Enhanced Adaptive Management Framework for Remediation of a Mercury Contaminated River

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Abstract

Uncertainties about future conditions and the effects of chosen actions, as well as increasing resource scarcity, have been driving forces in the utilization of adaptive management strategies. However, many applications of adaptive management have been criticized for shortcomings including lack of direct links between anticipated outcomes and management alternatives and the complexity of coordination of the series of decisions with stakeholder input or values. We supplement existing adaptive management approaches with a decision-analytical approach that guides initial selection of management alternatives and also allows for learning based on monitoring information and incorporation of stakeholder values. The model provides the remedial implementation team with transparent set of recommendations for further consideration. We illustrate the use of this enhanced adaptive management (EAM) framework to analyze remedial alternatives at a mercury-contaminated river, based on an understanding of the loading and behavior of mercury in the South River near Waynesboro, VA. The results show that the performance of alternatives is highly influenced by the importance placed on different objectives, by uncertainty in the contaminant loading model and by cost estimates. The process itself demonstrates that a decision model can link environmental models and short- and long-term monitoring information with management choices to help shape a remediation approach so that it provides information useful for adaptive incremental implementation.

I. Introduction

Adaptive management was first presented as a way to make decisions on course of action based on emerging information to improve outcome and reduce the uncertainty. It was advanced in the 1970s under the name "adaptive environmental assessment and management", as articulated by ecologists C.S. Holling (1978) and C.J. Walters (Johnson, 1999a; Lee, 1999). Adaptive management efforts have largely focused on resource management projects, such as the Everglades (REF, Convertino et al. 2014). Adaptive management approaches and applications have been the subject of multiple National Academies of Science reports, including one general review (National Research Council (NRC) 2003, 2004, 2006). One of the most important findings is that adaptive management has been inappropriately applied (NRC 2004). In many cases, the process of "trial and error" has been mislabeled as adaptive management. However, "trial and error" does not allow for learning from the outcome of the first approach nor does it develop *a priori* plans for changing management approaches as data reveals the outcome to be different from what was intended. Adaptive management requires that a range of approaches be evaluated, and a monitoring plan be developed such that a necessary change in approach can be anticipated.

Academic literature also includes significant criticisms regarding adaptive management implementation. One pertains to the cost of information necessary to carry out adaptive management techniques (Johnson, 1999b). Case studies show that scientific adaptive management relies excessively on the use of linear systems models, discounts nonscientific forms of knowledge, and pays inadequate attention to policy processes that promote the development of shared understandings among diverse stakeholders (McLain and Lee, 1996). To be effective, new adaptive management efforts will need to incorporate knowledge from multiple sources, make use of multiple systems models, and support new forms of cooperation among stakeholders (McLain and Lee, 1996). Indeed, the claim that adaptive management has failed to incorporate nonscientific forms of knowledge is a criticism that has shown itself again and again in the literature (Johnson, 1999b; Walters, 1997; McLain and Lee, 1996; Lee 1999).

We proposed an EAM that integrates decision analysis with physical models to provide managers with a framework for understanding how management plans should change based on a given state of information (Convertino et al., 2014). The proposed enhanced adaptive management approach requires the development of several components:

- A decision framework specifying the objectives of the project (e.g., reduced loading of a contaminant and improvement of ecological habitat);
- Enumeration of the trade-offs among these objectives (relative weights);
- Empirical results and physical models relating the main drivers and characteristics of the system, and how they impact the stated objectives;
- Linkages, assumptions or models to hypothesize the effects of management plan alternatives on the identified characteristics of the system and on the objectives.

In this paper we have developed an EAM approach to support remediation of a historically contaminated river, and applied to the South River, near Waynesboro, VA. From 1929-1950, Hg was used and disposed of at a former DuPont facility in Waynesboro, VA (Bolgiano, 1981). Hg was discovered in onsite soils and the nearby river system in the 1970's leading originally to a Fish Consumption ban for 130 river miles, and later a Consumption Advisory downstream of Waynesboro. In response to the mercury contamination, the state chose a Monitored Natural Recovery (MNR) plan and initiated a 100 year monitoring program in 1984. Because mercury levels in tissues of some species of fish were not declining as previously predicted, DuPont and the Virginia Department of Environmental Quality established the South River Science Team in 2001 to determine why mercury levels are not decreasing and how best to speed reduction in the methyl-mercury (MeHg) concentration in smallmouth bass. In order to maximize likelihood of remedial success and minimize risks and resource expenditure, a phased adaptive management approach to remediation is under consideration. One proposal is that remedial action begin in the first two mile stretch of the river adjacent to the outfall and proceed downstream. The EAM approach was developed for utilization in support of the South River, VA, and the relationships used in the model are from published literature from that region. However, specific Hg concentrations, flows, loading data, and bank management areas (BMAs) areas are hypothetical.

II. Materials and Methods

Case Application. The approach developed was designed to support incremental remedial action in the South River, VA. According to Bolgiano (1981), there was an estimated ~44 tons of mercury contamination in the South River floodplain and another ~800 kg Hg in the river sediment. Concentrations of Hg in the river banks, sediment, and the water column increase downstream of the former DuPont site peaking between RRM 5-10 for sediment Hg and RRM 10-15 for MeHg in water and fish. Results of several studies strongly suggest that the greatest source of Hg into the river is bank erosion, especially in the most contaminated reach from RRM 0 to RM 10. Additional sources of Hg to the river include Hg fluxes from deeper sediments to surface sediments, inflows from upstream, floodplain runoff, tributaries, groundwater, bank leaching, and residual seepage from the former DuPont plant outfall (Harris et al., 2012) Most of the riverbed is categorized as gravel though approximated 15% is made up of fine grained material. This fine-grained material is believed to be major site methylation in the river (Yu et al., 2011), producing the MeHg that biomagnifies in the food web and ultimately in smallmouth bass. In our hypothetical example, the concentrations and flow rates of the specific reaches of the river, their loading patterns, and the uncertainty associated with each of these measurements are hypothetical. The relationship between anticipated water column Hg concentration and the concentration of MeHg in smallmouth bass is based on the empirical relationship reported in Brent and Kain (2011). Supplementary tables include listing of the hypothetical loading and extent of BMAs included in the analysis for each alternative. The approach developed here was designed to be utilized as a screening tool and to support decisions in the context of planning and implementation of South River remediation.

Enhanced Adaptive Management (EAM) Model. EAM requires the development of a quantitative decision model that links the potential effects of remedial actions to the objective the actions are aimed to accomplish. The relationships between the effects and the outcomes should be based on empirical relationships, previous research, or expert hypotheses that can be measured and updated. In this case the decision model is a multi-attribute model (Figure 1). One attribute, the effectiveness in the reduction of smallmouth bass tissue MeHg, is predicted by a mass balance model which utilizes the specifics of a remedial action to determine potential changes in Hg concentration. The decision model allows quantitative effects analysis, and provides an archive of the most up-to-date understanding of the system and the relative priorities of stakeholders.

