Adaptive Management Facilitates Remedial Decision-Making in the Face of Uncertainty – 14171

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ABSTRACT

Remedial decisions are made following a remedial investigation in which the nature and extent of contamination are defined and a feasibility study in which the various alternatives are evaluated. For simple sites this process proceeds well because the cause of contamination and the effect of the remedy are well understood, and the selected remedial action has a high probability of being successful. However, for complex sites this decision-making process may become paralyzed because of the inherent uncertainty in factors such as the movement of contaminants through the system, the interaction between contaminated soil and the uptake by plants and animals, and the impact of source term removal on subsequent media contamination.

Adaptive management is an approach to decision-making that recognizes uncertainty, allows decisions to be made in recognition of this uncertainty, and improves and modifies the decisions in an iterative manner based on additional information gathered during implementation to reduce the uncertainty. The steps of the adaptive management process are to:

- Assess the problem – identify what is known, what is uncertain, and the implications of the uncertainty to the remedial action.
- Design the remedial action – base the design on the most likely scenario of problem definition, acknowledge and state the uncertainties, identify the triggers for change, and establish a mechanism to change the remedial action.
- Implement the remedial action – implement those actions that have a high probability of success recognizing the uncertainties.
- Monitor – monitor to determine if the remedy performs as designed, to determine if remedial action objectives are met, to reduce uncertainties, and to validate model parameters.
- Evaluate – evaluate monitoring results to determine if the remedy is effective and if the problem is appropriately defined.
- Adjust – use the monitoring results to redefine the problem or to modify the remedy.

The following three case studies on the Oak Ridge Reservation in Oak Ridge, Tennessee will be reviewed:

- Watershed remedial decision-making – Remedial decisions have been made on entire watersheds that include multiple actions and monitoring. The monitoring is used to evaluate performance of completed actions and to assess changes to the planned actions.
- Pond contaminated with polychlorinated biphenyls (PCB) - The action taken was to restore the pond to natural conditions that are much less conducive to PCB uptake in fish and includes draining the pond to remove those fish (gizzard shad and grass carp) that resuspend PCB-contaminated sediment, bioaccumulate PCBs, and eat aquatic vegetation and to restore fish to the pond (bluegill) that have food chains that minimize PCB uptake. A monitoring plan was developed as part of design and finalized at project completion.
- Groundwater – Watershed-scale groundwater decisions have not been made due to the uncertainty associated with off-site pathways, with finding and remediating dense non-aqueous phase liquids (DNAPL) in a karst hydrology, and the impact of treating the DNAPL source on down gradient water quality. Adaptive management may provide a means to make watershed-scale groundwater decisions in recognition of these uncertainties.

Adaptive management allowed the first two remedial decisions to be made and is a possible approach for making watershed-scale groundwater decisions. The most challenging problems with applying adaptive management to remedial decision-making are recognizing and accepting risk as an integral part of decision-making and being receptive to and prepared to change the remedies based on subsequent data and evaluation.

INTRODUCTION

In Oak Ridge, Tennessee, the U.S. Department of Energy (DOE) and its predecessor agencies have had a mission over the past sixty years of uranium enrichment, weapons production, and energy research. These activities left a legacy of radioactively and chemically contaminated soil, groundwater, surface water, sediment, and buildings on the Oak Ridge Reservation. The Oak Ridge Reservation was placed on the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 National Priorities List in 1989 (CERCLA), and the Department of Energy, the U. S. Environmental Protection Agency, and the Tennessee Department of Environment and Conservation signed a Federal Facility Agreement in 1992 that describes how remediation on the Oak Ridge Reservation will be performed.

Remedial decisions on the Oak Ridge Reservation have been made following a remedial investigation in which the nature and extent of contamination was defined and a feasibility study in which the various alternatives were evaluated. For simple sites this process proceeds well because the cause of contamination and the effect of the remedy are well understood, and the selected remedial alternative has a high probability of being successful. However, for complex sites such as the Oak Ridge Reservation this decision-making process may become paralyzed because of the inherent uncertainty in factors such as the movement of contaminants through the system, the interaction between contaminated soil and the uptake by plants and animals, and the impact of source term removal on subsequent media contamination.

