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RESEARCH OPPORTUNITIES FOR STUDIES OF CONTAMINANT TRANSPORT IN FLUVIAL SYSTEMS AT THE TIMS BRANCH - STEED POND SYSTEM, SAVANNAH RIVER SITE

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PREFACE

This report is based on discussions at a DOE-sponsored workshop on "Research Opportunities for Studies of Contaminant Transport in Fluvial Systems at the Tims Branch - Steed Pond System, Savannah River Site" held on March 4-, 2003, at the University of Georgia Conference Center at the Savannah River Site (SRS). The workshop brought together a diverse group of 33 scientists to discuss the scientific issues associated with contamination in riparian, fluvial, and hyporheic systems by examining the general scientific remediation challenges and research opportunities in such systems, using the Tims Branch – Steed Pond system, a uranium- and heavy-metal-contaminated riparian system at SRS, as a focal point.

The workshop included scientists from universities, national laboratories, and research centers with diverse research interests in environmental science ranging from molecular to field scales. SRS representatives were also present to provide site technical and environmental information.

The workshop was sponsored by the Environmental Remediation Sciences Division, Office of Biological and Environmental Research, Office of Science. The DOE liaisons were Patrick Jackson (Savannah River Operations Office) and Paul Bayer and Henry Shaw (Environmental Remediation Sciences Division, Office of Biological and Environmental Research, Office of Science). The workshop was organized and convened by a steering committee consisting of Paul Bertsch and Carl Strojan (Savannah River Ecology Laboratory); Catherine Lewis (SRS Soil and Ground Water Closure Projects); and Jack Corey, Michael Heitkamp, and Mikell Powell (Savannah River Technology Center). A list of workshop participants is included in Appendix D.

The workshop began with a series of overview presentations, followed by breakout sessions during which each working group discussed their assigned topic and prepared a written summary which formed the basis for this report. Breakout sessions were organized around three working group topics: 1) Soil chemistry, geochemistry and particle surface chemistry, 2) Transport in fluvial and ground water systems, and 3) Bacterial and phyto interactions with contaminants. The composition of each breakout group is listed in Appendix E. The workshop agenda is included in Appendix C.

EXECUTIVE SUMMARY

There was agreement among the workshop participants that riparian, fluvial and hyporheic systems represent a unique opportunity to advance science and to accelerate progress toward DOE's goal of achieving stable, protective and cost-effective end states.

A workshop to identify the scientific issues associated with contamination in riparian, fluvial, and hyporheic systems was held in March 2003 at the Savannah River Site (SRS). The workshop examined the general scientific remediation challenges and research opportunities in such systems and on Tims Branch – Steed Pond, a specific uranium- and heavy-metal-contaminated riparian system at SRS. The U.S. Department of Energy's (DOE) Office of Science, Environmental Remediation Sciences Division (ERSD), convened the workshop with co-sponsorship by the Savannah River Ecology Laboratory and the Savannah River Technology Center.

A diverse group of scientists representing a wide range of scientific disciplines came from academia, national laboratories, and research centers to develop recommendations for future ERSD research opportunities. There was agreement among the workshop participants that riparian, fluvial, and hyporheic systems represent a unique opportunity to advance science and to enable progress on DOE's environmental cleanup of contaminated sites.

Previous DOE-sponsored research on radionuclide and metal contamination has primarily focused on subsurface environments, and this work has resulted in significant scientific advances in our understanding of the subsurface processes regulating contaminant transport. The participants at this workshop documented both the critical need and the great promise for research on hydrological and biogeochemical processes controlling contaminant transport and fate in contaminated surface and near-surface systems. The approach of the workshop was to assess the Tims Branch – Steed Pond system at the SRS as an appropriate site to identify research needs that support potential remediation strategies.

Workshop participants quickly converged on several major recommendations for future ERSD research directions:

- The ERSD program should expand to include research on the fate and transport of contaminants in fluvial riparian systems. Contamination in fluvial riparian systems exists at many DOE sites and, even if currently uncontaminated, they represent ground water discharge points, which are of regulatory concern. Riparian and wetland systems are complex, representing areas where several environmental factors, such as varying soil chemistry, ground water and surface water systems, and significant biological activity interact simultaneously to influence contaminant behavior.
- The Tims Branch – Steed Pond system represents a good candidate site for research on hydrologic and biogeochemical processes controlling the fate and transport of contaminants in highly dynamic fluvial riparian systems. The system is located in a temperate region with metal-oxide- and organic-rich soils contaminated with metals and radionuclides of

widespread concern to DOE. The results of this research would be directly applicable to other sites.

- Potential remediation strategies for contaminants in fluvial riparian systems that would be critical for the successful remediation of these systems were identified, as were key scientific research areas needed to increase the understanding of hydrobiogeochemical factors controlling contaminant fate and transport.
- The importance and value of research into coupled processes in fluvial and riparian systems was a central outcome of the workshop.

1.0 INTRODUCTION

The U.S. Department of Energy's (DOE) Office of Science, Environmental Remediation Sciences Division (ERSD), has two major programs to establish the scientific understanding required to solve technical problems facing DOE's environmental cleanup effort. The Environmental Management Science Program (EMSP) funds a broad range of environmental research topics, with projects in subsurface contamination, nuclear materials, mixed waste, high-level waste, health/ecology/risk, and decontamination and decommissioning. The Natural and Accelerated Bioremediation Research Program (NABIR) is a more focused program that provides the scientific understanding needed to employ natural processes and to develop new approaches to accelerate those processes for the bioremediation of contaminated soils, sediments, and ground water.

These programs have made significant investments in research that has greatly enhanced the scientific understanding of biogeochemical processes controlling the behavior of contaminants in wastes and the environment as well as the human and ecological risks associated with contamination of DOE sites. Individual projects from the EMSP program are addressing (1) the fundamental science underlying transformations of metals in the environment, (2) the propensity of these materials to migrate further into the soil profile with time, and (3) the availability of these materials to the ecosystem through mechanisms such as biological uptake, inhalation, and ingestion. This understanding is necessary to quantify the risk of leaving materials in place versus removing materials, as well as to design and model possible remediation schemes. Research within the NABIR program is examining the biotransformation, biodegradation, and biogeochemical dynamics of contaminants, and the microbial community dynamics and ecology. These projects are examining the effects of various physical, chemical, and biological factors on the fate of uranium, technetium, plutonium, chromium, and mercury.

To date, much of DOE's research on radionuclide and heavy metal contamination has focused on understanding biogeochemical processes that control subsurface contaminant transport. However, DOE's environmental cleanup challenges encompass a wider range of physical and environmental conditions, including surface and near-surface contamination in wetter regions of more temperate climates. The Savannah River Site (SRS) in South Carolina is an example of a major DOE site where such conditions exist; the SRS's Tims Branch – Steed Pond system is a specific example of a floodplain – surface stream ecosystem that is representative of many contaminated areas in the DOE system. The Oak Ridge Reservation, the DOE closure sites in Ohio, the gaseous diffusion plants at Portsmouth, OH, and Paducah, KY, and potentially other sites in moist, temperate climates are other such examples. The Tims Branch – Steed Pond system contains a large inventory of uranium and nickel as well as smaller quantities of copper, zinc, lead, cadmium, and chromium. Additional background information on the Tims Branch – Steed Pond system is summarized in Appendix A.

The ERSD convened a workshop to explore the expansion of ERSD's fundamental research activities aimed at providing an understanding of contaminant fate and transport processes in fluvial, hyporheic, and riparian systems where surface and near-surface contamination presents remediation challenges. The research would lay the scientific foundation for acceptance of alternative minimally invasive remediation solutions for a flood plain - surface stream ecosystem such as Tims Branch – Steed Pond.

2.0 WORKSHOP RESULTS

Workshop discussions were organized into three breakout groups that were structured around the three major categories of processes affecting the fate and transport of radionuclides and metals in riparian systems: (1) soil chemistry, geochemistry, and particle surface chemistry, (2) transport in fluvial and ground water systems, and (3) bacterial and plant interactions with contaminants. Participants in each of these three breakout groups were also encouraged to discuss coupled processes involving the other two process-level categories. Breakout groups addressed the following overall topics; their results are presented in Sections 2.1 through 2.5:

1. Expansion of the Environmental Remediation Sciences Division (ERSD) Research into Fluvial and Surficial Bio-Geo-Hydrologic Systems

2. Key Research Needs on Physical, Chemical, and Biological Processes Controlling Fate and Transport of Contaminants in Riparian Systems

3. Suitability of the Tims Branch – Steed Pond System as a Site to Address These Research Needs

4. Additional Characterization and Monitoring Requirements to Support Research in the Tims Branch – Steed Pond System

5. Potential Remediation Strategies and Approaches

Specific questions for consideration during the breakout discussions are listed in Table 1 at the end of this chapter. The integrated results of these discussions are summarized in the sections below.

2.1 Expansion of ERSD Research into Fluvial and Surficial Bio-Geo-Hydrologic Systems

Workshop participants strongly recommended that ERSD expand its research program to include studies of the fate and transport of contaminants in fluvial and surficial bio-geo-hydrologic systems.

One of the primary means of transport of contaminants in the environment is by the movement of water and associated particulate materials (*e.g.*, suspended sediments). Exposure of humans or other organisms to the hazards posed by contaminants almost always requires the presence of the contaminant at or near the surface of the Earth, where it is accessible to the biota. In natural systems (*i.e.*, excluding situations where ground water is pumped to the surface by man), exposure to water-borne contamination occurs where the ground water outcrops at the surface in the form of springs, seeps, streams, and lakes or ponds. This interface between ground water and surface water is an important zone for biogeochemical activity and is a region of key regulatory concern. It is therefore logical to conclude that any program of research intended to elucidate the fate and transport of environmental contaminants with respect to their ultimate impact on human and ecological health must include research on surficial hydrologic systems and their associated chemical and biological components.

