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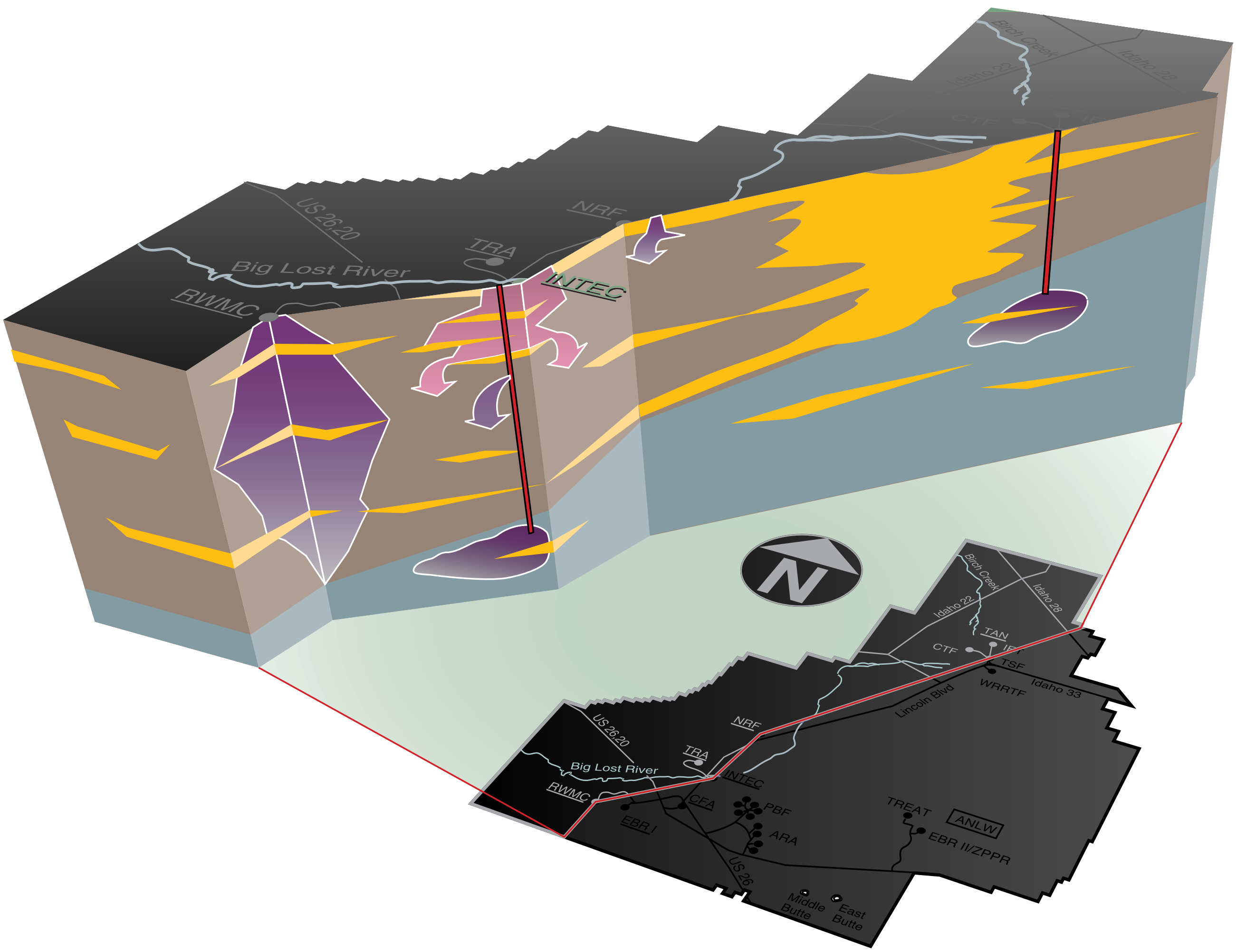

Idaho National Engineering and Environmental Laboratory
Idaho Falls, Idaho 83415

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Uncertain Predictions of Contaminant Behavior at INEEL: A Roadmap for Addressing Current Limitations through Vadose Zone Studies

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Idaho National Engineering and Environmental Laboratory
Bechtel BWXT Idaho, LLC
Idaho Falls, Idaho 83415

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ABSTRACT

The purpose of this document is to illustrate where uncertainties arise in predictions of contaminant behavior in the unsaturated region (vadose zone) between land surface and the underlying Snake River Plain Aquifer (SRPA) at INEEL and to underscore the scientific advances required to quantify and reduce that uncertainty. Although much has been accomplished and learned through the analyses of contaminated sites at the INEEL, significant gaps remain. In an effort to close the gaps, this report details limitations in analyses conducted thus far, and recommends specific actions to address the limitations. The focus of this document is on vadose zone analysis because processes in this region play a pivotal role in the behavior of subsurface contaminants, and frequently determine the options and opportunities available to management. Currently, vadose zone experts at the INEEL cannot with confidence predict the movement of water and contaminants through the heterogeneous fractured basalts and sediments comprising the vadose zone, and this results in highly uncertain environmental management decisions.

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1 INTRODUCTION

The purpose of this document is to illustrate where uncertainties arise in predictions of contaminant behavior in the unsaturated region (vadose zone) between land surface and the underlying Snake River Plain Aquifer (SRPA) at INEEL, to underscore the scientific advances required to quantify and reduce that uncertainty, and to present technical and programmatic approaches for achieving the necessary advances. The focus of this document is on vadose zone analysis because processes in this region play a pivotal role in determining the behavior of subsurface contaminants, and frequently determine the options and opportunities available to manage risk. The risk of interest here is that incurred to the public through use of subsurface water. At the INEEL, this water either exists as perched water in the vadose zone, or within the underlying Snake River Plain Aquifer (SRPA). The substantial inventory of contaminants that either exists at land surface, or that have been released into the environment at land surface will ultimately pass through the vadose zone and into those water sources. Understanding the behavior of contamination in the vadose zone is an important first step in protecting the sole source SRPA (56 FR 50634). By section this document:

1. Addresses the basis for contaminant management decisions, an understanding of which is necessary in order to prioritize research directions and to schedule specific research activities.

2. Describes the unique site conditions, including contaminant sources at the INEEL. Understanding specific site conditions is necessary in order to provide a context for lessons learned and to underscore the sources of uncertainty introduced in INEEL risk management decisions.

3. Summarizes lessons learned from completed analyses of, and remaining analyses facing the contaminant management programs. These lessons were derived from investigations of sites representing the larger INEEL contaminant inventories. Remaining issues and unanswered questions are posed from a practitioners perspective.

4. Summarizes the technology and knowledge gaps from a deployment perspective. These issues, observations and limitations incurred in current knowledge and practice have been compiled from the “Deficiencies in Vadose Zone Understanding at the Idaho National Engineering and Environmental Laboratory” (INEEL/EXT-99-00984) document and a review of lessons learned from site specific investigations reviewed in this document. This information represents a range of perspectives spanning the needs of contaminant management operations and vadose zone analysis practitioners.

5. Summarizes the technology and knowledge gaps from a development needs perspective. These gaps are presented from a science and technology development perspective. They have been compiled by reviewing “The DOE Complex-Wide Vadose Zone Science & Technology Roadmap: Characterization, Monitoring, and Simulation of Subsurface Contaminant Fate and Transport” (Sept., 2000), “Vadose Zone Science and Technology Solutions (Looney and Faulta, 2000), and “Research Needs in Subsurface Science” (NRC, 2000).

6. Presents the technical strategy to help resolve the current and future limitations. Justified by the complexity of problems faced at the INEEL in quantifying uncertainty, this section presents an overview of a multidisciplinary and multi-scale experimental program.

7. Presents a programmatic approach to achieve the necessary integration between the scientific community, environmental problem holders, stakeholders, regulators, and practitioners. This section suggests a short-term agenda listing activities for the next 2 years.

This document presents guidance for research that will help the site make wise and cost-effective risk management decisions minimizing the health impacts and long-term consequences of subsurface contamination.

1.1 INEEL Operations Background

The INEEL was originally established near Idaho Falls, ID (Figure 1-1) in 1949 as the National Reactor Testing Station (NRTS), and was devoted to energy research and related activities. The INEEL was known as the Idaho National Engineering Laboratory (INEL) between 1974 and 1997, and finally became the Idaho National Engineering and Environmental Laboratory in 1997. More nuclear reactors and a wider variety of reactor types have been developed, tested, and built at INEEL than at any other single location in the world. In addition, the INEEL has accepted spent nuclear fuel for temporary storage and processing from other DOE sites and from the DOD.

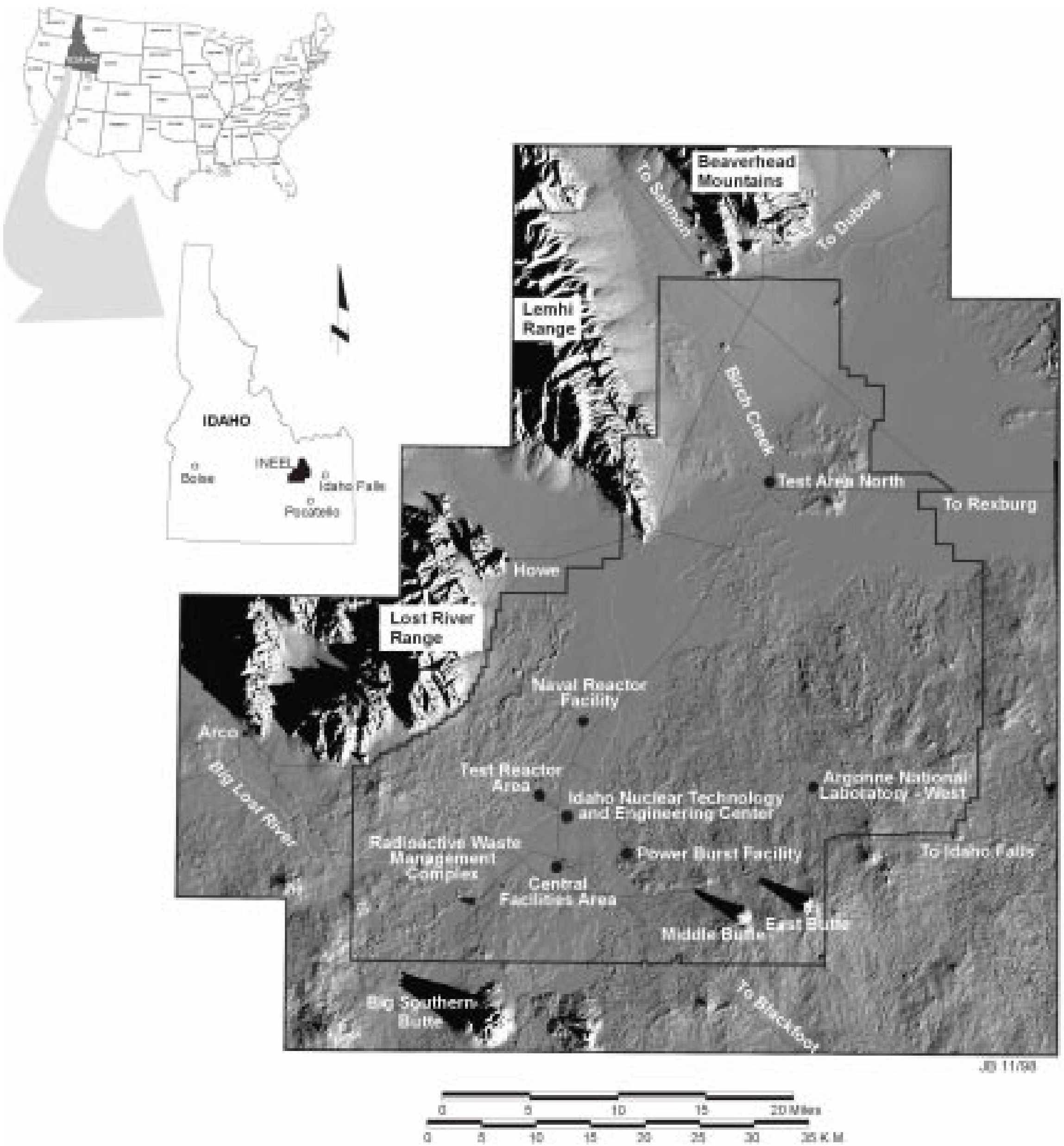

Figure 1-1 Map of the Idaho National Engineering and Environmental Laboratory.