Adaptive management is an approach to decision-making that recognizes uncertainty, allows decisions to be made in recognition of this uncertainty, and improves and modifies the decisions in an iterative manner based on additional information gathered during implementation to reduce the uncertainty.

ADAPTIVE MANAGEMENT

As stated above, adaptive management is an approach to decision-making that recognizes uncertainty, allows decisions to be made in recognition of this uncertainty, and improves and modifies the decisions in an iterative manner based on additional information gathered during implementation to reduce the uncertainty (Fig. 1). The foundations of adaptive management

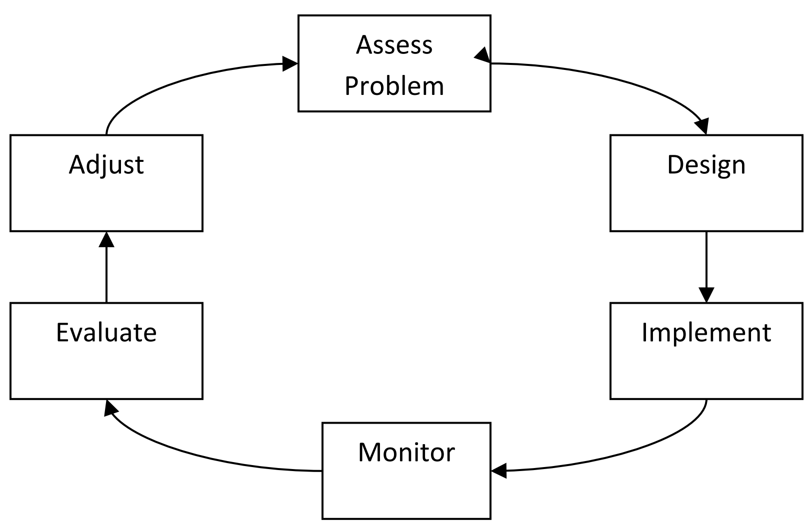

Fig. 1. Adaptive Management.

come from the field of industrial operation theory developed in the 1950s [1], and its use as a resource management technique began in the 1970s [2]. The National Resource Council studied the application of adaptive management to remediation at U.S. Navy facilities [3] and for the U.S. Army Corps of Engineers [4]. The most challenging problems with applying adaptive management are integrating all stakeholders into the decision-making process, developing political institutions that recognize and are amenable to change, and accepting risk as a part of decision-making.

The steps of adaptive management are defined below along with how each step is applied to remedial decision-making:

- Assess the problem – identify what is known, what is uncertain, and the implications of the uncertainty to the remedial action. The nature and extent of contamination, the likely end uses, the contaminants of concern, the risk assessment, and the remediation requirements are contained in remedial investigations for each watershed.
- Design the remedial action – base the design on the most likely scenario of problem definition, acknowledge and state the uncertainties, identify the triggers for change, and establish a mechanism to change the remedial action. Remedial alternatives are evaluated in a feasibility study for each watershed. Remedial alternatives are evaluated for each contaminated site as well as collectively. Based on an understanding of the uncertainties and the most likely outcome, a watershed record of decision contains the optimum set of remedial actions expected to meet the remedial action objectives. Included in the records of decision are monitoring requirements to assess performance as the remedial actions are implemented.
- Implement the remedial action – implement those actions that have a high probability of success recognizing the uncertainties. The set of remedial actions are implemented based on risk reduction, execution logic, and funding availability. As each remedial action is completed, a completion document is prepared that describes the completed remedial action and identifies any following monitoring required to evaluate performance.
- Monitor – monitor to determine if the remedy performs as designed, to determine if remedial action objectives are met, to reduce uncertainties, and to validate model parameters. A sampling and analysis plan is prepared for each watershed to establish and monitor baseline conditions, identify trends, evaluate performance of remedial actions, and identify new contaminant sites.
- Evaluate – evaluate monitoring results to determine if the remedy is effective and if the problem is appropriately defined. An annual Remediation Effectiveness Report and a Five Year Review are prepared that evaluate the performance of the remedial actions in each watershed. Based on these reviews, additional remedial actions or modifications to planned remedial actions are recommended.
- Adjust – use the monitoring results to redefine the problem or to modify the remedy. Based on the recommendations in these evaluations, changes are made to the watershed remediation plans.