Surface soils or ground water systems at the Savannah River Site, the Oak Ridge Reservation, the DOE's closure sites in Ohio, the gaseous diffusion plants at Portsmouth, OH, and Paducah, KY, and potentially other sites in moist, temperate climates are contaminated with metals, radionuclides, and other hazardous substances. Extensive wetlands exist at the Savannah River Site, in particular, and widespread contamination of some of these riparian systems presents a currently intractable problem for the site. Concerns also exist at the Hanford Site for the potential of contaminated ground water outcropping into riparian zones along the Columbia River. If rational decisions are to be made concerning remediation and long-term stewardship of these sites, then it is clear that a scientific understanding of the physical, chemical, and biological processes controlling contaminant fate and transport in these systems is needed.

Historically, the majority of the DOE-sponsored research on contaminant fate and transport has focused on the processes occurring in the subsurface, particularly in arid western regions of the United States. This emphasis has been justified by the need to understand the behavior of contaminants that have been released to the subsurface at DOE facilities in the west, such as the Hanford Site and the Idaho National Engineering and Environmental Laboratory, or those that may be released to the subsurface at the proposed Yucca Mountain repository for high-level nuclear waste. Even at these sites, where the primary contamination is, or would be, located tens to hundreds of meters below the surface, impacts on human and environmental health will only occur when the contamination approaches the surface, where it can interact with the surface and near-surface biota. Therefore, the interaction between contaminated ground water plumes and the surface water system is of primary importance. In general, the consequences of contaminant releases ultimately depend on the physical, chemical, and biological behavior of contaminants in surficial or near-surface systems. Research on such systems will have relevance to nearly all of the environmental remediation activities at DOE sites.

In some ways, assessing the fate and transport of a contaminant in the deep subsurface is less complicated than doing such an assessment for surficial or near-surface contaminants. Although rapid spatial variations in hydrological and chemical properties can exist, temporally stable or slowly varying physical and chemical conditions and biological communities are more typical of the subsurface. In contrast, near-surface conditions can change dramatically over both short distances and very short time scales. Near-surface conditions can change rapidly and dramatically due to episodic events such as storms and floods, in response to periodic (*e.g.*, diurnal and annual) cycles, and as geomorphic landscapes evolve. Biotic diversity is dramatically greater near the surface, increasing the number of possible biogeochemical interactions that must be considered in assessing the behavior of a contaminant. Reaction chemistry in this zone is not well understood (*e.g.*, why there are differences in the way different metals, such as nickel and uranium, move through the Tims Branch - Steed Pond system). The daunting task of trying to understand this complexity is tempered, however, by the relative accessibility of surficial and near-surface contamination for study.

Obviously, the problem of contamination of surficial soils, sediments, and hydrologic systems is not restricted to DOE sites. Similar problems exist throughout the United States and worldwide due to mine tailings and leachate, industrial activities, and defense activities.

Expansion of the ERSD's research program into fluvial and riparian systems could exploit and build upon progress of past DOE basic science research in biogeochemistry, as well as non-DOE funded work that focused on the fate and transport of chemicals and fertilizers in agricultural watersheds. An emphasis in this area would also offer unique opportunities to expand the understanding of coupled processes, which currently represents a major knowledge gap that limits our ability to predict the fate and transport of contaminants in the environment.

2.2 Key Research Needs on Physical, Chemical, and Biological Processes Controlling Fate and Transport of Contaminants in Fluvial and Riparian Systems

The emphasis of workshop discussions was on identifying key research needs to enable understanding the behavior of contaminants in fluvial, hyporheic, and riparian systems so that we can predict the fate and transport of contaminants in these systems. These are science gaps that relate to many of the potential remediation strategies discussed in Section 2.5 and that must be addressed to support the determination of the most appropriate strategies for a specific remediation effort. The key research needs identified by workshop participants are discussed in the following sections.

2.2.1 Key Research Need - Understanding the Current State of the System

Metals and radionuclides have been released to surface waters or have outcropped from ground water and been deposited in riparian zone sediments at several DOE sites. Even where contamination in the deep subsurface has been a focus at other sites, the discharge points to surface waters are of regulatory concern. Riparian systems represent diverse and complex systems with respect to the coupled physical, geochemical, and biological processes that control contaminant transport and fate. Contaminants released to, and then aged in, riparian sediments are subjected to numerous biogeochemical processes that occur over a wide range of spatial and temporal scales. Understanding the surface-chemical processes along with the complex dissolution-precipitation chemistry that controls contaminant behavior is key to predicting the fate of contaminants from the standpoint of transport and bioavailability, which are key elements in evaluating potential human health and ecological risks. Additional key elements include an understanding of the processes controlling the transfer of contaminants between trophic levels and a scientifically defensible identification of appropriate ecological endpoints for assessing risk.

Specific research needs include:

1. **Contaminant inventory, including speciation and mass balance.** Information is needed on the quantity, distribution, chemical speciation, and mass balance of contaminants currently present in the system (*i.e.*, what is there, how much, where is it located both two- and three-dimensionally, and when and how does it change?).

2. **Processes involved in "aging" of contaminants in riparian sediments under a range of spatially and temporally variable oxidation/reduction conditions.** It is known that the mobility and bioavailability of metals and radionuclides tend to decrease with time

following their introduction to the environment. The biogeochemical processes involved in this “aging” phenomenon have been examined to a limited extent in model systems but are poorly understood in complex multiphase systems. Thus, information leading to a better understanding of the controlling mineral/humic surfaces and solid phase speciation in “real” systems representing complex assemblages of metal oxide and humic substances is needed. Furthermore, little is known about the reversibility of the “aging” process in complex systems under varying geochemical conditions. Reversibility is a critical and poorly understood issue at all contaminated field sites; however, the dynamic nature of the riparian system is likely to result in complex sequestration mechanisms with differing degrees of reversibility. A fundamental understanding of the mechanisms controlling sequestration of metals and radionuclides and their reversibility in riparian sediments is critical to providing a scientific basis for the acceptance of naturally-based remediation strategies, such as monitored natural attenuation (MNA) or *in situ* stabilization. These remediation approaches are predicated on the low mobility and bioavailability of sequestered/stabilized inorganic contaminants.

3. **Role of dissolved and colloidal humic substances as well as microbial communities in controlling the solubility of metals and radionuclides in complex systems.** Natural organic matter serves a dual role in terms of regulating the solubility of metals and radionuclides. Solid-phase detritus and humic substances can act as highly reactive substrates for the sorption of metals and radionuclides, while soluble organic ligands and colloidal humic substances can facilitate the solubility of the metals and radionuclides. Many geochemical models suggest the importance of natural organic ligands in aqueous-phase speciation of metals and radionuclides. However, little is known about the importance of solid-phase humic substances relative to dissolved/colloidal organic constituents in regulating the solubility and controlling the aqueous-phase speciation of metals and radionuclides in organic-rich riparian sediments. Additionally, validation of these models over spatially and temporally variable conditions, such as those found in riparian zone sediments, is lacking. Finally, the spatial and temporal variability of microbial communities relative to their function requires investigation.

4. **Understanding the relationships between micro-scale and macro-scale behavior of metals in fluvial and riparian systems.** Explanations for the field observations at the Tims Branch - Steed Pond system are needed. Why, for example, do uranium and nickel appear to correlate on a system-wide scale when their geochemistry and bio-uptake in individual studies are quite different? Specific information is lacking on uranium and nickel colloids, pseudo-colloids, colloid aggregation kinetics, and the size distribution of uranium particles in the sub-micron range. Changes in speciation and bioavailability over the redox gradients should be identified, including the sources and identity of important oxidants and reductants, the microorganisms involved and population changes, and the products of oxidation and reduction and their impact on contaminants. Species quantification would help determine if the uranium is associated with an organic or inorganic phase. The influence of labile aluminum also needs to be addressed because the uranium may be co-associated with the aluminum.

5. **Behavior of uranium daughters.** As uranium undergoes radioactive decay, radioactive daughter products are produced that have very different biogeochemical behavior and thus very different potential for transport and/or bioavailability. Among the daughter products that may be of particular concern are radium and radon, which are expected to be relatively mobile. Any risk assessment and suggested remedial course of action must take into account the in-growth of daughter products and their potential for transport and uptake. Daughters to uranium may also be used as tracers.

2.2.2 Key Research Need - Understanding System Responses During Perturbations

Because the Tims Branch – Steed Pond system is subject to episodes of flooding and drying, physical, chemical and biological processes controlling fate and transport need to be evaluated under a range of conditions. This will support a determination whether or not storm events are a risk driver in this system. Examples of processes that should be evaluated seasonally and during episodic events include:

1. **Speciation and mobility of contaminants** under a wide range of conditions, including rainfall, pH, and anoxic and oxic conditions. The effects of seasonal cycling on acceleration of aging need to be determined.

2. **Seasonal and super-seasonal climate variability, and spatial variability in the system.** Specific issues are temporal variations in hydrology and sediment transport, including determination of aquatic loads from various erosion rates.

3. **System dynamics** both in terms of water flow and in terms of locations, amounts and formation/loss of geochemical and biological sub-environments over extended time periods. These systems are not static but are very dynamic. A good model understanding of how soil and sediments will be reworked over time (*e.g.*, geomorphology) is needed.

