, 3, and 6 had lower risk scores for the Fishing River Use endpoint, with distributions of risk skewed to the zero and low risk states, specifically 66 - 87.7% of the risk probability in the zero and low states throughout the risk regions (**Figure 2-12**).

Overall Risk. In analyzing the overall risk, Region 5 had the greatest risk with the highest risk scores. Region 4 and 2 had the next greatest risk, and Region 6 had the lowest total risk scores (**Figure 2-13**; **Table 2-3**). This pattern was also reflected in their risk distributions.

We also evaluated risk patterns between the endpoints. The Fishing River Use endpoint had similar risk scores as the bird species (**Table 2-3**). The Belted Kingfisher and Fishing River Use endpoints had similar risk distributions in Regions 3, 4, and 6 (**Figures 2-7, 2-12**). These endpoints made up the lower end of risk, whereas the other water quality endpoints made up the high end of the risk (**Table 2-3**). Overall, water quality endpoints were at higher total risk than the biotic endpoints in each risk region (**Table 2-3**).

Monte Carlo Modeling: Additive Risk Distributions. The distribution curves in **Figure 2-13** were created using Monte Carlo simulation with Latin hypercube sampling over 10,000 iterations in Oracle® Crystal Ball as a macro in Microsoft® Excel. The curves represent the sum of all the endpoints for each region, thus providing a total risk distribution for each region. The maximum possible combined risk score was 48. These distributions allowed us to compare overall risk between regions. The additive risk distribution curves for initial risk estimates in Regions 4 and 5 were shifted towards higher risk compared to other regions. The distribution for Region 6 was shifted towards lower risk (**Figure 2-13**).
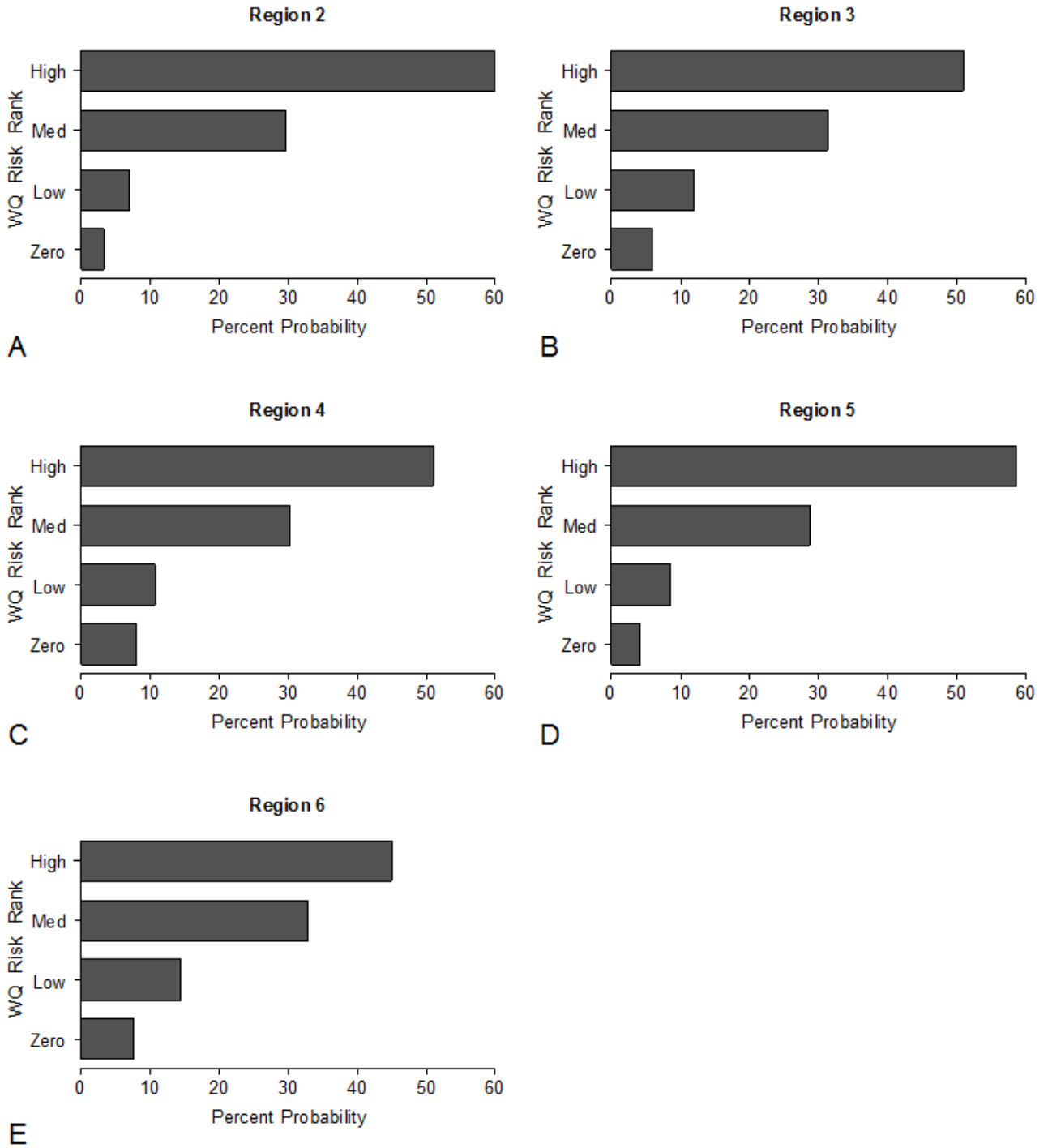
Figure 2-9. Probability distribution of risk to the Water Quality Standards (WQ) endpoint. All regions had a similar risk pattern, with risk skewed to the medium and high states.
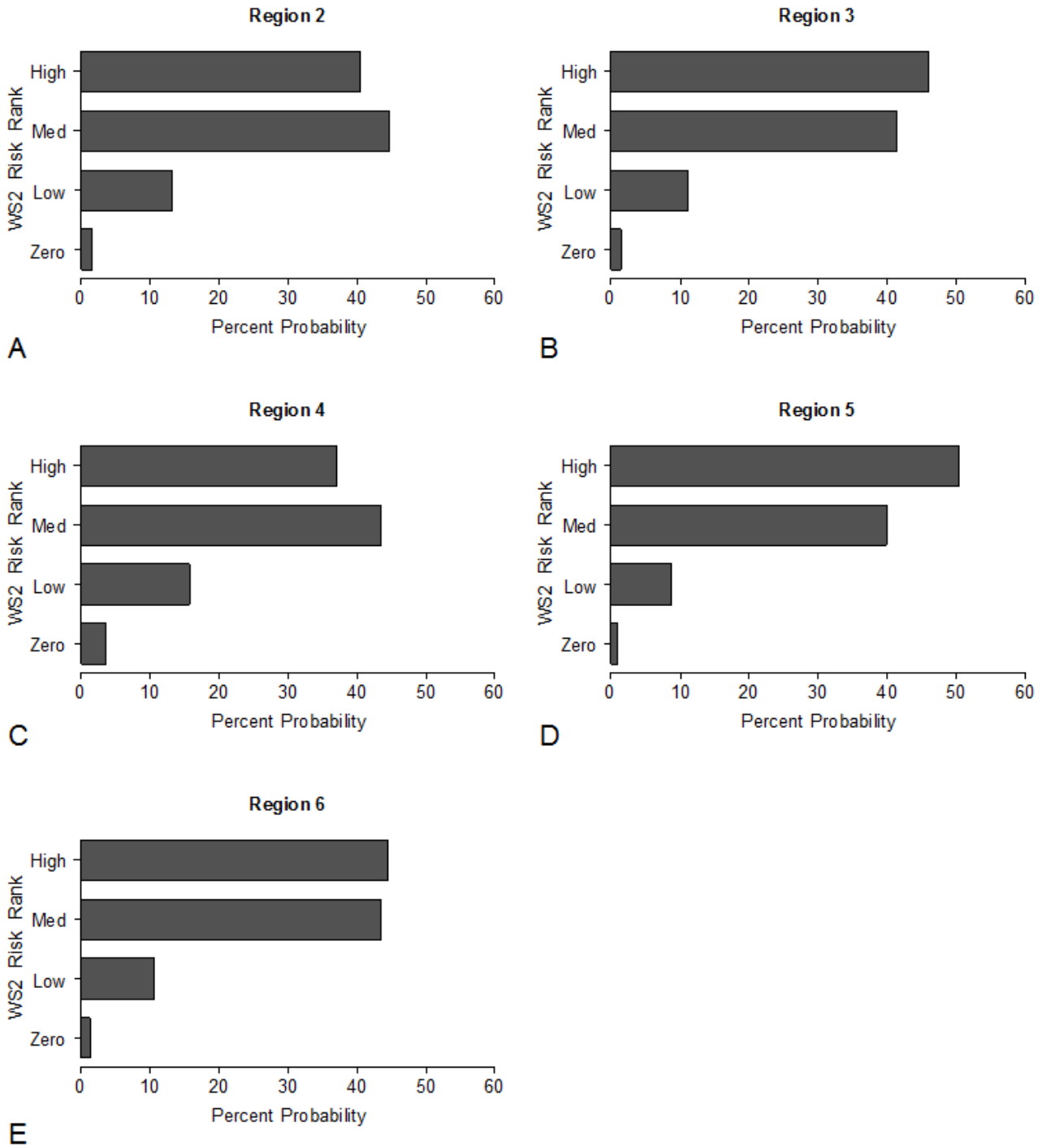
Figure 2-10. Probability distribution of risk to the Swimming River Use (WS2) endpoint. Risk was skewed towards medium and high in all regions.
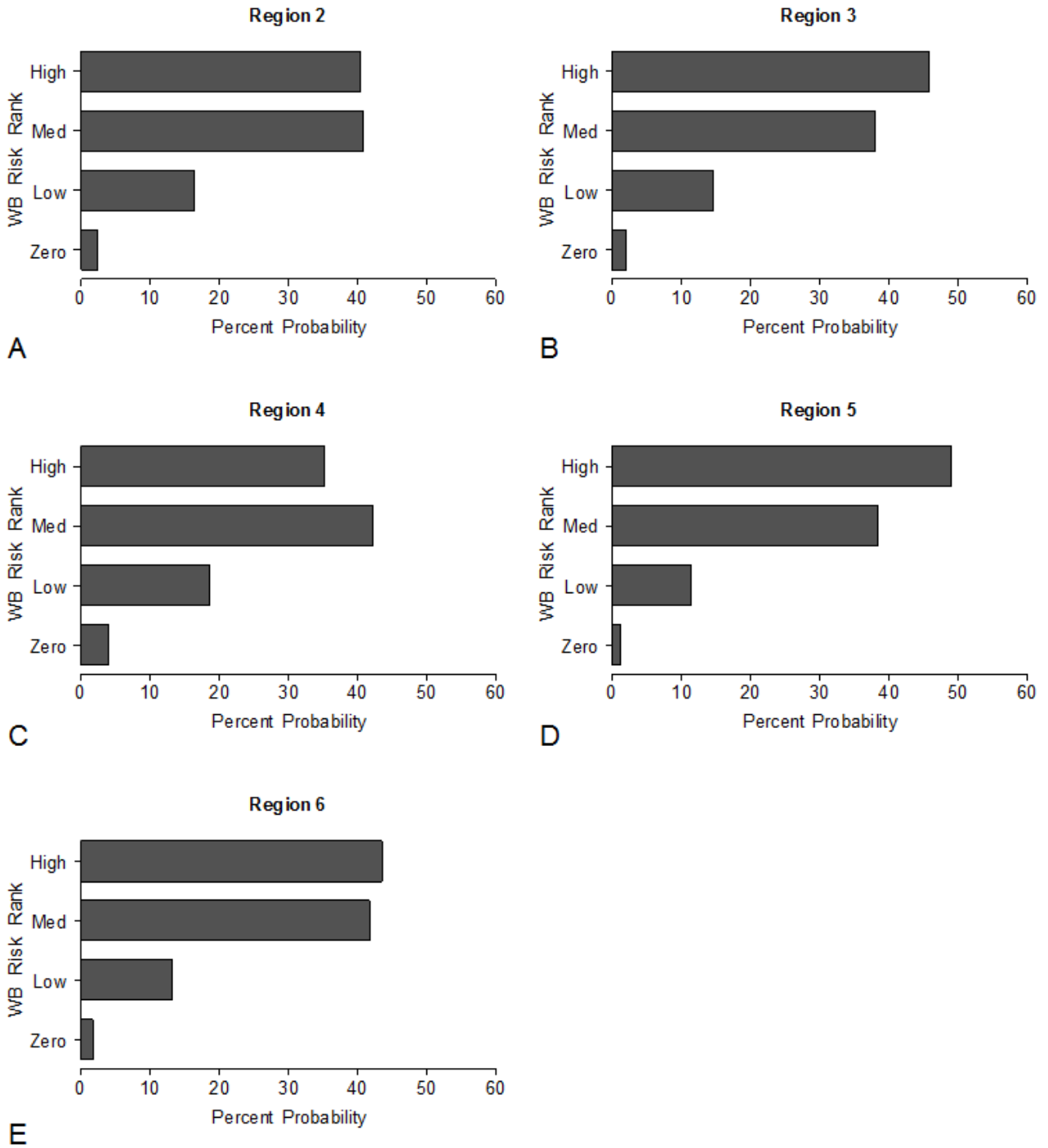
Figure 2-11. Probability distribution of risk to the Boating River Use (WB) endpoint. Risk was skewed towards medium and high in all regions.
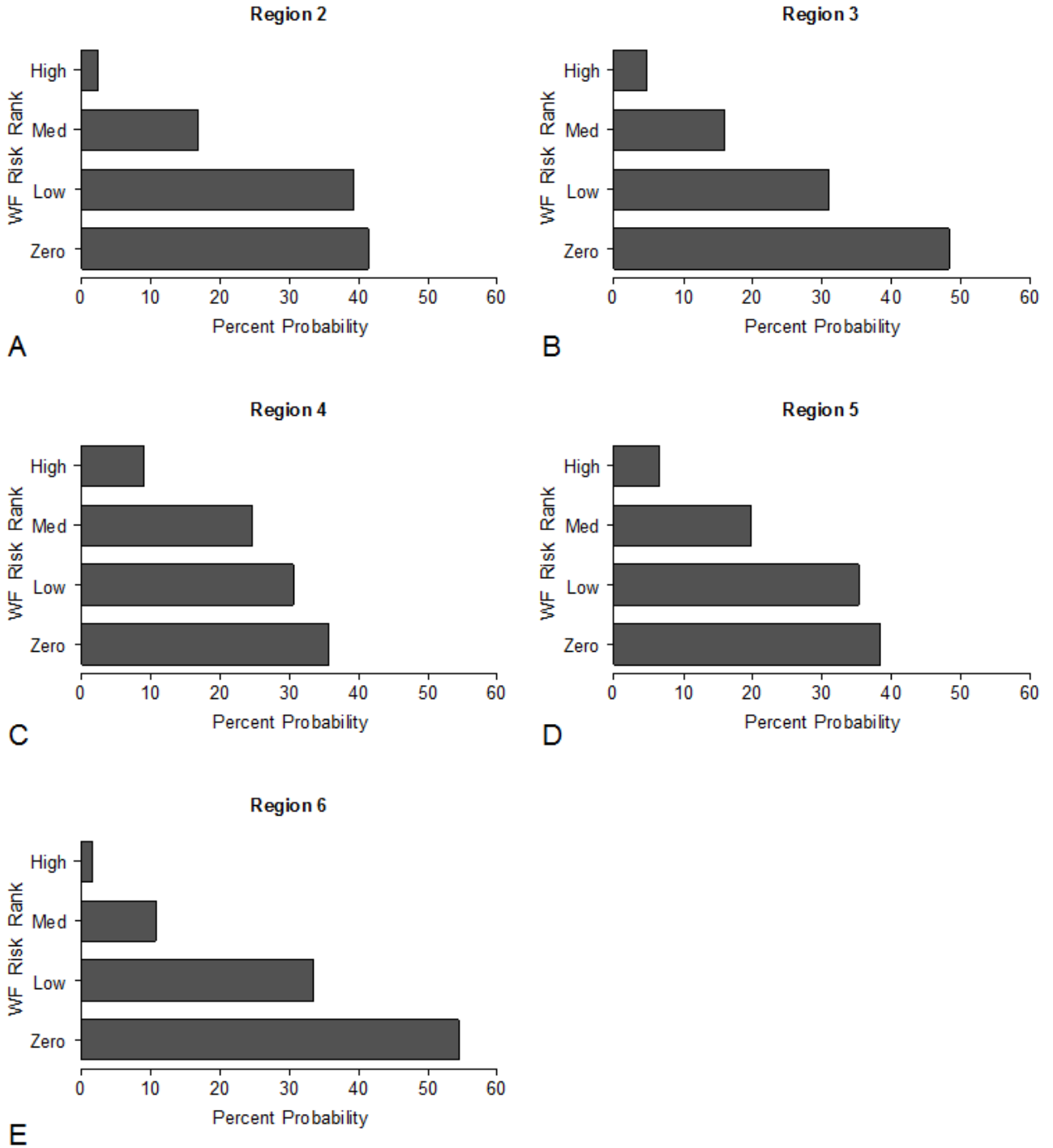
Figure 2-12. Probability distribution of risk to the Fishing River Use (WF) endpoint. Regions 4 and 5 had similar risk patterns, as did Regions 3 and 6 (skewed towards zero and low risk states).
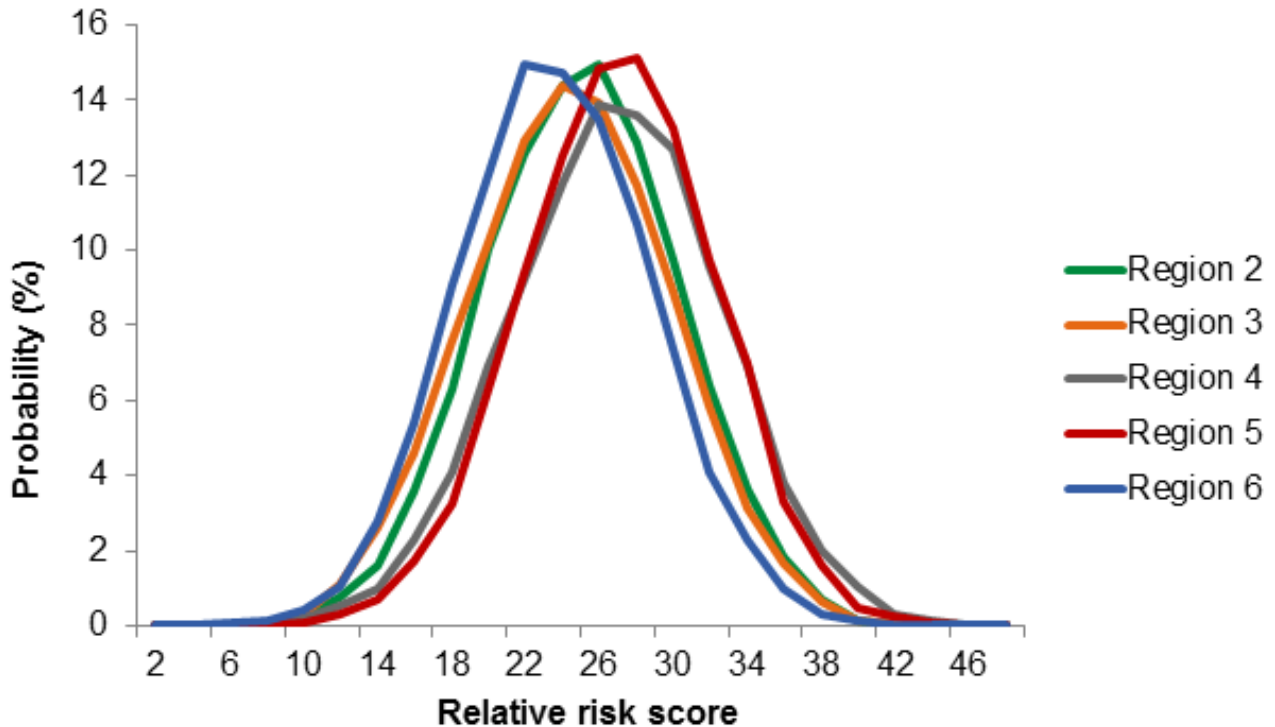
Figure 2-13. Additive risk distribution curves for all endpoints by risk region for the initial risk estimate BNs. The combined risk score has a possible range of 0 to 48.

2.11 Results of the Sensitivity and Uncertainty Analysis

The results of sensitivity analysis illustrated that the stressors most important to the biotic endpoints were a mix between the chemical stressors (mercury) and ecological stressors (river temperature, fish length, stream cover, etc.). A full summary of the top parameters in the sensitivity analysis can be found in **Table 2-4**.