As a result of its development, processing, and storage mission, radioactive, heavy-metal, and organic materials were generated and discharged into the shallow subsurface at INEEL. Historical spills and leaks from site operations, experimental activities, and production activities have also introduced hazardous and radioactive contamination into the subsurface soils and basalts. These combined releases have contaminated approximately 1 million m^3 of subsurface soils at 472 individual sites and 5 million m^3 of groundwater (IPAB-IS 2001). Unconfined contamination is managed by the Environmental Restoration Program under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA). In addition, there are also larger waste management activities that could result in subsurface contamination. These potential sources include chemicals contained in the tanks, bin sets, piping, etc. of operational facilities, and in buildings that are undergoing decontamination, decommissioning and dismantlement (D&D&D). The chemicals contained in these facilities pose unique management challenges to the High Level Waste (HLW), Nuclear Regulatory Commission (NRC), Waste Management (covered by the Resource Conservation Recovery Act, RCRA), and D&D&D programs. The magnitude of potential releases greatly exceeds that of historical releases because the volume of chemicals existing in tanks, piping, and buildings is significantly larger than those of known historical releases. Managing all contaminated sites and potential sources of contamination is one of the primary DOE-ID missions.

1.2 Contaminant Management

The framework underlying management of existing and potential releases at the INEEL is important for regulatory, timing, and technical reasons. The first reason for understanding the basis of management decisions is presented by differences in regulatory guidance. There are several bodies of law that attempt to manage the risk posed by contamination of the environment. CERCLA deals with releases (or substantial threats of releases) of hazardous substances, pollutants or contaminants after the law’s enactment. RCRA deals with the cradle to grave management of hazardous materials following its enactment, including requirements for operation and closure of hazardous waste storage, treatment and disposal facilities. The INEEL is an operating site. Current and future stewardship involves the integration of the risk management processes covered by all environmental laws. Decisions for managing future environmental risk will consider the impacts from the acceptable risk conditions achieved by CERCLA remediation and the impacts from RCRA compliant operations and closures. This comprehensive analysis introduces the uncertainty of predicting combined interactions as well as the uncertainties introduced by each individual risk management decision.

The range of time-lines provides the second reason to understand the basis of management decisions. For example, decisions concerning the primarily-affected areas at the INEEL will affect the subsurface environment for years to tens of thousands of years, and will be made over the next 50 years. Under CERCLA, near-term decisions made for known releases that exceed acceptable risk are based on current knowledge. After an action is taken, the effectiveness of the action must be evaluated every 5 years as long as a risk remains. At the INEEL, some contaminants have been removed, but others have been stabilized in place. Decisions for these contaminated sites may be changed as knowledge of transport and other geochemical interactions improves. Risk management decisions for remaining facilities and potential release sites will be made over the far-term as new facilities are added and as existing facilities are phased out. During this longer time span, there will be ample opportunity for scientific and technological developments to influence management decisions.

The third reason for understanding the decision basis lies in the fact that risk management is a several step process that spans evaluating current and future risk, engineering and employing risk mitigation, and subsequent long-term monitoring. During the evaluation process, a combination of science and technology is employed for hydrogeochemical characterization, determination of contaminant distributions, and prediction of hazards. Mitigation of future risk also involves scientific principles and brings in aspects of engineering and economics, while long-term stewardship requires the deployment of accurate, cost-effective, and robust-technology. At each of these stages, uncertainty is introduced into the performance measures underlying the management decision. Knowing that risk and concentration comprise the performance measures is a precursor to understanding the sources of uncertainty and provides a framework for quantifying the underlying uncertainty.

1.2.1 Timing: An Overview of the INEEL Decision Process and Status

The process of risk management for CERCLA sites has several steps encompassing evaluation of current and future risk, engineering and employing risk mitigation, and subsequent long-term monitoring. During the evaluation period, process knowledge and data are obtained and used to develop a Record of Decision (ROD) that documents the remedial actions required to mitigate existing or potential hazards. Possible remedial actions include removing or destroying selected contaminants, stabilizing contaminants in place, relocating contaminants to other locations at the INEEL, and relocating contaminants to locations off the INEEL. Following the development of the ROD, the Remedial Decision/Remedial Action (RD/RA) phase implements the mitigating actions. The following stage involves intermediate monitoring to evaluate contaminant status. After the remedial goals have been met, and 5-year reviews are favorable, the site may move to the stewardship program for long-term oversight. Facilities impacted by CERCLA at INEEL are summarized briefly below to provide an indication of time-lines.

The facilities at the INEEL are geographically separated as shown in Figure 1-1. They include Test Area North (TAN), Test Reactor Area (TRA), Idaho Nuclear Technology and Engineering Center (INTEC), Central Facilities Area (CFA); Power Burst Facility (PBF) and Auxiliary Reactor Area (ARA), Experimental Breeder Reactor (EBR), Radioactive Waste Management Complex (RWMC), and other the non-facility specific areas. To facilitate CERCLA remediation efforts, Waste Area Groups (WAGs) correspond to these distinct and geographically-separate functional-facility areas. corresponding to nine WAGs. Each area serves or has served a particular programmatic or support activity as summarized in Table 1-1.

Table 1-1. Summary of INEEL facilities and investigations.

Primary Facilities	Source of Contamination	Status	Remaining Investigations
TAN (WAG-1)			
TSF: handling, storage, examination, and research and development activities for spent nuclear fuel. The Process Experimental Pilot Plant is also located here and is undergoing D&D&D	Aquifer contamination via direct injection of low-level radionuclides, and high levels of cleaning solvents (TCE & DCE). The organics were determined during the RI to pose long-term health risks. The aquifer is the primary source of contaminants at TAN and limited vadose zone contaminant sources are present.	ROD in place, FS and post-rod activities are remediating an extensive TCE plume in the SRPA via natural attenuation	5-year reviews
IET: designed as a testing location for the nuclear jet engines developed under the Aircraft Nuclear Propulsion (ANP) Program in the 1950s and early 1960s.		currently undergoing D&D&D	
CTF: constructed for nuclear reactor tests and a support structure for TSF, ANP and IET.		inactive	
SMC: active facility manufacturing components for a U.S. Department of Defence nonnuclear weapons system.			
WRRTF: primarily consists of two buildings housing several nonnuclear tests, mostly for simulating and testing water systems used in reactors.			
*Contaminants, and a summary of evaluation status for primary facilities are reviewed in detail in Section 3.			

Table 1-1. Summary of INEEL facilities and investigations.

Primary Facilities	Source of Contamination	Status	Remaining Investigations
Test Reactor Area (WAG-2)*			
TRA: extensive facilities for studying the effects of radiation on materials, fuels, and equipment, including high neutron flux nuclear test reactors that have been used to conduct engineering and materials tests since 1952. Three major reactors have been built at TRA: (1) the Materials Test Reactor, (2) the Engineering Test Reactor, and (3) the Advanced Test Reactor (ATR). The ATR is currently the only major operational reactor within TRA.	Disposal of radionuclides and metals into a retention basin, warm waste pond, chemical waste pond, and cold waste pond, into well USGS-53, and into a disposal well. The primary contaminants of concern are H-3 and Chromium.	FS completed and the ROD is in place. The ROD has recommended terminating water disposal to the warm- and chemical-waste ponds as well as to the sewage lagoons. The ponds were also capped. Water is still discharged to the cold waste and evaporation ponds.	The initial evaluation suggested that the removal of surface discharge waters would result in decreased aquifer concentrations of H-3 and chromium. Data suggests that this is not occurring, and the site is being slated for reevaluation.
*Contaminants, and a summary of evaluation status for primary facilities are reviewed in detail in Section 3.			

Table 1-1. Summary of INEEL facilities and investigations.

Primary Facilities	Source of Contamination	Status	Remaining Investigations
***Idaho Nuclear Technology and Engineering Center (WAG-3)**			
INTEC: houses facilities for reprocessing spent nuclear fuel. Facilities include spent fuel storage and reprocessing areas, a waste solidification by calcination facility and related waste storage bins, remote analytical laboratories, and a coal-fired steam generating plant. Fuel storage operations began in 1952 and fuel reprocessing, the recovery of unused fissile uranium by reprocessing spent nuclear fuel for defense projects, was conducted from 1953 to 1994. From 1953 until calcination activities began (to convert radioactive liquid waste into a solid, more stable form), the liquid waste from fuel dissolution and extraction reprocessing activities was stored in the Tank Farm. The liquid was often extremely high in radioactivity (i.e., containing thousands of curies of activity), some of which remains in the series of underground stainless steel tanks enclosed in underground concrete vaults. These tanks also contain sodium which is another component of the waste stream. The tanks have not leaked. However, transfer lines that carried the radioactive liquids to the tanks have leaked and contaminated the surficial sediments and soils in several locations at the INTEC	Transfer lines and valve boxes carrying the high-level liquid waste have failed and leaked contaminating large volumes of soil at the surface and the water and materials comprising the vadose zone. Additional wastes were discharged directly into the aquifer, and into the vadose zone during times when the injection well casing failed. An entire suite of radionuclides comprise the contaminants, with Sr-90, I-129, Tc-99, Np-237, U, and Pu making the primary list.	Operational for the next 30 years. ROD and FS in place for contaminated areas outside of the Tank Farm, and the investigation is beginning for the contaminated soils within the Tank Farm. Contents of the Tanks and other facilities will fall under the jurisdiction of the RCRA and D&D programs. These evaluations will occur throughout the operational life span, and will require ongoing environmental impact statements (EISs).	See status column. OU 3-14 is investigating the contaminated soils within the Tank Farm. The HLW-EIS is in Draft form. The cumulative assessement is planned.
*Contaminants, and a summary of evaluation status for primary facilities are reviewed in detail in Section 3.			