4. **Plant-microbe interactions that affect contaminant mobility**, including functional stability of the rhizosphere and sediment microbial communities, and accumulation of contaminants by riparian biota.

5. **Bioavailability and trophic transfer of contaminants**, including quantifications of trophic transfer of contaminants under various conditions.

2.2.3 Key Research Need – Understanding How the Processes Are Coupled

Many of the processes controlling fate and transport of contaminants in the Tims Branch – Steed Pond system are coupled and must at some point be evaluated together. The emphasis of the EMSP and NABIR programs has been largely in subsurface environments, where a wealth of information on coupled biological and geochemical processes leading to the immobilization of contaminants has been generated. While some of this information is transferable to riparian systems, new challenges and research opportunities exist to provide the knowledge base needed to solve problems related to remediation and restoration of contaminated riparian corridors. Specific research needs include:

1. **Improved understanding of how surface and subsurface hydrology of the Tims Branch – Steed Pond system, chemical speciation of metals and radionuclides, and the physics of sediment transport affect ecological risk.**

2. **Coupling of metal and radionuclide geochemistry to the cycling of organic matter by the microbiota.** Organic matter cycling in near-surface sediments is much more dynamic and complex than in deep subsurface contaminated sites.

3. **Understanding of how succession of vegetation in the riparian zone affects contaminant transformations and transport, including subsurface transport.** In effect, this key research need is an attempt to study aging of the system (similar to aging of the contaminant in the system). This aging effect is unique to near-surface systems.

4. **Effects of microbial and rhizosphere processes to modify geochemical conditions that influence the stability of reactive mineral phases as well as contaminant solubility.** Biogeochemically controlled processes, typical of riparian zone sediments, lead to the establishment of temporally variable chemical gradients. Localized redox gradients induced by microbes in the rhizosphere of plants and by bioligands produced and exuded in the rhizosphere can have a profound influence on the aqueous- and solid-phase speciation of metals and radionuclides. Little is known concerning the spatial scales over which these processes operate or how cyclical changes induced via these biological processes influence the longer-term geochemical lability of the metals and radionuclides (*i.e.*, how these processes influence “aging” or sequestration reactions). In addition, little is known about the major sources of oxidants, reductants in these complex systems, or the biomineralized products (*e.g.*, ferrihydrite, lepidocrocite, *etc.)*. Fundamental understanding of the key biogeochemical processes controlling metal and radionuclide behavior is required to understand and predict the fate and transport of metal and radionuclide contaminants in riparian zone sediments. This understanding is also essential for implementing bioremediation or phytoremediation/stabilization strategies in such environments.

5. **Effects of steep redox gradients and contaminant distributions on microbial community structure and function.** Riparian and wetland systems are valued for their natural capacity for attenuating the concentrations of mobile contaminants. The synergy of high organic matter content, diverse microbial populations, and a wide range of geochemical conditions promotes the biodegradation of organics and biotransformation of metals and radionuclides. Little detailed information is available on the spatial variability of microbial community structure and function as related to steep redox gradients in riparian systems or on the influence of contaminant metals on microbial community structure or function. Understanding the major coupled biological and geochemical processes in such complex systems is critical for predicting their capacity for natural attenuation. This understanding is also needed to assess the potential efficacy of bioremediation for organics, metals, and radionuclides and the effect of co-contaminant metals on bioremediation strategies.

6. **Understanding the linkage between molecular-level information on metal and radionuclide contaminants and the bioavailability and trophic transfer of these contaminants.** While it is clear that the ability to predict the fate and transport of contaminant metals and radionuclides requires knowledge of their chemical speciation at the molecular level, there are few studies that have attempted to link this information to bioavailability and trophic transfer at broader scales. A variety of novel methods for providing molecular-level information on the chemical speciation of metals and contaminants in complex media have emerged in the past decade. The molecular-level speciation of contaminants is typically linked to the concept of bioavailability based on geochemical endpoints. How this information translates to the evaluation of ecological risk is poorly understood, often resulting in overly conservative assessment of risk. Interdisciplinary research employing novel spectroscopic and imaging methods along with advanced computational modeling is needed to link geochemical endpoints to appropriate biological endpoints that will enable us to better define appropriate ecological endpoints.

7. **Use of tracers to identify coupled processes and their relative impact on contaminant fate and transport.** Tracers and isotopes can provide a better understanding of how contaminants are moving through the system. More information on the initial discharge chemistry (*i.e.*, concentration and forms of contaminants, volumes, and other constituents) would enable identification of possible components (*e.g.*, uranium daughters) that can be used opportunistically as tracers. In addition to the original contaminants, there may be additional tracers associated with the original waste that may be useful. Introduction of new tracers that might be analogs for contaminants that associate with fine sediment and to document hydrology is also promising.

8. **Understanding of ecosystem management.** Ecosystem changes impose additional variability on the system that goes beyond meteorology and traditional cycles of the seasons and drought and rainfall. The effects of ecosystem changes on the microbial community structure and function need to be identified. Ultimately, the science and policies need to answer questions such as, “Is beaver perturbation viewed as positive or negative in terms of how it impacts the system or how it might impact a science program?”.

2.2.4 Key Research Need - Understanding Scales At Which The Processes Are Important

Much of our knowledge on chemical and biological processes that influence the speciation and mobility of metals and radionuclides is based on studies conducted at the bench scale under highly controlled conditions. Research is needed in the following areas:

1. **Effects of large-scale system processes such as hydrology on chemical and biological processes at the watershed scale.**

2. **Understanding of hydrological processes (typically characterized at the watershed scale) at smaller scales** to better understand advective and diffusive transport of contaminants and nutrients within the hyporheic zone.

3. **Geochemical scaling**. Scientific understanding of geochemical scaling, including reaction chemistry from the molecular to the field scale, is essential to support contaminant reactive transport at the field scale.

4. **Integration of data and processes across scales.** The important processes include atomic, molecular, surface, grain, fluvial channel, riparian, watershed, and landscape scale activities. This integration is difficult in a complex real system with dynamic and evolving geomorphology and with contaminant transport dominated by fine-grained sediment transport and organic matter.

5. **Advancement of current numerical models of fluid transport in the hyporheic zone to describe colloid and sediment transport.** The models also need to include terms to account for heterogeneities in the physical, chemical, and biological properties of the hyporheic zone that influence fluid flow. The models need to be tested using field data from the Tims Branch – Steed Pond system and relevant laboratory data.

6. **Influence of bedform-induced flow on characterization and contaminant containment and release.** This science need influences even the most basic data gathering. Standard sampling and characterization approaches, such as water and contaminant flux collection chambers, may not accurately reflect the influence of bedform-induced flow.

2.3 Suitability of the Tims Branch – Steed Pond System as a Site to Address These Research Needs

Workshop participants recommended consideration of the Tims Branch – Steed Pond site as an appropriate location for research on the fate and transport of contaminants in fluvial, hyporheic, and riparian systems. A number of reasons were given for this recommendation:

1. The primary contaminant in the Tims Branch – Steed Pond system is uranium. Uranium is the most common radionuclide contaminant in ground water/sediment systems at DOE facilities and is often found associated with other metals such as nickel, chromium, and copper (Riley et al., 1992; NRC, 1994). Uranium is a widespread contaminant introduced into the environment as a result of mining and manufacturing activities related to the nuclear power industry, detonation of uranium-containing munitions at Department of Defense facilities, and as a result of nuclear weapons materials production and processing at DOE facilities (Riley et al., 1992). Tims Branch is one example of such an environment. As a result of fuel and target fabrication operations in M-Area, large amounts of uranium (~43 metric tons), nickel, aluminum, and chlorinated hydrocarbons were released into Tims Branch.

2. Research at Tims Branch – Steed Pond would be applicable to many other sites, as discussed in Section 2.1. For example, the low ground water pH, high organic content soil, and the climate at this site are similar to those at Oak Ridge. General vegetation and microbe interactions would also be applicable at other sites such as Oak Ridge and certain Russian sites. The research may also be relevant for understanding the fate of "dirty bomb" contamination.

3. It is estimated that more than 97 percent of *all* gross alpha activity released to the environment from Savannah River Site facilities was as uranium discharged from M-Area operations, and a majority (~61 percent) was released over a 3-year period (Evans et al., 1992). This pulsed release of contaminants occurred concurrently with the massive erosion of iron oxide and clay rich sediments that were redeposited in a riparian system, providing a unique opportunity to examine aging mechanisms that control the behavior of uranium and metal contaminants in biogeochemically dynamic riparian sediments on decadal time scales. The unique nature of the contaminant release history and the existing background characterization data make the Tims Branch – Steed Pond system an excellent field site for research. The uranium release rates over time are known, which provides a uniquely well-defined temporal and spatial source term. Microspectroscopic data on this system suggest that uranium and nickel are partitioned to different phases that are generally spatially separated over tens of micrometers, with uranium being typically associated with organic rich phases and nickel with iron-oxide rich phases. Wet chemical extraction techniques reveal that a larger fraction of nickel has been transferred to more recalcitrant phases over time, albeit the solubility of nickel is much greater than that of uranium.

4. The Tims Branch – Steed Pond system is geographically located in the upper coastal plain of the Southeastern U.S., an area having some of the greatest biodiversity in North America. Thus, this system provides exciting opportunities and challenges for linking the geochemistry of uranium and metal contaminants to bioavailability, trophic transfer, and effects on biological receptors in order to develop new approaches to establishing ecological risk. Researchers from the Savannah River Ecology Laboratory and Westinghouse Savannah River Company have already performed a number of geochemical and biological studies at the Tims Branch – Steed Pond system. Information on processes controlling bioavailability of contaminants and transfer up trophic levels is critical to assessing the human health and ecological risks associated with metal and radionuclide contaminants, especially in the context of MNA or other minimally invasive remediation strategies based on physical or biogeochemical stabilization. In the absence of robust models for defining ecological risk, current risk calculations are overly conservative. Research information obtained at this site will be used to develop the knowledge base required to develop robust models to properly evaluate ecological risk. Such models require a fundamental understanding of the linkage between chemical speciation of metals and radionuclides and bioavailability and transfer up trophic levels.