The input parameters with the greatest influence on the Belted Kingfisher were mercury and fish length. For the Carolina Wren, mercury was an important parameter, as well as nest predation (**Figure 2-14**). Mercury body burden was the largest contributor to overall risk for both species of birds in Regions 3, 4 and 5. These regions also had the greatest quality of habitat and largest number of existing nests. River temperature was the main parameter driving the risk for both species of fish. Mercury was also an important input parameter for the smallmouth bass, whereas stream cover (submerged aquatic vegetation) was important for the white sucker (**Figure 2-14**). White suckers were more at risk and heavily affected by ecological stressors (stream cover and river temperature) than by mercury.

The entropy reduction results for the water quality endpoints indicated that most of the endpoints were influenced by the summer and winter river temperatures, as well as by discharge volumes (**Figure 2-15**). The Water Quality Standards endpoint was most influenced by summer dissolved oxygen and bacterial indicators (**Figure 2-15a**). The Fishing River Use endpoint was also affected by the summer dissolved oxygen levels, as well as by MeHg body

burden in fish (**Figure 2-15b**). The degree of entropy reduction values are presented in **Appendix 7** for the biotic and water quality endpoints.

Table 2-4. Summary of sensitivity analysis to biotic and water quality endpoints. The input parameters listed are those that had the greatest reduction in entropy for each endpoint. The number following the input parameter (e.g., **Mercury (5)**) indicated the number of regions in which that parameter was important in the sensitivity analysis.

Endpoint	Input parameter
Belted Kingfisher	**Mercury (5)** – Blood samples **Fish Length (5)** **Potential Habitat (2)** – Land use type (%) **Territory (3)** – Nests per length of river section (m)
Carolina Wren	**Mercury (4)** – Blood samples Nest Predation (5) **Potential Habitat (2)** – Land use type (%) Winter Air Temperature (4)
Smallmouth Bass	**River Temperature (5)** **Mercury (5)** – fish fillet mercury concentrations
White Sucker	**River Temperature (5)** **Stream Cover (5)** – Submerged aquatic vegetation cover (%) **Mercury (4)** – Fish fillet mercury concentrations **PAHs (1)**
Water Quality Standards	**Dissolved Oxygen (5)** - Summer dissolved O_2 **Bacteria (4)** – Bacteria indicators (*E. coli*) **River Temperature (3)** – Winter temperature **River Discharge (3)** – Summer & winter discharge
Fishing River Use	**Dissolved Oxygen (5)** – Summer dissolved O_2 **Methyl Mercury (4)** – Fish fillet MeHg concentrations **River Temperature (5)** – Summer & winter temperature
Swimming River Use	**Bacteria (4)** – Bacteria indicators (*E. coli*) **River Temperature (5)** – Summer & winter temperature **River Discharge (1)** – Summer Discharge
Boating River Use	**River Temperature (5)** – Summer & winter temperature **Bacteria (4)** – Bacteria indicators (*E. coli*) **River Discharge (1)** – Winter Discharge

Figure 2-14. Entropy reduction (sensitivity analysis) results for the Biotic endpoints.

2.12. Interactive use of the BN-RRM

After determining the parameters that had the greatest influence on the endpoints, we then calculated the reduction of risk when we set these parameters to the lowest state (100% in the zero state). For instance, if remediation achieved the zero state for mercury, we could see an 8-42% reduction of risk to the Belted Kingfisher, and a 16-35% reduction to smallmouth bass. If we achieved the zero state of low Summer Dissolved Oxygen, we would expect to see an 11-27% decrease in risk to the water quality standards and a 38-68% reduction of risk to the Fishing River Use endpoint. These results are in **Appendix 8**.

Results with Low Mercury. As described in the Low Mercury Scenario, we set the mercury nodes in all of the models (all endpoints, all regions) to the low risk state (100% low) and back calculated the BN. There was a decrease in risk to all biotic endpoints from 6-16% and a decrease in risk for the Fishing River Use endpoint by 18-25% for Regions 3, 4 and 5. There was no change to the other water quality endpoints, i.e., Swimming, Boating, and Water Quality Standards.
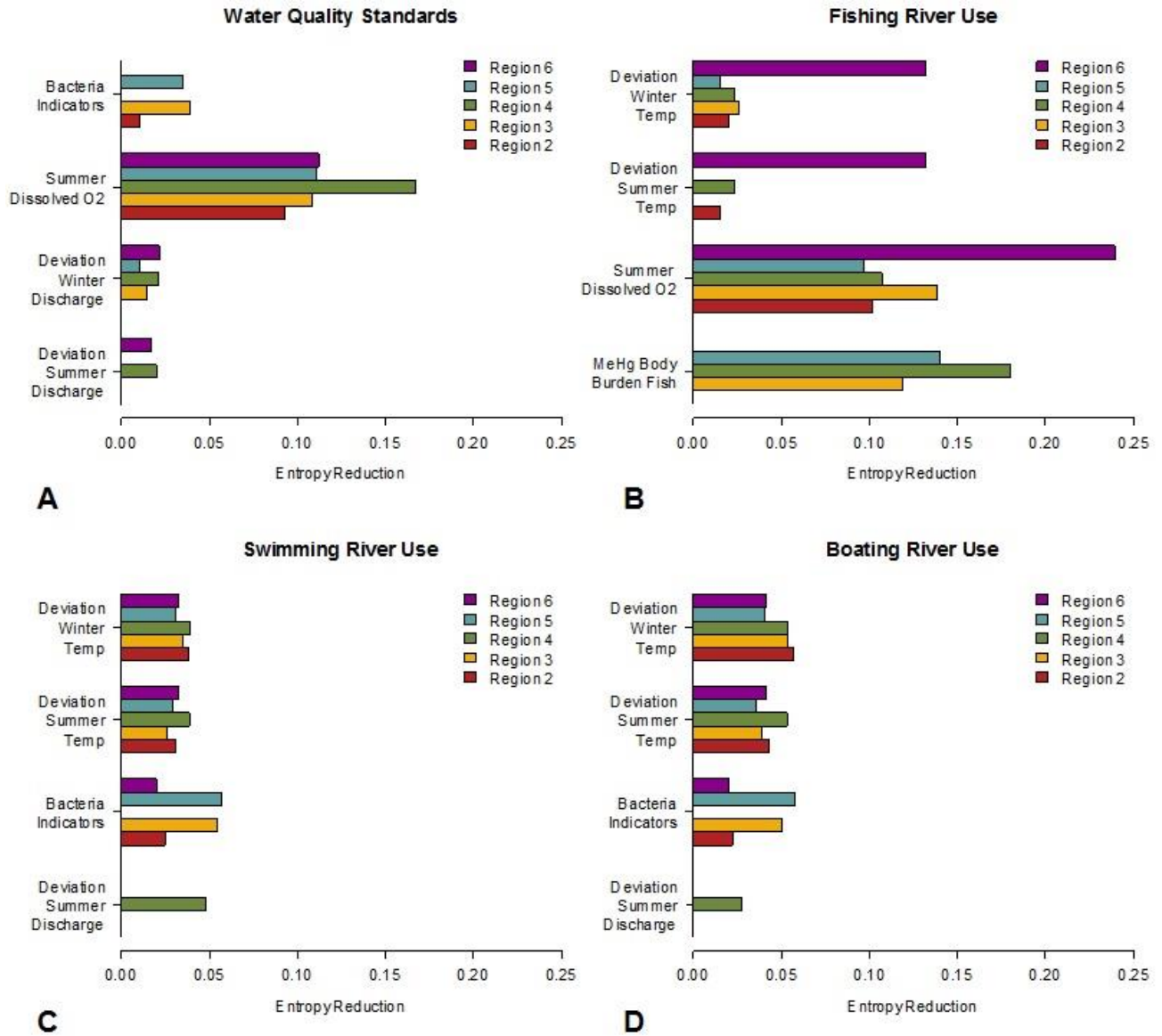
Figure 2-15. Entropy reduction (sensitivity analysis) results for the Water Quality endpoints.

The risk to Belted Kingfisher, Carolina Wren, and white sucker endpoints shifted from the medium and high states to the low risk state. The smallmouth bass and Fishing River Use endpoints shifted from high risk to the zero and low risk states. In some regions, the mercury input probabilities were already in the zero state so we did not change these nodes.

2.13 Discussion

2.13.1 Risk Estimates

Numerous trends in risk were revealed among the endpoints examined in this study, primarily between species of varying life histories and the water quality endpoints throughout the landscape of the study area. The risk scores for each endpoint are shown in **Table 2-3** for comparison.

Smallmouth bass risk is mainly influenced by river temperature and mercury, with a greatest overall risk in Region 5, downstream of the mercury source. We hypothesize that the concentration gradient of mercury body burden, which peaks in Regions 4 and 5, is a possible reason for this downstream trend in risk.

Smallmouth bass had a higher calculated risk compared with white suckers because they contain more mercury from feeding at a higher trophic level (Murphy et al. 2005). As such, smallmouth bass also may have a larger proportion of their mercury body burden in the form of methylmercury (Tom et al. 2010), the more toxic form of mercury. Smallmouth bass and white sucker risk scores even exceed those of their avian predator, the Belted Kingfisher, in most regions.

Carolina Wren and Belted Kingfishers generally were at lower risk than the fish endpoints. Bird species have a greater ability to sequester and eliminate mercury from their bodies by depositing it in their eggs and feathers, whereas fish do not have as sophisticated a method for mercury elimination (Cristol et al. 2008, Jackson et al. 2011a). The birds are generally thought to over-winter in the study area, but have access to nearby less contaminated river systems such as the Middle and North rivers. The prey organisms in these systems have much lower levels of mercury (White 2007, Cristol et al. 2008), making it possible for the birds to have only periodic exposure to mercury compared to fish confined to more continuous exposure in the South River.

Comparing risk scores and distributions suggests that achievement of Water Quality Standards and recreational use endpoints (with the exception of Fishing River Use) are at greater risk than the biotic species (**Table 2-3**). The most influential variables contributing risk to the water quality and recreational use endpoints were impacts from fecal coliforms (*E. coli* indicator species), as well as deviations in temperature and stream flow conditions. Risk to the Water Quality Standard endpoint was most influenced by potential impacts to stream benthic macroinvertebrate communities and from dissolved oxygen levels during the spring and summer months. Benthic macroinvertebrate communities are frequently assessed in biomonitoring programs because they are trophically diverse, as well as sensitive to pollutants and

environmental conditions. The South River was first listed as an impaired river in 1996 under section 303(d) of the Clean Water Act for failure to meet the federal standard for benthic macroinvertebrate assemblages. Impaired sediment quality and excess phosphorus were identified as the most probable stressors (USEPA 2009a). Our assessment implicated low stream flows relative to historic conditions and seasonally depressed dissolved oxygen levels (due to excess phosphorus) in the summer as other potential stressors on aquatic life in the South River.

Reduction in stream flow was also found to impact risk to recreational swimming and boating, in addition to changes in the water temperature regime. Recreational use and satisfaction are influenced by numerous social and environmental conditions; however, stream discharge has been shown to exert a strong influence on the perception of stream conditions and suitability for recreation. River recreational use increases with discharge up to a point, and then declines at high flow (Brown et al. 1992). Water quality, as assessed by regulatory metrics, has been shown to be less important to people when choosing whether to partake in river recreation. *Perceived* water quality, however, does. It encompasses the visual landscape, habitat structure for aquatic life, navigational safety, and visual and olfactory characteristics of the water and shoreline (Lant and Mullens 1991). Perception of a stream segment's suitability for recreational swimming has been shown to be the most sensitive indicator with regard to perceptions of water quality, although stream temperature and discharge are also factors considered.

The sensitivity analysis of the BNs for the biotic endpoints identified mercury and environmental stressors as the most influential contributors to risk. Though mercury is a significant contributor to overall risk for all species studied, it was not always the greatest contributor in all regions. Other environmental stressors, such as temperature, may be affecting fish species as much or more than the mercury. Stream temperature directly affects aquatic organisms through impacts on metabolic rates, activity levels, and life-history traits (Kerr 1966, Horning and Pearson 1973, Shuter et al. 1980, Armour 1993, Murphy et al. 2005).

Stream temperature is a function of heat load and discharge, both of which are influenced directly or indirectly by anthropogenic activities. Alteration of the stream environment is a necessary consequence of managing rivers for flood control and multiple uses, but surrounding land use patterns can indirectly alter the temperature regime (Whitledge et al. 2006). Removal of upland vegetation can lead to increased sediment volumes, changing channel morphology, riparian vegetation impacts, and increased convective and advective heat transfers between the atmosphere and stream surface with loss of canopy cover (Poole and Berman 2001).

Restoration of the riparian habitat surrounding the South River, especially in the high risk regions, would likely improve both actual water quality and perceived water quality. The South River Total Maximum Daily Load (TMDL) for *Aquatic Life Use (General Standard – Benthic)* recommended management practices of revegetation of barren areas and development of riparian buffers among other strategies to reduce erosion and sediment loading into the South River (USEPA 2009a).

If we analyze risk by regions instead of focusing on the individual endpoints, Regions 2, 4, and 5 were the regions at greatest risk. Though Region 4 was one of the regions with higher risk, it

was also a region for which we did not have complete data. As a result, many of the parameters were given a uniform distribution in the water quality models (e.g. the deviations in summer and winter temperature and deviations in summer and winter discharge). The greater uncertainty associated with the uniform distribution given these parameters could result in an underestimation of risk in this region. More consistent sampling in this region will provide the data needed to assess risk to the endpoints inhabiting this area with greater accuracy.

2.13.2 Using Sensitivity Results to Inform the Monitoring Plan

The South River Science Team is currently planning a long-term monitoring program. One of the benefits of a risk assessment that incorporates a sensitivity analysis is that the variables contributing the most to a risk prediction can be identified. This sensitivity analysis was completed for both the initial risk models and for potential management alternatives being proposed. The results from the sensitivity analysis provided a comprehensive list of the parameters that should be monitored currently and in the future. For further information and a list of proposed monitoring parameters, see **Section 4**.

2.13.3 Use of Bayesian Networks

Bayesian networks are an adaptive tool for ecological risk assessments that contain multiple chemical and non-chemical stressors. In this report, we have shown that,

1. Bayesian networks allow for the calculation of risks to four biotic and four water quality endpoints selected in this study.
2. Overall risk calculations are spatially explicit and can be compared between risk regions.
3. Bayesian networks are capable of synthesizing different forms of data such as measures of exposure, geographical and habitat surveys, and water quality parameters, as well as incorporating expert opinions provided by the SRST and other data sources.
4. Bayesian networks implicitly describe the associated uncertainty in each input parameter, as well as the uncertainty of each causal pathway as part of the sensitivity analysis.
5. Bayesian networks create a series of testable hypothesis that may be verified through field and laboratory studies.

BNs are effective at synthesizing the interactions of multiple stressors and calculating risk, but once the networks are in place, they may be used to identify parameters for remediation, as well as model the outcomes of different management and remediation scenarios. By evaluating the BNs in reverse, the overall risk output may be manually altered to identify target stressors and their sources for priority remediation. For example, based on the overall risk scores of the four species in this study, smallmouth bass in Region 5 appear to have the highest overall risk compared to all the other risk regions. Using the BNs, we can identify the principle contributing stressors, in this case mercury and river temperature, and determine the remediation goals that must be obtained to attain an acceptable amount of risk.

BNs are easily updated if new data become available. We recently updated all of the models with data provided by the SRST and URS Corporation as of January and February 2014. All of the models and results presented in this report utilized those data. Updating the models will be

especially useful in the future when management options have been implemented and the new data from these adaptive management actions incorporated into the model.

A major advantage of using BNs in risk assessments is their ability to model risk reduction scenarios for best management practices. The input parameters in the BN may be altered to model the predicted conditions under different management strategies or upon implementation of best management practices. Given data on how the management scenario will affect different stressors, the input parameters can easily be altered to reflect the conditions of each scenario under evaluation and calculate the overall risk. In the following sections, we will describe the application of BNs for weighing management alternatives.

3.0 EVALUATING MANAGEMENT OPTIONS FOR THE WATERSHED

Ecological managers often implement one or more management options without the direct integration of a quantitative risk assessment and evaluation of management alternatives. Throughout the decision-making process a manager should consider multiple stressors, as well as stressor interactions and the resulting effects. In this next phase of our study, we used BNs in a relative risk assessment model framework, the BN-RRM, to integrate two management options into existing risk assessment models for biotic endpoints and water quality endpoints in the SRSA. The two management options assessed were agricultural best management practices (Ag BMPs) and bank stabilization (BST). The primary management goal conveyed to us by South River managers was "no regrets, i.e., not make the site more impaired as the result of a management action. For example, reducing mercury levels to the detriment of habitat, loss of other species, degradation of water quality, or other environmental parameters.

This section introduces how the BN-RRM can be used to evaluate different management options in an adaptive management process. The next sections introduce adaptive management and the role risk assessment can play in that process. Next, we use two different scenarios to demonstrate how the BN-RRM can be used to estimate the changes in risk due to each management alternative. Finally, we discuss how an adaptive management process can be applied to the South River system.

3.1 Introduction to Adaptive Management

Decision-making for a contaminated site requires managers to connect the results of a risk assessment with the selection of a management strategy, though there is rarely quantitative integration of these two components. At contaminated sites there is a focus on the stressor of regulatory interest, however at most sites multiple stressors exist. The selection of one or more management options requires managers to make trade-offs between ecological risk, cost, effectiveness, and public opinion (Kiker et al. 2008). The same situation exists with the management of the South River where mercury is the main stressor of regulatory interest. In managing the SRSA, the primary management goal for the South River is "no regrets" and is defined as having no additional impact to the South River system due to management activities. To evaluate the "no regrets" goal a quantitative, spatially explicit process is needed to calculate the effects of a management option on risk and to evaluate potential unintended consequences to other endpoints.

3.2 BN-RRM and Adaptive Management

Adaptive management is an iterative process of "learning by doing," where managers learn about the consequence of current management practices through monitoring data and using the new knowledge to improve the next set of management decisions (Holling 1978, Nyberg et al. 2006). It has been proposed that Bayesian networks could easily be incorporated into an

adaptive management process although only a few examples exist (Howes et al. 2010, Shenton et al. 2011, Ayre et al. 2014, Hines and Landis 2014). By incorporating one or more management options into the BNs, managers can evaluate changes in risk and unintended consequences. Management strategies are often implemented with consideration of spatial variability, so it makes sense that the evaluation of management options would take into account regional variation in risk as well.

The BN-RRM can be adapted to an adaptive management process. In addition to integrating management into the BN-RRM, risk can be calculated for multiple scenarios by selecting a risk state in one or more nodes that then changes the risk distribution outcome (Ayre et al. 2014). The BNs can also be used to calculate the initial conditions necessary for a desired risk outcome. This is essentially a "back-calculation" where a risk state in the endpoint node is selected and the conditions required to meet the risk level are calculated (Ayre and Landis 2012).

The two management options evaluated in this study were Ag BMPs and bank stabilization (BST). Both were identified as feasible management options by the SRST. The incorporation of the management scenarios into the BN-RRM, builds on existing South River conceptual models and BNs created by Summers (2012) and Ayre et al. (Report 2013-1) for biotic and water quality endpoints. First, the two management options were integrated into the conceptual model for each endpoint. Then these conceptual models were translated into BNs. The BNs from the initial risk estimates models were used as the framework for the inclusion of the management scenarios to quantitatively evaluate management alternatives for the South River. The BNs were parameterized using a combination of South River monitoring data, exposure-response data, published studies, and expert elicitation. The output of each BN is a distribution that describes the likelihood of zero, low, medium, and high risk with the implementation of Ag BMPs or BST management options.

3.3 Model Construction and BN-RRM Process

3.3.1 Conceptual Model

Conceptual models depicting regional-scale causal pathways between sources, stressors, habitats, and endpoints for the South River were developed in the initial biotic and water quality ecological risk assessment we conducted (see **Section 2, Appendix 1**). Management options were integrated into these original conceptual models based on causal relationships between the management options and stressors (**Figure 3-1**). Both management options were incorporated in the model at the stressor link between source and habitat because they target a reduction in exposure to the stressor. One conceptual model was constructed for each of the four biotic endpoints, as well as a combined model for the four water quality endpoints (**Appendix 9 and 10**).