Table 1-1. Summary of INEEL facilities and investigations.

Primary Facilities	Source of Contamination	Status	Remaining Investigations
***Central Facilities Area (WAG-4)**			
CFA: originally housed Navy gunnery range personnel, administration, and warehouse space. Now provides craft, office, service, and laboratory space.	The vadose zone has been contaminated by leaching (1) of landfill waste from three landfills, (2) of mercury, nitrate, and other metals from a dry pond, and (3) of nitrate from the former sewage plant drainfield. Wastes resulting from operations at the Chemical Engineering Laboratory may have included simulated calcine, sodium nitrate, nitric acid, tributyl phosphate, uranyl nitrate, high grade kerosene, aluminum nitrate, hydrochloric and chromic acid, di-chromate solutions, terphenyls, heating oil, zirconium, hydrofluoric acid, trichlorethylene, and acetone.	ROD and FS are in place, resulting in caps over the ponds. Concerns exist about increased infiltration through the landfill covers and for the long-term performance of the covers.	
***Power Burst Facility (WAG-5), Auxiliary Reactor Area (WAG-6), and Experimental Breeder Reactor No. 1 (WAG-6)**			
WAG-6 includes 22 potential release sites divided into five OUs. Sites within these OUs include underground storage tanks (USTs), septic tanks, two reactor burial sites, a leach pond, a trash dump, a drainage ditch, and a radionuclide-contaminated soil area.			
PBF: Power Burst Facility consists of five separate operational areas: the PBF Control Area, the PBF Reactor Area (SPERT-I), the Waste Engineering Development Facility (SPERT-II), the Waste Experimental Reduction Facility (WERF) (SPERT-III), and the Mixed Waste Storage Facility (SPERT-IV). Collectively, the WERF, Waste Engineering Development Facility, and the Mixed Waste Storage Facility are known as the Waste Reduction Operations Complex.	30 potential release sites have been identified at PBF. Sources of contamination include past discharges to underground storage tanks, vadose zone injection wells, septic systems, and several surface ponds.		
*Contaminants, and a summary of evaluation status for primary facilities are reviewed in detail in Section 3.			

Table 1-1. Summary of INEEL facilities and investigations.

Primary Facilities	Source of Contamination	Status	Remaining Investigations
BORAX-1 (Boiling Water Reactor Experiment I): is a radioactive subsurface disposal area that contains radionuclide contaminated debris and reactor components buried in place after they were damaged during a planned power excursion in July 1954 that resulted in a steam explosion.	Cleanup and burial of the reactor was completed approximately 1 year after the excursion. Buried materials at the site consist of the reactor shield tank, activated metal scrap, and unrecovered fuel residue. The area was backfilled with clean soil, and gravel was mounded over for added shielding from the buried activated materials.	Both the BORAX-I and SL-1 burial grounds were evaluated as CERCLA sites as part of the FFA/CO (DOE-ID 1991) for the INEEL. The RI/FS analysis (Holdren, Filemyr, and Vetter 1995) did not indicate groundwater pathway risks for either of these sites. Predicted surface exposure risks resulted in the emplacement of basalt rip-rap covers at each of these sites.	The 5 year reviews process is applicable to the ARA ROD. WAG-6 was combined with WAG-10, for which no ROD is in place.
SL-1 (Stationary Low-Power Reactor No. 1) Burial Ground and ARA. The Auxiliary Reactor Area consists of four separate operational areas designated as ARA-I, ARA-II, ARA-III, and ARA-IV. This unit contains radionuclide-contaminated debris buried in two shallow pits and a single trench northeast of ARA-I and ARA-II. The debris resulted from a nuclear accident involving the SL-1 reactor in January 1961.	25 potential release sites have been identified at ARA. Sources of contamination include past discharges to underground storage tanks, septic systems, and several surface ponds. A low-level radioactive waste landfill and a large windblown contamination area associated with the cleanup of a 1961 reactor accident also are sources within ARA. The burial ground does not contain the core, fuel, pressure vessel, or miscellaneous other parts of the reactor. Primary contamination is wind-blown surface contamination and miscellaneous debris.		

*Contaminants, and a summary of evaluation status for primary facilities are reviewed in detail in Section 3.

Table 1-1. Summary of INEEL facilities and investigations.

Primary Facilities	Source of Contamination	Status	Remaining Investigations
***Radioactive Waste Management Complex (WAG-7)**			
RWMC: established in 1952 as a controlled area for the disposal of solid radioactive waste generated during INEEL operations. The facility is divided into two components: (1) The Subsurface Disposal Area (SDA) and (2) The Transuranic Storage Area (TSA). The SDA has been used for the disposal of radioactive and hazardous waste since 1952. It includes numerous pits, trenches, and vaults where radioactive and organic waste was placed, as well as a large pad where waste was placed abovegrade and covered. The pits and trenches were unlined, and spanned the depth of the 5 to 20-ft-thick surficial sediments of the SDA. The TSA has been used for the aboveground storage of transuranic waste since the 1970s.	From 1954 to 1970, waste was received from the Rocky Flats Plant in Colorado. The waste included organic solvents, high levels of radioactive liquids (including transuranic elements), oils, and contaminated clothing. Before transport to the RWMC, solvent waste was mixed with calcium silicate to create a semi-solid, grease-like compound. Over time, waste containers developed leaks, freeing waste to migrate through the underlying soils and sediments. Organic vapors, primarily carbon tetrachloride, have been found in the soils and sediments beneath the SDA, throughout the 580-ft-thick vadose zone and in the groundwater beneath the site. In addition to transient infiltration events, historical flooding has contributed to the migration of contaminants beneath the facility.	The ROD for PAD A is signed. The ROD for OCVZ is signed. An interim ROD for Pit 9 is in place. The RI leading to a ROD for the SDA is currently being conducted.	
Miscellaneous Sites (WAG-10)			
WAG-10: regional INEEL-related aquifer concerns that cannot be addressed on a WAG-specific basis. Specific sites currently recognized as part of WAG 10 include the Liquid Corrosive Chemical Disposal Area, the Organic Moderated Reactor Experiment, and former ordnance sites.	Miscellaneous surface sites and liquid disposal areas throughout the INEEL that are not included within other WAGs.		
*Contaminants, and a summary of evaluation status for primary facilities are reviewed in detail in Section 3.			

At the INEEL, 22 RODs have been signed including those for minor release sites, and management decisions regarding the bulk of historical releases at WAG-7, WAG-3, and WAG-10 will be made in the next 5 years. Remedial actions for signed RODs include actions for moving waste off site, placing contaminated soils in the INEEL CERCLA Disposal Facility (ICDF), and leaving contaminants in place. The important evaluations in progress are for the RWMC, the tank farm at INTEC, and the groundwater under INEEL. Additional analyses of potential hazards also remain for facilities that fall under the D&D&D program and for any new facilities that will require permitting and siting. Ultimately, stewardship of the INEEL will only be as effective as the understanding of cumulative risk from all sources allows.

A comprehensive analysis that considers cumulative impacts from all contaminant management decisions may result in re-evaluation of decisions already in place. The primary remaining decision points are listed in Table 1-2. from which, it is apparent that the decision time line spans roughly 50 years. During this time, advances can be made in characterization, monitoring, prediction, and waste stabilization that can impact regulatory decisions and remedial actions. Scientific and technological advancements can be incorporated into ongoing remedial actions by exercising the ROD amendment option provided by CERCLA (42 USC § 9601 et seq.) guidance, which states that new technology can be used at anytime during remediation of a waste site in addition to allowing its use following the 5-year ROD review. Determining areas where advances must be made requires an understanding of the decision basis, which varies across the INEEL, and is discussed below.

Table 1-2. Key remaining decision points.

Planning Date	Operation, Regulation, or Decision Point	Technical Issues in Reaching an End State
2003	WAG 7 ROD	Transport uncertainty
2003	WAG 1-07 Plume remediation completion	Cost effective long-term monitoring capabilities
~2005	OU 3-14 ROD (INTEC-Tank Farm)	Uncertainty in risk predictions
~2010	SDA Closure	Uncertainty in risk predictions
~2020	Advanced Mixed Waste Treatment Facility (AMWTF) closure	Adequate Characterization and Monitoring, risk prediction
2032	INEEL CERCLA Disposal Facility (ICDF) operations	Uncertainty in design, risk prediction, monitoring, characterization
2050	INEEL projected operational lifetime	Uncertainty in risk predictions, inadequate monitoring and characterization
D&D	CPP-603	Post closure monitoring
	TAN-607	
	TRA (ETR & MTR)	
	PBF	
	ATR/canals	
INEEL HLW	INTEC HLW Facility Dispensation	Dispensation of Tank Contents, Facility Piping, and Calcine. Risk prediction, post-closure monitoring, etc.

1.2.2 Technical Basis: Overview of Knowledge Gaps and Uncertainty Sources

At the INEEL, environmental management decisions are based on current and potential public health impact. There are essentially two measures of health impact: the first is an measure of risk, and the second is a maximum concentration level (MCL). Risk via ingestion as defined by the EPA is expressed by:

$$\text{risk} = \text{Exposure Factor}*\text{Toxicity}*\text{Contaminant Concentration} \quad (1)$$

and is composed of several elements including exposure factors and scenarios, contaminant toxicity, and contaminant concentration. The first two of these are dictated by the regulatory agencies and long term use of the land, while the third term provides the focus of the proposed research. The exposure factor is determined by land use scenarios, which includes residential, agricultural, and industrial use scenarios for land and water, and are determined by the EPA. Chemical and radiologic toxicity is contaminant specific and is also set by the EPA. The contaminant concentrations of interest here, are the concentrations of contaminants in subsurface waters that can be used for domestic, agricultural, and industrial purposes. The waters of interest are those that occur in harvestable quantities, and are found in the Snake River Plain Aquifer (SRPA), and those occurring in pumpable levels in the vadose zone.

For reference, the INEEL vadose zone is a dynamic system that is affected by seasonal changes in precipitation, plant growth, and changes in surface topography as depicted in Figures 1-2 and 1-3, and reviewed in detail in Section 3.