5. The Tims Branch – Steed Pond site consists of a small, dynamic and complex system that provides opportunities for testing concepts applicable to a number of DOE sites. The variability at this site provides an opportunity to test hypotheses in a small system.

Both the Savannah River Site and the regulators are hopeful that a viable remediation alternative to excavation can be found, so research on alternatives may have direct application to this site and potentially other aquatic sites.

2.4 Additional Characterization and Monitoring Requirements to Support Research in the Tims Branch – Steed Pond System

Workshop participants identified additional characterization and monitoring that should be done at the Tims Branch – Steed Pond site to support research studies on contaminant fate and transport. To effectively evaluate potential remediation strategies, one must understand the levels of each contaminant in the system and where the contaminants currently reside in the system. An immediate characterization need is to establish a mass balance of the contaminants (primarily uranium and nickel) in the Tims Branch – Steed Pond system. Source isotopes should also be identified. The study site should be expanded to Upper Three Runs to determine whether uranium has entered this system. Sampling of the Savannah River for depositional information is also recommended. This will be important for determining how much uranium and nickel has already been transported out of the Tims Branch – Steed Pond system and for monitoring the effectiveness of a remediation strategy.

To make this a viable site for fluvial and riparian research, several activities must be initiated. These include: (1) installation of stream flow gauges and piezometers and measurements of contaminant levels in sediment, suspended load, and dissolved load at several locations to support mass balance and export conceptualization; (2) additional data interpretation and sampling to develop an improved understanding of the spatial distribution of contamination; (3) clear definition of the remediation goals for Tims Branch and Steeds Pond within the Upper Three Runs system; and (4) identify and organize retrievable historical information such as waste inventories, flow records, aerial photography aerial gamma surveys, and other baseline data..

2.5 Potential Remediation Strategies and Approaches

Workshop participants discussed strategies and approaches for remediation of the Tims Branch – Steed Pond system and identified several potential alternatives. These alternatives could be applicable to other riparian systems. Participants also discussed the scientific gaps that would need to be filled to determine which remediation strategy would be most effective. They identified opportunities provided by the Tims Branch – Steed Pond system for addressing those science gaps. The remediation strategies are described in this section, and the science gaps and opportunities associated with each strategy are summarized in Appendix B.

The ultimate goal of any remedial action in the Tims Branch - Steed Pond system is protection of potential human and ecological receptors. In such fluvial and riparian systems, the principal ecological receptors are local – in direct proximity to contaminated sediments. The export of sediments and contaminants from the watershed may increase potential human and ecological exposure.

The main driver for remediation of the Tims Branch – Steed Pond system is particle-associated uranium and nickel that are transported downstream and to the riparian zone through episodic flooding. Steed Pond and Pond 25 are the primary catchments in the system where sediment and contaminants have accumulated. However, the possibility exists that future flooding could further the transport of the contaminants downstream and outside the Savannah River Site boundary.

A variety of remediation strategies are viable for such systems. As discussed below, some of these strategies leave most of the metals and/or radionuclides in the system, while others attempt to remove them. Those methods that leave contaminants in the system use a variety of geochemical, biological, and isolation approaches to mitigate local ecological impacts - limiting uptake, toxicity, and trophic transfer - and also to control contaminant export. Fundamental new scientific information is needed to document the viability, robustness, and long-term stability of mitigation and system controls. The baseline technology is removal – a strategy that is often costly and that can result in significant collateral environmental damages in fluvial and riparian systems as well as increased worker exposure. Focused research can play a key role in identifying where removal is necessary and in making such actions more surgical and cost effective. However, future use of the site and the eventual end-state must be defined before an appropriate remediation strategy can be selected.

The workshop participants identified and organized remedial strategies into four categories: (1) watershed manipulation, (2) contaminant and sediment stabilization, (3) contaminant and associated sediment removal, and (4) monitored natural attenuation. Some optimized combination of actions from these four categories represents the appropriate solution for the Tims Branch – Steed Pond system and for other contaminated fluvial/riparian systems. The workshop participants considered these remediation categories as they identified fundamental scientific gaps and current limitations in the ability to couple processes at various scales.

Table 2 at the end of this section was developed after the workshop to provide a qualitative assessment of the various remediation categories discussed by the workshop participants. A clear inference from Table 2 is that all of the technical solutions based on a single discipline have major weaknesses, while solutions that properly couple the hydrological, geochemical and biological sciences are more robust and potentially more cost effective. The importance and value of coupled processes in fluvial and riparian systems was a central outcome of the workshop. The four remediation categories are discussed below.

2.5.1 Watershed Manipulation

Watershed manipulation is based on minimizing the export of fine-grained sediment and the associated contaminants by controlling and managing water, modifying geomorphology, and other techniques. Different variants of this approach may isolate contaminants from the biosphere and provide conditions that may support geochemical and biological stabilization within the system. The limited historical information from the period in which the Steed Pond dam was intact suggests that watershed manipulation has played a significant role in limiting contaminant export in the past.

As with all of the potential solutions, watershed manipulation methods will need to be robust to both seasonal and super-seasonal variability, to couple with stabilization methods, and to be reliable over an extended period (*e.g.*, build in redundancy and design to avoid sudden releases).

One particular feature of the Tims Branch – Steed Pond system is the presence of areas of ground water recharge and areas of ground water discharge to surface water. If an associated stabilization process, such as anaerobic reduction of uranium, is desired, the inflow of aerobic ground water could be explicitly controlled. Similarly, watershed manipulations can be positioned to exploit existing geomorphology and to target current upstream areas of highest accumulation or to provide downstream collection prior to Upper Three Runs. Finally, each watershed manipulation approach generates different types and distributions of sub-environments. The coupling of this information to geochemical and biological scientific information would support proper selection of the watershed manipulation technique. Specific watershed manipulations and their key characteristics are:

1. **Reduce anthropogenic flow –** A large fraction of the base flow, especially above Steed Pond, is anthropogenic (process and runoff water and treated ground water from the pump and treat system).

2. **Dam(s) –** Dam construction would provide for flood control and establishment of anaerobic conditions in the sediments behind the dam that would, in turn, promote uranium bioreduction and immobilization. With any kind of dam solution, potential dam failure should always be taken into consideration. Different dam situations include:
    a. *Single dam* to provide traditional sediment accumulation and hydrologic stabilization.
    b. *Series of dams* to provide redundant sediment accumulation, increased capacity, more long-term stability, and more emergent plants.
    c. *Beaver dams and associated control structures* to work like a series of dams. Beaver dams alone may not have sufficient long-term stability, so additional controls that would minimize transport would likely be necessary.

3. **Engineered Wetland –** Geomorphology, plant community and other factors would be modified to stabilize flow and set up conditions for stabilization.

4. **Other forms of sediment trapping –** rip rap, installation of deep pools as a downstream protective sediment trap, *etc.*

2.5.2 Stabilization

Stabilization processes rely on geochemical interactions, biological processes, and/or physical barriers to reduce contaminant bioavailability; to reduce sediment mobility, uptake, and trophic transfer; and to reduce any toxic effects. Both geochemical and biological processes would work best when coupled with watershed manipulation techniques. Specific examples of stabilization techniques include:

1. **Geochemical stabilization** - Geochemical stabilization could be performed through surface application, injection or mixing of geochemical amendments, or by creation of optimized environments (*e.g.*, reducing environments).
    a. Redox-related stabilization such as chemical reduction of uranium
    b. Addition of materials that precipitate contaminants or that shift contaminants from labile forms into more stable forms

2. **Stream bank capping (physical)** - Stream bank stabilization either through riprap or capping would not necessarily prevent flooding of the riparian zone but would reduce uranium transport through erosion.

3. **Biological stabilization** - Biological stabilization processes are similar to geochemical stabilization processes, except that opportunities expand to include plant-based processes, phytostabilization, and processes that operate in concert with microbial ecosystems. Interestingly, the workshop participants suggested a variety of phytostabilization mechanisms ranging from physical stabilization of fine-grained sediment to contribution of organic matter and stabilizing compounds.

2.5.3 Removal

Removal processes involve physical, chemical or biological methods that extract or consolidate and then collect contamination. The methods range from aggressive, comprehensive removal actions to hot spot removal to phytoextraction. Many coupled variants are possible, such as enhanced erosion combined with sediment collection. Most of the removal processes result in relatively high-cost, short-term risks, and adverse collateral damage to the riparian ecosystem. Large removal actions are also expensive. Despite such shortcomings, removal methods are typically presumed to be the default action or response – without further science, the removal of Steed Pond sediment is the current baseline remediation. In general, the workshop participants felt that more limited removal actions coupled with other activities may provide equal or better environmental protection at a lower cost. Example removal actions include:

1. **Dredging**
2. **Hot spot removal**
3. **Enhanced erosion/collection**
4. **Phytoextraction**

2.5.4 Monitored Natural Attenuation

The EPA uses Monitored Natural Attenuation (MNA) to refer to the reliance on natural attenuation processes (within the context of a carefully controlled and monitored site cleanup approach) to achieve site-specific remedial objectives within a time frame that is reasonable compared to that offered by other more active methods. Natural attenuation includes a variety of physical, chemical, or biological processes that, under favorable conditions, act without human intervention to reduce the mass, toxicity, mobility, volume, or concentrations of contaminants in soil or ground water. The use of MNA will require additional basic scientific research to identify when it is an appropriate strategy and may require entirely new tools and approaches (*e.g.*, using ecosystem indicators, improved ways to measure and interpret trophic transfer, improved methods to determine the significance of biological and ecological measurements, and other tools and approaches). A riparian zone is currently developing along the Tims Branch – Steed Pond system and should provide natural stream bank stabilization and opportunities for natural phytoremediation to occur.