Relative Risk Model
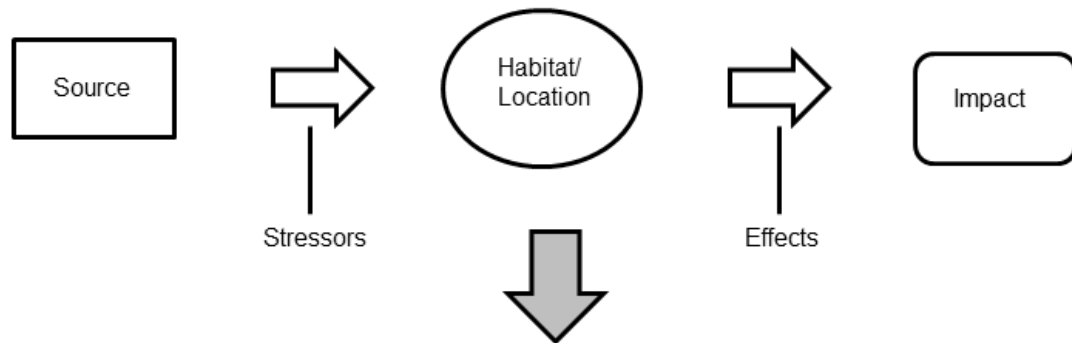
Relative Risk Model with Management
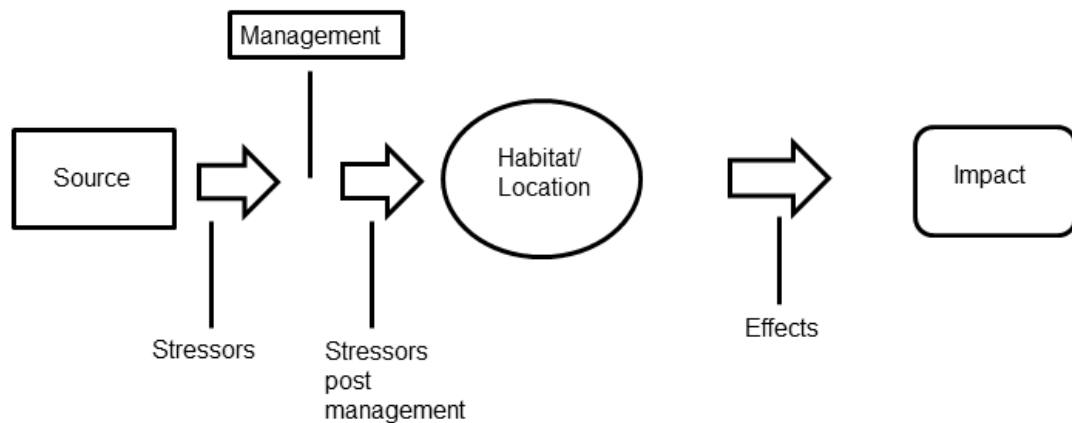
Figure 3-1. The structure of the relative risk model (Landis and Wiegers 1997, 2005) shows the causal pathway between source, stressor, habitat, effects, and impacts. Management was integrated into the relative risk model (bottom diagram).

3.3.2 BN-RRM Process

The BNs were derived directly from the conceptual models and incorporated the management scheme with each source of stressor, habitat, effect, and endpoint represented by nodes and links (**Figure 3-2**). The links represent causal relationships between the set of nodes. The BNs maintain the tiered nature and linear flow of the conceptual models as described in Section 2.4.
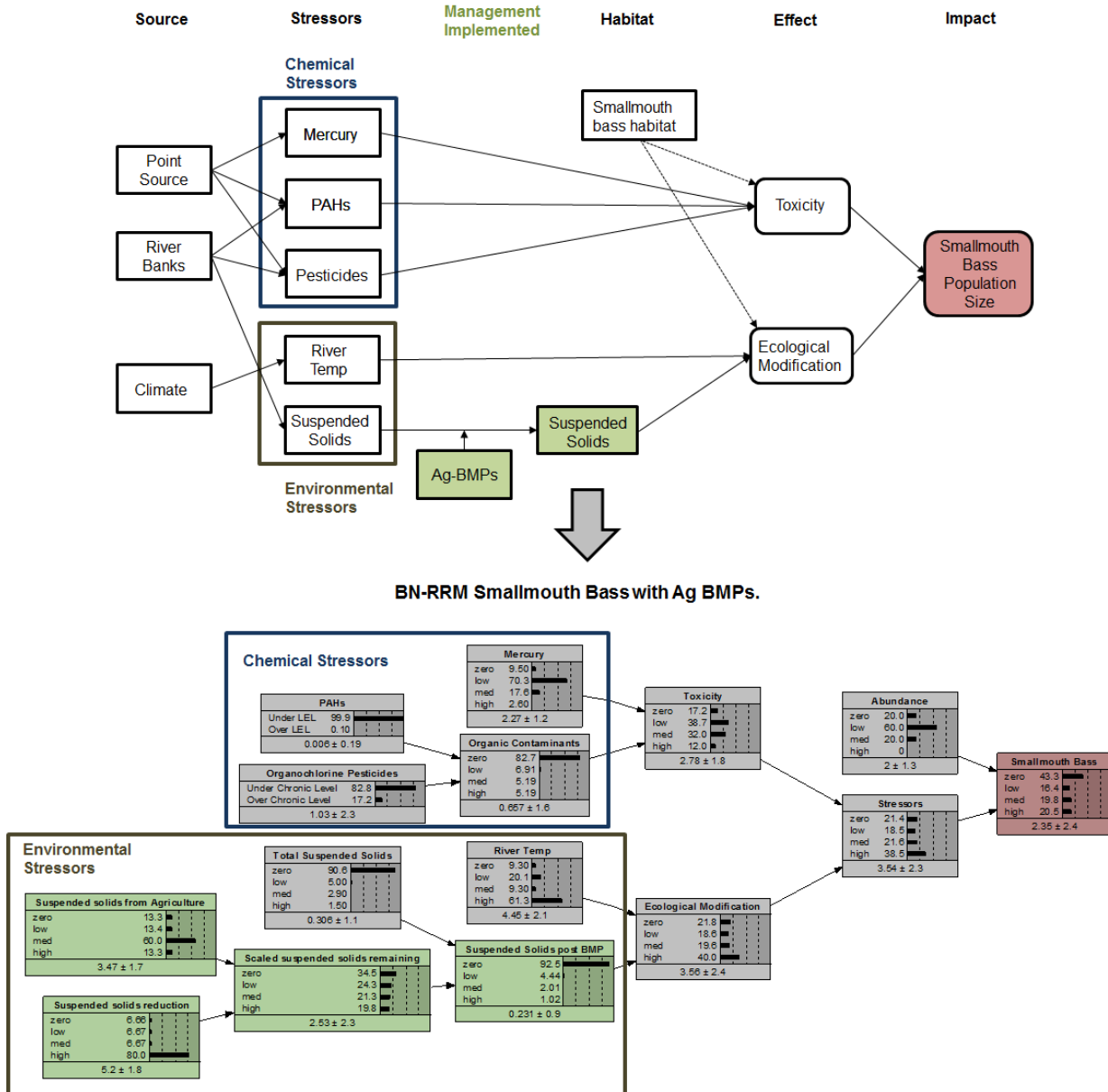
Figure 3-2. The conceptual model for smallmouth bass risk with Ag BMPs management transformed into a BN. The BN maintains the conceptual model structure that describes causal relationships between stressors, habitats, and endpoints. Green boxes in the BN-RRM denote Ag-BMPs. The red box denotes the endpoint.

3.4 BN-RRM with Adaptive Management

3.4.1 Integrating Management Options into the BNs

The original BN-RRM models were derived from models presented and analyzed in Section 2. The Ag BMPs option and the BST option were separately incorporated into the original BN-RRM model and reanalyzed to evaluate the effects of each on the risks to the endpoints. These two

management options were included in the BNs separately because they target different stressors.

Best management practices (BMPs) are defined as the most cost-effective, efficient and practical methods to address a problem or guide an action (Logan 1993). Agricultural BMPs reduce environmental impacts from agricultural activities while considering agricultural productivity, feasibility of implementation, ability to implement the BMPs, and effectiveness of them. A wide range of Ag BMP options exist and multiple practices are often implemented together. Our research assessed the combination of Ag BMPs that included practices such as reduced tillage, roll hipping, and cover crop residues in winter described in Cullum et al. (2006) and Sheffield et al. (1997).

Bank stabilization is a common management practice at sites with eroding contaminated sediment. In the South River, a BST pilot study was conducted from 2009-2012, during which mercury concentrations were monitored in different media pre- and post- BST implementation. Two types of BST, enhanced vegetative and structural, were applied in various combinations along the pilot banks. Enhanced vegetative stabilization stabilizes an eroding bank using the existing soils and slope. This process may include canopy management, enhancing native vegetation, at-risk tree management, placement of reactive amendments and toe protection (Anchor QEA and URS 2013). Structural BST also stabilizes a bank using the bank soils and slope, but may include more invasive construction techniques such as bank reshaping, reactive amendments, slope stabilization through vegetative stabilization, and hard slope stabilization like riprap and toe protection. Each bank section in the pilot study was evaluated before one or both techniques were used. Our assessment of BST management option evaluated the pilot study methodology, as it is specific to the South River.

3.4.2 Ag BMPs Management Option

Agricultural BMPs were integrated into BNs for the Belted Kingfisher, smallmouth bass, Water Quality Standards, Swimming River Use, and Boating River Use because pathways exist from the stressors targeted by Ag BMPs to the endpoint. Agricultural BMPs reduce total suspended solids, total phosphorus, and *E. coli* (Sheffield et al. 1997, Line et al. 2000, Cullum et al. 2006, Meals et al. 2010).

The three Ag BMP management nodes that were incorporated into the BNs describe the stressors that come from agricultural land use practices, the percent reduction of the stressors by Ag BMPs, and the amount of the stressors remaining after Ag BMPs are implemented (**Figure 3-3**). This combination of nodes determines the reduction of the stressors due to Ag BMPs based on the amount of the stressor attributable to agricultural practices.

Parameterization. The Benthic Impairment TMDL study for the South River was used to parameterize the Ag BMPs management BNs. The TMDL study estimated that 70.2% of total suspended solids, 58% of total phosphorus and 89.6% of *E.coli* come from agricultural sources (Engineering Concepts, Inc. 2009). Studies by Cullum et al. (2006) and Sheffield et al. (1997) were used to estimate Ag BMP reductions of total suspended solids, total phosphorus and *E. coli.* Cullum et al. (2006) reported 58% reduction of total suspended solids and 32% reduction of total phosphorus, but did not monitor changes in bacterial abundance. Sheffield et al. (1997)

reported a 90% reduction of total suspended solids, 64.5% reduction of total phosphorus, and 51-77% reduction of fecal bacteria. These reduction estimates were used to define the input distributions for Ag BMPs management nodes. Confidence in estimates from the Benthic Impairment TMDL, Cullum et al. (2006), and Sheffield et al. (1997) were explicitly described by the node distributions.

Figure 3-3. Bayesian network to calculate risk to smallmouth bass with Ag BMPs in Region 2. In the Ag BMPs BNs, the management nodes are green, the endpoint node is reddish-brown, and the other nodes are grey.

Ag BMPs Conditional Probability Tables. The conditional probability tables (CPTs) in the child node represent the interactions between the parent nodes in the model. Each possible combination of states that can occur between the parent nodes becomes a line in the CPT with an associated conditional probability distribution. The parent node interactions may produce addition, synergistic or reduction effects. In this context, reduction effects refer to the action of one variable that reduces exposure of another variable, thereby resulting in a shift in exposure to a lower state in the child node (e.g. going from a medium state to a low state). Reduction interactions can occur when one environmental variable inhibits exposure to or toxicity of another variable. Nodes that represent adaptive management treatments will also act to reduce the exposure to and/or toxicity of a stressor. Input nodes associated with Ag BMPs and bank stabilization management generally have reduction effects within the CPT.

Conditional probability tables quantify the relationship between parent nodes by outlining possible combinations of parent states, each of which is assigned a probability distribution. There are a number of techniques we can use to assign the conditional probability distributions in the CPTs of the child node. For instance, we can:

- Use a mathematical or quantitative approach

- Use a qualitative approach with peer-reviewed scientific literature and evidence if data are lacking
- Combine quantitative and qualitative approaches
- Complete the tables using judgments from expert elicitation

In the management models for the South River, most of the CPTs were completed using the mathematical approach (see **Appendix 12** for an example calculation). States of the parent and child nodes were already defined by in the parameterization process (see **Appendix 11** for more information on how these states were defined). The quantitative ranges for each state of the parent nodes were multiplied together to obtain a range of possible values for the child node. After we establish the overall range, we compare this range to the predefined state of the child node to obtain a distribution. We assume equal probability of values between the lower and upper end of the calculated range. The number of occurrences in each categorical state provides the conditional probability distributions for the child node. In instances for which this mathematical approach was not possible, CPTs were completed using expert elicitation.

3.4.3 Bank Stabilization Management Options

Bank stabilization was integrated into the BNs for all biotic and water quality endpoints because this management option affects stressor pathways in all the models. In a literature review of BST, no published studies were found that documented environmental changes after BST. The BST management option was incorporated into the BNs (**Figure 3-4**) using a combination of South River BST pilot study data (Anchor QEA and URS 2013) and expert elicitation. The BST pilot study used a combination of vegetative and structural stabilization procedures, so the evaluation of the BST management option assumes this methodology for present and future stabilization projects.

Parameterization: Pilot Study Data. Pilot study data were used to estimate the effects of BST management on the mercury stressor to the biotic endpoints and Fishing River Use endpoint. The pilot study reported mercury concentration minimums and maximums for pore water, as well as the average mercury concentration in sediment throughout the study area (Anchor QEA and URS 2013). Quantitative data were not reported for any other parameters.

Parameterization: Fish Fillet Mercury. Trends in minimum and maximum pore water mercury concentrations were used to estimate changes in mercury body burden for smallmouth bass and white sucker, as well as changes in Fishing River Use because these were the best available data. Throughout the study period, half of the minimum pore water samples showed increased mercury concentrations, whereas the other half of the samples showed decreased mercury concentrations (Anchor QEA and URS 2013). As a result, the zero and low risk states for mercury body burden were assigned a 50% probability of increasing and a 50% probability of decreasing with BST management.

Nearly all maximum pore water mercury concentrations in later samples were lower than the initial samples, therefore the medium and high mercury risk states had 100% probability of decreasing based on these data. The pore water concentrations may not directly reflect changes in surface water mercury because the relationship between the two is complex

(Sophocleous 2002). The uncertainty in changes to mercury body burden in fish with BST management was reflected in the input distributions.
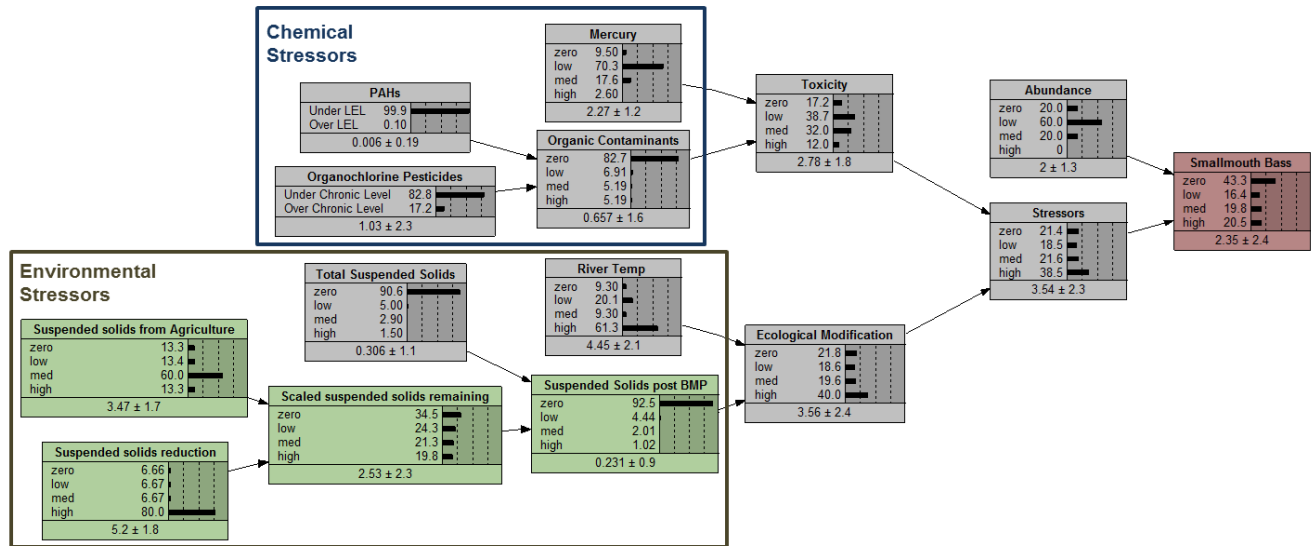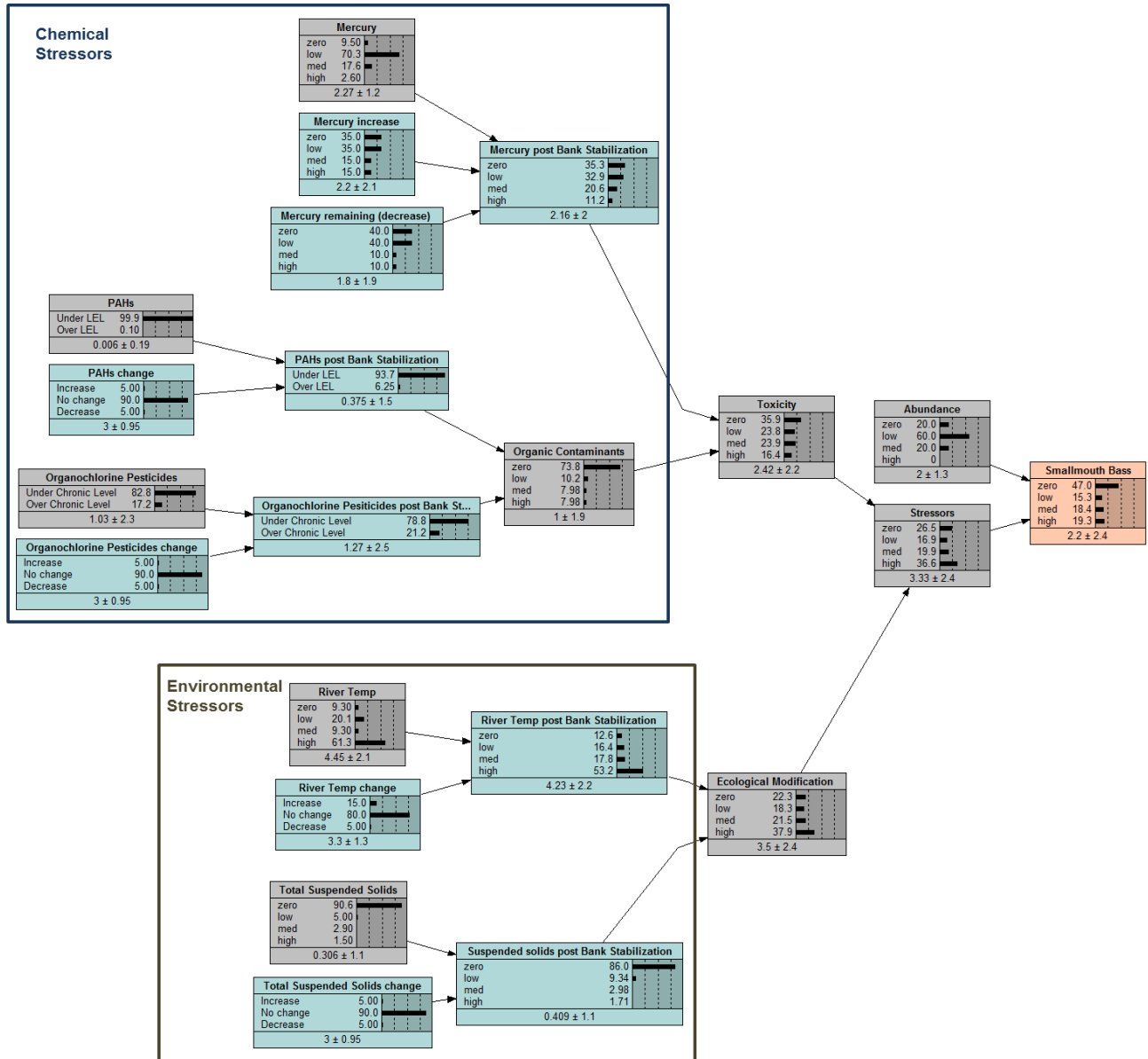

Figure 3-4. Bayesian network to calculate risk to Smallmouth Bass with BST option in Region 2. In the BST BNs the management nodes are bluegreen, the endpoint node is orange, and the other nodes are grey.

Parameterization: Bird Blood Mercury. We used two methods to relate the pilot study data to bird blood mercury levels. First correlations were calculated using the SRST database for: water column total mercury (THg) concentration vs. bird blood MeHg concentration; pore water THg vs. bird blood MeHg; water column MeHg vs. bird blood MeHg; and pore water MeHg vs. bird

blood MeHg for Belted Kingfisher and Carolina Wren. The results were that there were insufficient data to determine viable correlations.

The second method entailed estimating bird blood MeHg concentrations from the SRST data using river and floodplain biomagnification factors for the South River (Wang et al. 2013). These calculations underestimated bird blood MeHg concentrations. The correlations and the biomagnification factors did not accurately predict bird blood mercury so pilot study data trends described above were used.

The effects of BST on bird blood MeHg was assigned an almost equal distributions for three potential outcomes: an increase, no change, and a decrease for the avian species. There was a slightly higher probability of decrease because the maximum and average mercury concentrations in the pore water and sediment decreased in the pilot study data (Anchor QEA and URS 2013).