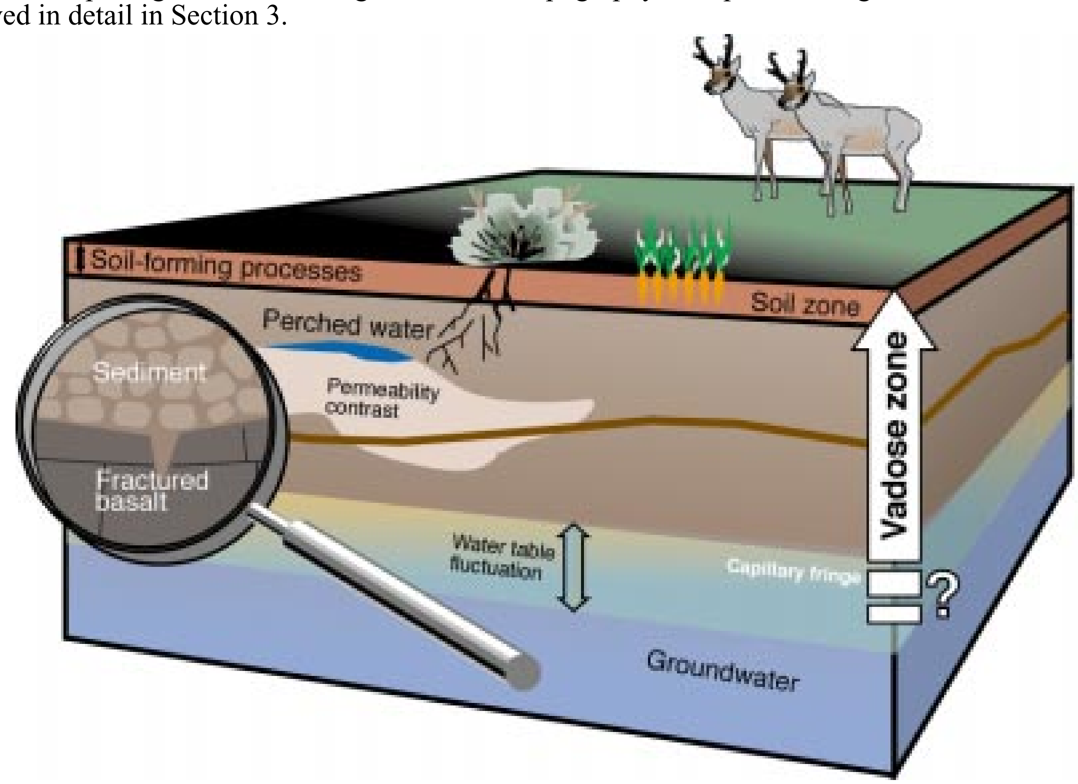

Figure 1-2 Conceptual model of the vadose zone at the INEEL.

At depth, contrasts in the properties of geologic media affect the flow and distribution of water, allowing the formation of perched water. As shown by the northeast cross-section, the general nature of the lithology of the INEEL is composed of sediments interlayered with basalts. The major sources of currently contaminated groundwater at the INEEL are from the INTEC injection well (Site CPP-23) and two TAN injection wells, (TSF-05 and TSF-23 IPAB-IS 2000). The primary sources of contaminants at land surface originate at INTEC and the RWMC.

To evaluate risk stemming from the use of subsurface water, contaminant concentrations in saturated regions (perched water and within the aquifer) are used as opposed to soil pore-water concentrations. These concentrations are spatially and temporally variable, and depend on the release history of contaminants and on the travel path through the vadose zone. To evaluate current risk, contaminant concentrations are measured at a limited number of locations, and assumptions are made about their spatial continuity and distribution. To evaluate future risk, contaminant concentrations must be predicted over time frames of interest to regulators and to the public. The prediction interval depends on specific contaminants and on the management decision. Time frames can span several months for interim actions or can span 10,000 years for permanent storage of long-lived radionuclides. Environmental management decisions made at INEEL have traditionally relied on predicting future contaminant concentrations with models starting with release history and matching current measurements. Because of our lack of understanding of subsurface phenomena and our inability to translate point measurements over spatial scales, there are large uncertainties associated with these predictions of future contaminant behavior.

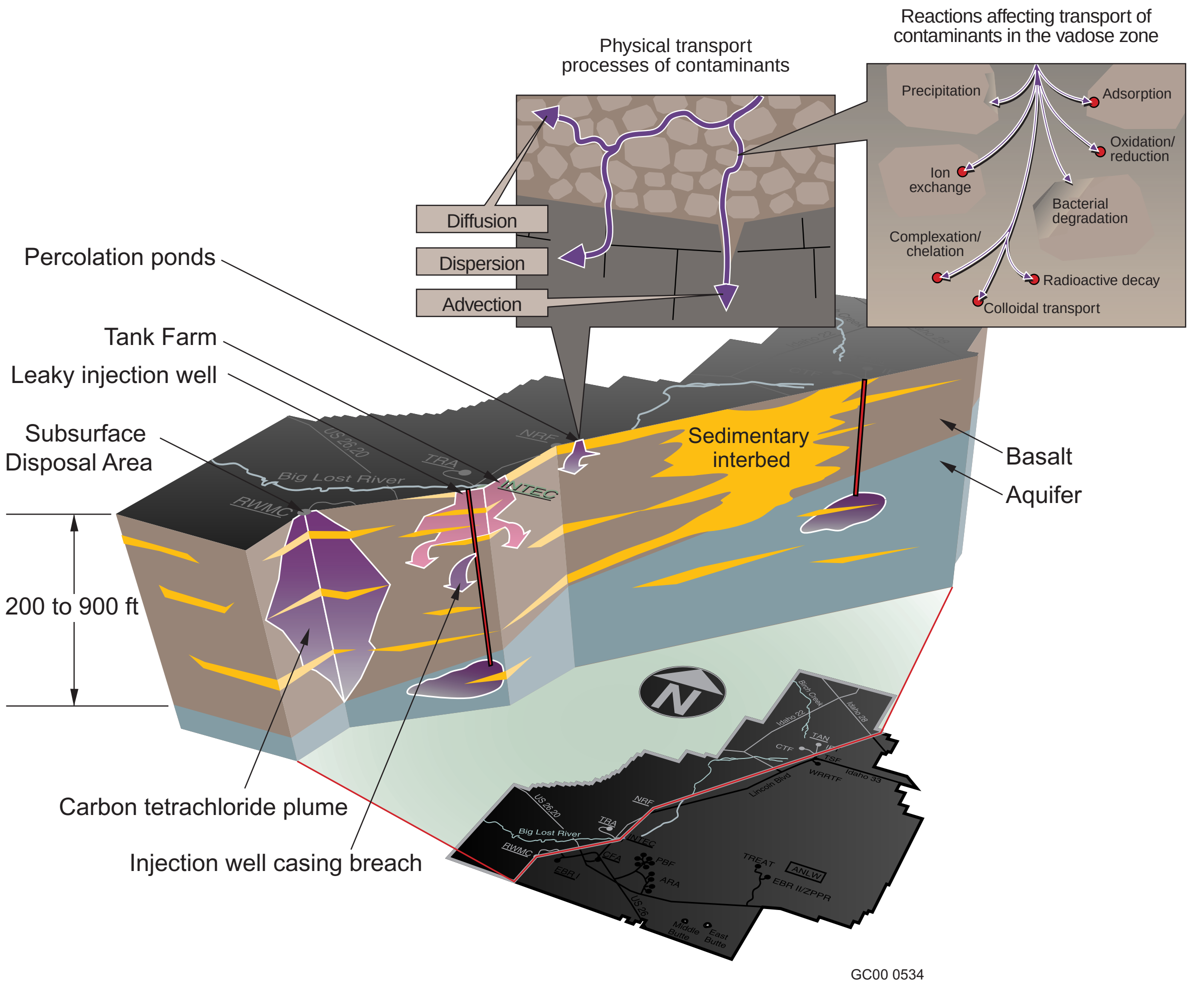

Figure 1-3 Conceptual model of contaminant distributions within the INEEL vadose zone.

Information about hydrogeochemical properties or state variables (i.e., pressure, moisture content, and concentration) in highly heterogeneous porous media, such as the fractured basalt-sediment materials underlying the INEEL, are always uncertain to some degree. We have a limited ability to quantify heterogeneous physical, biogeochemical, and hydrologic properties and their nonlinear relationships to state variables. The data are used in computer models, generally employing simplified algorithms, to describe transport and transformations to predict future contaminant behavior. Uncertainty imbedded in the estimates of parameters, state variables, infiltration rates, and contaminant sources are then propagated and compounded in the modeling process, resulting in a large degree of uncertainty in predictions of contaminant concentrations.

In systems at risk, the EPA typically sets drinking water contamination goals to fall within the 1E-6 to 1E-4 risk range. One interpretation of this range is that risk must be predicted within a factor of 100 to make environmental decisions regarding remedial actions. The range also suggests a need to quantify the uncertainty of all components used in modeling contaminant fate and transport, and to understand how to manage the distribution of uncertainty between data sets and functional relationships. To minimize erroneous environmental management decisions, uncertainties in predictions of future contaminant behavior need to be understood and quantified.

The relative importance of parameters and processes in determining the uncertainty is currently unknown. Additionally, parameters and state variables are not typically measured with methodology allowing assessment of uncertainty. However, the sources can be generally categorized as follows:

- **Theory uncertainty** addresses our ability to approximate the real world with a conceptual model. Models used as the basis for decision making need to capture relevant processes (e.g., flow, transport, and transformation) at the level of detail necessary to describe the governing phenomena at relevant temporal and spatial scales. The individual processes included in the models determine which parameters and state variables must be quantified. In addition, each process model determines the required characterization methods and data density.

- **Parameter uncertainty** is introduced in heterogeneous environments and must be quantified in context of the process models used to analyze the information. Interpretation of measured parameters over varying distances (i.e., spatial scales) is one of the key challenges facing subsurface environmental predictions, and the issue is probably best known as the scaling phenomena. An additional source of parameter uncertainty is introduced through the interpretation of measurements of different parameters made over disparate volumes. An example is provided by measurements of water potential obtained using a limited volume sampling device (e.g., an advanced tensiometer) and measurements of water content obtained using volume averaged geophysical techniques: the result doesn't necessarily describe accurately the relationships between water potential and water content, which is needed to predict unsaturated water flow.

  Important issues relevant to spatial scaling encountered during predicting transport and transformation at the INEEL include determining how to a) incorporate microscale biogeochemical processes into field scale prediction, b) how to extend observations of flow through single fractures to predict field scale transport, and c) how to interpret measurements of water content and water potential over volumes representative of field scale transport. At the INEEL, the parameter space includes biologic, geologic, geochemical, and hydrologic variables for the fractured basalt and the interlayered sediments comprising the Snake River Plain system.

- **Interpretation uncertainty** is introduced through use of indirect estimates of state variables, and by analyzing data in the context of incorrect process models. An example of the first includes using electrical geophysical signals to infer moisture content in heterogeneous media. An example of the second includes inferring hydraulic conductivity in layered sediment and fractured basalt media using a Theis curve approximation developed for radially symmetric flow in confined homogeneous aquifers. In each of these examples, it is not clear what is being measured or how to interpret the obtained values, increasing the overall model uncertainty.

- **Source estimate uncertainty**: is introduced when reconstructing historical release inventory and duration when the discharges are poorly (if at all) documented. The problem is compounded when the end state of a facility is yet to be determined, and when sampling facility contents is impossible. The potential for exposing personnel to hazardous conditions often precludes our ability to investigate contaminated sites, operational facilities, or facilities with unknown dangers.

Specific examples of uncertainty introduced in analyses conducted for operational programs have been noted and are presented in Section 3. As a precursor, an overview of the INEEL geological- hydrological- chemical- biological setting is presented in Section 2.