2.5.5 Coupled Solutions

Coupled solutions combine the desirable characteristics of the various categories above. They are coupled both in terms of the scientific principles and the engineering. Many combinations are possible, depending on where the science leads. Examples include watershed manipulation that limits sediment transport, coupled with geochemical and biological stabilization to protect the local ecosystem. The long-term stability of the system would be ensured by setting up watershed manipulation in such a manner that the geochemical and biological environments needed are maximized and that they are protected to the extent possible from adverse seasonal and super-seasonal fluctuations. The coupled end-state would be evaluated using improved science-based measures to properly document that MNA is protecting both the local ecosystem and the general environment.

TABLE 1
SPECIFIC QUESTIONS USED TO INITIATEDISCUSSION IN BREAKOUT SESSIONS

TOPIC	QUESTIONS
Current Understanding of Contamination Problem at Tims Branch – Steed Pond	What is the current understanding of the potential transport pathways and mechanisms for movement of the contaminants (might need to focus the question on specific contaminants, *e.g*., uranium and nickel, or on classes of contaminants, *e.g*., inorganics) in the Tims Branch – Steed Pond system?
	What are the pathways for potential human exposure to the contaminants in the Tims Branch – Steed Pond system?
	What are the potential ecological impacts of the contamination in the Tims Branch – Steed Pond system (*e.g.*, through trophic transfer)? What are indicators of these impacts?
Research Needs and Opportunities at Tims Branch – Steed Pond	What scientific questions related to the fate and transport of contaminants and the attendant risks to people and the environment does the Tims Branch – Steed Pond system lend itself to investigating?
	What research needs to be done to delineate and characterize the present extent of contamination in the Tims Branch – Steed Pond system?
	What information (laboratory characterization, mapping, field surveys, *etc*.) is required to establish future fate of the contaminants in the Tims Branch – Steed Pond system?
	What measurements or other information are needed to monitor movement of contaminants in the Tims Branch – Steed Pond system?
	What research is needed to determine the potential for human exposure and to understand trophic transfer and potential ecological impacts of the contaminants in the Tims Branch – Steed Pond system?
	What research is needed to determine the potential for natural attenuation of the contaminants in Tims Branch – Steed Pond?
	What research is needed to identify remediation options for primary contaminants of concern at the Tims Branch – Steed Pond system?
	What research is needed to determine the potential for natural attenuation of contaminants in Tims Branch – Steed Pond?
	What research is needed to develop an active remedial approach for the primary contaminants of concern at Tims Branch – Steed Pond?
Broader Implications of Tims Branch – Steed Pond Remediation Research	How will laboratory and field research on the Tims Branch – Steed Pond system help address contaminant transport issues at other contaminated sites?
	What is the potential for transferring remediation approaches to other contaminated sites at the Savannah River Site or other DOE sites?

TABLE 2. QUALITATIVE ASSESSMENT OF REMEDIATION OPTIONS FOR FLUVIAL AND RIPARIAN SYSTEMS SUCH AS TIMS BRANCH - STEED POND

Technology	Estimated Effectiveness local ecological (1)	minimizing export (2)	stability to variability and natural perturbation (3)	sustainability (4)	long term robustness (5)	viability (6)	suitability in fluvial and riparian systems (7)	near-term characterization (8)	long term monitoring (9)
Watershed Manipulation									
Single Dam	● / ?	◎ / ○	○ / ?	○ / ●	○ / ?	○	○ / ?	○	○
Series of Dams	○ / ?	◎ / ○	○ / ?	○ / ●	○ / ?	○	○ / ?	○	○
Beaver Dams and Associated Structures	○ / ?	◎ / ○	● / ?	○ / ●	○ / ?	○	◎ / ?	○	○
Engineered Wetland	○ / ?	◎ / ○	● / ?	○ / ●	○ / ?	○	◎ / ?	○	○
Sediment traps (riprap, downstream basin…)	○ / ?	◎ / ○	● / ?	○ / ●	○ / ?	○	○ / ?	○	○
Stabilization									
Geochemical	◎ / ?	● / ?	● / ?	○ / ?	○ / ?	○ / ?	○ / ?	●	● / ?
Biological (microbial)	◎ / ?	● / ?	● / ?	○ / ?	○ / ?	○ / ?	○ / ?	●	● / ?
Phytostabilization	○ / ?	○ / ?	● / ?	○ / ?	○ / ?	○ / ?	◎ / ?	●	● / ?
Removal									
Dredging	●	● / ?	◎	◎	◎	●	●	◎	◎
Hot spot removal	● / ?	○ / ?	○ / ?	○ / ?	○ / ?	○ / ?	○ / ?	● / ?	○ / ?
Enhanced erosion / collection	●	● / ?	○ / ?	○ / ?	○ / ?	●	●	● / ?	○ / ?
Phytoextraction	○ / ?	○ / ?	● / ?	○ / ?	○ / ?	○ / ?	○ / ?	●	● / ?
Monitored Natural Attenuation	?	?	?	?	?	?	◎ / ?	● / ?	● / ?
COUPLED PROCESS SOLUTION	◎ / ?	◎ / ?	○ / ?	◎ / ?	◎ / ?	○ / ?	◎ / ?	○ / ?	○ / ?

KEY:

◎ better <-------------> ○ ● worse

? SCIENCE NEEDED

NOTES:

1 effectiveness in limiting ecotoxicity, uptake, and/or trophic transfer
2 effectiveness in limiting primarily export of fine grained sediments and associated contaminants and secondarily in limiting disolution aqueous release
3 effectiveness with natural seasonal and super-seasonal variability cycles of wetting and drying
4 effectiveness continues with minimal maintenance and operation
5 stability with respect to failure (e.g., sediment collection capacity exceeded, dam breakage, etc.)
6 cost effectiveness, stakeholder acceptance, implementability
7 minimizes adverse collateral impacts
8 relative amount of characterization scaled to MNA alone = ◎ and coupled solution = ●
9 relative monitoring scaled to MNA alone = ● and coupled solution = ◎

3.0 CONCLUSIONS AND SUMMARY OF RECOMMENDED ACTIONS

The Tims Branch – Steed Pond workshop concluded with a closeout session in which each of the three breakout groups reported their answers to the five overall questions asked of them at the beginning of the workshop. There was strong consistency among the recommendations of each group; these recommendations are summarized below.

1. Should the Environmental Remediation Sciences Division (ERSD) program be expanded to include research on fluvial and surficial bio-geo-hydrologic systems?

Yes. Workshop participants strongly recommended that ERSD expand its research program to include fate and transport of contaminants in fluvial and surficial bio-geo-hydrologic systems. The interface between ground water and surface water is vital for understanding the fate and transport of contaminants and their impact on human and ecological health. Riparian systems are also scientifically valuable as a unique zone involving interactions between microorganisms, plants, soils and inorganic mineral surfaces, and flowing water. Expansion of the ERSD program into riparian systems would also offer the potential to expand the understanding of, and push the frontiers of science related to, coupled processes. This is a worthy scientific goal in its own right, but answering some of the current gaps in scientific understanding of the behavior of contaminants in these systems could have very important practical impact by reducing the need to make overly conservative assumptions about environmental risk, which lead to overly conservative and costly remediation actions. Making scientifically sound decisions about remediation and long-term stewardship at DOE sites depends on further research in this area. Further, research on fluvial and surficial bio-geo-hydrologic systems would be relevant not only to DOE sites, but also to many other sites in the United States and worldwide with contamination due to various defense, mining, and industrial activities.

2. What are the key science issues that an expanded ERSD program should address?

The key science issues are overarching considerations that cross the four major categories identified in Table 3 as affecting contaminant fate and transport. Key science issues identified during the workshop fall into a few major themes: understanding the current state of the system, understanding what happens during perturbations, understanding the scales at which these processes are important, and understanding how the processes are coupled. The major science issues for each theme are summarized in Table 3.