Parameterization: Structure of BST Expert Elicitation. Expert elicitation was used to estimate effects of BST management on the following stressors: total suspended solids/turbidity, river temperature, submerged aquatic vegetation, discharge regime, dissolved oxygen levels, PAHs, organochlorine pesticides, bacteria inputs, and total phosphorus. Two experts were surveyed in a formal elicitation. Both experts were also involved in the South River BST pilot study. This may have introduced bias into the elicitation results (McBride and Burgman 2011), but our methods for the elicitation were constructed to minimize bias associated with their personal experience on the South River restoration projects.

In the expert elicitation survey, the experts were asked to draw on their cumulative experience with BST to address ten scenarios. Expert elicitation research suggests that more accurate results are obtained when experts estimate frequency instead of probability (McBride and Burgman 2011). The survey asked the experts to estimate the frequency, out of 10 sites, that they would expect a 50% increase, a 50% decrease, or no change in a stressor with BST management. McBride and Burgman (2011) also recommended using intervals that are perceived similarly by most individuals. In this case, 50% increase, and 50% decrease were used because it was likely that the experts perceived the quantities of doubled and halved in a similar way.

The results from our BST expert elicitation questionnaire are summarized in **Table 3-1**. The frequencies reported by the experts were averaged. If the average frequency for a state was 0, the state was assigned a frequency of 0.5 to allow for back-calculations (**Table 3-1**). The frequencies were then used as input distributions for the BST management input nodes.

Parameterization: Belted Kingfisher Habitat Expert Elicitation. The BST experts were not surveyed about habitat effects for either avian species because it was not in their area of expertise. Expert knowledge was elicited instead from Dr. Dan Cristol to help us understand the likely effects of BST management on Belted Kingfisher habitat since they nest in the steep slopes of the riverbanks. Dr. Cristol is a member of the SRST and has published numerous papers on birds in the South River, as well as on mercury toxicity to birds (Brasso and Cristol 2008, Cristol et al. 2008, Condon et al. 2009, Hawley et al. 2009, Jackson et al. 2011a, Jackson

et al. 2011b). Dr. Cristol stated that if BST is implemented without the explicit consideration of Belted Kingfisher nests, the stabilization efforts would eliminate the Belted Kingfishers (Dan Cristol written communication, 2013). The primary scenario of BST assumed that explicit consideration is given to Belted Kingfishers nests because the Kingfisher Habitat node maintains the initial risk assessment input distributions.

Table 3-1. Bank stabilization expert elicitation survey results. Frequencies and input distributions are presented. These inputs were the same for all endpoints.

Model Variable		Expert 1	Expert 2	Average	Prior
Total Suspended Solids	Increase 50%	1	0	0.5	5
	No change	8	10	9	90
	Decrease 50%	1	0	0.5	5
River Temperature	Increase 50%	1	2	1.5	15
	No change	8	8	8	80
	Decrease 50%	1	0	0.5	5
Submerged Aquatic Vegetation	Increase 50%	1	0	0.5	5
	No change	8	5	6.5	65
	Decrease 50%	1	5	3	30
Discharge Regime	Increase 50%	0	0	0	1
	No change	10	10	10	98
	Decrease 50%	0	0	0	1
Dissolved Oxygen	Increase 50%	1	0	0.5	5
	No change	8	10	9	90
	Decrease 50%	1	0	0.5	5
PAHs	Increase 50%	1	0	0.5	5
	No change	8	10	9	90
	Decrease 50%	1	0	0.5	5
Organochlorine Pesticides	Increase 50%	1	0	0.5	5
	No change	8	10	9	90
	Decrease 50%	1	0	0.5	5
Bacteria Inputs	Increase 50%	0	2	1	9.5
	No change	10	8	9	89.5
	Decrease 50%	0	0	0	1
Total Phosphorus	Increase 50%	0	0	0	1
	No change	10	8	9	89.5
	Decrease 50%	0	2	1	9.5

The Belted Kingfisher elimination scenario, where BST management does not avoid Kingfisher nests, is represented in another BN where only the *Territory* and *Potential Habitat* stressors

affect the Kingfisher's risk. Both *Territory* and *Potential Habitat* nodes have 100% probability of high risk to reflect the elimination of Kingfisher habitat in the region. This scenario results in the highest possible risk to the Kingfisher. The *Toxicity* and *Ecological Parameters* nodes are disconnected from the endpoint because if Belted Kingfisher habitat is eliminated in the region, they would not be exposed to toxicological and environmental stressors.

Bank stabilization CPTs. Conditional probability tables for the BST nodes were calculated using the same approach described in the Ag BMPs CPTs section. Descriptions of nodes in the BST management BNs are in **Appendix 13**.

3.5 Model Evaluation: Sensitivity and Uncertainty Analysis and Interactive Uses of Model

The sensitivity analysis and uncertainty presentation are in Section 2.9. A brief summary follows in the next paragraphs.

3.5.1 Sensitivity derivation by Entropy Reduction Analysis
An entropy reduction analysis was completed on the endpoint node in each BN using Netica™ (Norsys Software Corp. 2010). Netica™ calculates the degree of entropy reduction that nodes contribute. The output from the entropy reduction analysis described the influence that each parent and child node has on the endpoint (Pollino et al. 2007, Hines and Landis 2014). Only input nodes are reported in this entropy reduction analysis because those nodes are targeted by Ag BMPs and BST.

3.5.2 Uncertainty
Uncertainty is explicitly represented in the BNs by the distributions representing the frequency of each state within the nodes. (Varis and Kuikka 1999, Marcot et al. 2006b). The degree of uncertainty was determined by the data and available knowledge. Other sources of uncertainty include the simplification of a system with a mathematical model, natural variation or randomness of parameters, and subjective judgment during model parameterization (Hines and Landis 2014).

3.5.3 Influence Analysis Methodology for Bank Stabilization
We completed an influence analysis (Marcot 2012) to examine the range in efficacy of the bank stabilization treatments. Influence analysis can be used to evaluate different outcome scenarios by setting model input variables to a given state and comparing the changes in model output or risk to the endpoints. The influence analysis we performed for BST compares the original results for Bank Stabilization management (i.e, the "Most Likely" scenario) to a "Best Case" and "Worst Case" scenario given the implementation of bank stabilization management treatments. By comparing these scenarios, we can quantify the boundaries or range of distributions that are possible with the implementation of the bank stabilization management. This type of influence analysis can be useful in decision making, as well as in the communication of both risk and uncertainty (Marcot 2012).

To perform the influence analysis, we altered the *input* nodes that specifically relate to the bank stabilization treatments/management (the blue/green nodes in the bank stabilization models).

For example, in the Belted Kingfisher model, five input parameters are affected by bank stabilization: Turbidity, Submerged Aquatic Vegetation Change, Organochlorine Pesticide Change, PAHs Change, and Mercury Change. We provide an example of how the influence analysis was completed using one of these nodes, the Turbidity Change for the Belted Kingfisher (**Figure 3-5**).

The Turbidity Change node addresses the probability of change in turbidity due to bank stabilization management. There are three possible states; bank stabilization could decrease turbidity, increase turbidity or result in no overall change to turbidity. In the Most Likely Scenario for the Belted Kingfisher, the Turbidity Change has probabilities of 5% Increase, 90% No Change, and 5% Decrease (**Figure 3-5a**). To determine the Best Case scenario, in this case the greatest reduction in turbidity, we removed the original probabilities and entered a 100% probability of the Decrease state (**Figure 3-5b**). By altering the Turbidity Change node to 100% Decrease, we are stating that the bank stabilization management is efficient at reducing turbidity in the region. The resulting reduction in turbidity is observed in the Turbidity Post Bank Stabilization child node. We observed a shift in the zero state from 69.7% (in the Most Likely Scenario; **Figure 3-5a**) to 89.4% with the Best Case scenario (**Figure 3-5b**). The reduction of turbidity in the Turbidity Post Bank Stabilization is propagated throughout the model, eventually leading to a reduction of risk to the Belted Kingfisher endpoint node.

The Worst Case scenario for Turbidity Change represents an **increase** in turbidity in the region when bank stabilization is implemented due to the in-stream activities associated with stabilizing the stream banks. To calculate this Worst Case scenario, we set the Turbidity Change node to 100% in the Increase state (**Figure 3-5c**). We observe an effect in the Turbidity Post Bank Stabilization child node as the distribution shifts from zero to low. The likelihood of Turbidity post Bank Stabilization being in the low state increases from 27.3% (**Figure 3-5a**) to 85.2% in the worst case scenario (**Figure 3-5b**). The increase in turbidity propagates to the Belted Kingfisher endpoint node, eventually leading to an increase in risk to them in Region 2 where BST is implemented.

The Best and Worst Case examples address one input node for the Belted Kingfisher specifically related to Region 2. To determine the Best and Worst Case scenarios for the Belted Kingfisher in each region, this process was repeated for the four additional bank stabilization treatment input nodes: Submerged Aquatic Vegetation Change, Organochlorine Pesticide Change, PAHs Change, and Mercury Change. A comparable influence analysis was completed for each endpoint in each region.

3.6 Results: Patterns of Risk to the South River after Management

These management options have not been implemented along the South River. The results presented below are the predictions of risk based on results from literature studies and pilot studies of these various management options.

A. Most Likely Scenario. Bank stabilization has 90% likelihood of no change to turbidity, 5% likelihood of reducing turbidity, and 5% likelihood of increasing turbidity.

Note: For a complete view of the initial model (Belted Kingfisher Region 2) see Appendix 15-1.

Turbidity

zero	80.5
low	16.8
med	2.60
high	0.10
	0.446 ± 0.96

Turbidity post Bank Stabilization

zero	69.7
low	27.3
med	2.71
high	0.30
	0.673 ± 1.1

Turbidity change

Increase	5.00
No change	90.0
Decrease	5.00
	3 ± 0.95
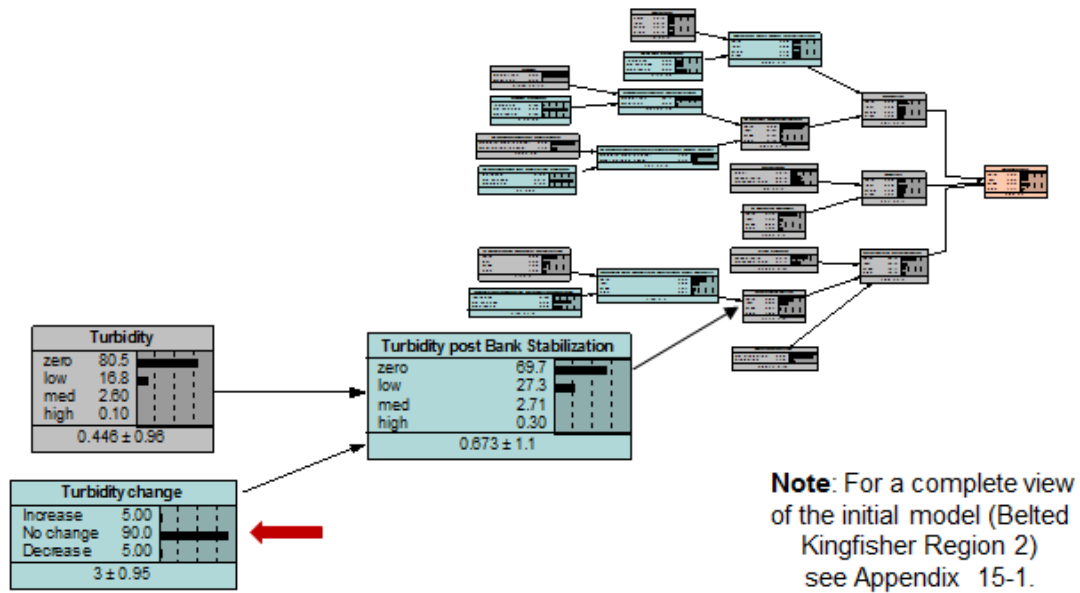
B. Best Case Scenario. Bank stabilization has 100% efficacy in reducing turbidity.

Turbidity

zero	80.5
low	16.8
med	2.60
high	0.10
	0.446 ± 0.96

Turbidity post Bank Stabilization

zero	89.4
low	9.14
med	1.39
high	.065
	0.242 ± 0.74

Turbidity change

Increase	0
No change	0
Decrease	100
	0
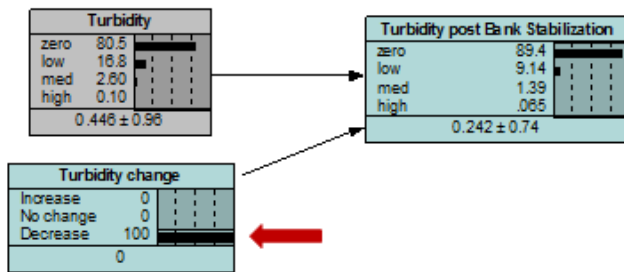
C. Worst Case Scenario. Bank stabilization has 0% efficacy in reducing turbidity; turbidity increases 100% with implementation of stabilization practices.

Turbidity

zero	80.5
low	16.8
med	2.60
high	0.10
	0.446 ± 0.96

Turbidity post Bank Stabilization

zero	10.5
low	85.2
med	3.37
high	1.01
	1.9 ± 0.84

Turbidity change

Increase	100
No change	0
Decrease	0
	6

Figure 3-5. An Influence Analysis to evaluate the efficacy of BST in Best and Worst Case scenarios compared to the original Most Likely scenario in reducing turbidity to the Belted Kingfisher.

3.6.1 Ag BMPs Management Option

Agricultural BMPs did not change the likelihood of risk states by more than 5%, though all distributions shifted slightly towards lower risk (**Figures 3-6** through **3-12**). The likelihood of risk to Belted Kingfisher decreased in the high, medium, and low risk states and increased in the zero risk state (**Figure 3-6**). smallmouth bass, Water Quality Standards, Swimming River Use, and Boating River Use had a decreased likelihood of high risk and increased probability of 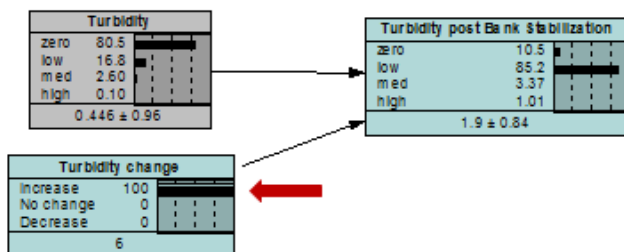risk in the medium, low and zero risk states (**Figures 3-7** through **3-10**). On the landscape scale, the spatial pattern of risk to the endpoints in the risk regions was also unchanged compared to initial risk estimates. The figures of the Ag BMP Bayesian networks are in **Appendix 14**.

3.6.2 Bank Stabilization Management Options

Bank stabilization management changed the risk distributions for Belted Kingfisher, smallmouth bass, and Fishing River Use (**Figures 3-6, 3-7, 3-11**). The distribution outcome did not change the likelihood of risk states by more than 10% for the other endpoints. The spatial risk pattern was altered only for Fishing River Use (**Figure 30**). The figures of the BST Bayesian networks are in **Appendix 15**.

Belted Kingfisher risk had a 100% likelihood of high risk if Kingfisher nests were not avoided during BST management. These distributions were skewed towards zero and low risk in the initial risk calculations. In contrast if Kingfisher nests were avoided, the risk distributions were not affected by BST management.

Carolina Wren risk distributions remained skewed towards zero risk in Regions 2 and 3, and peak at low and medium risk in Regions 4, 5, and 6 (**Figure 3-12**). There was less than a 3% change in likelihood for risk states under BST management.

With BST, the smallmouth bass risk distributions shifted in Regions 3, 4, 5, and 6 (**Figure 3-7**). Likelihood of high risk decreased 11% and 13% in Regions 4 and 5, respectively. In Regions 3-6, likelihood of zero risk increased 10-13%. In Region 6, the distribution changed so that the majority of the likelihood was in the zero risk state.

The likelihood of a change in risk state for white sucker distributions was less than 7% with BST management. The distributions were skewed towards zero risk, except in Region 2 where risk was split between the zero and high states at 30% and 50% likelihood, respectively (**Figure 3-13**).

Water Quality Standards risk distributions changed only slightly with the addition of BST management. Risk was skewed towards high with greater than 50% likelihood (**Figure 3-8**). All regions had less than 5% likelihood of zero risk.

Risk distributions to the Fishing River Use endpoint were changed in Region 6. The initial risk distribution was skewed towards zero risk. Under BST management, the distribution remained skewed towards zero risk, but the likelihood of zero risk decreased by 18% and the high risk likelihood increased from 2% to 15% (**Figure 3-11**). The general upstream-downstream risk pattern changed in Region 4. With BST management, Fishing River Use risk was highest