Decision Model. The decision model was designed to reflect the decision process for selecting the best remedial alternative and the expected effects of implementation of that alternative. The objectives in undertaking remedial action are considered to be (1) a reduction in MeHg in smallmouth bass tissue, which is considered the effectiveness of the alternative, (2) cost, including implementation and maintenance over 20 years, (3) the preservation of ecological resources, as reflected in the potential of an alternative to create habitat and avoid risks to the ecological community, and (4) implementability, as reflected in constructability and land owner support. The relative importance of each of these objectives is reflected in a series of weights; the initial weighting scheme was set at 40% effectiveness, 30% cost, 20% ecological effects, and 10% implementability.

An initial set of alternatives were developed for the case study (Table 1). The alternatives are different combinations of measures including vegetative bank stabilization, MNR, and outflow source control in the reaches closest to the outfall. Each alternative was then evaluated based on its performance on each of the 4 objectives. The effectiveness objective reflecting the anticipated average concentration of MeHg in smallmouth bass 20 years post alternative implementation was calculated according to monitored river conditions, an empirical Hg transfer equation, and the local efficacy of the interventions at each BMA. A mass balance model with this input data is utilized to produce the overall effectiveness score for each alternative. The reduction in Hg loading from any specified BMA following was initially set at 90%, 2% and 100% for vegetative bank stabilization, NMR and outflow source control, respectively. The initial efficacies of the interventions are based on expert judgment, pilot studies and monitoring results. A range of probable costs for each alternative was also calculated based on the mean, minimum, and maximum probable cost of implementing and maintaining each measure and its extent. The performance of each alternative on the remaining objectives, implementability and ecological effects, were specified on a high-medium-low (1, 0.5, 0) scale and are reported in Table 3. These initial parameters would be expected to be updated utilizing data collected following implementation.

Alternative Effectiveness. The mass balance model utilizes the concentrations and flow rates in and out of the specific reaches of the river, the anticipated efficacy of remedial alternatives, and an empirical relationship between water column THg and smallmouth bass tissue MeHg derived by Brent and Kain (2011) for the South River.

From these inputs, calculations are utilized to predict loading patterns, water column Hg, and smallmouth bass MeHg in each reach once the concentrations return to a steady state following the impacts of the remedial actions. Therefore, Hg concentrations reflect the maximum predicted decline in loading following implementation of remedial actions. For vegetative back stabilization, this reduction is hypothesized at 90% of the individual BMA loading achieved approximately 3 years after implementation (South River Remediation Proposal, AnchorQEA – in production). The time anticipated for reduction in mercury loading for MNR is 2% in three years, while the reduction in upstream source loading would be immediate. Many of the parameters of the model can incorporate uncertainty, including water column Hg concentration, individual BMA loading rates and anticipated costs. For the initial calculations, river flow rates and water column Hg concentrations were included as point values, while the uncertainty in Hg unit loading to the river from erosion at each BMA was captured through the use of a triangular function. Each triangular function has three inputs- the minimum possible value, the most likely value, and the maximum possible value.

To calculate the effectiveness of each remedial alternative, or the anticipated change in MeHg in smallmouth bass tissue, the river was first split into five reaches, each two miles in length starting with RRM 0 at the original point source of mercury contamination and ending at RRM 10. The mass balance equation was then applied to each reach to calculate the initial mass of Hg entering the water column in the reach annually, or the initial external Hg loading, $\dot{M}_{in,ext(t0)}$,

$$\dot{M}_{in,ext(t0)} = C_{out\ (t0)} * Q_{out} - C_{in(t0)} * Q_{in}. \qquad \text{Equation 1}$$

C_{out} and C_{in} represent the concentration of Hg in the water column entering and exiting the reach annually; Q_{out} and Q_{in} represent the volumetric flux of water entering and exiting the reach annually; t_0 indicates the time prior to implementation of any remedial action. Use of this approach assumes the water in the reach is fully mixed such that the water column concentration of Hg exiting the reach, C_{out} is equal to the water column concentration of Hg within the reach.

Once the initial loading is known, the new loading after the alternative is implemented and once the system reaches a new steady state water column concentration ($t=t_1$), is calculated as,

$$\dot{M}_{in,ext(t1)} = \dot{M}_{in,ext(t0)} - \Delta\dot{M}_{in,ext(t1-t0)}, \qquad \text{Equation 2}$$

where $\Delta\dot{M}_{in,ext(t1-t0)}$ is the change in the rate of THg mass entering the water column in the reach from all local, external sources. To calculate this change in loading, the left and right banks of each river reach were further divided into individual 0.2 mile-long BMAs each of which has its own Hg soil concentration and annual Hg unit loading rate. Remedial measures were then hypothetically applied to the river, to specific reaches, and to any of the individually BMAs (supplementary tables). The expected change in annual Hg unit loading to each reach (kg Hg/yr-mile), $\Delta\dot{M}_{in,ext(ti+1-ti)}$, was calculated for each of the five remedial alternatives based on the sum of the initial Hg unit loading in each

BMA, and the anticipated percent reduction in that loading expected from implementing the remedial alternatives.

Next the mass balance equation (Equation 1) is rearranged to solve for the new concentration of Hg in the water column within and exiting each reach at the new steady state, $C_{out(t1)} = (Ci_{n(t1)}*Q_{in} + \dot{M}_{in,ext(t1)})/Q_{out}$. Finally, the new MeHg concentration in smallmouth bass tissue (the alternative effectiveness) is calculated using the empirical equation derived by Brent and Cain (2011),

$$Hg_{Fish} = 1/(11.682*Hg_{Water} + 0.282). \qquad \text{Equation 3}$$

Hg_{Fish} is the size normalized smallmouth bass fish tissue MeHg concentration; Hg_{Water} is the concentration of THg in the water column (written as $C_{out(t1)}$ above). In this case, the bass is assumed to have a home range equal to RRM0-RRM10 so that the effectiveness value is Hg_{Fish} value averaged over the five reaches.

Assumptions. The decision model is designed to calculate a relative value score for each remedial alterative given the anticipated effects of implementation. The model contains several assumptions that impact the calculation of scores. The model contains no temporal component. Instead, it calculates the change in Hg once the system reaches a steady state. We can specify the time anticipated to steady state associated with the change. For example, we hypothesize that the vegetative bank stabilization reduces Hg loading by up to 90% over 3 years. The model reflects this 90% loss of new mercury loading, and monitoring results should be taken to update this assumption 3 years after implementation. The model also does not consider the effects of storms though they are known to have a significant impact on the introduction and movement of total Hg through the river system. Storms are expected to impact both the flow and Hg concentration in the system, and can be considered by adjusting those initial values. Costs, including maintenance for 20 years, are included in the model only using current value. The weight assigned to each objective weight assumes that the majority of the value of remediation is reduction on MeHg concentration in smallmouth bass, and that cost is 30% of the consideration. These weights will play a significant role in determining the highest ranked management alternative, as detailed in our sensitivity analysis. Under these initial assumptions, the relative value of each remedial action has been calculated. The structure of the decision model and its output are intended to provide detailed information to a remedial action team who would then consider what additional information needs to be collected or considered to make a decision.