WATERSHED REMEDIAL DECISION-MAKING

The remediation strategy on the Oak Ridge Reservation is based on watersheds. The Clinch River bounds the Oak Ridge Reservation on three sides, and there are active creeks that flow down the valleys to the Clinch River. These surface water systems are fed by runoff from rainfall and by the groundwater that continually discharges to the surface streams. As much as 90% of the water entering the ground flows rapidly through highly porous, shallow soil, which contains most of the contaminated sites, before discharging to nearby surface water. Consequently, the primary pathway for contaminant migration is through shallow groundwater to surface water which then flows offsite. Because of abundant rainfall, contaminant transport by shallow subsurface flow to surface waters, and the presence of contaminated sites in defined watersheds, a watershed strategy became the basis for environmental restoration. Watershed management is applied by grouping contaminated sites into five watersheds (Fig. 2).

The watersheds are used to:

- identify, assess, and prioritize contaminant releases
- make remedial decisions
- evaluate remedial effectiveness

Contaminants released from the contaminated sites accumulate in floodplain soils and aquatic sediments. Contaminants not retained, or those remobilized, are released to the surface waters and subsequently offsite to the Clinch River. Therefore, the surface water acts as an integrator of contaminant flux, and integration points (Fig. 2) are identified in each watershed at which contaminant releases can be tracked, prioritized, and assessed. Once the baseline monitoring and characterization are completed and the cleanup objectives are defined, the contribution of each remedial action toward achieving the objectives can be estimated and assessed at the

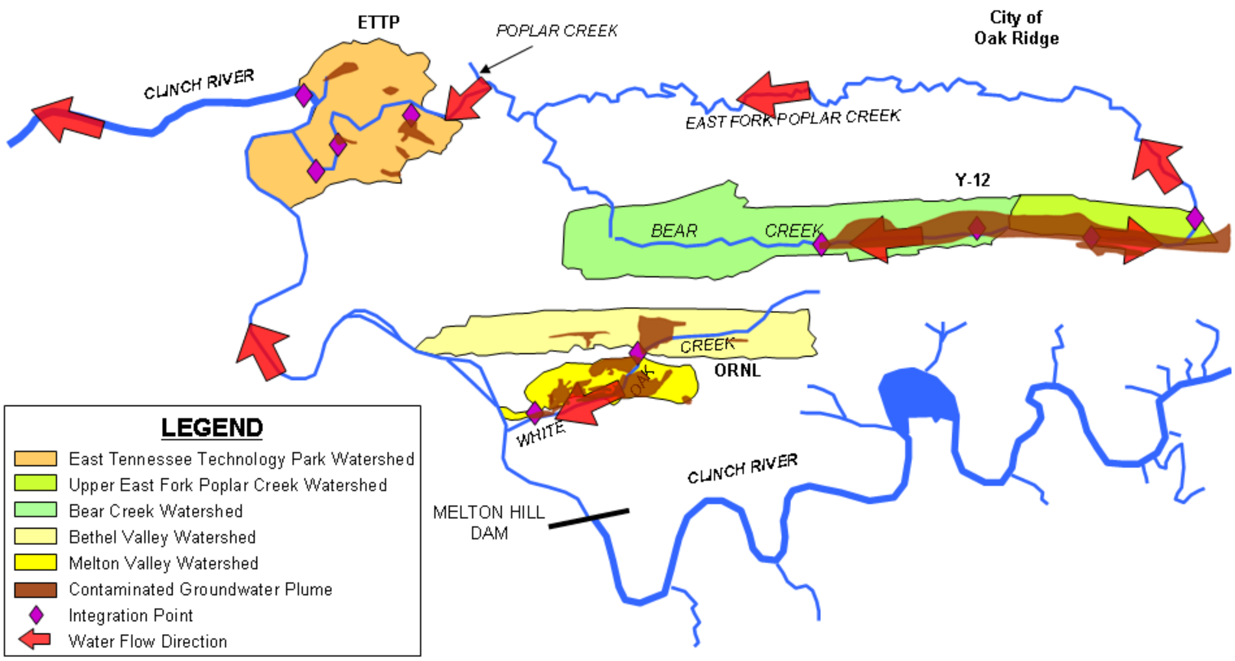

Fig. 2. Watersheds and Integration Points.

watershed integration point. Through surface water monitoring both the specific performance of each action and the cumulative progress toward achieving the cleanup objectives can be assessed.