TABLE 3
SUMMARY OF KEY RESEARCH NEEDS

Section	Specific Research Needs
2.2.1	1. Contaminant inventory, including speciation and mass balance 2. Processes involved in "aging" of contaminants in riparian sediments under a range of spatially and temporally variable oxidation/reduction conditions 3. Role of dissolved and colloidal humic substances as well as microbial communities in controlling the solubility of metals and radionuclides in complex systems 4. **Understanding the relationships between micro-scale and macro-scale behavior of metals in fluvial and riparian systems** 5. Behavior of uranium daughters
2.2.2	1. Speciation and mobility of contaminants 2. Seasonal and super-seasonal climate variability, including temporal variations in hydrology and sediment transport and determination of aquatic loads from various erosion rates 3. System dynamics during variable/changing conditions over extended times 4. Plant-microbe interactions that affect contaminant mobility, including functional stability of rhizosphere and sediment microbial communities, and accumulation of contaminants by riparian biota 5. Bioavailability and trophic transfer of contaminants
2.2.3	1. Improved understanding of how the surface and subsurface hydrology of the Tims Branch – Steed Pond system, chemical speciation of metals and radionuclides, and the physics of sediment transport affect ecological risk 2. Coupling of metal and radionuclide geochemistry to the cycling of organic matter by the microbiota 3. Understanding of how succession of vegetation in the riparian zone affects contaminant transformations and transport, including subsurface transport 4. Effects of microbial and rhizosphere processes to modify geochemical conditions that influence the stability of reactive mineral phases as well as contaminant solubility 5. Effects of steep redox gradients and contaminant distributions on microbial community structure and function 6. Understanding the linkage between molecular level information on metal and radionuclide contaminants and the bioavailability and trophic transfer of these contaminants 7. Use of tracers to identify coupled processes and their relative impact on contaminant fate and transport 8. Understanding of ecosystem management practices and their impacts on contaminant fate and transport
2.2.4	1. Effects of other larger-scale processes such as hydrology on chemical and biological processes at the watershed scale 2. Understanding of hydrological processes that are typically characterized at the watershed scale at smaller scales 3. Geochemical scaling 4. Integration of data and processes across scales 5. Advancement of current numerical models of fluid transport in the hyporheic zone to describe colloid and sediment transport 6. Influence of bedform-induced flow on characterization and contaminant containment and release

3. Is the Tims Branch – Steed Pond site the right location for these kinds of research?

Workshop participants identified many reasons why the Tims Branch – Steed Pond system would be a good location for research into fate and transport in riparian systems. Applicability to other DOE and non-DOE sites was an important feature. Uranium, the primary contaminant of concern at Tims Branch – Steed Pond, is the most common radionuclide contaminant in ground water and sediment systems at DOE sites. Almost all DOE sites have either riparian ecosystems or are located near fluvial systems, making uranium fate and transport findings directly relevant elsewhere. In addition, the low pH, high organic content, and climate at Tims Branch – Steed Pond resemble conditions at the Oak Ridge Reservation.

Historical features of the Tims Branch – Steed Pond system make it attractive for specific types of studies. For example, the contaminant release history – pulsed discharge of uranium from the M-Area operations at the Savannah River Site during a narrow period of time – presents an opportunity to study aging effects and develop, then evaluate, conceptual models for sorption-desorption reactions. Tracer tests could be used, both from historical information and through introduction, to provide understanding of how contaminants move through the system.

Current operational conditions at the site provide opportunities for experimental design, such as the presence of control sites for toxicity studies; the existence of a wide variety of conditions to be tested within a small system; and the ability to control access, water sources, and timing. It is also important that the regulators are receptive to scientifically sound alternative remediation strategies and that there is adequate time to develop such a strategy.

One of the intriguing aspects of the Tims Branch – Steed Pond system is its great biodiversity, which could lead to studies that explore the links between geochemistry with bioavailability, trophic transfer, biological receptors, surface water – ground water interaction, sediment transport and ultimately ecological risk. Further, comprehensive studies in this area could lead to a robust conceptual model for MNA.

Overall, workshop participants felt that the most attractive feature of the Tims Branch – Steed Pond system is the possibility for studying coupled physical, hydrological, geochemical, and biological processes. Understanding the linkages between these processes is crucial for designing scientifically defensible remediation solutions that will endure over the long-term, both at Tims Branch – Steed Pond and elsewhere.

4. What remediation strategies and approaches should be considered for the Tims Branch – Steed Pond site?

The main driver for remediation of the Tims Branch – Steed Pond system is the deposition and transport of particle-associated uranium downstream and to the riparian zone through episodic flooding. Steed Pond and Pond 25 are the primary catchments in the system where sediment-laden uranium has accumulated, although -flooding could transport the uranium further downstream and outside the Savannah River Site boundary. The baseline remediation strategy is removal, an approach that is both expensive and disruptive to the ecosystem. However, because the regulators have provided adequate time to develop a cost-effective and scientifically defensible remediation strategy for this site, focused research can help identify where removal is necessary and how to make such actions more surgical and cost effective.

Workshop participants identified and organized remedial strategies into four categories:

1. Watershed manipulation
    a. Anthropogenic flow reduction
    b. Dams
    c. Engineered wetland
    d. Sediment trapping methods
2. Stabilization
    a. Geochemical stabilization
    b. Stream bank capping
    c. Microbial biostabilization
    d. Phytostabilization
3. Removal
    a. Dredging
    b. Hot spot removal
    c. Enhanced erosion/collection
    d. Phytoextraction
4. Monitored Natural Attenuation

Each strategy was evaluated in terms of science gaps and research opportunities. The appropriate remedial strategy for the Tims Branch – Steed Pond system may be an optimized combination of actions from these four categories. The coupled nature of the fundamental processes at work would be addressed by combining these remediation strategies.

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APPENDIX A – BACKGROUND INFORMATION ON THE TIMS BRANCH – STEED POND SYSTEM

A.1 Savannah River Site

The Savannah River Site is located in the southeastern coastal area of the United States in the State of South Carolina. It is bordered to the west by the Savannah River and Georgia and is close to several major cities, including Augusta, GA, and Aiken, SC. The Savannah River Site, owned and operated by the U.S. Department of Energy, is a 777 km^2 former nuclear weapons production facility constructed during the early 1950s to produce the basic materials, primarily tritium and plutonium-239, used in the fabrication of nuclear weapons for the nation's defense programs.

A.2 Tims Branch – Steed Pond Study Site

An important step in the nuclear weapons materials production cycle at the Savannah River Site was the manufacture of fuel and target assemblies for nuclear reactors in the site's M-Area (see Figure 1). The site began manufacture of aluminum-clad nuclear reactor fuel and target elements in M-Area in 1954, and the discharge of process wastewater from these facilities led to extensive contamination of a nearby riparian ecosystem and underlying ground water. Waste materials such as aluminum forming and metal plating wastes were discharged primarily into Tims Branch, a second-order stream system flowing into a 16 km^2 drainage basin of the Savannah River and its tributaries, with a fraction of the materials diverted to an M-Area settling basin. Effluent discharge directly into Tims Branch ceased in 1982, and in 1989 the M-Area settling basin was removed from service, stabilized, and capped.

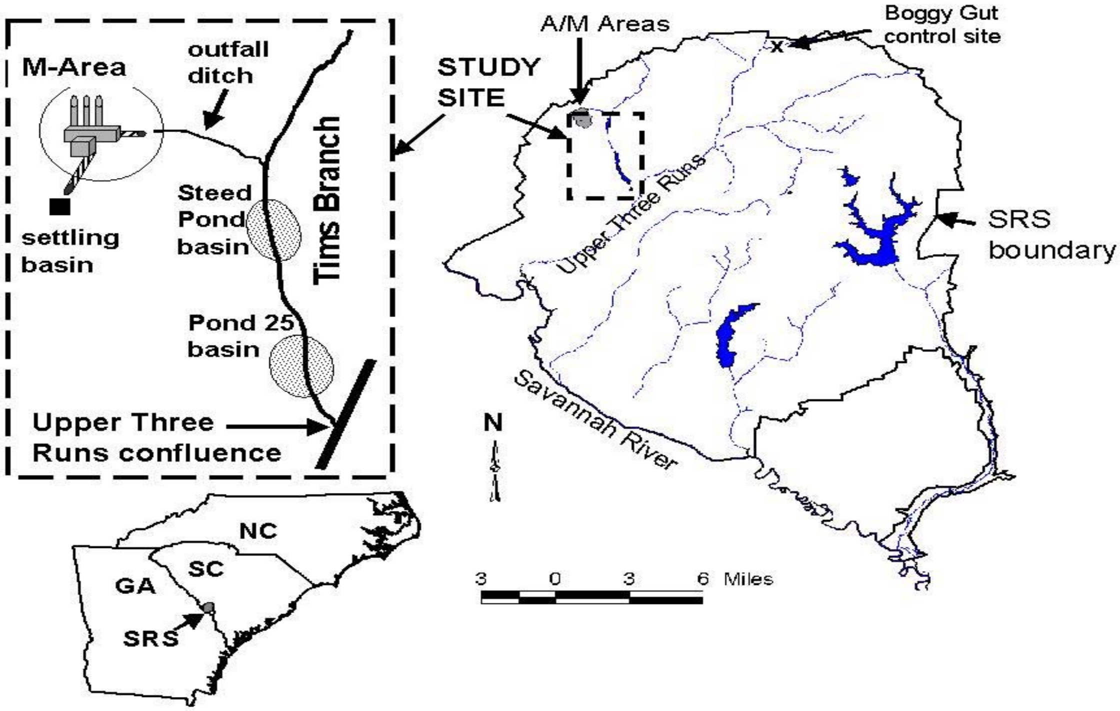
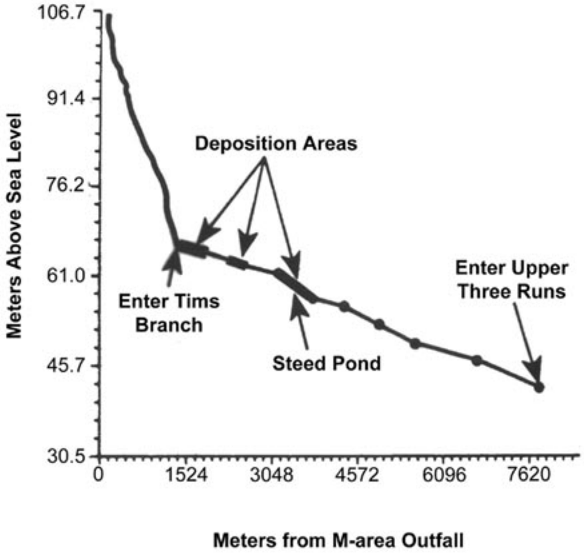


Figure 1. Map of Tims Branch – Steed Pond System

Large quantities of depleted and natural uranium, nickel, and aluminum entered the system, as well as lesser amounts of copper, zinc, lead, and chromium. Associated wastes such as nitric, phosphoric, and sulfuric acids and sodium hydroxide were also discharged. Uranium deposition is the biggest regulatory concern in the Tims Branch – Steed Pond system, with a total uranium inventory estimated at ~ 43,500 kilograms (Pickett, 1990). This constitutes 97 percent of the total gross alpha activity released by the SRS, the majority of which occurred between 1966 and 1968 (Evans et al., 1992). Nickel also appears to be a particular challenge at this site. Preliminary studies indicate that trophic transfer and resultant impacts appear more significant for nickel than for uranium.