Prioritization of Remedial Alternatives. The model uses the mass balance model and the performance of the alternatives on each objective to calculate the relative value of each alternative. Multi-attribute value theory is used to compare the alternative using a local scale for each criteria and objective (Linkov and Moberg, 2012). The “value” of each alternative is a normalized score for each objective with the highest performing alternative(s) given a value score of 1, and the lowest performing alternative given a 0. The total utility, $U(\boldsymbol{a})$, for that alternative, $\boldsymbol{a}$, is then calculated as a weighted sum across the four objectives,

$$U(\boldsymbol{a}) = w_1 \cdot V_1(a_1) + \ldots + w_n \cdot V_n(a_n)$$, (Keeney and Raiffa, 1976)

where a_i is the performance score of alternative $\boldsymbol{a}$ on objective O_i for $i = 1$ to n, $V_i(a_i)$ is the value of alternative $\boldsymbol{a}$ reflecting its performance on criterion O_i and w_i is the weight of criterion O_i where $\Sigma w_i = 1$.

Monitoring after Implementation. The model is designed to reflect an understanding of the current conditions within the river. Another output of the model, therefore, is a series of measurements that should be taken in order to update the model, reduce uncertainty and increase understanding of the relationship between parameters that influence the predicted outcomes. The parameters form the basis of a short- and long-term monitoring plan which is necessary to inform the ranking of alternatives in the second phase of implementation.

III. Results and Discussion

Alternative Performance. The model generates a range of scores reflecting the value and uncertainty associated with each remedial alternative (1-5) under the current conditions and reflecting the current understanding of the system. The alternatives with the highest mean value would be considered the "best" choices for further consideration and investigation. The evaluation of the current case resulted in the relative ranking of the alternatives shown in Figure 2. The highest performing alternative is alternative 3 (vegetative bank stabilization of all reaches in RRM 0-6 with an identified Hg loading rate exceeding 0.5 kg/yr-mi) with a mean utility score of 0.56, followed closely by alternatives 2 (vegetative bank stabilization of reaches in RRM 0-6 with Hg loading rate exceeding 1 kg/yr-mi) and 1 (MNR) with mean utility scores of 0.52 and 0.50, respectively. Alternative 4 (alternative 3 with added upstream source control) received a mean utility score of 0.43 though it has the largest uncertainty with a range of possible utility from 0.18 to 0.71. Alternative 5 (upstream source control) scored the lowest with an average of 0.33 and a probable range of 0.25 to 0.41. MNR performs worse than that alternative and more limited bank stabilization (Alternative 2), but has the least uncertainty because of the low rate of Hg reduction (2%) and the small range of potential costs for this alternative. The upstream source control adds uncertainty to the performance of Alternative 4 and 5 because of the range in the cost of complete reduction in source control. This uncertainty reduces the mean performance of those alternatives that include source control. Though the possible utility scores for most of the alternatives overlap because of uncertainty in cost and unit Hg loading rates, the probable ranges reflect somewhat more conclusive rankings. Still, under this initial weighting scheme, there is no clear best or worst alternatives.

Water column total Hg and smallmouth bass MeHg. The mass balance module predicts changes in water column total Hg after the expected time to reach a steady state following alternative implementation has passed. The estimated mean water column total Hg concentrations in each reach for each alternative are shown in Figure 3A. Alternatives 3 and 4, which include the most extensive bank stabilization result in the lowest mean water column total Hg concentrations after RRM 2, followed by alternative 2 with less extensive bank stabilization and finally alternatives 1 and 5, those not involving any bank stabilization, are predicted to result in the highest mean total Hg concentrations in the water column. Again, uncertainty in the annual unit Hg loading at each BMA results in a large range of possible water column total Hg concentrations for alternatives 2, 3 and 4. At river mile 8, this uncertainty results in no significant difference between the bank stabilization alternatives, though MNR and upstream source control alone have significantly higher total Hg concentrations (Figure 3).

The anticipated MeHg concentration in smallmouth bass tissue is predicted based on the predicted water column total Hg concentrations derived from the mass balance model. The change in bass tissue MeHg concentration is only anticipated after the fish mercury uptake reaches a next steady state, which is predicted to be roughly the time required for the water column to equilibrate plus the generation time of the smallmouth bass. The concentration is predicted from the Brent and Kain (2011) equation relating total Hg in water and fish tissue MeHg. Mean predicted concentrations are shown in Figure 3C for each alternative. As expected, the predicted amount of bass tissue MeHg under each alternative corresponds to the amount of water column total Hg estimated above.

Objective weights. The model assumptions include an assumption that the objectives have different levels of importance, and therefore, different weights were placed on the four objectives – effectiveness, cost, ecological effects and implementability (Figure 4). The original distribution of weight among the objectives was 40% effectiveness, 30% cost, 20% ecological effects, and 10% implementability. With these weights, Alternative 3 provided the highest mean utility value but included significant uncertainty in its performance. Other weighting schemes were also considered. If 100% of the objective weight is placed on the effectiveness in reduction of MeHg in smallmouth bass, Alternative 4 has the highest mean value of all the alternatives. Alternative 4 is the most aggressive alternative and includes both upstream source control and extensive bank stabilization. However, the uncertainty associated with effectiveness in this alternative stretched the performance such that its range of possible utiltity overlaps all the other alternatives. A third weighting scheme placed half of the objective weight on effectiveness and half on ecological effects. Under this condition, Alternative 4 still has the highest value. Emphasizing ecological effects, which has been scored along a high-medium-low scale with no uncertainty, reduces the uncertainty to a level that Alternative 4 completely outperforms Alternatives 1 and 5. The last distribution of objective weight was a 50-50 split of the weights between cost and implementability. In this case, MNR and Alternative 2, limited bank stabilization, outperform the other alternatives because they have the lowest cost, the smallest anticipated range of costs, and are expected to have the least resistance in implementation.

Monitoring Plan. The EAM approach includes the production of a list of parameters that should be monitored in the short-term and in the long-term to update the model, reduce uncertainty and learn from initial implementation efforts. In this case study, the parameters in the model that would need to be monitored at the reach level would be the concentration of total Hg in the water column and corresponding flow rate; these should be monitored as each implementation is expected to ready equilibration (short-term). To monitor the impacts of vegetative bank stabilization, individual BMA should be assessed in the short-term for potential loading, Hg uptake by biota adjacent to the bank as a proxy for the reduction of mercury loading, bank stability, ecological metrics as a proxy for ecological health and habitat enhancement, and land owner acceptance. Following the initial implementation, these data should be utilized to update the decision model before future actions are considered. Long-term monitoring should include total Hg in the water column and MeHg in smallmouth bass. These data should be used to update the relationships in the decision model and determine to what extent the objectives of the remedial action are being met with the current approach. Completion of this process in the first two mile reach of the river provides a a foundation for learning following implementation which is valuable as remediation efforts proceed further downstream.

IV. Implications

The EAM approach is designed to assist and focus decision-making underadaptive management. EAM includes a decision model which is used to predict the expected outcomes in response to implementation of different remedial alternatives. The decision model serves as both an archive of the understanding of the system as it relates to the decision objectives, and a way to compare different courses of action. As an example of its first function, the model predicts MeHg concentration in smallmouth bass once a new steady state is reached. It does not provide a mechanism or a prediction of changes in the distribution of Hg in the system. It is not an ecological or conceptual site model. It provides a simple description of the relationship between actions (remedial alternatives) and their impacts on the decision objectives (reduction in MeHg in smallmouth bass, cost, etc.). The decision model forces a quantitative evaluation of alternatives and a relative value score is calculated for each one. This score is based on a combined evaluation of how well the alterative meets all the objectives. Therefore, the performance of each remedial alternative can be compared and the evaluation provides information to the remedial action team on additional information or clarification that would distinguish the alternative actions.