The watershed records of decision contain performance goals to be met and a series of remedial actions designed to achieve them. Obviously, there is uncertainty associated with the ability of these remedial actions to be successful in meeting the performance goals, and adaptive management is applied. Based on the record of decision, a schedule is prepared for each watershed for all of the required actions. Simultaneously with implementation of the actions, monitoring is performed to evaluate the performance of the actions and to adjust the plan if necessary.

In the case of the East Tennessee Park, monitoring uncovered the release of hexavalent chromium into one of the creeks. As buildings were demolished and basements were filled, the shallow groundwater flow path was altered, and it encountered a source of hexavalent chromium. The source of the chromium was never found, but the remediation plan was adjusted to install groundwater extraction wells and a treatment plant for the contaminated groundwater.

At the Upper East Fork Poplar Creek watershed, mercury is the primary contaminant of concern. Fig. 3 demonstrates the reduction of mercury over time but illustrates that performance objectives still are not met. The monitoring performed in the watershed allows the ongoing performance to be evaluated and also allows the sources of mercury to be identified (Fig. 4). Based on this information consideration is being given to modifying the current set of projects to construct a treatment plant for mercury-contaminated storm flow. As a better understanding is gained of sources of mercury, of movement of mercury from the soil to the surface water and to the fish, and of treatment of mercury, the plan for remediation of the watershed is being revised.

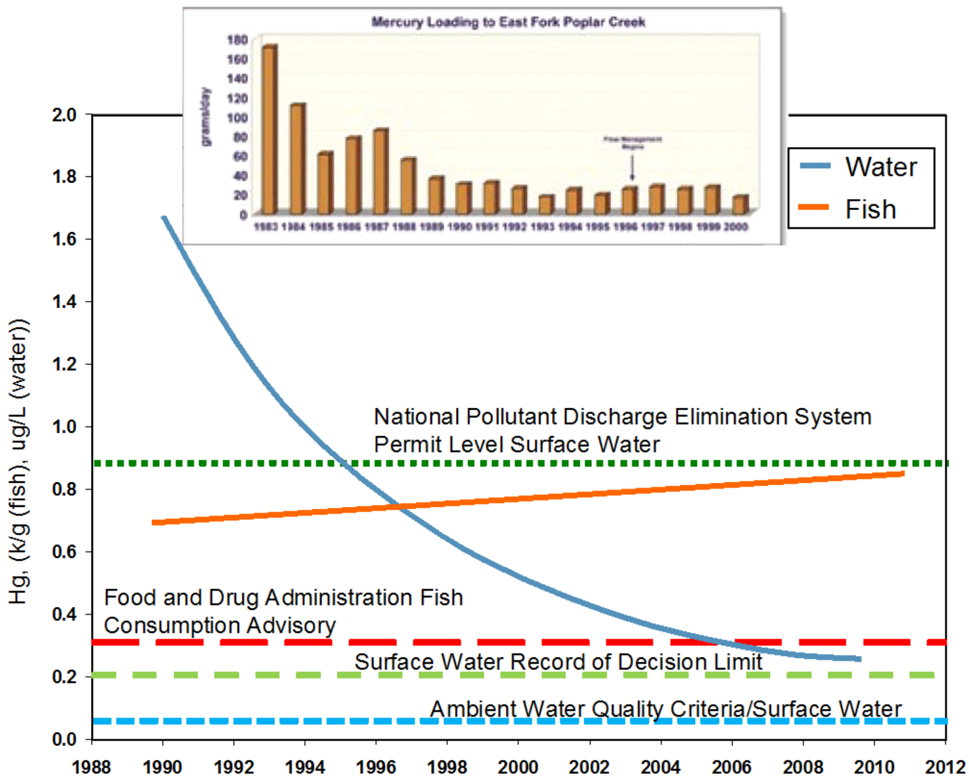

Fig. 3. Mercury Concentrations in Upper East Fork Poplar Creek Watershed.