Stream slopes on the discharge canal to Tims Branch are initially as high as 3 percent and decrease abruptly at the main stream channel (see Figure 2). Slopes of 0.4 percent are typical in depositional areas and continue for approximately 3.2 kilometers to the confluence with Upper Three Runs, a tributary of the Savannah River. This stream morphology has had a strong impact on the deposition of metals and metal-laden sediments. Steep slopes and extensive erosion during peak discharges limited contamination of the streambed nearest the initial point of discharge. Instead, deposition primarily occurred in natural and man-made impoundments, *i.e.*, beaver ponds, wetlands, and farm ponds, which functioned as settling basins for contaminated sediments. It has been estimated that maintenance of Steed Pond as a wetland ecosystem retained up to 70 percent of the radionuclide release within the sediments (Evans et al., 1992; Pickett, 1990; Bertsch, 1994). Estimates from the M-Area settling basin suggest that releases of nickel and uranium were similar in magnitude, although trophic transfer studies at Steed Pond indicated a shift in contaminant ratios with a considerable loss of nickel from the system relative to uranium, indicating a significantly higher nickel bioavailability (Punshon et al., 2003).



Stream slopes from M-Area outfall to Upper Three Runs (after Evans et al., 1992)

Figure 2. Tims Branch – Steed Pond System Slopes

A.3. Current Understanding of Potential Mechanisms for Future Contaminant Movement, Human Exposure, and Trophic Transfer

The fate and transport of contaminants in the Tims Branch – Steed Pond system is currently believed to be driven by the following overall processes:

1. Sediment transport and contaminant remobilization during episodic events and redeposition downstream
2. Contaminant speciation
3. Bioavailability

A.3.1 Sediment Transport

The flow path of discharges from M Area has an erosional section from M Area to the confluence with Tims Branch and depositional areas downstream to the confluence of Tims Branch with Upper Three Runs (Figures 1 and 2). In the erosional section, the ditch contains little contamination and has taken the morphology of a deeply incised stream that has cut through several soil formations rich in clay and silt. The consequences of this erosion are sequestration of dissolved metals, alteration of downstream sediment characteristics, variability of sediment properties, and burial or dilution of contaminated sediments in the depositional areas downstream, principally at Steeds Pond and Pond 25. Significant deposition of contaminants and suspended sediments occurred within Steed Pond, which now contains an estimated 70 percent of the uranium that was released (Evans et al., 1992; Pickett, 1990; Bertsch et al., 1994; Batson, 1994).

The Steed Pond dam ruptured in 1984, draining the pond and exposing the contaminated sediments, which are subject to erosion in areas that remain unvegetated. The pond has had numerous events of draining and filling and the water level is now down to pre-pond levels; the area now exists as an unconfined wetland system prone to periodic erosion, causing contaminant export and the potential for a significant change in metal bioavailability. In situations such as Steed Pond, offsite transport is exacerbated by a combination of selective erosion of unvegetated "hot spot" areas and association of contaminants with an easily dispersible clay fraction. Extensive characterization and risk assessment of contaminant transport in the Tims Branch – Steed Pond system has not been performed yet. Hence, the appropriate remediation strategy (*e.g.*, natural attenuation, stabilization, or contaminant removal) cannot yet be accurately determined or appraised.

Characterization work to date has shown that the sediment is acidic and highly weathered, consisting of clay to silty clay loam. A reduced zone is confined by oxidized zones and provides tremendous chemical gradients. The large amount of iron (50-60 percent non-crystalline in Steed Pond sediments) may be a factor in the natural attenuation of metals; iron could be dissolving and re-precipitating in this very dynamic system. The system has both oxic conditions with fresh flow and high nitrate and anoxic conditions where standing water exists. Conditions are always changing, making it difficult to know when the system will reach equilibrium or to use today's conditions to predict tomorrow's.

Transport of uranium and nickel out of the Tims Branch – Steed Pond system during base flow is not a concern; routine sampling has found dissolved metal concentrations at or below background levels (Hayes, 1986). However, studies of the Tims Branch – Steed Pond system have shown that maximum flux estimates determined from base flow measurements potentially underestimate the amount of uranium transported; approximately 1500-2800 percent more uranium was transported to Upper Three Runs during storms or flooding than under base flow conditions. The greatest amount of uranium was transported at peak discharge rates (Batson et al., 1996).

A.3.2 Contaminant Speciation

Complicated redox, mineralogical, and sorptive chemistry make it difficult to predict the behavior of uranium in the environment. Uranium (VI) forms soluble complexes in most surface water and ground water, but uranium (IV) forms highly insoluble solid phases such as uraninite. Uranium (VI) solubility is affected by common ligands such as phosphate, carbonate, and sulfate and is pH dependent (Langmuir, 1997). In natural systems under aerobic, acidic conditions, uranyl (UO_2^{2+}) is typically the dominant aqueous species. In less acidic conditions, various uranium (VI) carbonate complexes tend to exist and increase uranium (VI) solubility. Uranium (VI) also forms stable complexes with dissolved organic carbon and also binds effectively with iron and manganese oxides and clays (Li et al., 1980). Studies of the Tims Branch – Steed Pond system have found that the greatest percentage of the uranium mobilized during storm events is associated with chemically labile forms (Batson et al., 1996).

With respect to the natural attenuation of metals, sequential extractions suggest very different partitioning is occurring for uranium and nickel. Nickel appears to map to iron. Uranium maps to calcium and organic detritus. Novel methods for aqueous speciation of uranium and nickel have shown that the nickel exists in low molecular weight complexes while the uranium is associated with dissolved organic carbon. The nickel is more labile than the uranium in sediments. Organic carbon is the primary availability control for uranium and is secondary for nickel. Conversely, iron oxides are the primary control for nickel and secondary for uranium. Heterogeneity is found at the micron scale. In spite of comparable sediment concentrations, nickel appears to be significantly more available than uranium in the riparian sediments. Nickel is distributed across all fractions, including substantial amounts in very labile water-soluble and exchangeable fractions (Sowder et al., 2003). There is also evidence for dynamic biogeochemical cycling in the sediment-detritus system, especially iron and organics. The role of aluminum in the system is not known at this time, but it appears to be co-associated with uranium.

A.3.3 Bioavailability and Trophic Transport

Studies of the Tims Branch – Steed Pond system have shown that nickel uptake in plants and small mammals exceeds that for uranium by two to four orders of magnitude in leaves and two orders of magnitude in muscle (Punshon et al., 2003). Studies of the growth of native organisms on uranium- and nickel-amended agar plates showed that uranium does not appear to be very bioavailable. These studies also found four microorganisms that appear to be resistant to nickel in high concentrations. Preliminary studies demonstrate greater selective pressure from nickel versus uranium. Resistance to nickel by native metal-resistant species appears to decrease with increasing pH. Tree rings have also been found to show nickel spikes following high antecedent soil moisture. Resuspension from dried sediments is a potential issue for uranium, whereas biological uptake is a concern for nickel.

A.4. Cleanup Issues for the Tims Branch – Steed Pond System

Of the 515 current waste sites at the Savannah River Site, the highest priority sites for cleanup are those that have significant impact to onsite workers or offsite population. Many others, such as the Tims Branch – Steed Pond system, will be addressed in the future without significant immediate impact to the population.

Currently, excavation and removal is the only baseline remediation mechanism, but this approach is impractical given the estimated cost in excess of $100 million for Steed Pond alone. The extreme disruptions that excavation and removal can cause to the ecosystem must also be taken into consideration.

The existing regulatory timeframe for remediation is 2015, subject to continuing negotiations. The regulators anticipate that science will provide remediation methods that are improvements over the baseline excavation method, thereby reducing both the ecological and the financial impact. The regulators have thus allowed adequate time for the Savannah River Site to incorporate these anticipated improvements into development of a cost-effective and scientifically defensible remediation strategy.

APPENDIX B – SCIENCE GAPS AND OPPORTUNITIES FOR REMEDIATION STRATEGIES

Remediation Category	Specific Strategy	Science Gaps	Opportunities at Tims Branch - Steed Pond
Watershed Manipulation	Anthropogenic flow reduction		• Use of tracers to document hydrology. Identify tracers associated with the original waste that could be used, and/or induce new tracers that might be analogs for materials that associate with fine sediment. Tims Branch – Steed Pond has a documented uranium source and a narrow pulse of discharge. • Managing discharges allows for including controls in experimental design.
	Dams	• How would a catastrophic flood that causes breaching of the dam affect contaminant mobility? • What is the capacity of the anaerobic sediment for uranium and nickel reduction and immobilization? If this is not sufficient, what additional modifications to the system could enhance uranium and nickel bioimmobilization? • Does alteration of the currently developing riparian zone by dam construction change contaminant metal bioaccumulation in the food chain? • Would a dam change the rate of uranium mass transfer? Would it create a potential for remobilization? • What are the effects of the dam on the microbial communities and ecosystem? • Should a dam be built in a losing reach or an area where ground water enters the system? • How long could a dam be expected to last and would that be adequate? • How will the inclusion of any of the dams change the large-scale watershed hydrology of the system?	• Fundamental, long-term studies that look at the entire watershed and take into account the system's complexity are possible. • The presence of areas of recharge and areas of discharge at the site allows for interesting controls and studies. • The variability of conditions at the site allows for testing several concepts in the same system. • Since the site has already been so altered, there is an opportunity to understand the background processes of human-induced effects.