This decision model forms the backbone of the EAM plan. The other two critical aspects of any adaptive management approach are monitoring/evaluation, and learning and adjustment. Following implementation of any action, a series of short- and long-term endpoints need to be monitored and the process analyzed for any lessons to be learned. These measurements, and their implications, should be incorporated into any future decisions. The EAM approach allows for inclusion of the new monitoring results into the model, reducing uncertainty and allowing for a new assessment of the system. Changes in the model as a result of monitoring or a re-evaluation of the cost or implementability of different alternatives can be incorporated and used to update the predicted effects and value of a remediation alternative. Therefore the learning and adjustment phases of the process are simplified by allowing circulation of an updated decision model and a re-analysis of new alternatives given the increased understanding of the system. EAM should focus the remedial implementation team on collecting those data that are material to the decision, and those factors that allow better predictions of the behavior of the system. It also should restrict discussion of future actions through previous specification and quantification of the decision objectives; these are not expected to change significantly over the life of the project.

Development of a case study for the South River, VA provides insight into the type and quality of outcomes anticipated using the EAM approach (Figure 9). These results are the type of details that should be considered by a remedial action team in advance of their decision to proceed in a specific course of action. They indicate that, if the remedial action team places a high value on the reduction in smallmouth MeHg, then further consideration should be given to extensive bank stabilization. However, if cost and implementability are the main concerns, then MNR or more limited bank stabilization is a course of action that should be considered. Uncertainty in bank loading and costs result in large, often overlapping, ranges of possible utility scores for the alternatives. Because reducing these uncertainties could change the relative rankings of the alternatives, the remedial action team may want to study these areas further. Because the distribution of weights among the objectives influences the relative ranking of alternatives, the relative importance of the objectives is an issue that should also be researched by the remedial implementation team. Application of the model to the available data in the South River may produce similar outcomes. The analysis generated through the EAM approach provides a structured, transparent evaluation of the alternatives which can be used in guidance or as a screening tool by the remedial implementation team. As the tool is calibrated to reflect the understanding and priorities of the team during the actions in the first reach of the river, the tool becomes more useful in processing future monitoring results and specification of thresholds for switching between alternative actions. The updated tool is valuable in the scrutiny and evaluation of remedial alternatives in the downstream reaches.

Divergence from traditional adaptive management approaches. The EAM approach to adaptive management outlined here differs from traditional approaches to adaptive management in several significant ways (Convertino et al., 2014). Development and choice of a management plan under this approach begins with development of a structured decision model for a specific project. The critical objectives must be agreed upon in advance as well as the relative importance of these objectives in the form of weights.

The application described here utilized published literature, the results of pilot studies and expert judgment to build an EAM model and demonstrate the utility of the approach. In order to implement this tool in the South River remediation context, a substantial effort would have to be made not only to clarify objectives and weights but also to incorporate specific metrics for ecological effects and implementability. Additional results of pilot studies, physical models and conceptual models may be incorporated to link characteristics and drivers with the management objectives. Historical data should be analyzed to provide reasonable estimates for Hg concentration, flow rates and bank loading as well as the uncertainty in these parameters for each BMA. Implementation of EAM requires more problem framing and data analysis as the process is begun than traditional adaptive management.

Benefits of this approach. There are several reasons for utilizing EAM. The approach ensures that: (1) Adaptive management clearly links decisions to science, monitoring information, and management choices rather than on *ad hoc* choices; (2) Delays resulting from debates about the best adaptation to monitoring results are reduced (3) Monitoring plans can be evaluated based on the contribution to improving the decision model (4) Remedial plans can be updated quickly as new information is gained and uncertainties are reduced. A monitoring plan in an adaptive management context has value only if it might affect the understanding of the system in a way that impact future actions. The worth of each monitoring plan can be assessed by trading off the improvement in the knowledge of the likelihood of future scenarios and the benefits in terms of better adjustment of the decision and future costs of monitoring (Wintle et al. 2010). EAM can link science, monitoring information, and management choices by helping to shape monitoring plans so that they provide information useful to future remedial action.

Perhaps the most important benefit of the approach is that it quantitatively links management decisions to technical understanding of the system to be managed and monitoring information. Analysis and refinement of these linkages provides an opportunity to learn more about the functioning of the ecosystem, to update the projected outcomes of alternative approaches, and to change the model as conditions change in the system. The best adaptation to any specific monitoring result would be determined before the results are compiled, making project management more efficient. In short, these enhancements focus the remedial action team on developing the necessary frameworks and models that allow the anticipated benefits of adaptive management to be realized.

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Figure Captions

Figure 1. A schematic of the decision model utilized in the EAM case of remediation of historic Hg contamination is shown. The remedial alternatives need to be specified in terms of their efficiency, and the total Hg reduction expected in each compartment (orange boxes). The efficiency and Hg reduction are utilized in a mass-balance calculation (river schematic) which determines the anticipated change in Hg loading. The loading change in compared to empirical data (inserted graphs) which allows a prediction of the water column Hg concentration and the smallmouth bass tissue Hg concentration anticipated following equilibration after implementation. The effectiveness of the remedial alternative, as indicated by the anticipated reduction in smallmouth bass MeHg, is combined with the estimated cost, ecological effects and implementability of that alternative to calculated a payoff associated with that specific remedial approach.

Figure 2. The initial evaluation of remedial alternatives from the case study is shown. The alternatives are ranked according to their mean performance; the uncertainty is not shown on this figure. For each alternative, black boxes indicate the mean and standard deviation of 1000 simulations across the range of probable values. The green box shows the highest and lowest possible scores achieved with the maximum and minimum probable values for that alternative, respectively. The blue boxes show the range of scores between the probable value and the possible value for each alternative; above the mean is the range of scores between the maximum probable and the maximum possible while the minimum range is below. The largest range of uncertainty is the result of uncertain bank loading. For Alternatives 3 and 4, which contain a great deal of vegetative bank stabilization, the large percent reduction in loading results in a large range of uncertainty in the resulting effectiveness. The range in cost associated with source control increases the uncertainty in Alternatives 4 and 5. Alternative 3 outperforms Alternative 5, and overlaps the other Alternatives in performance under the initial weighting scheme.

Figure 3. Hg concentration predictions from the mass-balance model for the initial alternatives are shown. (A.) The mean predicted water column concentrations in ng/L are reported for each alternative for each reach of the river as calculated by the mass balance model. Alternatives 1 and 5 result in higher predicted Hg concentrations then the other alternatives along the length of the river. (B.)The uncertainty in anticipated water column Hg concentration at river mile 8 is shown as predicted by the mass balance model. Below the graphical display are the calculated values for the maximum, minimum and mean concentration of Hg (ng/L). Alternatives 1 and 5 are anticipated to result in higher mercury levels in this stretch of the river. The other alternatives cannot be distinguished because of the uncertainty in the loading multiplied by the anticipated rate of reduction. (C.) The mean predicted concentrations in smallmouth bass tissue (mg/kg) are reported for each alternative for each reach of the river as calculated by the mass balance model. Following from the water concentrations, Alternatives 1 and 5 result in higher fish tissue concentrations than the other options.