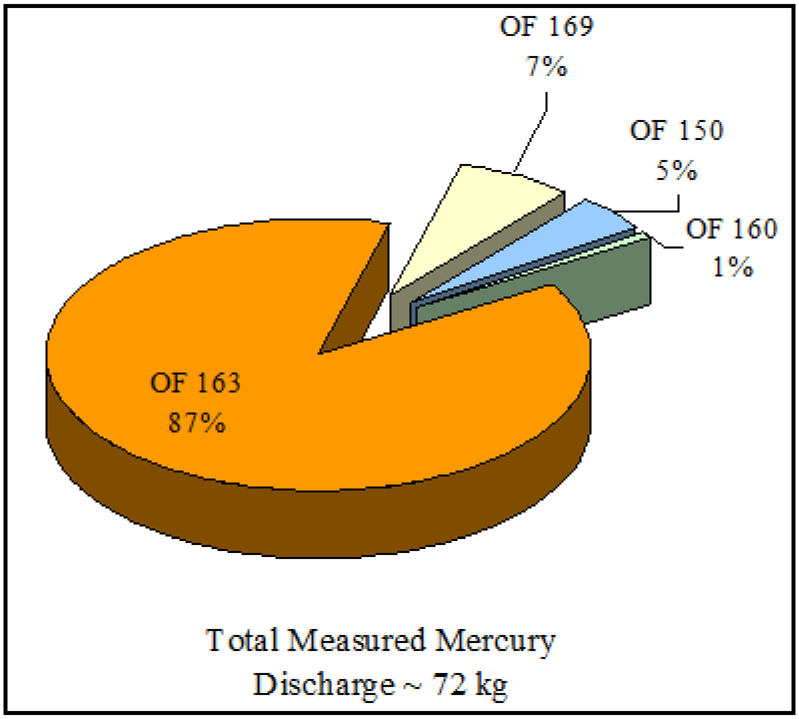

Fig. 4. Mercury Concentrations in Upper East Fork Poplar Creek Watershed from Various Outfalls (OF).

POND CONTAMINATED WITH POLYCHLORINATED BIPHENYLS

The K-1007-P1 Holding Pond at the East Tennessee Technology Park is contaminated with PCBs. The principal source of PCBs in the fish is the pond sediment which became contaminated over the years from historical storm drain releases. The sediment in the pond acts as a continuing source of PCBs in fish. Fish PCB concentrations in the pond prior to remediation exceeded both human health and ecological risk thresholds.

Because of the difficulty and cost of removing contaminated sediments from the pond, and strong public support for a “non-destructive remediation option”, the project team developed an unconventional, less costly, but potentially more risky remedial approach to clean-up. The action selected to remediate the K-1007-P1 Holding Pond, termed the Ecological Management and Enhancement option, was designed to restore the pond to natural conditions that are much less conducive to PCB uptake in fish. Manipulations include modifications of the fish community, plant community, wildlife community, and water quality. Specifically, the remedy included:

- draining the pond
- removing fish that resuspend PCB-contaminated sediment, bioaccumulate PCBs to high levels (e.g., lipid rich species), and eat aquatic vegetation

- establishing a dominant fish population of low-bioaccumulating species, such as bluegill
- planting aquatic vegetation to limit sediment resuspension
- minimizing erosion and nutrient additions though riparian plant improvements and removal and control of geese
- monitoring to document the pond condition, support trend analysis, and identify adjustments to the plan

The remedial action was designed to be flexible and adaptive over time, depending on how the pond's ecology and PCB levels responded. Baseline, operational, and performance monitoring were required as part of the action, each with a different purpose and timeline in addressing the needs of the project (Fig. 5). Baseline monitoring was conducted in advance of the action to provide data for comparison after the remediation. Operational monitoring was performed to ensure that the ecological enhancement measures were implemented as intended and to evaluate whether remedial modifications were needed to attain the design end state. Performance monitoring, which focused on PCB concentrations in fish, was conducted to determine if remediation levels have been met. A review of this data will form the basis for concluding that either the remediation levels have been met or trending toward a successful endpoint or the remedy is not effective and that additional actions, an alternative remedy, or modifications to the remedy may be needed.