(medium and high risk states combined) in Region 4 with a probability of 38%, but Region 6 risk was higher than Region 5 (probabilities of 36 and 32% respectively).
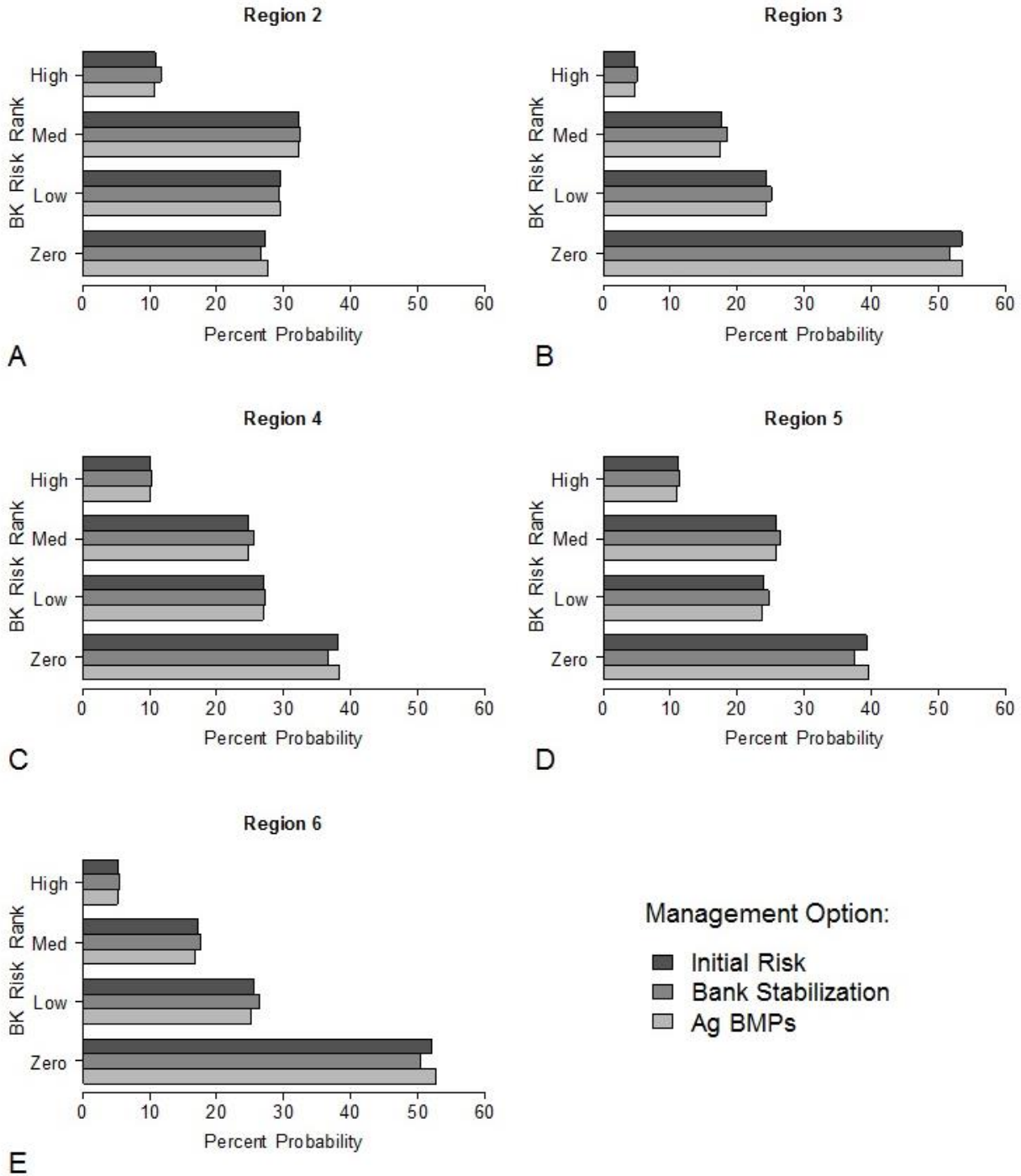
Figure 3-6. Belted Kingfisher (BK) initial risk estimates, risk with BST and Ag BMP management options, assuming nest avoidance. With both management options, there was little change in risk compared to the initial risk estimates.
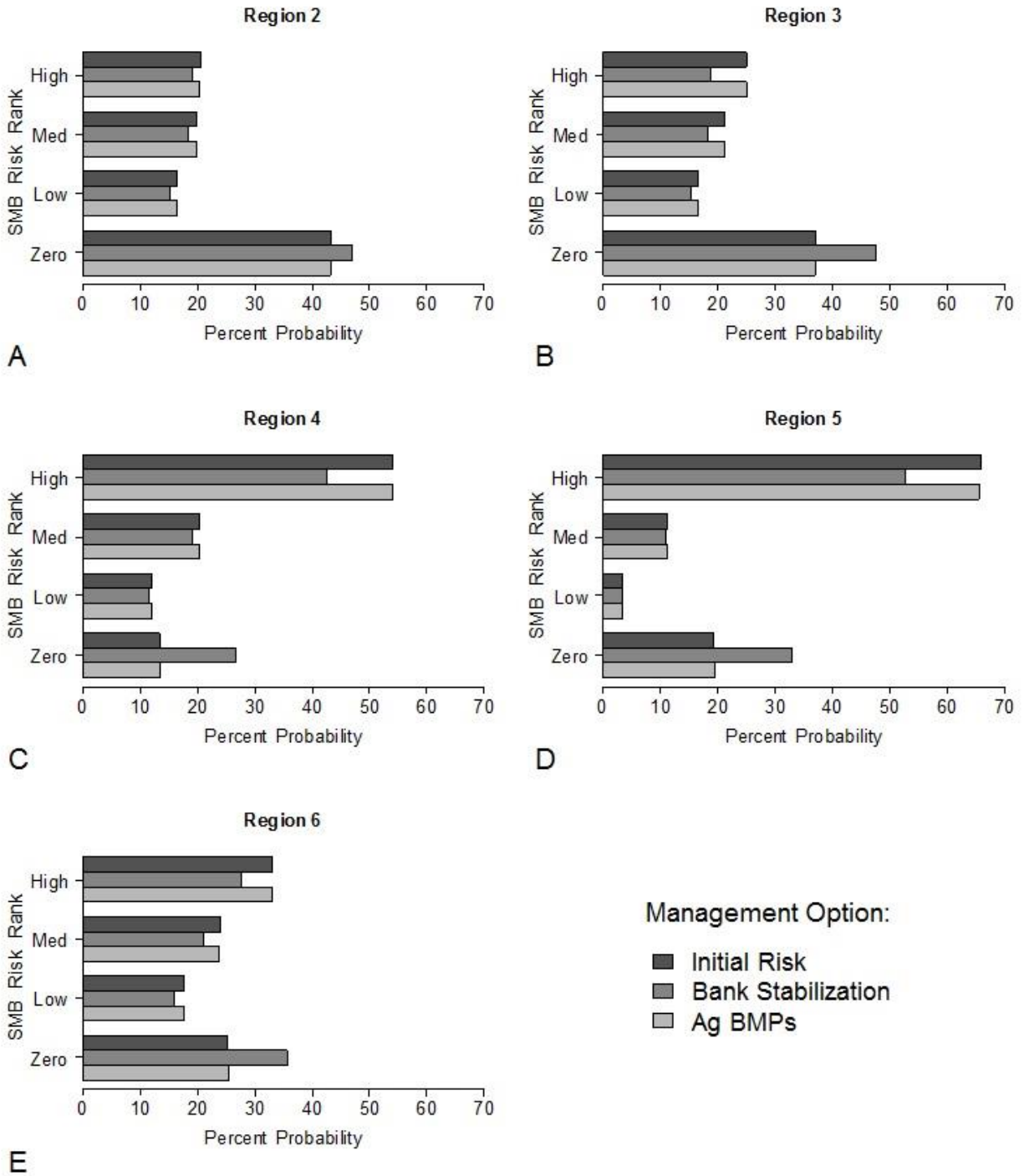
Figure 3-7. Smallmouth bass initial risk estimates and both Ag BMPs and BST options. Bank stabilization reduced risk to SMB more than Ag BMPs.
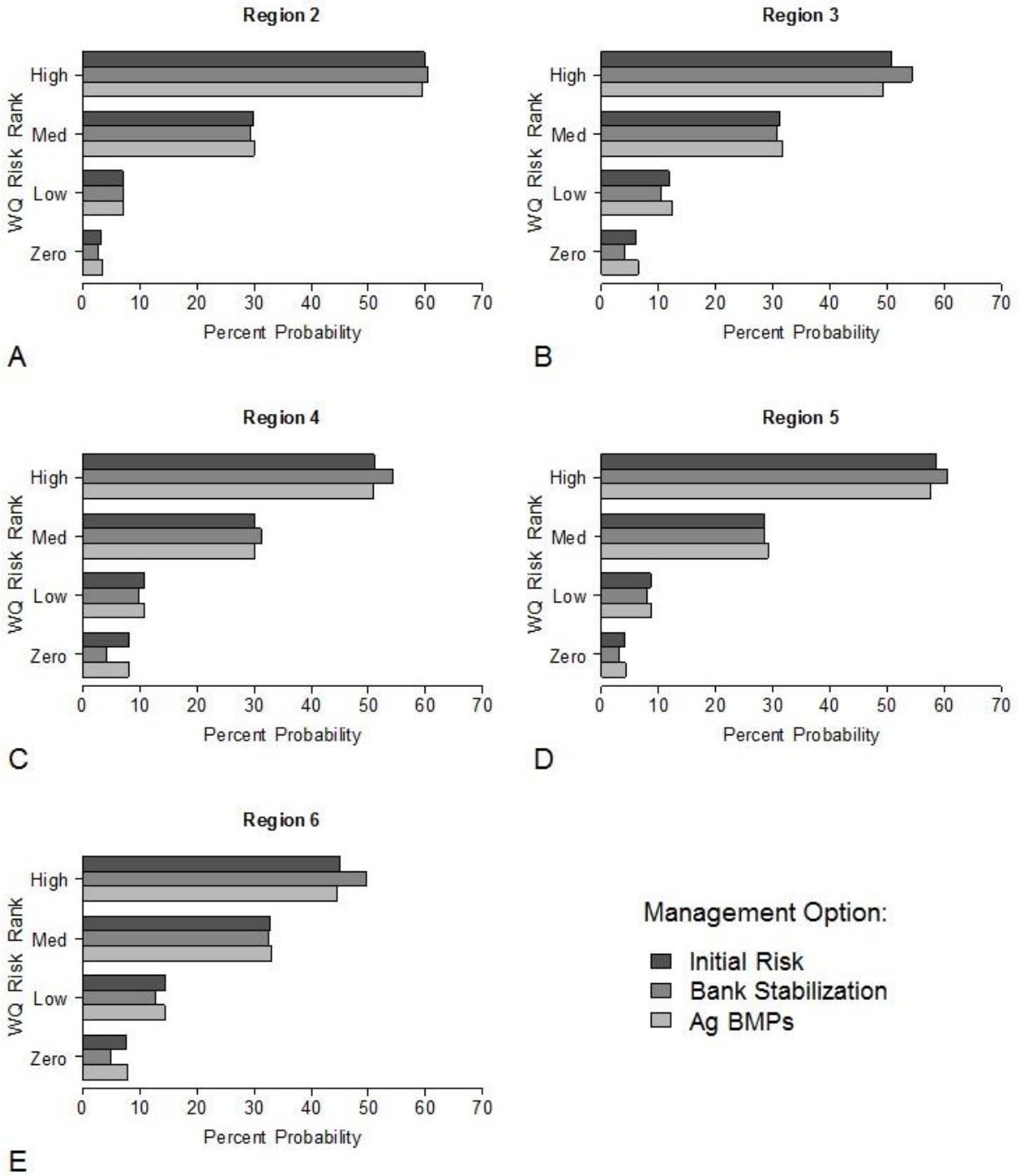
Figure 3-8. Water Quality Standards (WQ) initial risk estimates and risk with both BST and Ag BMP options.

The risk distributions for Swimming River Use and Boating River Use remained relatively similar with BST; however, there was a slight increase in risk in the high state. All distributions were skewed towards high risk. There was over 40% likelihood of high risk, and over 35% likelihood of medium risk (**Figures 3-9, 3-10**).
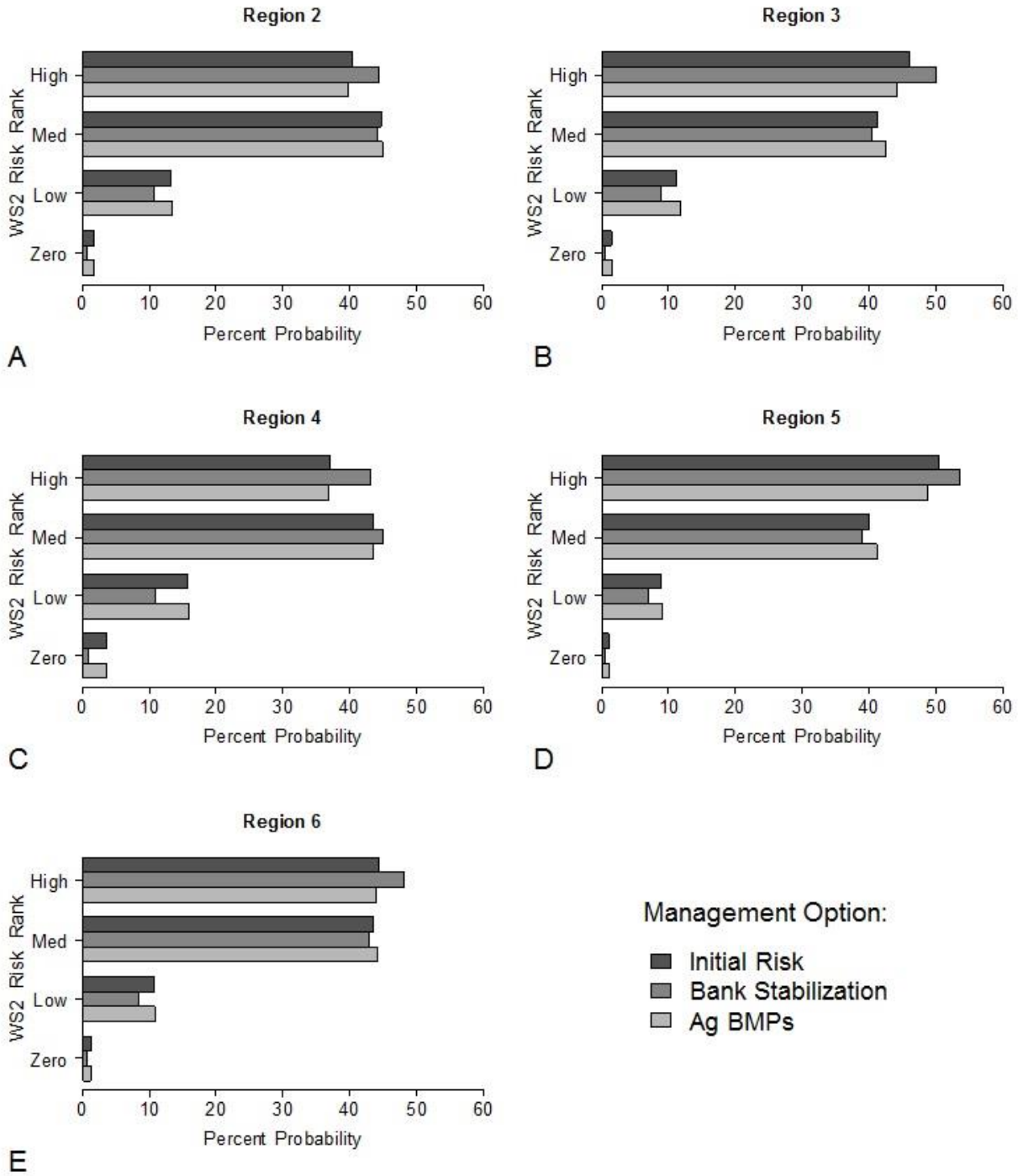
Figure 3-9. Swimming River Use initial risk estimates and risk with BST and Ag BMP options. In all scenarios, risk remained in the medium and high risk states.
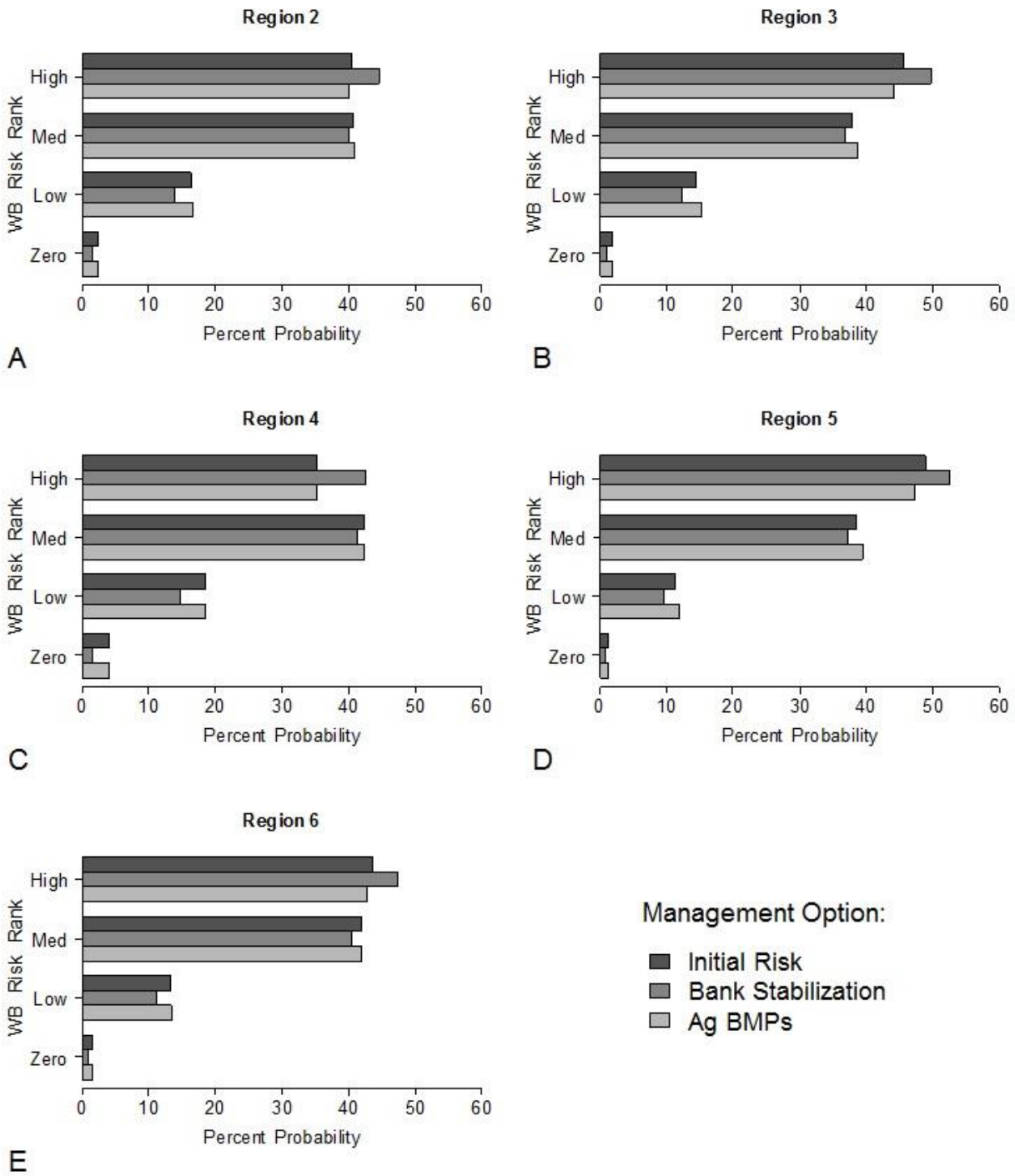
Figure 3-10. Boating River Use initial risk estimates and risk with both BST and Ag BMP options. Overall risk patterns showed that risk remained in the medium and high risk states with the various management options.
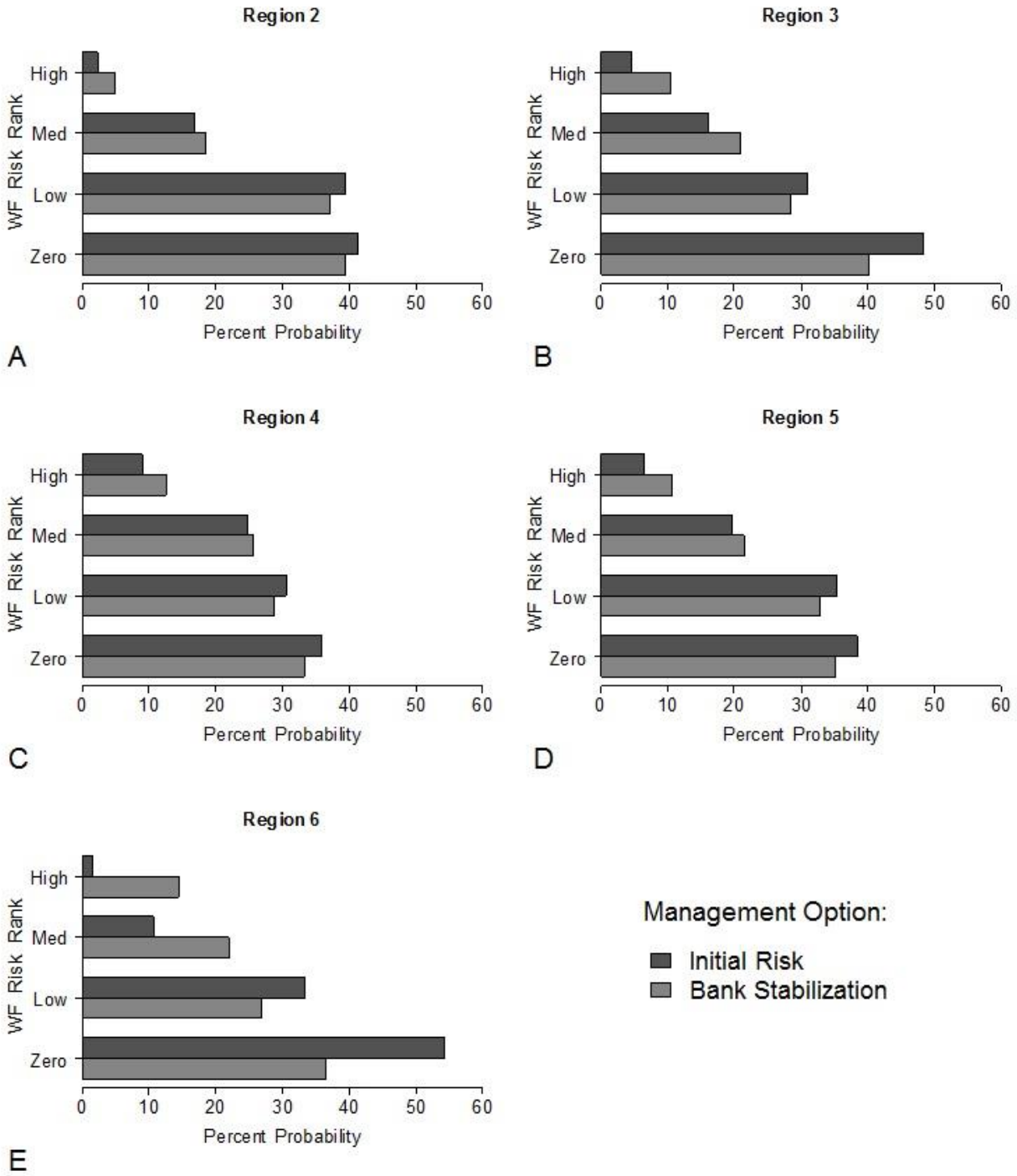
Figure 3-11. Fishing River Use initial risk estimates and risk with BST option. Ag BMPs are not shown because they did not alter input parameters for this endpoint.
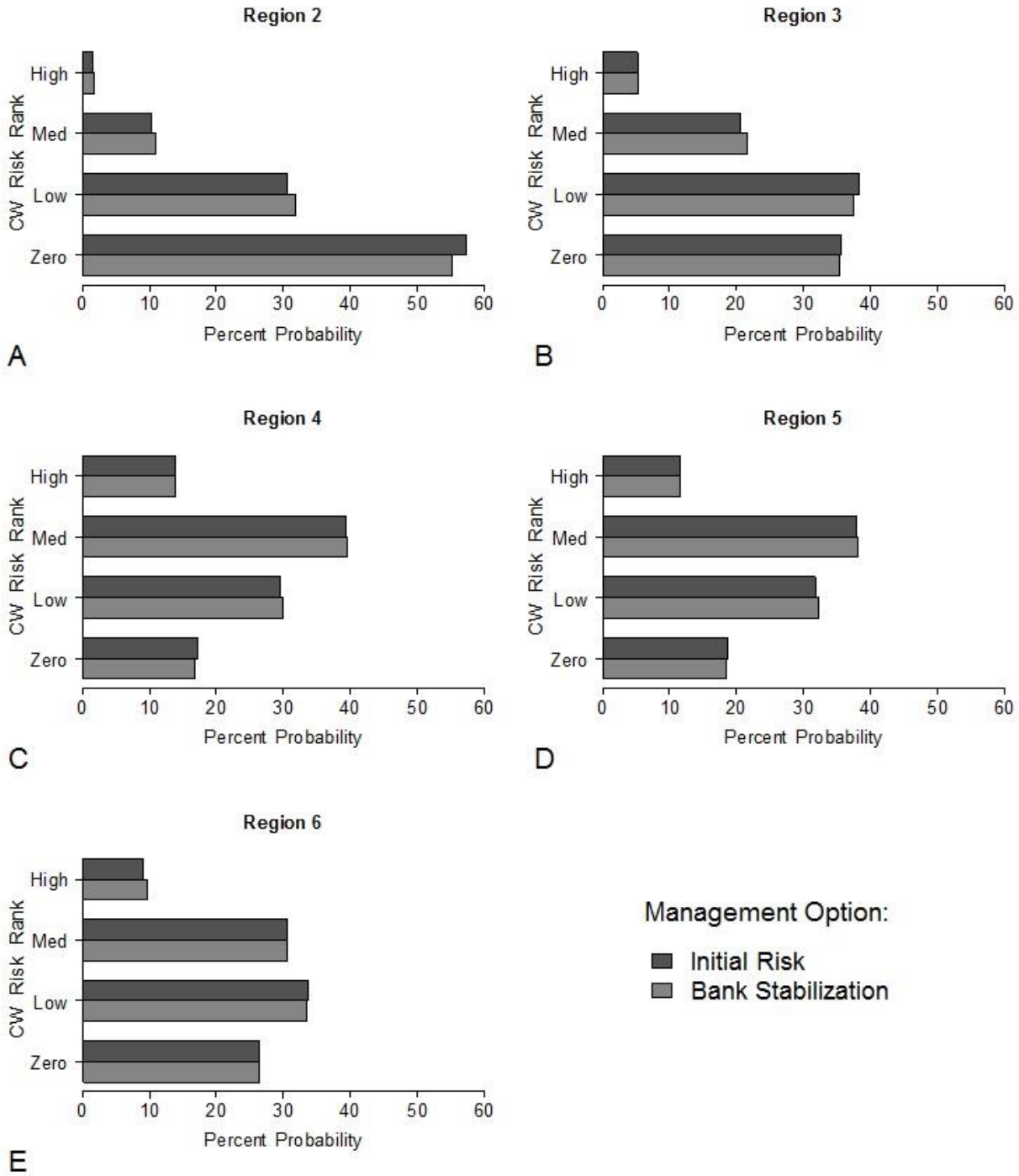
Figure 3-12. Carolina Wren initial risk estimates and risk with the BST option. Ag BMPs are not shown because they did not alter input parameters for this endpoint.
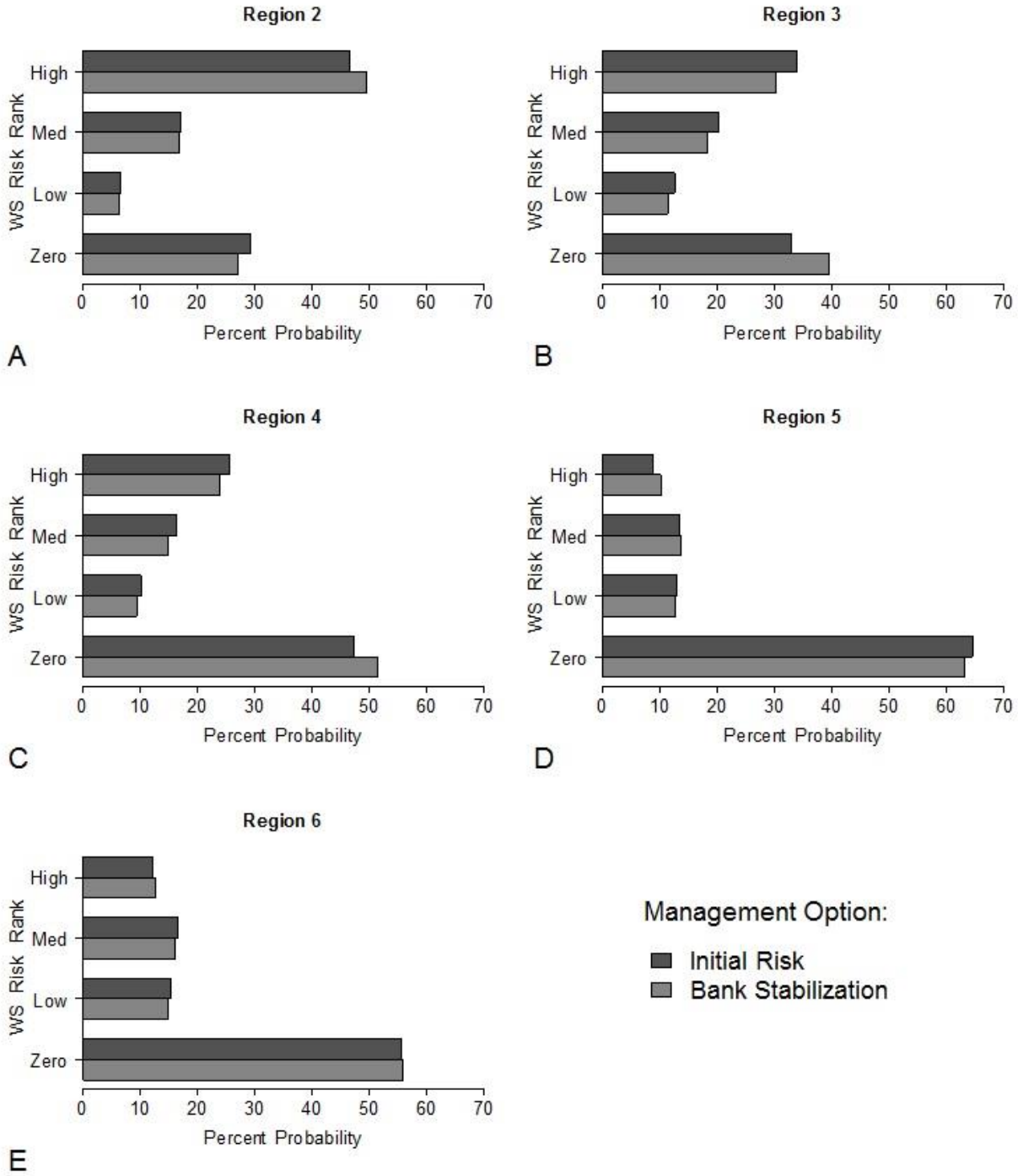
Figure 3-13. White sucker initial risk estimates and risk with the BST option. Ag BMPs are not shown because they did not alter input parameters for this endpoint.