Figure 4. A basic sensitivity analysis of the effect of the objective weights on the – performance of remedial alternatives. (A.) The original weighting scheme of 40% effectiveness, 30% cost, 20% ecological effect, and 10% implementability results in Alternative 3 providing the highest value but including a significant amount of uncertainty in its performance. (B.) For this calculation, 100% of the objective weight was placed on the effectiveness of the alternative in reduction in smallmouth bass MeHg concentration. The most aggressive alternative, Alternative 4 which includes both upstream sources control and extensive bank stabilization, has the highest mean value. (C.) For this calculation, 50% of the objective weight was effectiveness and 50% was ecological effects. Again, Alternative 4 has the highest mean value, and the reduction in uncertain associated with the inclusion of ecological effect allows it ot outperform Alternatives 4 and 5. (D.) In the case with 50% of the objectives weight on cost and 50% on implementability, Alternatives 1 and 2 outperform the other alternatives. These two alternatives have the lowest cost, the smallest range of potential cost and are anticipated to be most acceptable to land owners.

Figure 5. The process for EAM as demonstrated by the case study is outlined here. Beginning at the top, the river conditions and change in total Hg loading in response to each alternative are estimated based on monitoring and pilot study results. These are then input into the mass balance to calculate the water column total Hg concentration and the smallmouth bass tissue MeHg concentration both initially and following alternative implementation. The smallmouth bass tissue concentrations are then entered into the decision model along with performance scores for the other objectives and preference weights and a relative ranking of alternatives is calculated. Based on the outcome of the decision model, an alternative is selected and implemented. Metrics that relate to parameters in the decision model are monitored according to the monitoring plan and updated as necessary. The process then repeats with the latest information gathered through monitoring and research.

Table 1. Remedial alternatives considered in the case study.

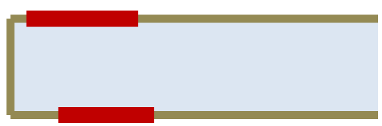
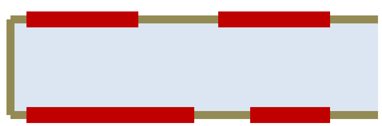
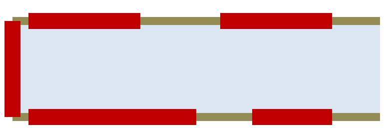
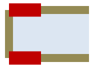
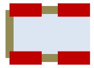
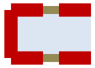
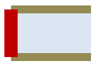
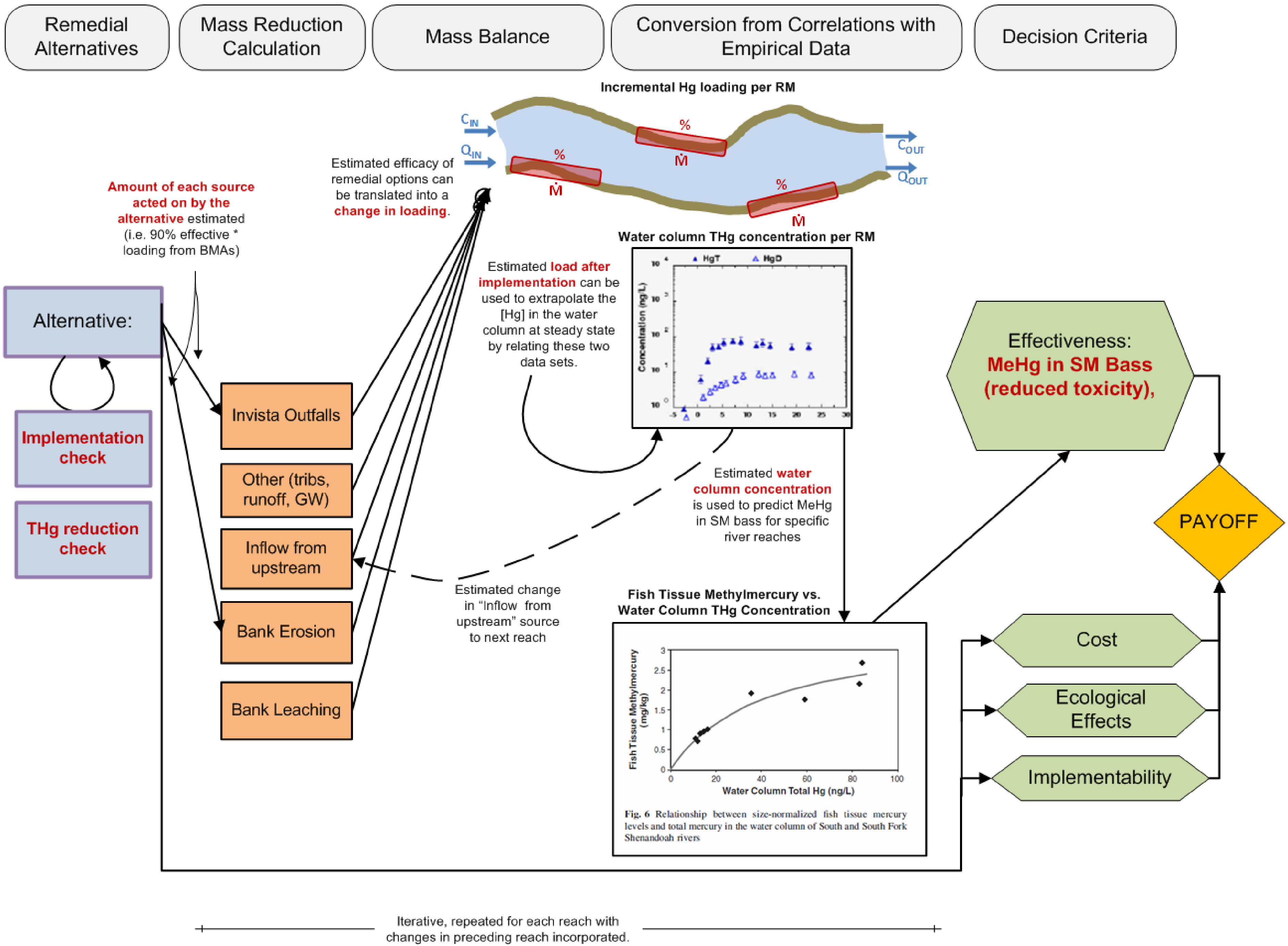
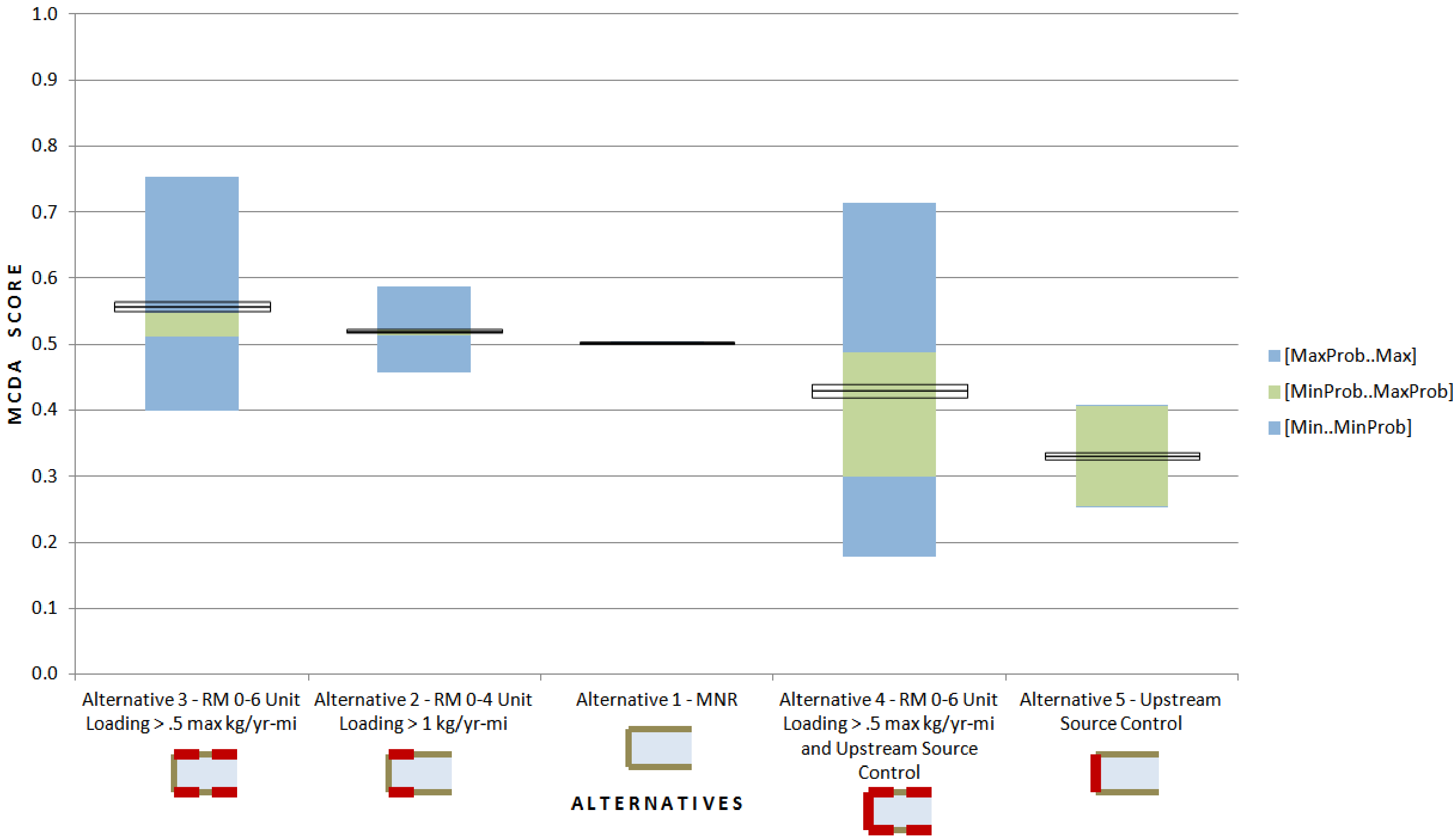
Symbol	**Description of Alternatives**
	(1) Monitored Natural Recovery (MNR)
	(2) Enhanced vegetative bank stabilization of banks in river mile 0-4 with loading > 1 kg/yr-mi
	(3) Enhanced vegetative bank stabilization of banks in river mile 0-6 with loading > 0.5 kg/yr-mi
	(4) Enhanced vegetative bank stabilization of banks in river mile 0-6 with loading > 0.5 kg/yr-mi, in addition to upstream source control
	(5) Upstream source control