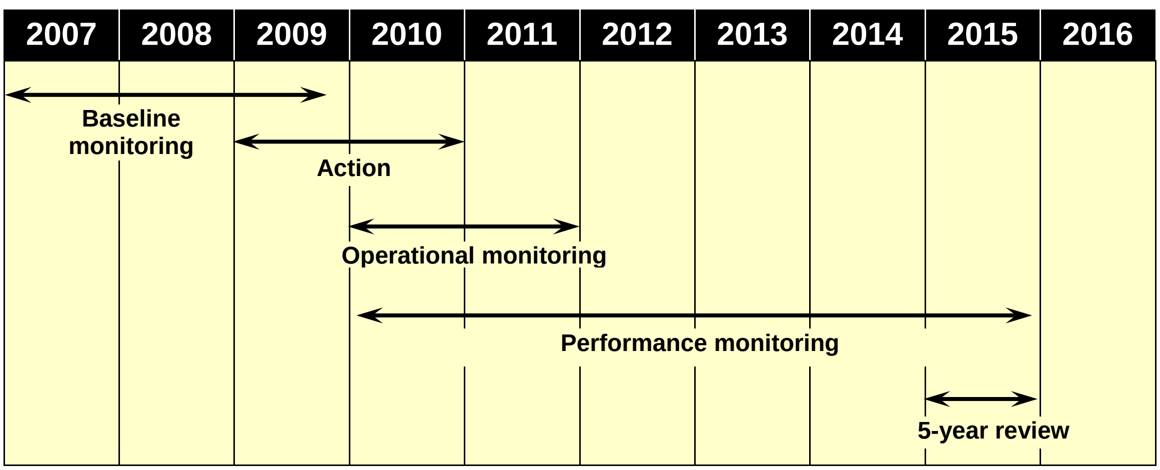

Fig. 5. Monitoring Plan Time Line for the K-1007-P1 Holding Pond.

Operational monitoring data collected two years prior and two years after the action suggest that the desired water quality, plant community, and wildlife manipulations are progressing well toward the desired end state, although in each case changes are continuing and a stable end-state has not been reached. Total suspended solids decreased from around 20 mg/L to 6 mg/L, percent plant cover increased from near zero to over 80% at the east side of the pond (Fig. 6), and the number of geese at the pond decreased from approximately 40/survey to less than 2. In contrast to these positive changes, the fish community monitoring has found that some undesirable species are increasing in numbers and/or biomass. However, the performance monitoring results, relative to baseline, are encouraging: PCB concentrations in bluegill fillets have decreased from approximately 3 µg/g prior to the actions to 2 µg/g post-action, while bluegill composite concentrations have also decreased (Fig. 7). It is likely that it will take a number of years for the pond conditions to stabilize such that the success or failure of the remedy is fully determined.

Fig. 6. Changes in Plant Coverage between the End of the First Year of Planting in 2009 (top) and after Two Growing Seasons in 2011 (bottom).