2 INEEL GEOLOGIC, HYDROLOGIC, CHEMICAL, AND BIOLOGIC SETTING

Contaminants originating at or near land surface must past through the vadose zone prior to reaching the Snake River Plain Aquifer. While in the vadose zone, they undergo flow, transport, and transformation processes. These processes are dominated by the media comprising the subsurface, by surface water sources, and by the spatial distribution of properties used to describe the subsurface media. The geologic media are caricatured in Figure 2-1.

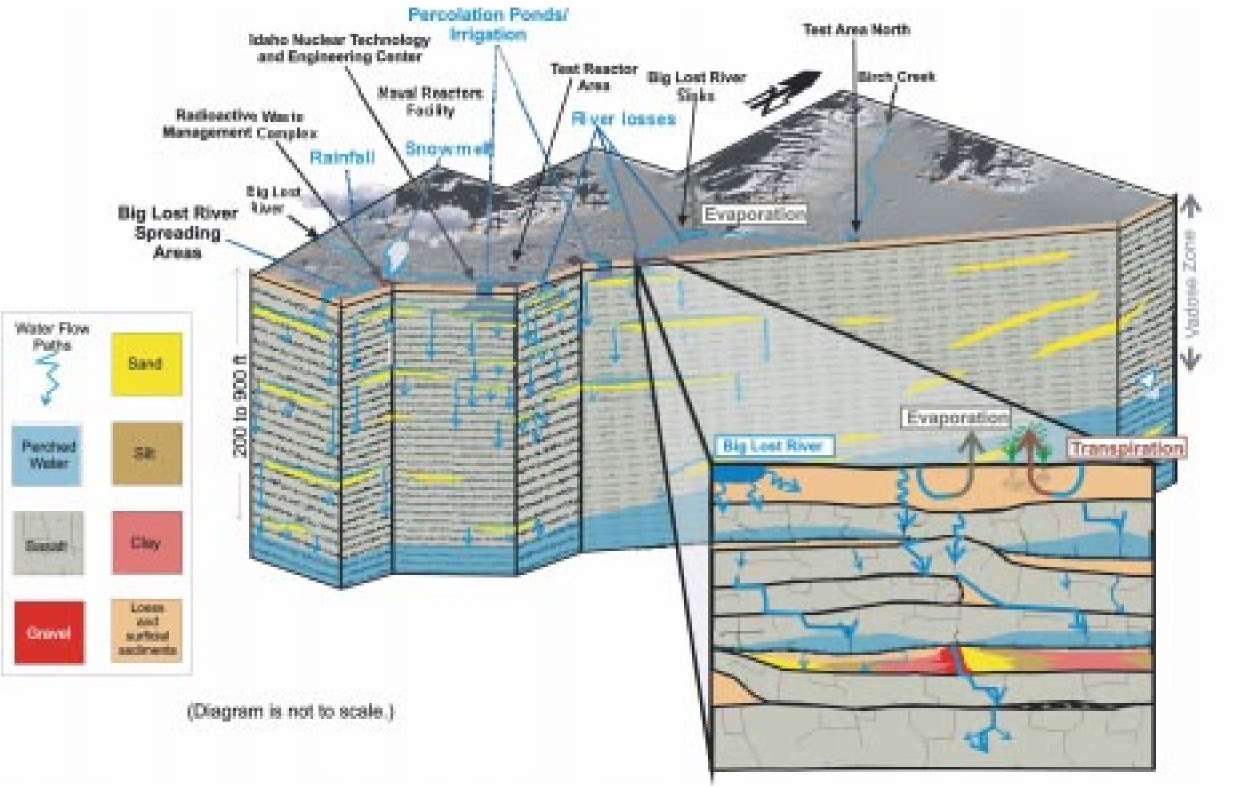

Figure 2-1 Geohydrologic cartoon of the vadose zone at the INEEL

In general, quantifying the movement of water through the INEEL subsurface is extremely difficult. The complexity originates with the spatially variable lithostratigraphy that gives rise to highly variable hydraulic and geochemical properties. The complexity is increased by temporal changes in the hydrologic regime caused by seasonal changes in infiltration, temperature, and barometric conditions, and is further confounded by large surface and anthropogenic water sources. Quantifying contaminant transport is even more difficult because of limited access locations through vertical wells in areas where horizontal permeability appears to be the dominant control. Access, coupled with an inability to obtain volume integrated samples makes contaminant detection problematic. This difficulty is coupled with that introduced by unknown contaminant inventories and release histories for contaminants emanating from heterogeneous waste disposal sites and near surface pipe leaks.

As a geologic system, the subsurface is comprised of highly heterogeneous fractured basalts interlayered with sedimentary deposits. The processes governing water and air movement, and those determining contaminant transport and transformation in this system are not well quantified, measured, monitored or predicted. As a result, there are many different possible processes involved, each requiring a different means of quantification and parameterization.

In this section, the focus is on presenting the natural geologic and hydrologic controls at the INEEL. It also presents a brief summary of possible processes governing the movement of fluids, which covers the movement of liquids and vapors. Understanding the mechanisms controlling water movement is key in predicting the transportation and transformation of contaminants in solution, while understanding vapor phase transport is key to predicting the distribution of volatile contaminants. As a system, predicting fluid movement requires an understanding of the interaction between lithostratigraphic features, moisture conditions, and of the influences of barometric pressure and temperature. In the section that follows, anthropogenic controls including contaminant and water sources provide the focus where specific examples of past investigations are presented to illustrate specific research needs.

2.1 Regional and Geologic Framework

2.1.1 Regional Geologic Setting

The INEEL is located near the northwestern margin of the Eastern Snake River Plain (ESRP), and lies in an area influenced by two distinct geologic provinces (see Figure 1-1). The ESRP is a northeast-trending zone of late tertiary and quaternary volcanism that transects the northwest-trending, normal-faulted mountain ranges of the surrounding basin and range province. The topographically subdued ESRP, the dominant geomorphic feature of southern Idaho, is a relatively aseismic region in the midst of the high-relief, seismically active basin and range province.

Volcanic and sedimentary rocks of the Snake River Plain form a 60 to 100-km-wide belt, extending about 600 km from the Idaho-Oregon border to the Yellowstone Plateau. Volcanic rocks consist of late tertiary rhyolitic rocks and latest tertiary to holocene basaltic lava flows. At least 1 km of basaltic lava flows and intercalated sediments has accumulated in the eastern Snake River Plain following the rhyolitic volcanism related to the passage of the Yellowstone mantle plume. About 2 km of subsidence of the eastern plain in the past 4 million years have allowed the basalts and sediments to accumulate and have confined their emplacement and deposition to the current boundaries of the plain.

2.1.2 Quaternary Surficial Deposits and Sediment Interbeds

Most lava flows in the INEEL region are Pleistocene in age, have been subaerially exposed for several hundred thousand years, and are, therefore, blanketed with unconsolidated sedimentary deposits of eolian, alluvial, and lacustrine origin (Scott 1982) (see Figure 2-2). Though little is known of the detailed Quaternary lithostratigraphy of the ESRP subsurface, data from INEEL drillcores (Figure 2-3)generally indicate that relatively long (10^5-year) periods of sedimentation and volcanic quiescence, represented by major sedimentary interbeds, were punctuated by relatively brief ($<10^2$- to 10^3-year) episodes of basaltic volcanism, the latter represented by rapidly emplaced lava-flow groups (Kuntz and Dalrymple 1979; Kuntz et al. 1979, 1980; Champion, Lanphere, and Kuntz 1988; Anderson and Lewis 1989; Anderson 1991). The present distribution of surficial deposits is probably qualitatively analogous to that of subsurface deposits, involving intermittent blanketing of lava flows by loess, and the deposition of fluvial/lacustrine sediments in low-lying areas between constructional volcanic zones. The following discussions provide information derived from examination of surficial deposits in the INEEL area, but they can be viewed as models for depositional processes responsible for sediment interbeds between lava flows at depth.

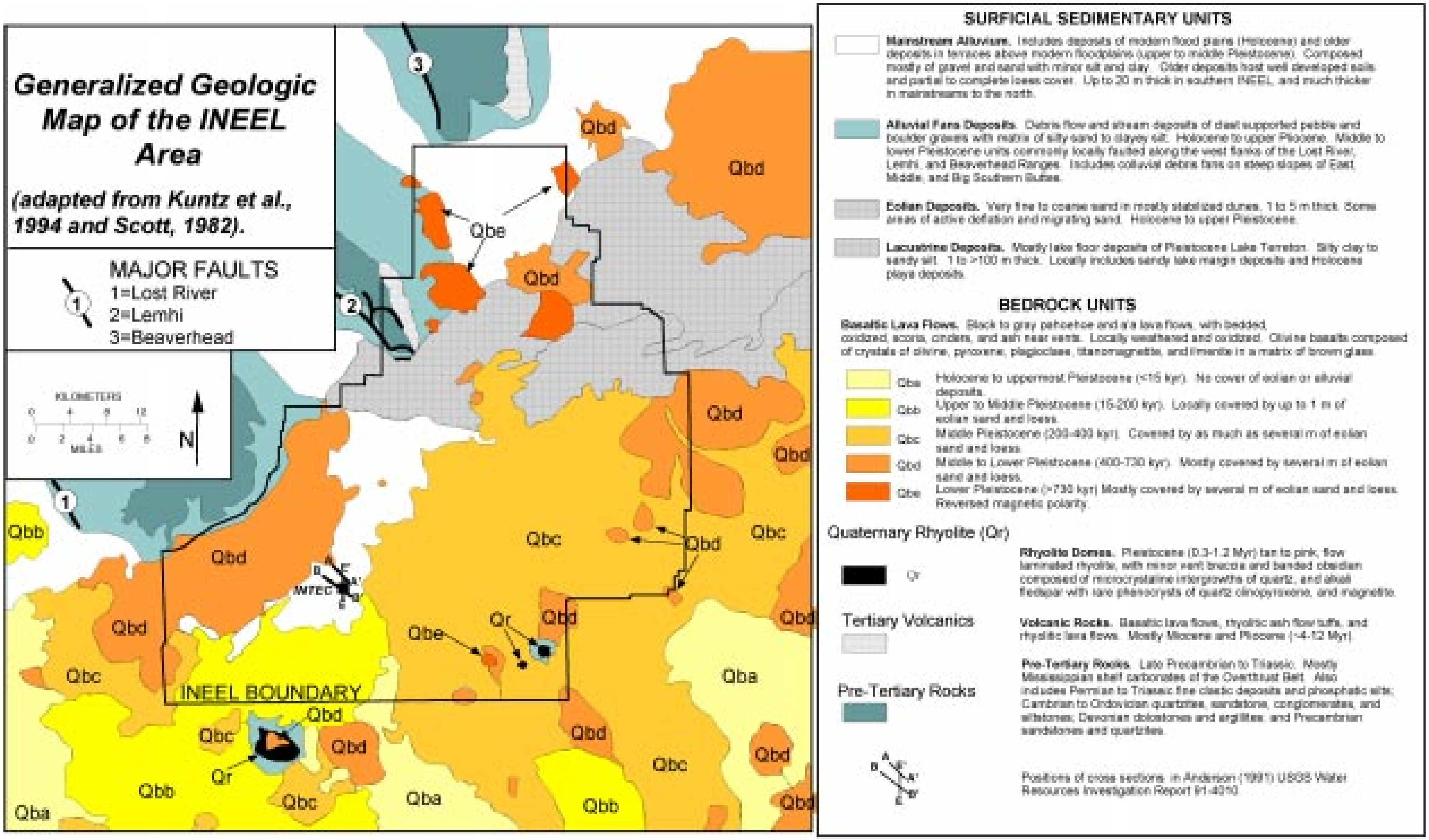

Figure 2-2 Geologic map of the INEEL area showing five Quaternary lava-flow groups.