Table 2. Initial performance of each remedial alternative on the decision objectives.

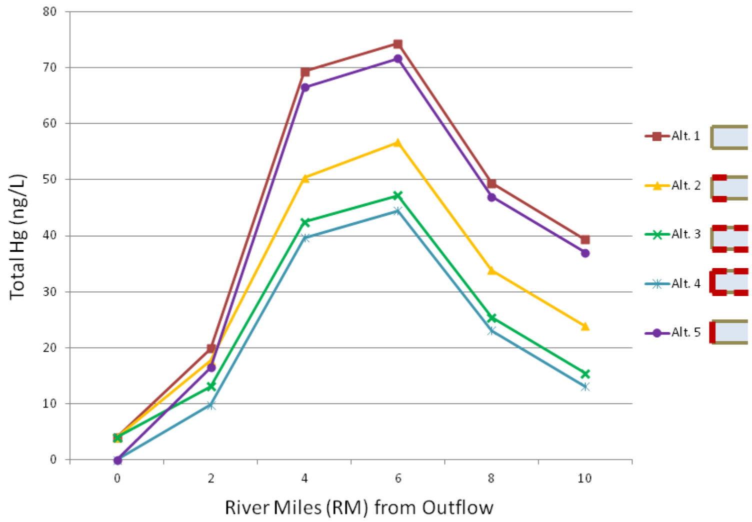
Aspect	Description	Alternative Score				
						
Efficacy of remedial action	For each remedial action, the anticipated reduction in the influx of mercury needs to supplied. For this example, the vegetative stabilization of banks was assumed to be 90% effective and monitored natural recovery is assumed to be 2% effective. Outflow reduction from upstream source control was calculated to reduce the entering Hg concentration upstream of river mile 0 to 0 ng/L.					
Implementation and Maintenance Cost	The range of costs (minimum to maximum) is estimated according to the type and amount of each remedial alternative to implemented.	0	$5-10M	$19-38M	$59-158M	$40-120M
Performance Risk	The risk of mechanical failure of remediation measures is estimated along the range of low (0) to high (1) according the type of stabilization and its extent.	0	0.5	0.5	0.5	0
Land Owner Approval	Support for remediation projects is estimated on the range of low (0) to high (1) according to level and extent of the disruption anticipated, the anticipated efficacy, and the number of landowners that will be involved.	1	0.5	0.25	0	0.25
Benefits - Habitat creation	The potential for habitat creation was ranked for each alternative from low (0) to high(1) according the length of bank modification.	0	0.25	1	1	0
Risk - Ecological function, community	Risk to ecological function from implementation from each alternative was ranked as high (1) to low (0) according to the extent of the disruption along the river bank.	0	0.25	1	1	0


Remedial Alternatives
Mass Reduction Calculation
Mass Balance
Conversion from Correlations with Empirical Data
Decision Criteria
Incremental Hg loading per RM
C IN
Q IN
C OUT
Q OUT
%
Ṁ
Estimated efficacy of remedial options can be translated into a change in loading.
Amount of each source acted on by the alternative estimated (i.e. 90% effective * loading from BMAs)
Alternative:
Implementation check
THg reduction check
Invista Outfalls
Other (tribs, runoff, GW)
Inflow from upstream
Bank Erosion
Bank Leaching
Water column THg concentration per RM
HgT
HgD
Concentration (ng/L)
Estimated load after implementation can be used to extrapolate the [Hg] in the water column at steady state by relating these two data sets.
Estimated water column concentration is used to predict MeHg in SM bass for specific river reaches
Estimated change in "Inflow from upstream" source to next reach
Fish Tissue Methylmercury vs. Water Column THg Concentration
Fish Tissue Methylmercury (mg/kg)
Water Column Total Hg (ng/L)
Fig. 6 Relationship between size-normalized fish tissue mercury levels and total mercury in the water column of South and South Fork Shenandoah rivers
Effectiveness: MeHg in SM Bass (reduced toxicity),
PAYOFF
Cost
Ecological Effects
Implementability
Iterative, repeated for each reach with changes in preceding reach incorporated.