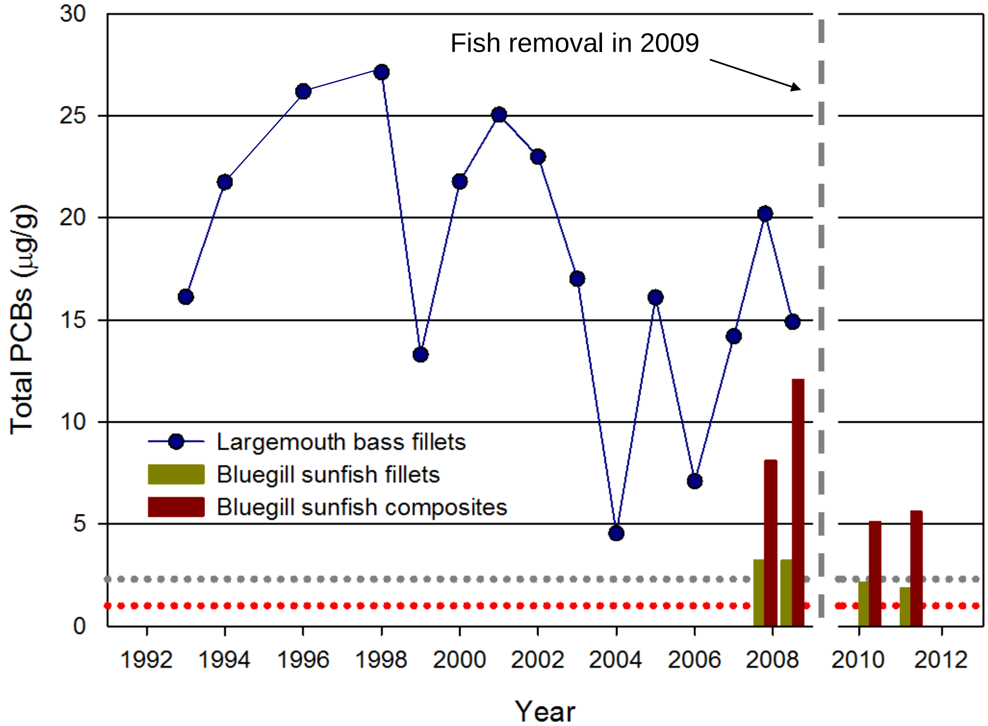

Fig. 7. Mean concentrations of PCBs in Fish from K-1007-P1 Holding Pond, 1993-2011. (Dotted red line signifies PCB goal of 1 µg/g in fillets. Dotted grey line signifies PCB goal of 2.3 µg/g whole body.)

GROUNDWATER

Fig. 2 locates the contaminated groundwater plumes on the Oak Ridge Reservation. While many actions have been taken to control sources of groundwater contamination and to prevent plume migration, no final decisions have been made at the watershed-scale for groundwater remediation. The reasons for this lack of decision-making include:

- Source control actions are not complete, so their effect on groundwater plumes is not known.
- Fractured bedrock and karst geology create complex groundwater issues.
- The location of, migration of, and successful treatment of dense nonacqueous phase liquids are not well understood.
- There is limited data to define potential pathways for contaminant transport through deep groundwater to off-site locations.

Because of these uncertainties, there is a reluctance to make watershed-scale groundwater decisions. Recently, a project was initiated to make the first water-shed scale groundwater decision on the Oak Ridge Reservation on a portion of the East Tennessee Technology Park. The soil remediation and source removal actions had been completed, and there was limited groundwater contamination. A remedial investigation/feasibility study was completed, and a proposed plan was drafted. Currently, work on making this groundwater decision has stopped due to the remaining uncertainties and the possibility that the remedy will either fail or prove inadequate.

However, adaptive management might allow this groundwater decision to be made by recognizing and acknowledging the uncertainty and by modifying the remedy based on additional information gathered during implementation. Rather than viewing the remedial process as linear in which once the decision is made and implemented there is no change, the remedial process should be viewed as iterative (Fig. 2) in which the decision is continuously evaluated and changed as necessary.

CONCLUSIONS

Adaptive management is a tool that allows remedial decisions to be made in the face of uncertainty. Adaptive management is successfully being applied on the Oak Ridge Reservation to make and adjust large-scale watershed remediation and a small-scale contaminated pond remediation and may be used to make watershed-scale groundwater decisions.

The most challenging problems with applying adaptive management to remedial decision-making are recognizing and accepting risk as an integral part of decision-making and being receptive to and prepared to change the remedies based on subsequent data and evaluation. Rather than viewing the remedial process as linear in which once the decision is made and implemented there is no change, the remedial process should be viewed as iterative in which the decision is continuously evaluated and changed as necessary.

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