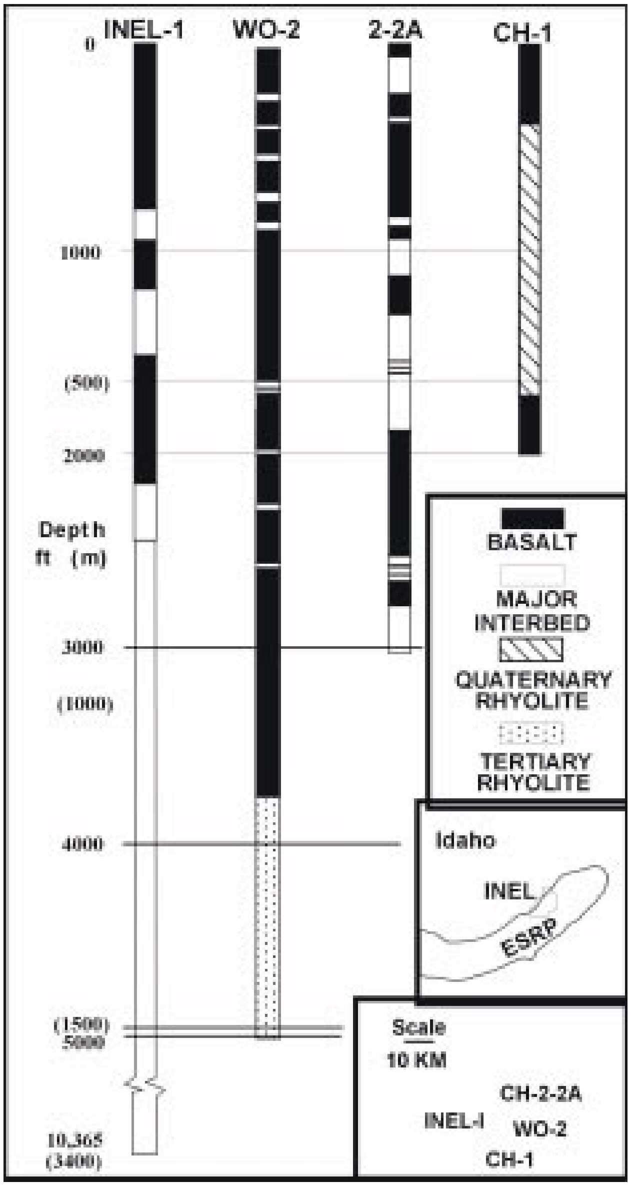

Figure 2-3 Simplified lithologic logs of four deep INEEL drill holes.

Alluvial deposits. Alluvial deposits of two types are found in the INEEL area: alluvial-fan deposits and mainstream alluvium. Alluvial fans are developed on the steep lower flanks of basin-and-range mountains and contain clastic material of local origin, commonly subangular or subrounded, moderately sorted gravel, dominated by Paleozoic carbonate clasts.

Mainstream-alluvial deposits are associated with the channels of the Big Lost River, Little Lost River, and Birch Creek, which longitudinally drain the northern Basin and Range province and flow southward onto the ESRP (Pierce and Scott 1982). None of these streams reaches the Snake River to the south. Instead, their ephemeral waters percolate into permeable lava flows and sediments at the Lost River Sinks of the northern INEEL, a local recharge area for the Snake River Plain aquifer. Mainstream deposits are generally better sorted, rounded, and bedded than those of alluvial fans, and clasts are predominantly quartzite, chert, silicified Eocene volcanic rocks, and other resistant lithologies.

Lacustrine Deposits. Volcanic eruptions and tectonism have periodically impounded the Snake River and its tributaries, forming lacustrine basins or areas of impeded drainage (Malde 1982; Howard, Shervais, and McKee 1982; Scott et al. 1982; Hackett and Morgan 1988). In the INEEL region, the axial volcanic zone obstructed drainage from areas north of the ESRP. During glacial/pluvial periods, the resulting basins received more runoff than now, and contained large shallow lakes, in contrast to the present small playas of the Lost River Sinks. One such basin in the area that is now the northern INEEL was occupied by Lake Terreton, from which Pleistocene deposits have been cored in the upper part of Drillhole 2-2A (see Figure 2-2). Lake Terreton formerly covered a wide area near the present Mud Lake. Its shoreline generally follows the 4,800-ft. topographic contour on the ESRP and is marked by beaches, bars and deltas. Lake Terreton sediments are the major source of material for Holocene dunes to the northeast.

Eolian Deposits. Pleistocene loess deposits are widespread on the ESRP, and reach their greatest thickness along its southeastern margin. Several episodes of loess deposition are inferred from studies of loess stratigraphy and paleopedology (Pierce et al. 1982; Lewis and Fosberg 1982; Scott 1982). Holocene basalt flows on the ESRP have accumulated little or no loess (Kuntz et al. 1986), indicating that major loess deposition ceased about 10 to 15 ka. Late Pleistocene basalt flows and geomorphic surfaces are overlain by a single loess blanket, whereas older surfaces are generally mantled by several loess units, separated by paleosols or erosional surfaces. Pierce et al. (1982) identified two widespread loess units in southeast Idaho: the upper loess (Unit A) was deposited about 10 to 70 ka, while the lower (Unit B) is dated less specifically but probably accumulated about 140 to 200 ka. Dunes and sheets of Holocene eolian sand near

Mud Lake (see Figure 2-2) are deflated from the alluvial surfaces of the Lost River Sinks, and from the abandoned shoreline, and floor of former Lake Terreton to the southwest.

2.1.3 Sediment Interbed Distribution and Thickness

The distribution and lithology of sedimentary interbeds within the basalt section beneath the INEEL area exerts a strong influence on the flow of groundwater in both the vadose and saturated zones. It has been postulated that a thick sequence of fine-grained, relatively impermeable, lake sediments in the Mud Lake area impede groundwater flow and cause the steep gradient in the water table there (Lindholm et al. 1983; Lindholm and Goodell 1986; Garabedian 1989). In contrast, interbed distribution and lithology may enhance aquifer flow in the central part of INEEL. The distributions of interbeds in a cross section that traverses the Big Lost River and extends from the Plain margin to East Butte (see Figure 2-4) show that numerous interbeds lie beneath the present course of the river and that they become less numerous and thinner with distance from the river. There is likely to be a mixture of both coarse-grained (sands and sandy gravels representing channel and terrace deposits) and fine-grained (silts and silty clays laid down as overbank deposits) interbeds deposited by the Big Lost River as it was pushed back and forth by lava-flow emplacement during the past several million years. Eolian deposits of both loess and sand also are likely to be present.

Based on drill hole information from throughout the INEEL, two interpretations of interbed distribution are shown in Figure 2-4, one assuming a very short horizontal continuity of interbeds (more of a river channel interpretation), and one assuming a long horizontal continuity of interbeds (perhaps representing broad flood-plain development such as the river exhibits today). In either case, however, there is a concentration of northward-elongated (perpendicular to the plane of the cross section) alluvial interbeds in the central portion of INEEL. The presence of these interbeds beneath most of the major facilities at INEEL provides important controls on transport of water and contaminants in the vadose zone.

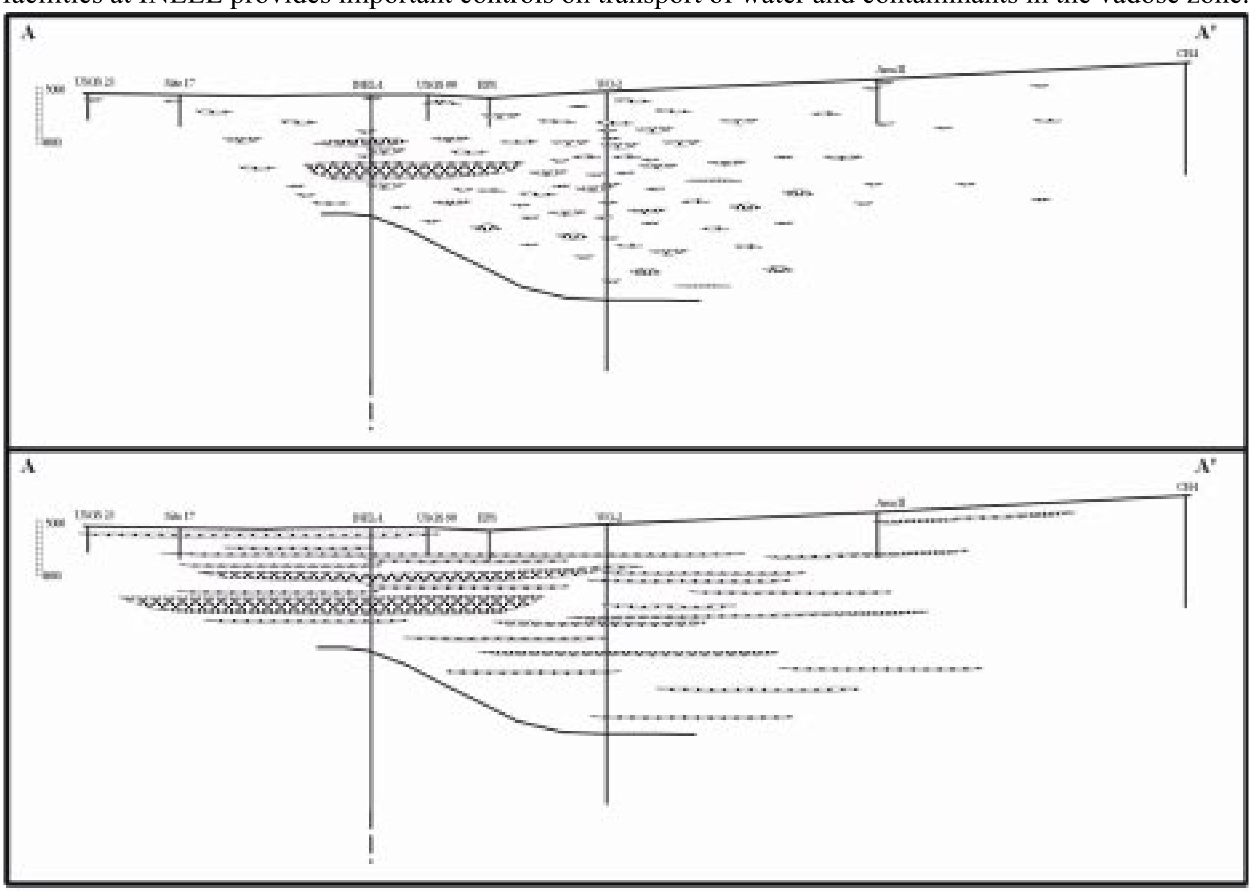

Figure 2-4 Sediment interbed distribution across the INEEL.