3.7 Sensitivity and Uncertainty Analysis

3.7.1 Sensitivity as measured by Entropy Analysis Results
The results of the sensitivity analysis are presented graphically in **Figures 3-14** through **3-17**. The detailed scores are listed in **Appendix 17***.*

Biotic endpoints. Mercury was the top risk contributor to Carolina Wren and Belted Kingfisher in most risk regions for both management options. The management options did not change the main risk contributors to the bird endpoints (**Figure 3-14**). River temperature was the primary risk factor influencing smallmouth bass and white sucker in the initial risk BNs (see **Section 2**). Mercury had the second highest influence on smallmouth bass and third highest influence on white sucker. In many regions, river temperature was twice as influential as mercury on the fish species. Agriculture BMPs did not alter the influence of input parameters on smallmouth bass (**Figure 3-15**). The mercury reduction input parameter was used in place of the original mercury parameter as a main risk contributor to the fish species with BST management (**Figure 3-14**). For both fish species, the river temperature remained an influential parameter, along with stream cover for the white sucker in the BST management option scenario (**Figure 3-14**).

Abiotic endpoints. Overall, summer dissolved oxygen levels deviations from average river temperature, and bacteria indicators most strongly influenced risk to the water quality endpoints in the initial risk estimates (see **Section 2**). Additionally, methylmercury body burden in fish was consistently one of the main risk contributors to Fishing River Use. The integration of Ag BMPs and BST did not change the top risk factors influencing Water Quality Standards, Swimming River Use, and Boating River Use (**Figures 3-16, 3-17**). For Fishing River Use, summer dissolved oxygen levels became the most important risk factor with BST management option (**Figure 3-17**).

Deviation in river temperature was more sensitive in the BST management than the deviations in water discharge for the Water Quality Standards endpoint. Summer dissolved oxygen still was the most important parameter along with bacteria indicators contributing to risk. For the Swimming and Boating River Use endpoints, there was little to no change in the sensitivity of input parameters with the BST management (**Figure 3-17**; for comparison see **Section 2**).

3.7.2 Influence Analysis Results for Bank Stabilization
Bank Stabilization Management Scenario Results. Only the Water Quality Standards, smallmouth bass, and Fishing River Use endpoint figures are shown below. These endpoints had the greatest percent change for the biotic (smallmouth bass) and water quality (Water Quality Standards and Fishing River Use) endpoints. Additional tables describing the percent change calculations for the other endpoints are located in **Appendix 16**.

The bank stabilization Worst Case Scenario defined the upper range of possible risk to the endpoints from low efficacy of the stabilization efforts and/or additional exposure to stressors as a result of stabilization activities. In the Worst Case Scenario, risk distributions for most endpoints shifted towards higher risk compared to the risk calculation for BST management, however the degree of this shift differed among endpoints. Risk distributions of the Belted Kingfisher and Carolina Wren did not change. Smallmouth bass risk increased in Regions 4, 5,

and 6. In Region 5 there was a 25% increase in likelihood of high risk, resulting in a total high risk likelihood of 77% (**Figure 3-18**). The smallmouth bass risk distribution for Regions 4 and 6 shifted so that it was skewed towards high risk under the Worst Case Scenario by 17 and 14%, respectively. The skew in the White sucker risk distribution did not change. For Water Quality Standards the likelihood of high risk increased by 17-20% so the distributions were shifted towards high risk (**Figure 3-19**). Risk distributions for Fishing River Use, which were skewed towards zero and low risk in the Most Likely Scenario, shifted to the medium and high risk states. As a result, the likelihood of medium and high risk increased 8-12% and 7-20%, respectively (**Figure 3-20**). Water Quality Standards, Swimming River Use and Boating River Use risk distributions were skewed towards high risk under the Worst Case Scenario.
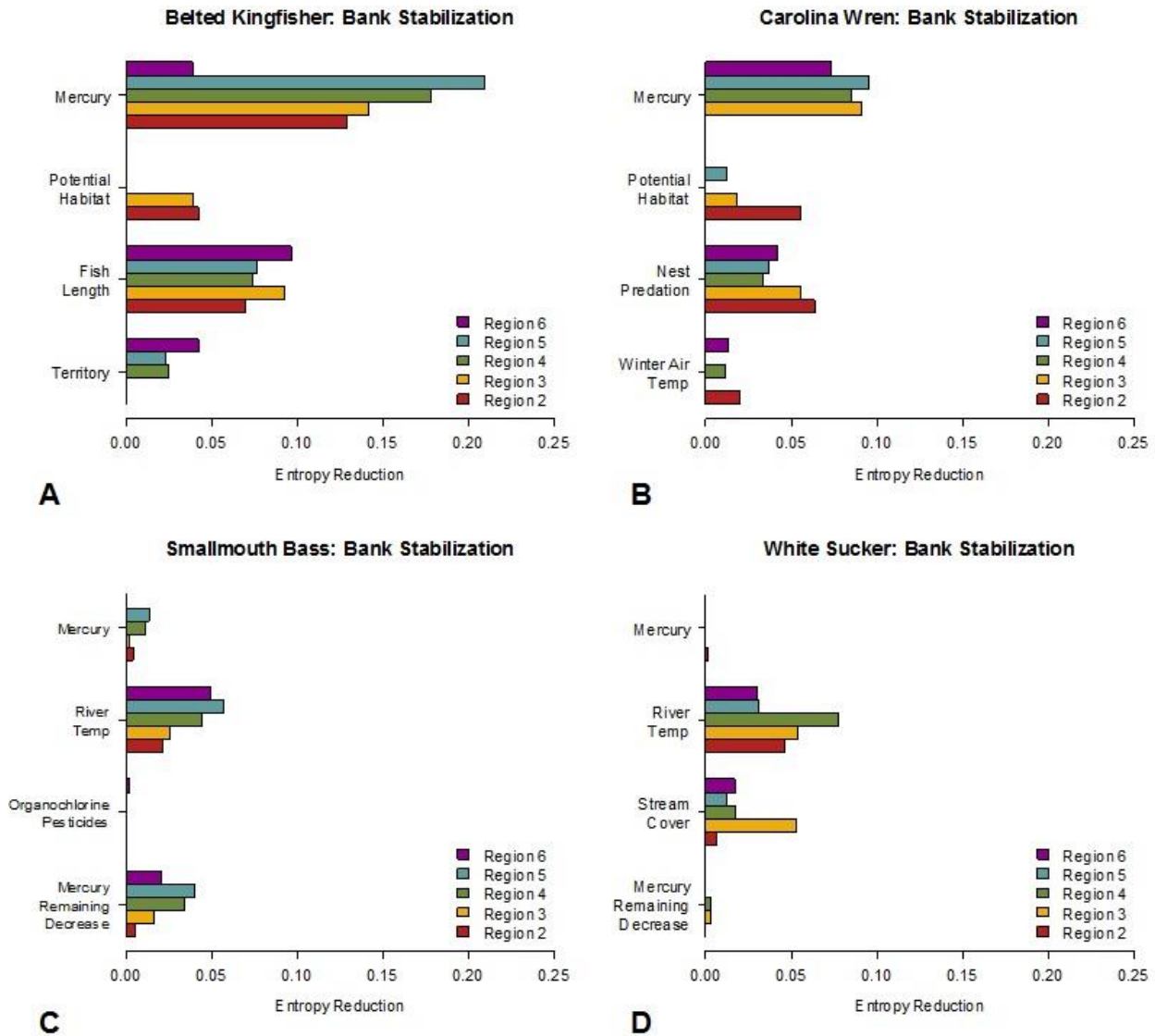
Figure 3-14. Entropy Reduction results for the biotic endpoints with the BST option.

The bank stabilization Best Case Scenario described the lower range of possible risk given high efficacy of the stabilization efforts and little or no additional exposure caused by stabilization activities. The skew of the risk distribution for Belted Kingfisher and Carolina Wren did not change under the Best Case Scenario. Under this scenario, Smallmouth bass risk distributions shifted from the high to zero by 10-15% in Regions 4 and 5 (**Figure 3-18)**. Similarly, the white sucker risk distributions shifted by 7% towards zero risk. Water Quality Standards, which were skewed towards high risk in the Most Likely Scenario exhibited a more even distribution of medium and high risk under the Best Case Scenario (**Figure 3-19**). Risk distributions for Fishing River Use became more skewed towards zero risk with 16-19% greater likelihood of zero risk (**Figure 3-20**). Swimming and Boating River Use risk distribution skews did not change.
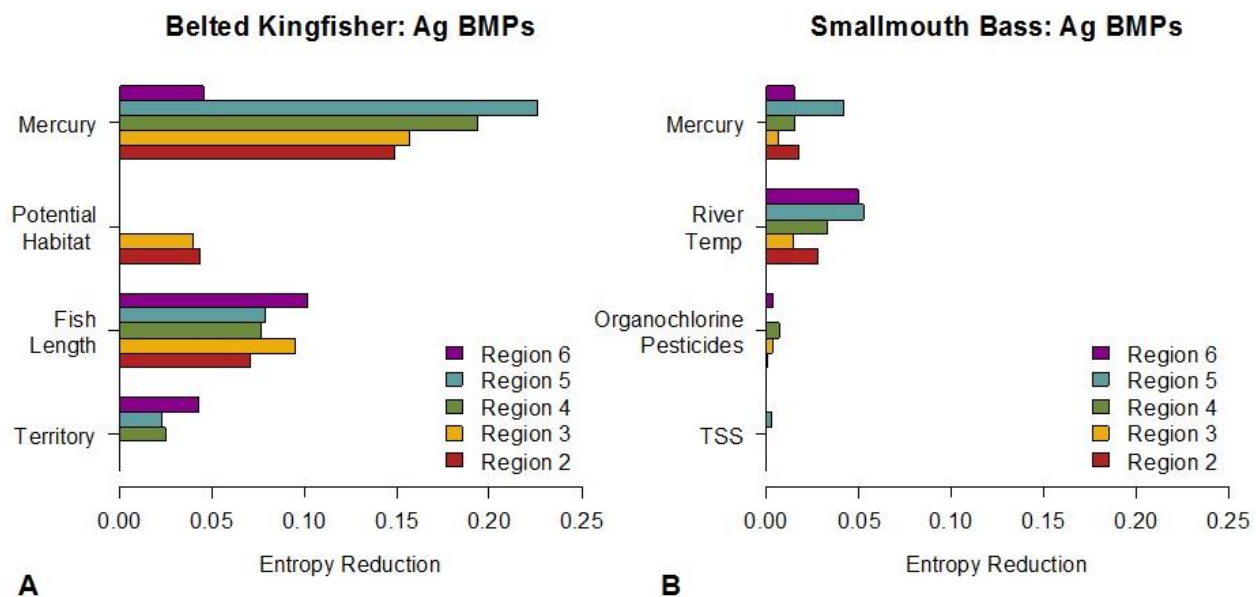
Figure 3-15. Entropy Reduction results for the biotic endpoints with the Ag BMPs option.

3.8 Discussion
In this research, we describe the development of conceptual models with management options for biotic and water quality endpoints. Risk distributions with Ag BMPs management and BST management were calculated to assess any changes in risk compared to the initial risk calculations. An entropy analysis on each BN identified important future monitoring parameters. Additive risk curves depicted the change in overall risk distribution with the management options.

3.8.1 Agricultural Best Management Practices
The integration of Ag BMPs in the BNs had little impact on risk. There was a small reduction of risk to some endpoints, but risk remained primarily similar to the initial risk estimates. Although implementing Ag BMPs would not reduce water quality endpoint risk distributions to low risk, the low risk to Belted Kingfisher and smallmouth bass would be sustained. Agricultural BMPs are a