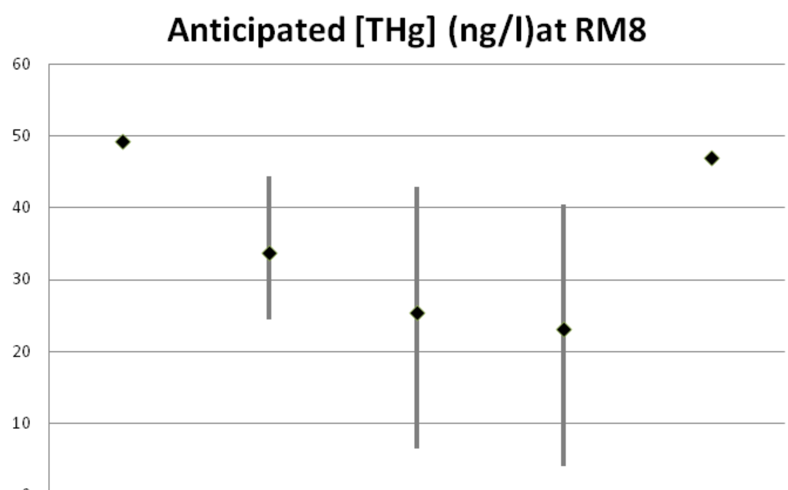


MCDA SCORE
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Alternative 3 - RM 0-6 Unit Loading > .5 max kg/yr-mi
Alternative 2 - RM 0-4 Unit Loading > 1 kg/yr-mi
Alternative 1 - MNR
Alternative 4 - RM 0-6 Unit Loading > .5 max kg/yr-mi and Upstream Source Control
Alternative 5 - Upstream Source Control
ALTERNATIVES
[MaxProb..Max]
[MinProb..MaxProb]
[Min..MinProb]

A.

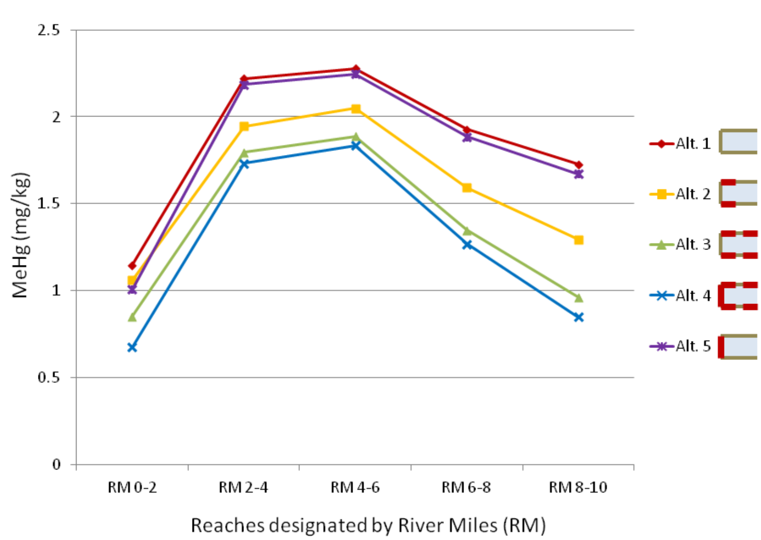


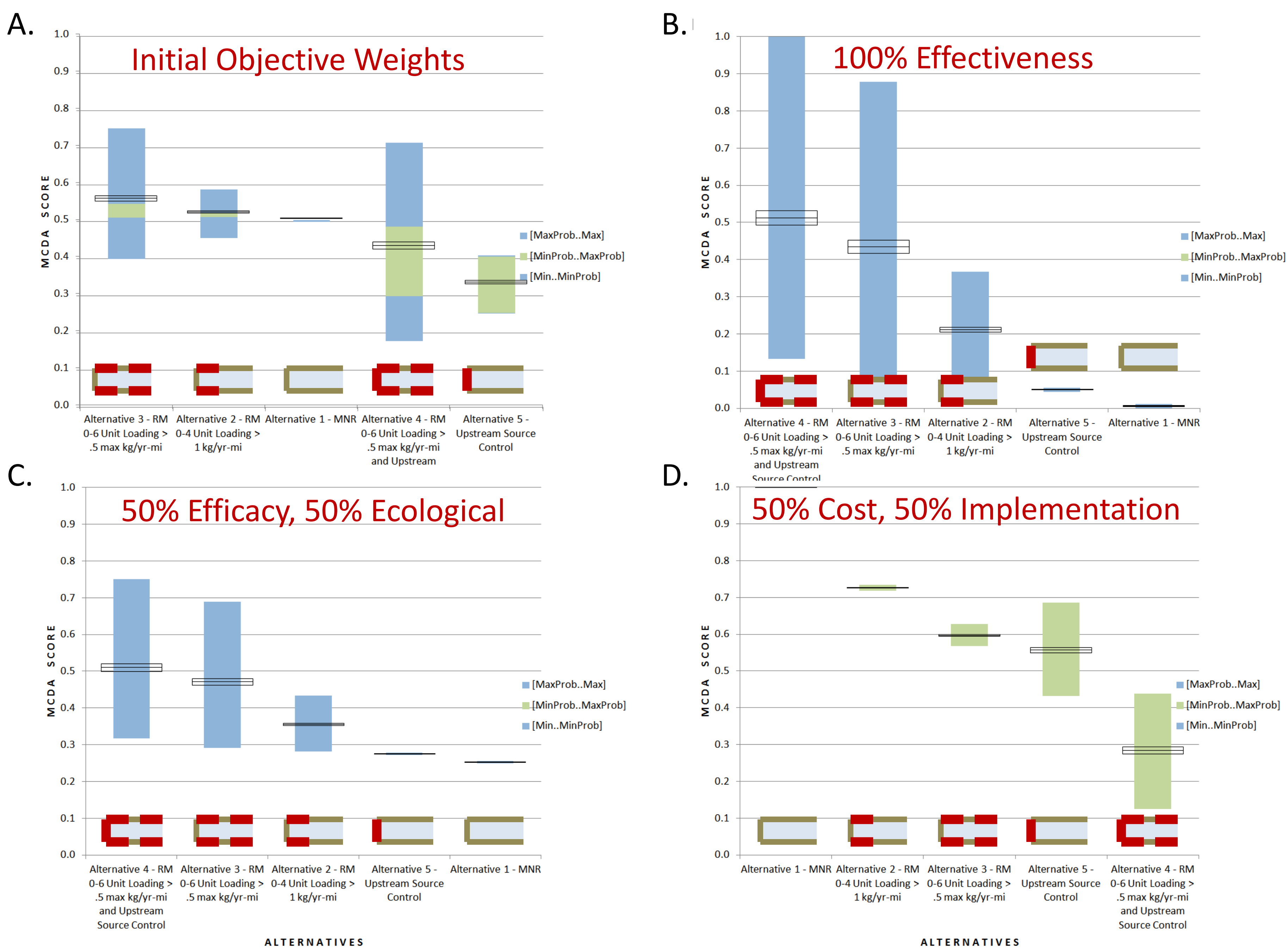
B.