Remediation Category	Specific Strategy	Science Gaps	Opportunities at Tims Branch - Steed Pond
	Engineered wetland	• What natural processes (*e.g.*, beaver activity or plants in the developing riparian zone that immobilize uranium and nickel) can be incorporated into the wetland architecture? • Will natural processes lead to a wetland? • What are the metal uptake and immobilization processes in the rhizosphere? What is the stability of those processes (*e.g.*, reversibility)? • How do riparian biota bioaccumulate metals and radionuclides during dry periods? • What is the effect of humification on contaminant bioavailability?	• The low gradient at the site allows chemistry studies. • The inflow of aerobic ground water could be explicitly controlled.
	Other forms of sediment trapping	• What would be the changes in hydrodynamics in Steed Pond? • What would be the effects on particle transport versus aqueous transport rate? • How would nickel behavior change? • How do plants remobilize contaminants through riprap and other barriers? • How could the physical stabilization media be optimized for chemical and biological factors for contaminant stabilization?	
Stabilization	Geochemical stabilization	• Can anoxic conditions be maintained? • What are the adverse effects of biogeochemical additives? • What is the biological effect of phosphate amendments? • What uranyl phosphates would form? • Is there enough sulfur in the system to immobilize nickel? • What are the products of oxidative and reductive processes? What are their impacts on contaminants? • What is the role of aluminum? • What percentage of the uranium leaves the site on particles? • What phase is sequestering uranium?	• Understand interactions between uranium and organics. • Study aging effects and conditions. • Understand microbial turnover of iron oxides and other remobilization processes.
	Stream bank capping (physical)	• How can the stabilization medium be designed and deployed to achieve optimal chemical and biological immobilization of uranium and nickel?	

Remediation Category	Specific Strategy	Science Gaps	Opportunities at Tims Branch - Steed Pond
	Microbial biostabilization	• What is the effect of aerobic microbial activity on contaminant mobility? • What complexation to organisms exists? How do seasonal changes affect this? • Which microbial populations control contaminant mobility?	• A large number of types of microorganisms exist at the site commensurate with the large variations in redox conditions and water chemistry at this site.
	Phytostabilization	• What controls nickel and uranium bioavailability? • What is the bioavailability of uranium on very small particles? • What is the behavior of the uranium daughters? • What are the spatial soil particles (*e.g.*, transmission changes)?	• Generate data on chemical speciation in plants. • Investigate chemical stability in the rhizosphere. • Long-term study is possible to see optimal levels.
Removal	Dredging		
	Hot spot removal		
	Enhanced erosion/collection	• What is the amount of dissolved versus particulate matter and how does it behave in solution?	• Studies of colloid transport may be possible.
	Phytoextraction	• What is the bioavailability of uranium and nickel under oxic versus anoxic conditions?	
Monitored Natural Attenuation		• How does existing vegetation contribute to contaminant stabilization? • How does the current succession of vegetation in the riparian zone affect contaminant transport? • What is the effect of aging on immobilization? Are particles incorporated or buried under soil? • How do flooding and drying cycles change contaminant speciation and mobility? • What are the effects of ecosystem change on the microbial community structure and function? • How robust are existing plant and microbe communities? • What is the role of humics with radionuclides? How do humics influence radionuclide fate and transport through the system? Is this phenomenon greater for other metals? • Do perturbations from beavers represent a positive or negative effect?	• The site could contribute to development of a model for natural attenuation or natural retention. • A wide range of possible conditions (rainfall, pH, anoxic environment, etc.) could be studied. • The system's current fundamental controlling processes, especially how organic carbon is controlling the mobility of contaminants, could be determined before starting remediation. • Seasonal cycling could be studied to watch reductive cycles; this could elucidate monitoring criteria for MNA. • The dynamics of a system continually in disequilibrium could be studied. • Ecological risk studies in the riparian zone, including identification of risk drivers and risk receptors, could be undertaken. • The site knows when and how much uranium and nickel were released, making the study of aging effects plausible. • Sediment transport through episodic events could be quantified.

Remediation Category	Specific Strategy	Science Gaps	Opportunities at Tims Branch - Steed Pond
Coupled Solutions		• Do redox changes alter trophic transfer? • What is the link between geochemistry and trophic transfer? • What is the effect of hydrology on geochemistry, microbiology, and plant communities?	• The site has features that encourage the integration of data gaps and science, such as integration of hydrologic modeling, geomorphology studies, tracers, *etc*. • DOE technologies that have already been developed could be validated and advanced. • Research in determining the coupling between microbial and geochemical interactions could move from the laboratory to the field.

APPENDIX C – AGENDA

OFFICE OF SCIENCE WORKSHOP - MARCH 4-6, 2003

"Research Opportunities for Studies of Contaminant Transport in Fluvial Systems at the Tims Branch – Steed Pond System, Savannah River Site"

Day One- March 4		Jack Corey, SRTC, Moderator
8:00a.m.	Registration and light refreshments	
8:30	Welcome and introductions	Alice Doswell, DOE-SR, and Teresa Fryberger, Office of Science
8:40	Overview of SRS	Paul Deason, SRTC
9:10	SRS Remediation Projects	Paul Huber, ER
9:40	Overview of the Environmental Remediation Sciences Division and workshop purpose	Teresa Fryberger, Office of Science
10:10	Break	
10:30	Doing science in support of DOE remediation efforts: Lessons learned from Hanford	Mike Thompson, DOE-RL
11:00	Keynote speech: "Hydrodynamic coupling of stream flow and flow in permeable sediments: Implications for contaminant mobility and transport"	Aaron Packman, Northwestern U.
11:45	Lunch	
12:45p.m.	Tims Branch-Steed Pond overview	
	History, characterization, and previous and ongoing studies (60min)	Paul Bertsch, SREL
	Remediation time line (15 min)	Jerry McLane, ER
2:00	Virtual Site tour	
	Introduction	Paul Bertsch, SREL
	M-Area source term	Brian Looney, SRTC, and John Pickett, WSRC retired
2:45	Break	
3:00	Outfall to Steed Pond: Sediment geochemistry	Andrew Sowder, SREL
	Pond 25: Bioavailability and trophic transport in lower Tims Branch	Tracy Punshon, SREL
	Concluding remarks	Paul Bertsch, SREL
4:45	Field tour of control site for Tims Branch-Steed Pond System	
5:45	Social hour at the SREL Conference Center	
6:45	Group dinner and discussions at the SREL Conference Center	

Day Two - March 5		
8:00a.m.	Refreshments (coffee and doughnuts)	
8:30	Charge to workshop participants	Teresa Fryberger, Office of Science
9:00	Split into breakout sessions to identify scientific needs and opportunities:	
	1. Soil chemistry, geochemistry and particle surface chemistry	Paul Bertsch, SREL
	2. Transport in fluvial and ground water systems	Brian Looney, SRTC
	3. Bacterial and phyto interactions with	Gill Geesey, INEEL

	contaminants	
Noon	Lunch	
1:00p.m.	Continue breakout sessions	
3:30	Return to single group and report on breakout sessions	Session Chairs
4:30	Action items and path forward	Henry Shaw, Office of Science
5:00	Adjourn	

Day Three - March 6

8:30a.m.	Session Chairs, supported by EnviroIssues, develop draft session reports	Session Chairs EnviroIssues
12:30	Adjourn	

APPENDIX D – WORKSHOP ATTENDEES

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APPENDIX E – BREAKOUT GROUPS FOR SRS WORKSHOP

Breakout Group	Participant	Affiliation
Soil chemistry, geochemistry and particle surface chemistry	Paul Bertsch (Breakout group leader)	Savannah River Ecology Laboratory/University of Georgia
	Diane Blake	Tulane University
	Ken Buesseler	Woods Hole Oceanographic Institute
	Jonathan Chorover	Arizona State University
	Andy Felmy	Pacific Northwest National Laboratory
	Scott E. Fendorf	Stanford University
	Bruce Honeyman	Colorado School of Mines
	Jon Icenhower	Pacific Northwest National Laboratory
	Dan Kaplan	Savannah River Technology Center
	Mary Neu	Los Alamos National Laboratory
	John Zachara	Pacific Northwest National Laboratory
	Maverik Zavarin	Lawrence Livermore National Laboratory
Transport in fluvial and ground water systems	Brian B. Looney (Breakout group leader)	Savannah River Technology Center
	Marcus Flury	Washington State University
	James Hunt	University of California - Berkeley
	Philip M. Jardine	Oak Ridge National Laboratory
	Jerry Miller	Western Carolina University
	Aaron Packman	Northwestern University
	John Seaman	Savannah River Ecology Laboratory/University of Georgia
	Louis Thibodeaux	Louisiana State University
	Andy Tompson	Lawrence Livermore National Laboratory
	Jiamin Wan	Lawrence Berkeley National Laboratory
Bacterial and phyto interactions with contaminants	Gill Geesey (Breakout group leader)	Idaho National Engineering & Environmental Laboratory/Montana State University
	D. Craig Cooper	Idaho National Engineering & Environmental Laboratory
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