plausible management option (low cost, low effort), however, initial risk from the targeted stressors is already minimal. The input distributions (priors) for total suspended solids, turbidity, and bacteria are primarily in the zero and low risk states, indicating that these stressors are not the main risk drivers. This was confirmed by the entropy analysis. Agricultural BMPs align with the main "no regrets" management objective for the South River because endpoint risk should not increase. This management option is therefore worth implementing because the output distributions would likely shift towards lower risk and Ag BMPs will help the South River move towards TMDL compliance. Furthermore, implementing the Ag BMPs can also be a preventative management option, reducing future risk related to agricultural practices.
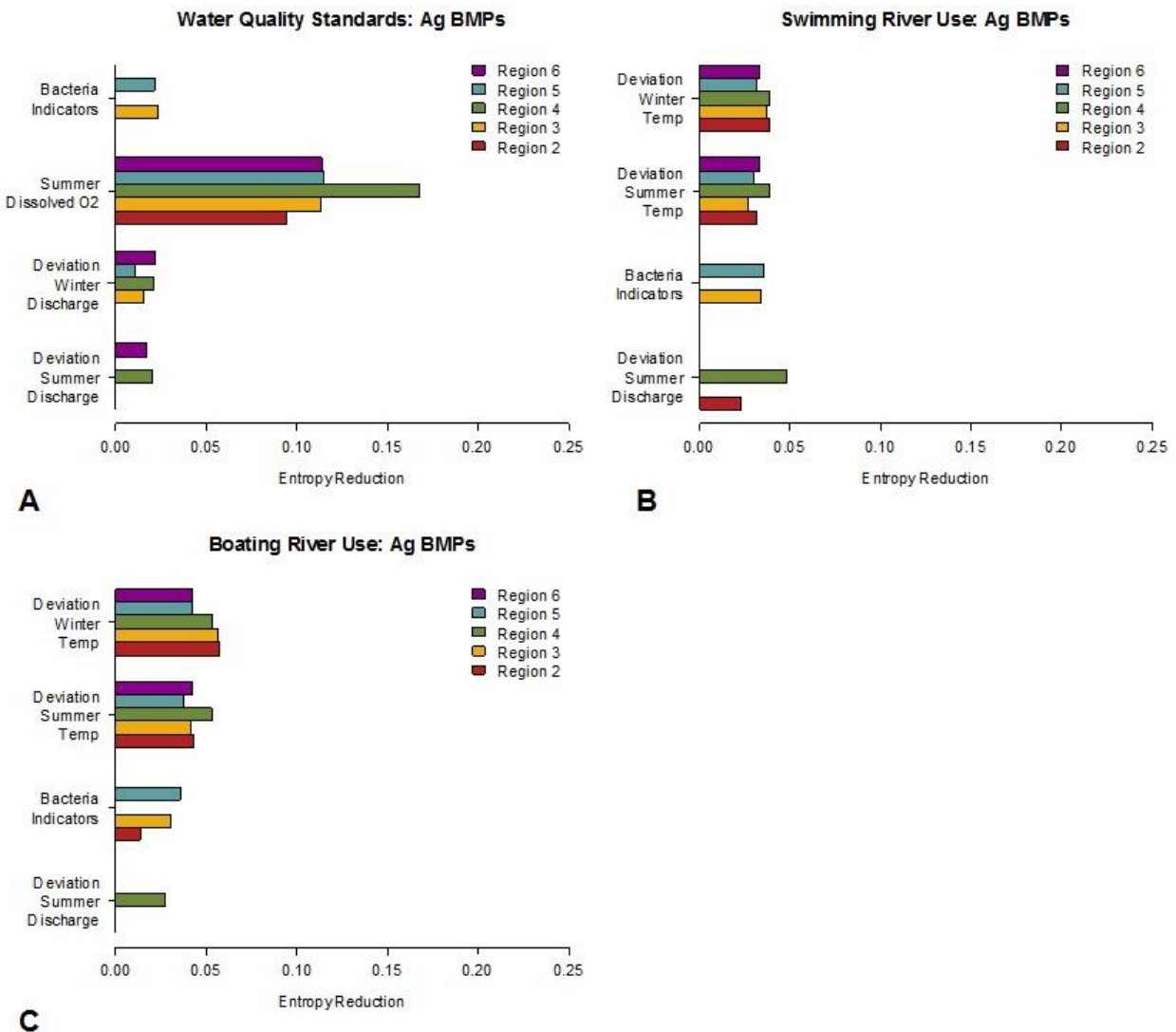
Figure 3-16. Entropy reduction results for the water quality endpoints with the Ag BMPs option.
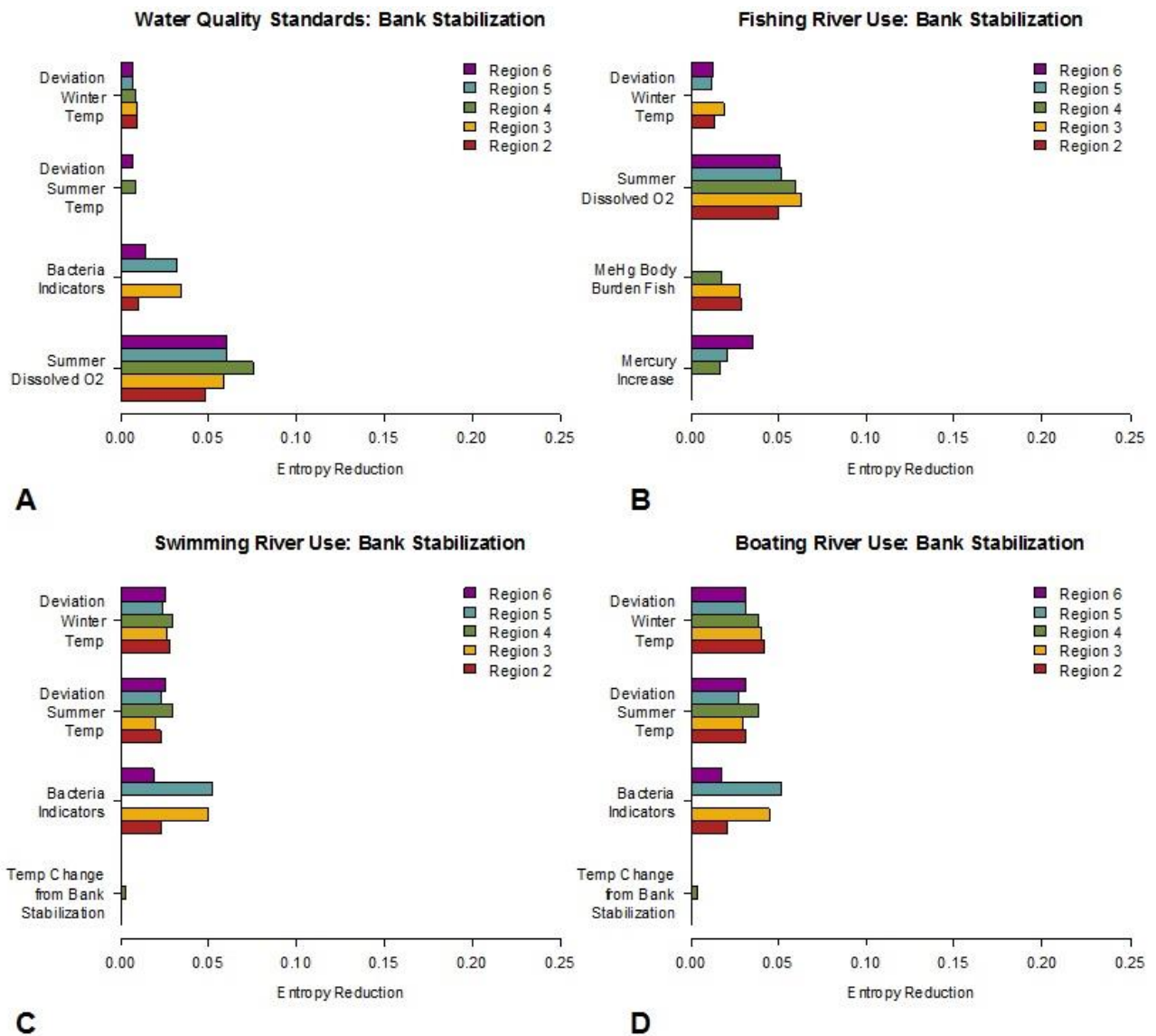
Figure 1-17. Entropy reduction results for the water quality endpoints with the BST option.
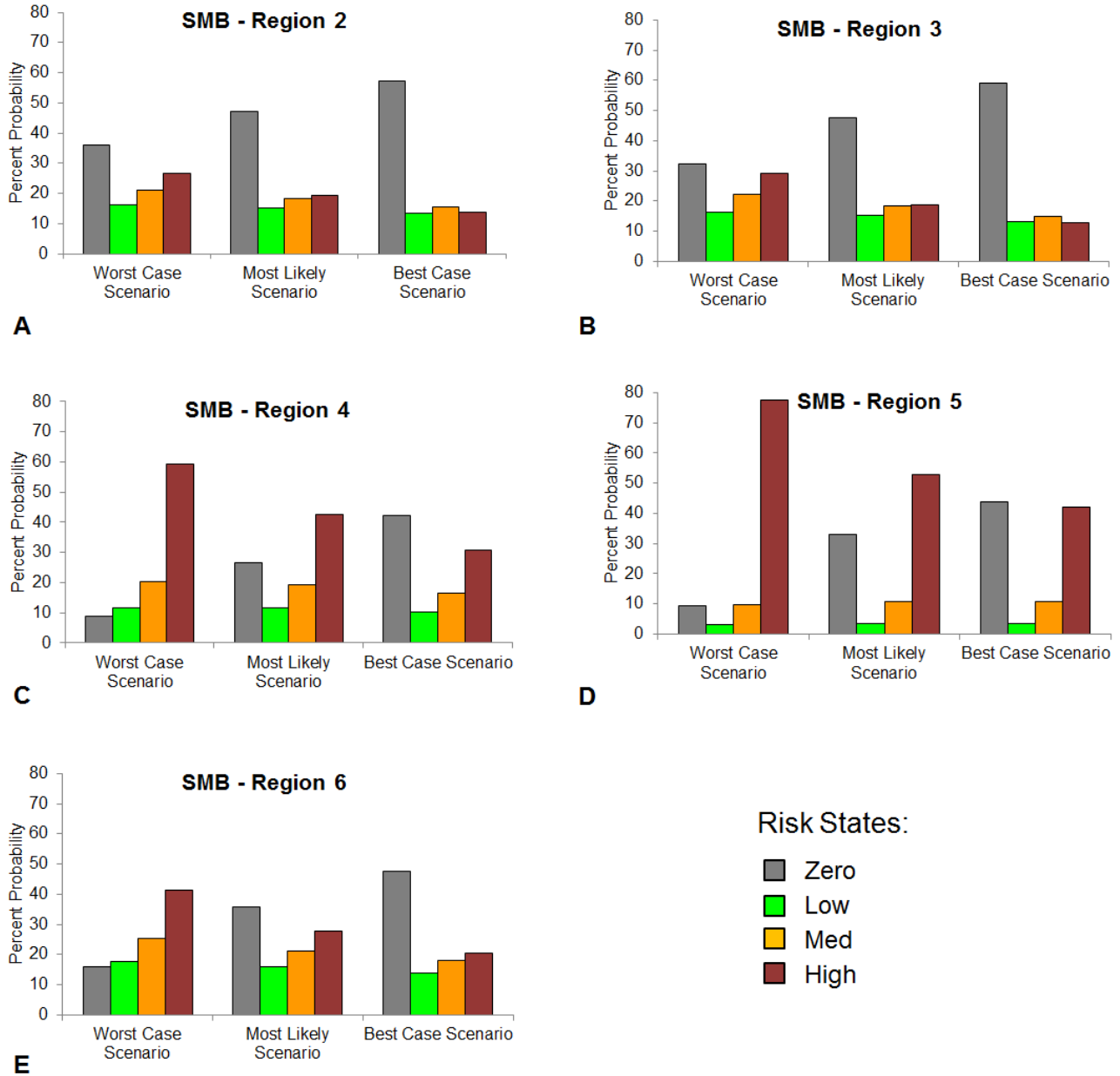
Figure 3-18. Bank stabilization scenarios for the smallmouth bass endpoint. These three scenarios show the Worst Case, Best Case, and Most Likely results for risk to SMB given the implementation of bank stabilization. Note that Regions 2 and 3 were at lower risk than Regions 4-6. Region 5 was at greatest risk in all three scenarios.

3.8.2 Bank Stabilization

Bank stabilization would not meet the "no regrets" management criteria for Belted Kingfisher if BST were to be completed without explicit avoidance of Kingfisher nests. The ability of BST to achieve "no regrets" for most of the remaining endpoints is less clear. In looking at overall risk patterns, the shape of the risk distribution for Carolina Wren, white sucker, Water Quality

Standards, Swimming and Boating River Use would not change. For instance, the Water Quality Standards, and Boating and Swimming River Use endpoints still display a pattern of risk skewed to the medium and high-risk states. If, however, we look more closely at the predicted probability distributions with the implementation of BST, we see an increase in risk up to 7% in the high-risk state for many endpoints and regions. This brings up the question of acceptable
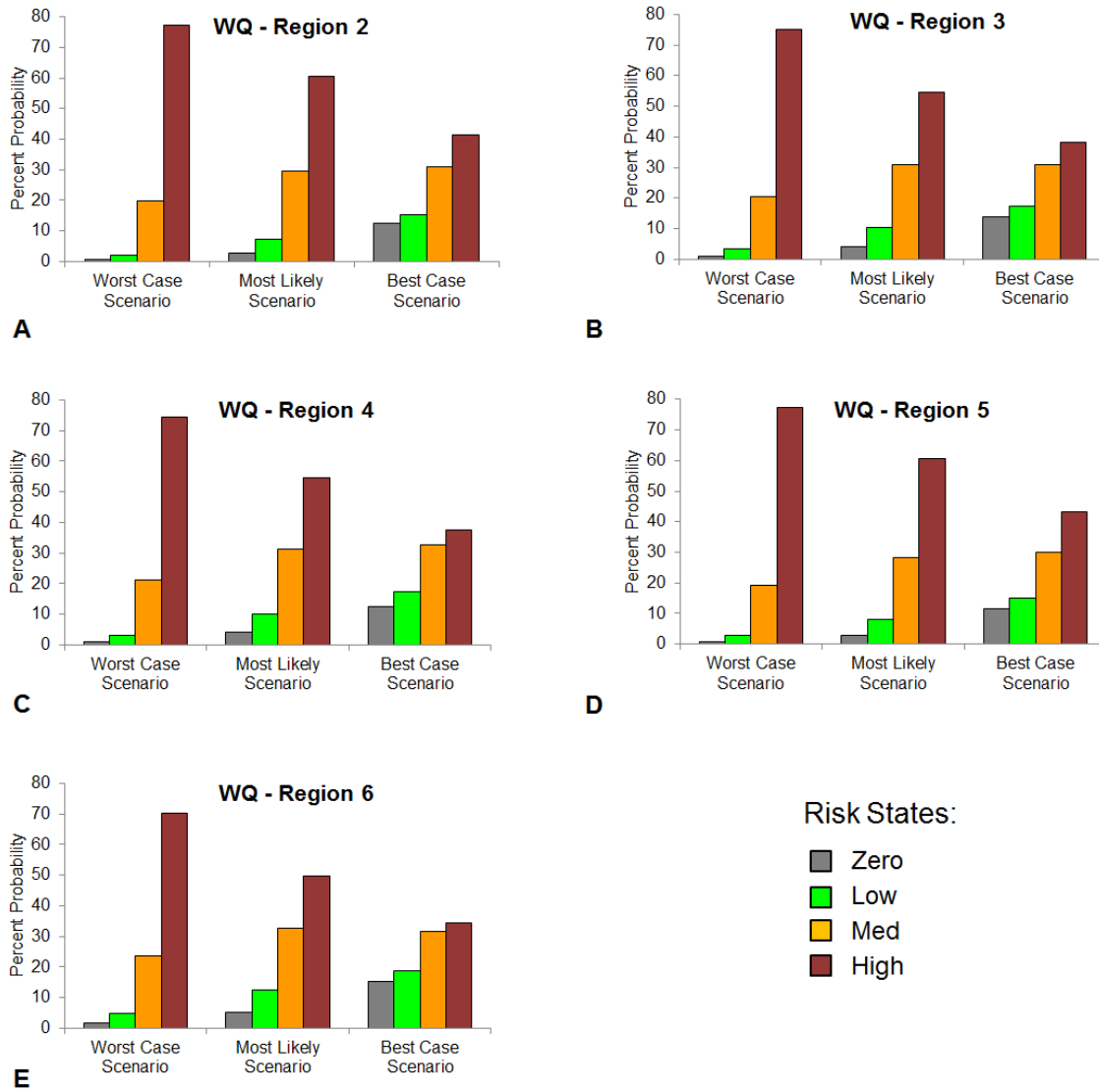
Figure 3-19. Bank stabilization scenarios for the Water Quality Standards endpoint. These three scenarios show the Worst Case, Best Case, and Most Likely results for risk to WQ given the implementation of bank stabilization. There was a similar risk pattern for all of the regions, where risk was skewed to the high state in all scenarios.

risk and what constitutes 'no regrets' as determined by the stakeholders of the South River. Stakeholders must also decide whether the "no regrets" goal is applied similarly to all endpoints, or more to some endpoints versus others. These are things to consider in moving forward with the implementation of management options.

Figure 3-20. Bank stabilization scenarios for the Fishing River Use endpoint. These three scenarios show the Worst Case, Best Case, and Most Likely results for risk to WF given the implementation of bank stabilization.

With the BST management, we expect a reduction of risk to smallmouth bass across many regions. Further, BST would reduce risk in Region 6 so that zero risk has the greatest likelihood. BST would not change the skew of Fishing River Use risk distributions since overall the majority of risk remains in the zero and low states. The likelihoo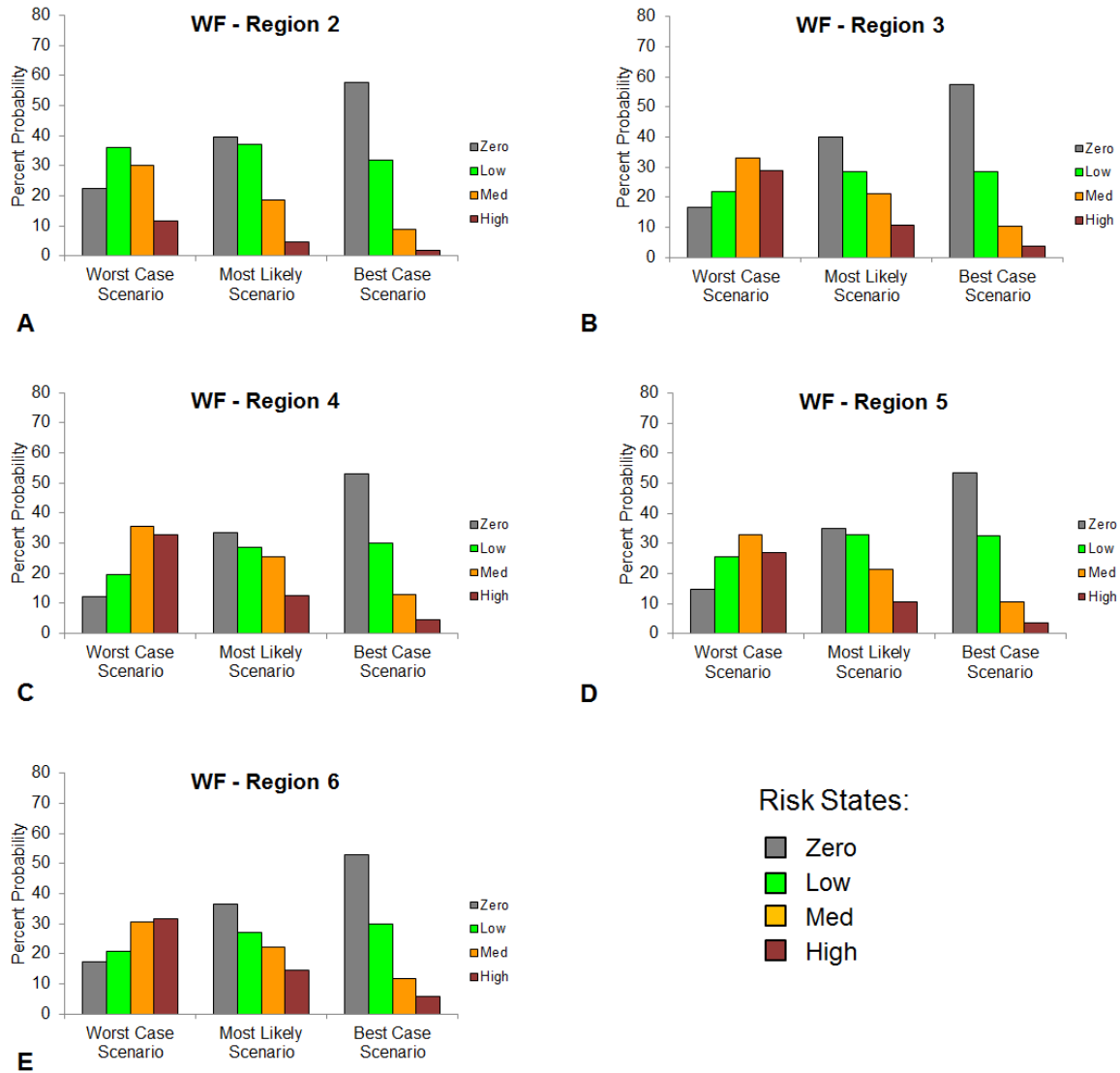d of zero risk, however, would decrease 20% in Region 6, resulting in a shift to the medium and high-risk states. This may be considered unacceptable to managers.

The bank stabilization Best and Worst Case Scenarios bracket the risk outcomes for BST management and further evaluates the potential for unintended consequences. The skew in the risk distributions for Belted Kingfisher, Carolina Wren, Water quality Standards, Swimming River Use, and Boating River Use would not change under either scenario, meaning there is greater certainty as to the effects of BST on these endpoints. Risk would remain skewed to zero or high risk, depending on the endpoint in question.

For the other endpoints, the effects of BST is less certain and the scenarios lead to different possible distributions of risk. Best and Worst Case Scenarios provide a range of possible risk to these endpoints. While the Most Likely Scenario represents our best estimation of the effects of BST on these endpoint, the Best and Worst Case Scenarios are possible outcomes and should be considered in decision making. For example, risk to smallmouth bass in Region 6 could be considerably higher under the Worst Case Scenario than the Most Likely Scenario versus being skewed towards zero under the Best Case Scenario. The Fishing River Use risk distributions, which are zero to low in all risk regions under the Most Likely Scenario shift towards medium and high risk under the Worst Case Scenario. In short, there is a wide range of risk outcomes that could occur with the implementation of BST management for these endpoints. At best, BST is highly effective at reducing stressor loads or exposure to those stressors. At worst, BST is ineffective at reducing stressors, and activities associated with BST may in fact increase stressor loading and/or exposure.

3.8.3 Application of BNs in South River Management

Using these BNs, South River managers can evaluate management scenarios by implementing one or more options, then monitoring key risk factors known for influencing other variables, and then updating the BNs to initiate the next decision cycle in adaptive management. An example of updating the BNs to inform future management is provided in **Figure 3-21**. In this example, the smallmouth bass BN in Region 6 was updated three subsequent times with the probabilities calculated for stressor nodes with BST as the new input distributions for the model. The distributions in **Figure 3-21** illustrate how risk changed through time with the updated inputs. In this simulation, smallmouth bass risk decreased the most in the first time step, and continued to decrease through the next three steps, but at a slower rate. Mercury was used in this example; however, we also updated the input distributions using the "post BST" nodes for the following parameters: PAHs, organochlorine pesticides, river temperature, and total suspended solids.