The thickness of sediment interbeds is extremely variable at both local (even within individual interbeds) and regional scales (see Figure 2-5 and Table 2-1.). Thickness statistics were developed from the electronic database of well lithologies developed by Anderson et al. (1996).

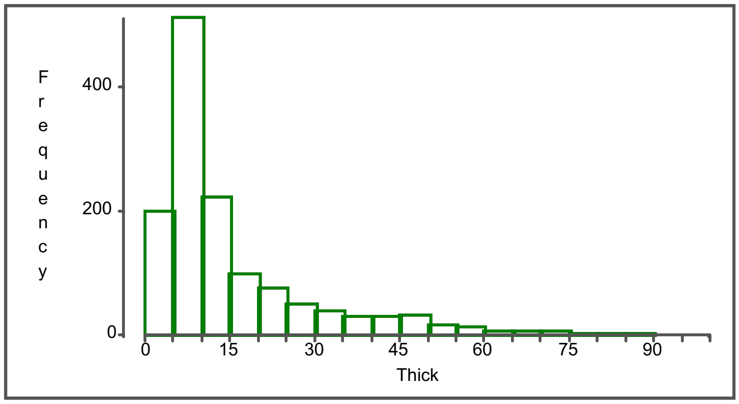

Figure 2-5 Histogram for sediment interbeds from all INEEL wells.

Table 2-1. Thickness statistics for sediment interbeds from all INEEL wells.

Minimum	1
Maximum	533
Median	9.0
Mean	10.9
Standard deviation	0.4

Additional analysis shows that there is a tendency for interbed thickness to be greater in the northern than in the southern portions of the INEEL because of the presence of thick lake sediments there. There may be significant aliasing of the data because no attempt was made to account for different depths of wells. Some of the thickest beds occur only deep in the deepest boreholes, and because there are only a few deep boreholes, the data set is likely skewed toward thinner interbeds.

2.1.4 Characteristics of Basalt Lava Flows

Lava flow Facies: During Emplacement of ESRP basalt lava flows, molten rock is continuously supplied to the advancing flow front through lava tubes. The solidified crust on the top, bottom, and ends of the lava flows is kept inflated by the pressure of the molten material in the interior of the flow. As the flow front advances, the crust at the end of the flow is laid down and overridden by the new lava, and the upper crust is stretched, broken, and fissured by movements of magma beneath. This bulldozer-tread type of emplacement mechanism produces distinctive facies within each lava flow. An idealized section showing distribution of vertical and horizontal facies variation in ESRP-basalt-lava flows is shown in Figure 2-6. From bottom to top, basalt lava flows typically are composed of a basal rubble zone, a lower vesicular zone, a massive columnar jointed zone, and upper vesicular and fissured zone, and a cap of platy-jointed crust.

The near vent facies of lava flows are typified by thin, vesicular, platy flows (shelly pahoehoe). Also pyroclastic ash and breccia layers are commonly interleaved within the thin flow layers. With distance from the vent, the shelly pahoehoe grades rapidly into the layered facies structure, described above, which typifies the medial and distal portions of the lava flow (see Figure 2-6). Deflation pits, in which solidified crust has subsided over areas where lava has drained away, are common throughout the flow but more numerous near the terminus.

Lava Flow Dimensions—There is a great range in length, area, and thickness of lava flows in the INEEL area (see Table 2-2.). The length and area measurements are for lava flows exposed at the surface, and are measured from geologic maps (Hackett, Smith, and Khericha 2000). The thickness measurements are mostly from drill hole information in the Radioactive Waste Management Complex area, augmented by measurements made of lava flow thickness in cliff faces in the Box Canyon area, to the west of INEEL (Knutson et al. 1989, 1992).

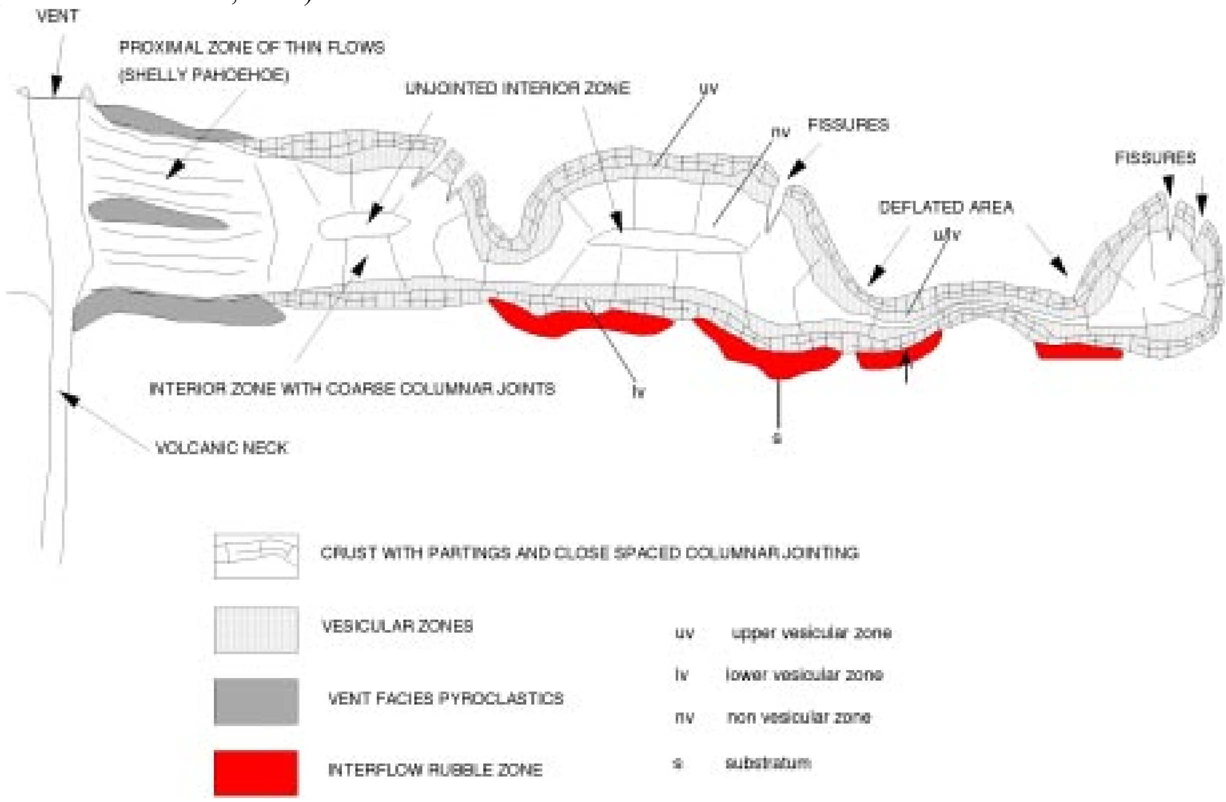

Figure 2-6 Longitudinal cross section of a typical basalt lava flow on the Eastern Snake River

Table 2-2. Statistics of lava flow dimensions.

	Length	**Area**	**Thickness**
	(km)	**(km^2)**	**(m)**
Minimum	0.1	0.5	1
Maximum	31	400	34
Range	30.9	399.5	33
Mean	12.4	96.5	
Median	10	70	7
Standard deviation	7.9	94.2	
Number of measurements	46	43	641

2.1.5 Surface Topology

The surface of the INEEL is a relatively flat, semiarid, sagebrush desert. Predominant relief is manifested either as volcanic buttes jutting up from the desert floor or as unevenly surfaced basalt flows or flow vents and fissures. Elevations on the INEEL range from 1,460 m (4,790 ft.) in the south to 1,802 m (5,913 ft.) in the northeast, with an average elevation of 1,524 m (5,000 ft.) above sea level (Irving 1993).

Irrigated farmlands exist adjacent to approximately 25% of the INEEL boundary (Becker et al., 1996). Lands acquired for the NRTS were originally under control of the BLM and were withdrawn through public land orders in 1946, 1949, and 1950. Until these withdrawals, the land was used primarily as rangeland. From 300,000 to 350,000 acres within the perimeter of the INEEL have been opened to grazing through permits administered by the BLM. Since 1957, approximately 1,386 km^2 (535 mi^2) in the central portion of the INEEL have been maintained as a grazing exclusion area. Historically, portions of this central core have been used as bombing and gunnery ranges. Currently, the largely undeveloped central portion of the INEEL is reserved for ecological studies of sagebrush-steppe ecosystems (Becker et al., 1998).

Bordering the INEEL on the north and west are mountain ranges: the Lost River Range, the Lemhi Range, and the Beaverhead Mountains (see Figure 1-1). Agricultural lands, U.S. Forest Service lands, and U.S. Bureau of Land Management (BLM) lands surround the remainder of the INEEL and are managed as rangeland. As discussed in the following section, intermittently flowing waters from the mountain ranges in the northwest portion of the INEEL contribute to infiltration and overland flows.

2.2 Infiltration and other Water Sources

Anthropogenic activities, precipitation, and infiltration of surface-water contribute to contaminant migration through the vadose zone. The spatial distribution and temporal duration of these water sources is highly variable and depends on their origin. Anthropogenic water sources are largely associated with INEEL facilities, and include process waste water discharges, leaks from water transfer lines, and lawn irrigation, etc. Water sources associated with long-term facility operations are fairly uniform, while other discharges are seasonal. Commonly, the receptors of discharged water (e.g., ponds, cribs, infiltration galleries, etc.) are scattered and represent a small portion of the land base. Precipitation and snow accumulation are both distributed nonuniformally over the land surface. In some years, rainfall and snow melt occurs in sufficient quantity to fill, and to overflow, normally dry channels. In other years, different watersheds yield more water, resulting in a dissimilar distribution of water to the land. All of these water sources has the potential to transport contaminants to the underlying aquifer. The relative contribution to vadose zone infiltration from the various sources is a function of surface topology, season, and local weather condition.