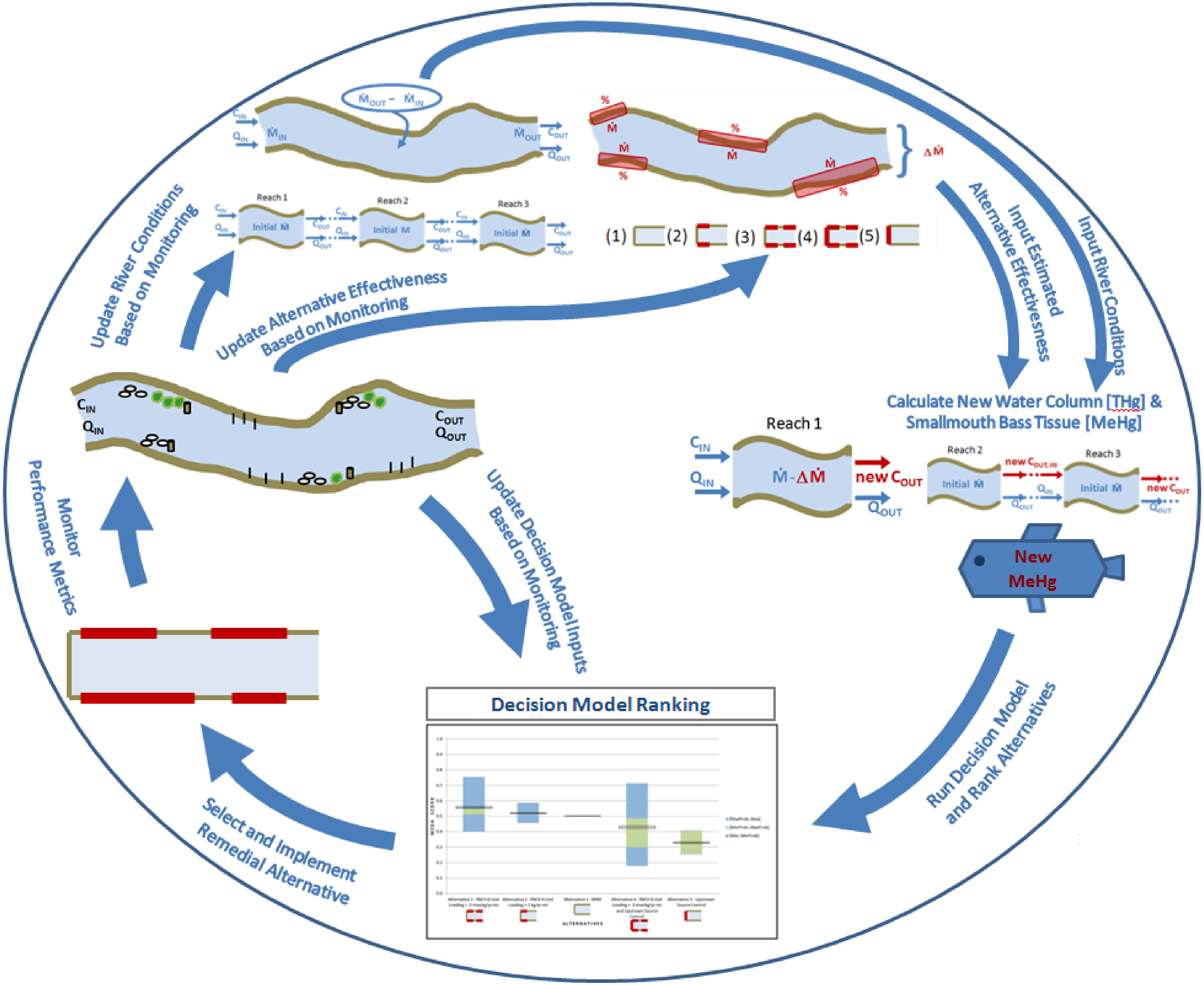


	Alt 1	Alt 2	Alt 3	Alt 4	Alt 5
Maximum	48.79718079	24.50761031	6.425799019	4.072857843	46.44423961
Minimum	49.84190766	44.36796042	42.88584474	40.53290356	47.48896648
◆ Mean	49.33963689	33.83610761	25.4443142	23.09137303	46.98669571

C.




A.
Initial Objective Weights
MCDA SCORE
[MaxProb..Max]
[MinProb..MaxProb]
[Min..MinProb]
Alternative 3 - RM 0-6 Unit Loading > .5 max kg/yr-mi
Alternative 2 - RM 0-4 Unit Loading > 1 kg/yr-mi
Alternative 1 - MNR
Alternative 4 - RM 0-6 Unit Loading > .5 max kg/yr-mi and Upstream
Alternative 5 - Upstream Source Control
B.
100% Effectiveness
MCDA SCORE
[MaxProb..Max]
[MinProb..MaxProb]
[Min..MinProb]
Alternative 4 - RM 0-6 Unit Loading > .5 max kg/yr-mi and Upstream Source Control
Alternative 3 - RM 0-6 Unit Loading > .5 max kg/yr-mi
Alternative 2 - RM 0-4 Unit Loading > 1 kg/yr-mi
Alternative 5 - Upstream Source Control
Alternative 1 - MNR
C.
50% Efficacy, 50% Ecological
MCDA SCORE
[MaxProb..Max]
[MinProb..MaxProb]
[Min..MinProb]
Alternative 4 - RM 0-6 Unit Loading > .5 max kg/yr-mi and Upstream Source Control
Alternative 3 - RM 0-6 Unit Loading > .5 max kg/yr-mi
Alternative 2 - RM 0-4 Unit Loading > 1 kg/yr-mi
Alternative 5 - Upstream Source Control
Alternative 1 - MNR
ALTERNATIVES
D.
50% Cost, 50% Implementation
MCDA SCORE
[MaxProb..Max]
[MinProb..MaxProb]
[Min..MinProb]
Alternative 1 - MNR
Alternative 2 - RM 0-4 Unit Loading > 1 kg/yr-mi
Alternative 3 - RM 0-6 Unit Loading > .5 max kg/yr-mi
Alternative 5 - Upstream Source Control
Alternative 4 - RM 0-6 Unit Loading > .5 max kg/yr-mi and Upstream Source Control
ALTERNATIVES



Update River Conditions Based on Monitoring
Update Alternative Effectiveness Based on Monitoring
Reach 1
Reach 2
Reach 3
Initial Ṁ
(1)
(2)
(3)
(4)
(5)
Input Estimated Alternative Effectiveness
Input River Conditions
Calculate New Water Column [THg] & Smallmouth Bass Tissue [MeHg]
Ṁ - ΔṀ
new C_{OUT}
New MeHg
Monitor Performance Metrics
Update Decision Model Inputs Based on Monitoring
Decision Model Ranking
Run Decision Model and Rank Alternatives
Select and Implement Remedial Alternative