Risk curves with Ag BMPs emphasize that Ag BMPs meet the "no regrets" management criteria because the risk curves did not change. When the initial total risk curve for all endpoints is compared to those for BST management, the curve for Region 5 shifts toward lower risk. So

although risk to individual endpoints may increase with BST in some of the risk regions, it may make sense to implement BST in Region 5 since risk was lowered.
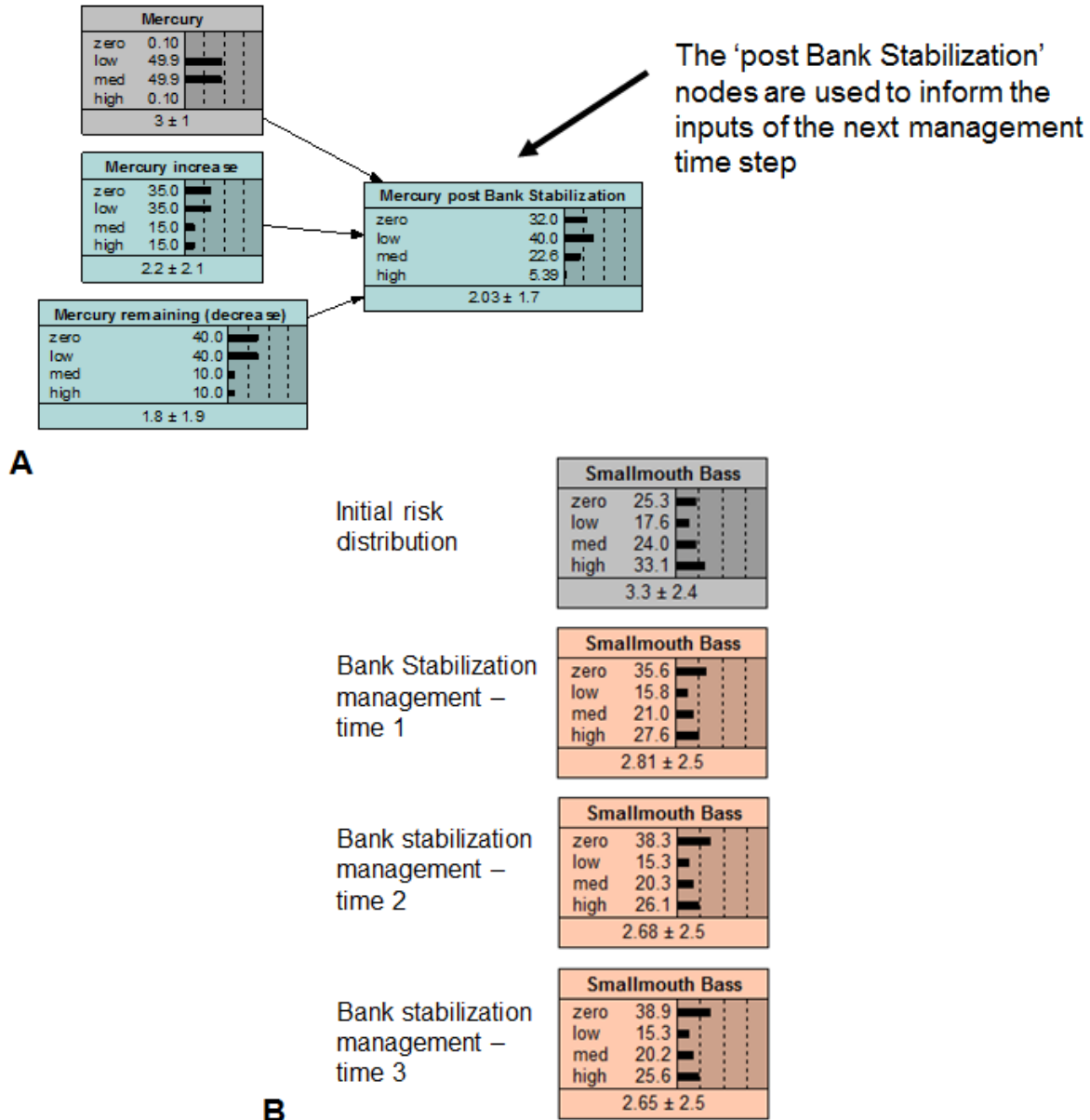
Figure 3-21. Risk with BST management can be recalculated risk over time. In this case, risk to SMB is recalculated three times, using data from post-BST management. The probabilities calculated in the stressor post-BST management nodes (A) were used as the input distributions for the next time step (B).

The entropy reduction analysis for each endpoint gives managers a list of monitoring parameters in the order of their influence on an endpoint's risk. Monitoring these stressors is

important for updating risk in using an adaptive management approach. From the entropy reduction analysis, it is clear that river temperature must be monitored more extensively to calculate risk to fish species. Mercury was most important to the avian species, but was also a risk driver to the fish species and Fishing River Use. Suggested monitoring parameters for the other water quality endpoints are summer dissolved oxygen levels and deviation from summer and winter average river temperature (see **Section 4**). River temperature is a major risk factor influencing water quality endpoints, as well as both fish species. Managers of the South River should consider options that may reduce risk from this stressor.

Using the back-calculation feature of BNs, managers can estimate initial conditions that produce a specific risk level. This type of analysis may initiate discussion and evaluation of additional management options. The initial conceptual models and BNs we constructed that do not include management options can serve as a starting point for the evaluation of additional management alternatives.

The results of our research can also be used in combination with other studies of the South River in the adaptive management planning and implementation cycle. A recently completed study by John W. Green (personal communication, 2014), used statistical modeling to estimate predicted reductions in mercury concentrations in surface water and sediment if BST removed 100% of mercury from the banks. Green also calculated the number of samples necessary to detect the calculated change in surface water and sediment mercury concentrations. Using the statistical models developed by Green, we could calculate the number of samples needed during monitoring to detect the expected changes in fish fillet mercury modeled using the BNs with BST management.

3.8.4 Next Steps for Management along the South River
There are currently plans to implement BST along sections of the South River as part of the RCRA remediation plan. Our BNs can be used to identify areas where BST is likely to cause increased risks, as well as help managers prioritize monitoring parameters. Because management of the South River is long-term, an adaptive management implementation cycle may be 10-15 years; however, the BNs can be updated more frequently to provide updated estimates of risk as more data are collected post-remediation.

Every site has multiple stressors, and trade-offs are a reality for managers. Other factors beyond ecological risk may be considered in the decision-making process including cost, human health risk, and stakeholder approval (Kiker et al. 2008). The BNs in this study have incorporated two management options into a risk assessment framework in doing so, we have created a method by which other factors that may be considered in the decision-making process can be incorporated into the model as well.

4.0 SUGGESTED PARAMETERS FOR LONG-TERM MONITORING OF THE SOUTH RIVER

One of the issues in designing a monitoring plan for the long-term management of a resource is the question of what to measure. In June of 2014 we were asked to suggest parameters based upon the results of our risk assessment activities. This section summarizes those findings.

4.1 Basis for parameter selection

Section 2 and 3 describe the use of the entropy analysis to identify the variables that are most important in determining the output from each risk assessment model. The same process was conducted for both the initial risk assessment and the assessment of each of the proposed management options afterwards. The methods and results of the entropy analysis are reported in those sections.

The results from the sensitivity analysis provided a comprehensive list of the parameters that should be monitored currently and in the future. The most important parameters for each endpoint are listed in **Table 4-1**. The methods for the sensitivity analysis of the initial risk assessment can be found in **Section 2.9** and the results in **Section 2.11**. The methods for the evaluation of the management options are located in **Section 3.5** and the results in **Section 3.7**. In addition to the sensitivity analysis results, we also added parameters for which we had limited sampling data to our list of recommended monitoring parameters.

4.2 Parameters from the initial risk assessment

The monitoring parameters for each of the endpoints are based on the parameters that have the greatest influence on risk to the fish, birds, and water quality endpoints. The parameters are listed from top priority on down, 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. These parameters are listed in **Table 4-1 Part 1**.

4.3 Parameters from the management options

It is not yet clear what management options will be implemented or their exact design. The sensitivity analysis for each, however, provides indications of what variables should be monitored as the option is implemented. Those variables are listed in **Table 4-1 Part 2**. Note that the lists are very different. The parameters for Ag BMPs are focused on the water quality parameters. Bank Stabilization has a much broader list since the option is expected to impact the availability of the mercury and alter the habitat upon construction.

As a management option is considered for implementation it is important to start monitoring the parameter(s) beforehand, as well as afterwards. In that way the evaluation can use a "Before and After Control-Impact" design (BACI) (see Conquest 2000, Clements 2004, Clements and Rohr 2009). The methodology has proven useful in many situations and the data analysis tools have become much more applicable to ecological structures.

Table 4-1.   **Part 1**. Recommended monitoring parameters to include in the monitoring program that will support the South River risk assessment. These parameters had the greatest influence on risk to the fish, birds, and water quality endpoints. Parameters are listed from top priority down; the numbers in parentheses indicate the number of risk regions in which the parameter was important. The parameters in **Bold** are the parameters we would like SRST to add to its monitoring plan.

Endpoint	Input parameter
Belted Kingfisher	**Mercury (5)** – Blood samples **Fish Length (5)** **Potential Habitat (2)** – Land use type (%) **Territory (3)** – Nests per length of river section (m)
Carolina Wren	**Mercury (4)** – Blood samples Nest Predation (5) **Potential Habitat (2)** – Land use type (%) Winter Air Temperature (4)
Smallmouth Bass	**River Temperature (5)** **Mercury (5)** – fish fillet mercury concentrations
White Sucker	**River Temperature (5)** **Stream Cover (5)** – Submerged aquatic vegetation cover (%) **Mercury (4)** – Fish fillet mercury concentrations **PAHs (1)**
Water Quality Standards	**Dissolved Oxygen (5)** - Summer dissolved O_2 **Bacteria (4)** – Bacteria indicators (*E. coli*) **River Temperature (3)** – Winter temperature **River Discharge (3)** – Summer & winter discharge
Fishing River Use	**Dissolved Oxygen (5)** – Summer dissolved O_2 **Methyl Mercury (4)** – Fish fillet MeHg concentrations **River Temperature (5)** – Summer & winter temperature
Swimming River Use	**Bacteria (4)** – Bacteria indicators (*E. coli*) **River Temperature (5)** – Summer & winter temperature **River Discharge (1)** – Summer Discharge
Boating River Use	**River Temperature (5)** – Summer & winter temperature **Bacteria (4)** – Bacteria indicators (*E. coli*) **River Discharge (1)** – Winter Discharge

Table 4-1   **Part 2**. Recommended management monitoring parameters to address the lack of site-specific data and decrease uncertainty as management alternatives are implemented.

Management Type	Input Parameter
Agricultural Best Management Practices (Ag BMPs)	Total suspended solids Total phosphorus *E. coli* levels
Bank Stabilization	Total suspended solids Fish fillet mercury concentrations Bird blood mercury concentrations Stream cover Habitat alteration (habitat loss for the Belted Kingfisher) Dissolved oxygen Discharge

4.4 Parameters for the reduction of uncertainty

Examining the different sources of the data and their respective impacts on the uncertainty associated with the data inputs we had to use has resulted in us formulating suggestions regarding future monitoring to reduce the uncertainty. These suggestions are presented in **Table 4.2** and are organized by risk region.

Risk region 1 has not been sampled so uncertainty regarding all endpoints is large compared to the other risk regions. Given this situation, a set of risk assessment models could not be built so that reliable comparisons could be made with the other risk regions. Also Region 1 is upstream of the source of mercury, is a source of nutrients, influences water temperature, and has a number of agricultural, residential and small manufacturing sites with associated potential sources of contaminants that can influence downstream sites. Especially after implementation of the management options, information on Region 1 may provide information regarding confounding factors influencing the outcomes of some of the other models.

In Region 4, water quality data are important to several of the endpoints and as such more data, comparable to those collected by a USGS gauge station would reduce uncertainty. In Region 5 relatively few samples reported PAH and pesticide levels. More data would identify whether these results are isolated pulses or chronic releases to the river, as well as help quantify concentrations more accurately.

Region 6, the South Fork of the Shenandoah River, had relatively few sampling data. We understand that this is just downstream of the South River and its importance was understood later on in the risk assessment process than the other sites. A number of variables are listed in **Table 4.2** that would improve the risk estimate for that region.

In the current database, the data are from samples collected more than five years ago. These variables are listed by the endpoint that they inform in **Table 4.2**. For example, River

Temperature was one of the parameters with the greatest influence on the endpoints, however, the last available data were from 2011. Updating these data would enable us to update 6 out of the 8 endpoints in the model.

Table 4.2   Data needs for reduction in model uncertainty.

Region	Monitoring Data
Region 1	Sampling of parameters listed in Table 4-1 (Parts 1 and 2)
Region 4	River Temperature, discharge and DO data
Region 5	PAH & Pesticide data (more data samples)
Region 6	**Belted Kingfisher:** fish length, turbidity **Carolina Wren:** Hg Blood **Smallmouth Bass & White Sucker:** Hg Tissue **Water Quality:** Total Phosphorus, MeHg for all fish **Fish stocking**
All Regions	**Belted Kingfisher:** Mercury, pesticides, turbidity, SAV (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 DO, Winter DO, E. coli (limited samples across all regions)

5.0 HUMAN HEALTH RISK ASSESSMENT

The next focus for the South River risk assessment process is the integration of the human health risk assessment with the ecological risk assessment. We will assess risk to human health, recreation, and ecosystem services of the South River through the fully integrated BN-RRM model. Fish, water, and soil are routes of Hg exposure to the human population. The current ecological assessment covers risk to two of these pathways, fish and water. In the human health risk assessment (HHRA), human Hg exposure from soils will also be evaluated. Current human health guidelines on Hg exposure limits will be used to set ranking schemes and determine risk to human health and recreational use in the river and its floodplains. These endpoints will then be combined with biotic and water quality endpoints to assess overall risk to ecosystem services. As with previous work, these risk estimates will be compared across regions of the study area.

5.1 Goals and Objectives

To expand on the relative risk assessments for biotic and water quality endpoints, we are currently working on a human health risk assessment (HHRA) for the South River. The human health risk assessment will be integrated with the ecological risk assessment already conducted, which includes both the biotic and water quality endpoints (**Figure 5-1**). The integration process began with endpoint selection and construction of the conceptual model and will continue through risk analysis and risk communication stages. Integration of the HHRA and ERA will provide a more holistic picture of risk by producing coherent and comparable results that can be used by risk managers to understand human, as well as ecological relationships, weigh tradeoffs, and guide management decisions.

5.2 Integrating Ecological and Human Health Risk Assessment

The World Health Organization International Program on Chemical safety (WHO IPCS) has defined integrated risk assessment as a "science based approach that combines the processes of risk estimation for humans, biota and natural resources in one assessment" (2001). Integrated risk assessment may offer many advantages in managing natural resources, human health, and ecological risk with few drawbacks, yet there are few examples of such integrated risk assessments in the published literature to date.

Integrated risk assessment differs from a more traditional approach of conducting parallel risk assessments, in which risk for human health and ecological endpoints are calculated independently, but used to manage the same site or stressor. The parallel approach is problematic for a number of reasons. Independent risk assessments that are based on different assumptions or conditions (chemical concentration, temporal and

spatial scale, etc.) make it difficult to compare results in a useful way (Suter 2003, Bridges 2003). In contrast, integrated risk assessment can provide a clearer and more accurate picture of community or structure-wide effects and overall risk.

Critics of integrated risk assessment cite the increased complexity and potential cost of such risk assessments (Munns 2003). However, each of these arguments can be addressed with the appropriate risk assessment tools. A thorough understanding of the system, sufficient data, and the use of BNs will allow us to integrate human and ecological models in a time- and cost- effective manner. BNs provide a useful tool for organizing information and visualizing complex relationships between models. Much of the data used in the biotic and WQ models will be used in the human health risk assessment.

An integrated risk assessment of the South River will ensure that risks to human and non-human endpoints are calculated on the same scale, under the same conditions, and given the same assumptions. This will allow us to calculate overall risk and provide a better picture of risk to understand trade-offs and guide management decisions. Shared conceptual models will ensure that integration is present throughout the entire risk characterization process. Common methods for weighing evidence, expressing uncertainty, and conveying risk will ensure that results are coherent and comparable across disciplines and applicable to management of the South River.

5.3 Model Construction

Using the original conceptual model for biota and water quality as a template, we have drafted three additional conceptual models for human health, recreation, and ecosystem services for the South River (see **Appendix 18).**

Human Health. The human health conceptual model consists of sources of stressors (chemical and non-chemical) that are connected to the human health endpoint through specific routes of exposure. While mercury is the primary focus of the human health model, other potential stressors include PAHs, organochlorine pesticides, suspended solids and *E. coli*. While all stressors in the human health model were considered in either the biotic or WQ models, sources and exposure pathways for human health may differ from previous models.

The human health model is divided into two primary routes of exposure, as identified by the SRST Human Exposure team: dietary exposure (food sources and drinking water) and physical (dermal) exposure from contact with soil and river water). Cumulative dietary exposure from garden crops, livestock, fish, waterfowl, and wildlife will be assessed using data collected by URS Corporation and the SRST. Soil and river contact includes mercury, PAHs, and pesticide exposure for residents and recreational users.

Recreation. This model combines the river use endpoints from the original WQ model with two additional floodplain use endpoints to represent risk to all recreational activities relating to the South River. Intermediate recreational endpoints will include Hunting and Birding/sightseeing, which will be used to derive an Overall Recreation endpoint, i.e., all recreation endpoints combined.

Ecosystem Services. This human-centric risk assessment will combine human health, water quality standards (as an indicator of public health), recreational use, and the SR fishery to assess risk to overall utility of the river and provisioning of ecosystem services. This model builds on all previous and concurrent models (human health, recreation, water quality, and biotic) to provide a picture of overall use of the South River by the communities that depend on its services.
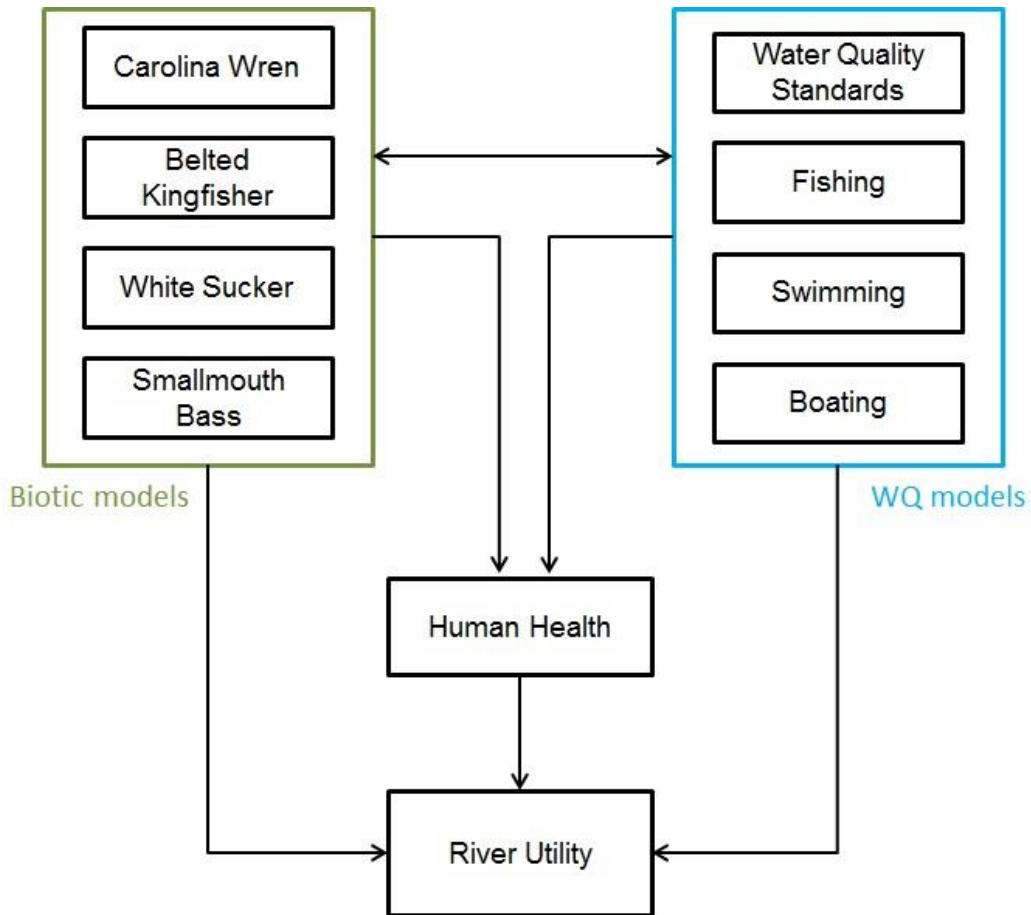
Figure 5.1 Integrated risk assessment for the South River. Biotic, Water Quality, and Human Health models are connected by shared model parameters, conditions, and assumptions.

5.4 Timeline

Following a thorough literature review, we completed the conceptual models described above during the summer of 2014. These conceptual models formed the framework for BNs that have been parameterized with site specific data and ranking schemes based on both human health regulatory criteria and relevant scientific literature. Input distribution frequencies, i.e., prior probabilities, were derived from site-specific monitoring data from SRST and URS Corporation. We have initial risk estimates for all three models and will complete uncertainty and sensitivity analysis by Fall 2014.

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