Historical infiltration of anthropogenic water contributes to widespread contaminant redistribution within the vadose zone across the INEEL (with the possible exception of the RWMC facility). In addition to ponds, sewage lagoons, and pipe leaks, injection wells for disposing of steam and process water have been used to discharge water in the vadose zone. The amount of water from anthropogenic sources can be large, e.g., on the order of millions of gallons per month (Mg/month). For example, DOE/ID (1997) has estimated that service waste water discharges to the INTEC percolation ponds are on the order of ~2 Mg/day. Sources of anthropogenic water at CFA include the Dry pond, the former sewage plant drainfield, and the experimental calcining waste pond. At TRA, most of the process water between 1965-1982 was injected into a deep disposal well. Thereafter (to at least 1987), the cold water waste pond accepted ~200 Mg/year (Hull, 1989). At TAN, two anthropogenic sources of water have been documented (Martian, 1999): disposal of 1 Mgal/month in the TSF-07 disposal pond, and up to 4.23 Mgal/month in the TSF-05 injection well from 1955 to 1972. Being associated with facilities, most of the water is discharged near known contaminant sources. Consequently, the discharged water not only transported contaminants contained in the waste water, but also contaminants existing in the subsurface from other sources.

Natural precipitation provides a highly variable source of water that infiltrates through the vadose zone. At the INEEL, precipitation occurs throughout the year (rain and thunderstorms in the summer and snow in the winter) with the heaviest accumulations occurring in the spring and early summer. Based on a

38-year historical record, the annual average precipitation is approximately 22 cm/year, with a maximum of 36 cm/year, and a minimum of 11 cm/year (Clawson et. al., 1989). Most of the precipitation events were less than 0.25 cm/day (Sagendorf, 1996).

Although the INEEL is in a relatively dry climate, summer thundershowers can deliver a significant amount of precipitation. Analysis of historical INEEL precipitation records indicates that accumulations greater than 2.5 cm/day have occurred in 8 of 38 years at CFA and in 9 of 14 years at TAN. In two of the storms, the rainfall rate was at least 2.5 cm/hr (Clawson et. al., 1989). The high rainfall rates can create temporary ponding conditions in topographic lows and can result in overland flooding.

Snow fall history and snow depth at INEEL have been recorded only at CFA. According to these records, the annual total average snow fall is 70.1 cm, and ranges from 17.3 to 151.6 cm. A typical winter has snow cover from mid-November to mid-April (Clawson et. al., 1989). Moderate to strong surface winds crossing the plains of the INEEL result in spatially and temporally variable snow drifts exceeding depths of 1 m. These drifting events contribute to localized enhanced recharge (Martian and Magnuson, 1994) as the snow melts. Episodic infiltration events are attributed to rapid melting of the snow due to warm winter winds and to higher temperatures in the spring.

Recharge to the aquifer, through the vadose zone, occurs along ephemeral streams entering the INEEL. The Big Lost River, Little Lost River, and Birch Creek periodically flow onto the ESRP from watersheds in the northern Basin and Range province. The extent to which they flow into the INEEL depends on the yearly snowpack and rainfall. During high flows, water is diverted to the Spreading Areas near southwest INEEL, and during normal flows, the water percolates through the channel bottoms into the permeable lava flows and sediments. It is estimated that as much as 9,820 Acre ft/Yr (0.74 cm/day) of water either infiltrates into the subsurface or evaporates from the Big Lost River between the INEEL Diversion and the gauging station at Lincoln Blvd. near INTEC.

Precipitation, water discharged to ponds, and surface water are subject to evaporation prior to infiltrating into the subsurface at INEEL. It is estimated that the total potential evaporation is on the order of 90 cm/year from surface sources and seasonally-saturated soils. Following infiltration into the subsurface, the water is subject to evapotranspiration. Between 15 and 22.5 cm/year of evapotranspiration is attributed to the sparse native vegetation of the Snake River Plain, which is approximately equal to the average total precipitation (Hull, L.C., 1989). The depth over which evaporation occurs in the subsurface has been estimated to vary between 28-148 cm by Martian (1995), who determined that 80% of evapotranspiration occurs between May and October, and that evaporation depth is highly correlated to localized soil lithology at the SDA.

Although the total yearly evapotranspiration has the potential to exceed precipitation, localized infiltration occurs to significant depths and very rapidly following episodic precipitation events and near anthropogenic water sources. A wide range of infiltration rates has been estimated at INEEL and appears to be correlated to local surface topography and soil lithology. Recharge rates through RWMC undisturbed sediments, as determined by chlorine-36 measurements, indicate that infiltration ranges from 0.36-1.1 cm/year (Cecil et. al, 1992). In a similar study conducted within the SDA, chlorine-36 was not detected in the upper several meters of the soil profile, presumably indicating a recharge rate sufficient to wash the chlorine-36 from the soil profile.

Localized infiltration can be of many orders of magnitude greater than the average precipitation due to local surface topology. McElroy (1993) estimated that 56 cm of water infiltrated at a CFA neutron access tube when only a total of 12.2 cm of precipitation occurred during the previous winter months. The corresponding monitoring location was in a shallow ditch near a plowed road, suggesting the importance of surface topography and snow drifting. This can be contrasted to an average infiltration within the SDA of 8-12 cm/yr (Martin, 1995).

In addition to local topology, soil disturbances can increase infiltration rates, depending on the nature of the disturbance and soil type. A study sponsored by the USGS (Shakosky, 1993) instrumented undisturbed and adjacent disturbed (simulated waste trench) soils outside the SDA. She concluded that construction of the waste trench has destroyed the natural impeding soil structure, enhancing infiltration within these disturbed areas.

The underlying fractured basalt is believed to act as a barrier, appearing to inhibit water movement into the basalt until the overlying sediment approaches saturation. Perched water forms very rapidly as documented by Sisson and Hubbell (1999) who measured a soil-water pressure pulse migrating at rates of 1-3 m/day at depths of 15 m through fractured basalt following an episodic infiltration event. Subsequent drainage of the perched water also occurred very rapidly as illustrated in Figure 2-7.

The primary significance of surface water sources lies in the creation of overland flooding, localized ponding, and rapid infiltration. The proximity of these water sources to sources of chemicals has lead to widely distributed contamination at depth throughout the vadose zone at INEEL. Capturing the effects of these transient infiltration events poses significant monitoring and characterization challenges.

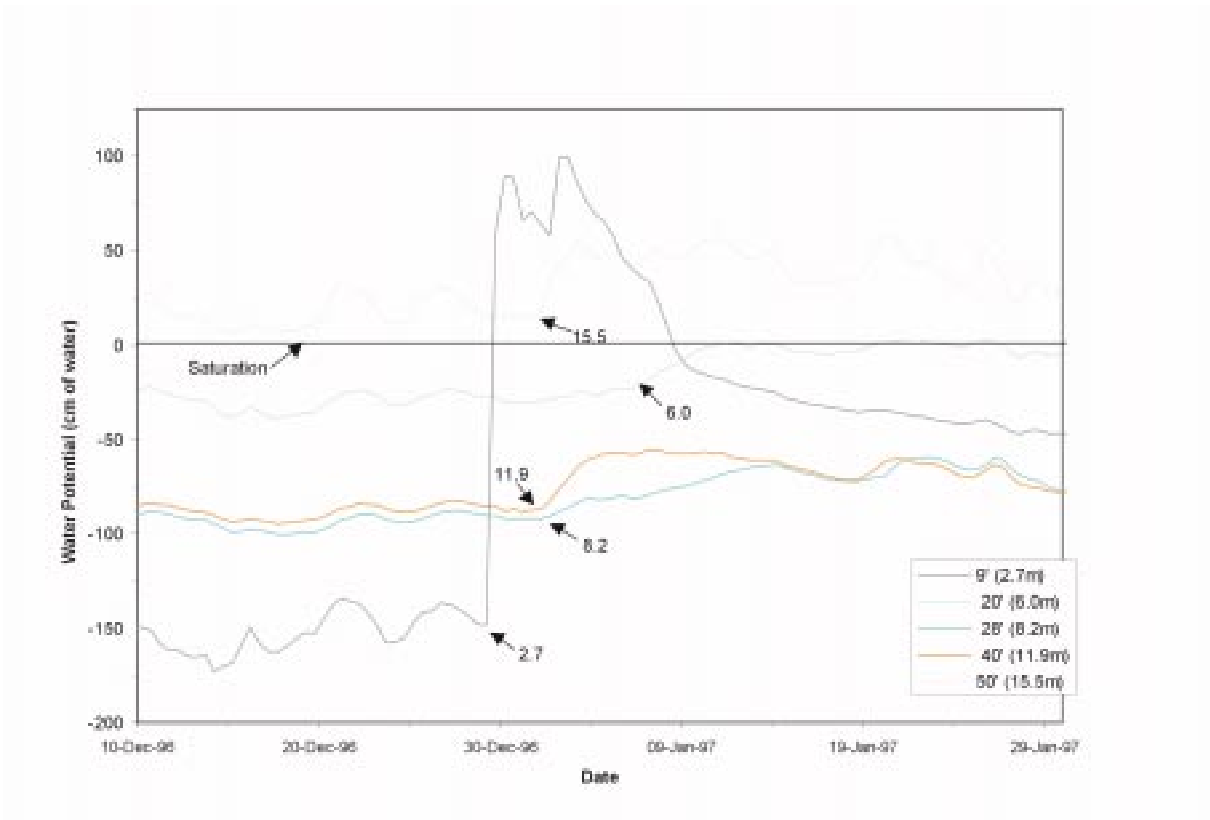

Figure 2-7 Water potential responding to rapid winter snow melt events in the 5-well site.

2.3 Processes Determining Fluid Migration

Under the temperature and moisture conditions found at the INEEL, chemicals largely migrate as either liquids or vapors through the surficial sediments, fractured basalt, and sedimentary interbeds. Liquid water, non-aqueous phase liquid organics, vapor-phase chlorinated organics, and vapor-phase water are the principle compounds moving through the subsurface at INEEL. Understanding the fundamentals of fluid behavior in porous media and knowing the structure of the subsurface pore geometry are essential for obtaining insight into contaminant flow and transport. The direction of fluid movement is determined by the gradient in the total potential (gravitational plus pressure) of each fluid. The rate of fluid migration and relative saturation at a specified capillary pressure are functions of pore geometry. Porous media with smaller pores will have a higher fluid content than porous media with larger pores at the same capillary pressure. Prediction of fluid fluxes at the pore scale requires knowing the pore geometry at every point, which is not technically feasible. Consequently, prediction of fluid fluxes are commonly based on volume-averaged processes. This requires that the effects of variations in pore geometry be described via hydraulic properties, which may not necessarily account for the effects of heterogeneities on fluid flow.

Measurement uncertainty is introduced through disparate measurement volumes, through interpretation of indirect estimates of state variables, and by interpreting data in the context of different process models. An example of the first is measuring water potential with an advanced tensiometer that measures water potential over a limited volume and measuring water content with geophysical techniques that yield average values over much larger volumes. The results don't necessarily describe accurately the relationships between water potential and water content, which is needed to predict unsaturated water flow. An example of the second includes using electrical geophysical signals to infer moisture content in heterogeneous media, where the electrical response is itself spatially variable. An example of the third includes inferring hydraulic conductivity for media dominated by film flow along fracture walls. To reduce the uncertainty in fluid flow and transport predictions, variably saturated flow parameters must be obtained that reflect the heterogeneous nature of the subsurface, and the correct processes describing flow must be determined.

In Figure 2-8, some of the processes by which liquid water can move through the subsurface conditions at INEEL are shown.

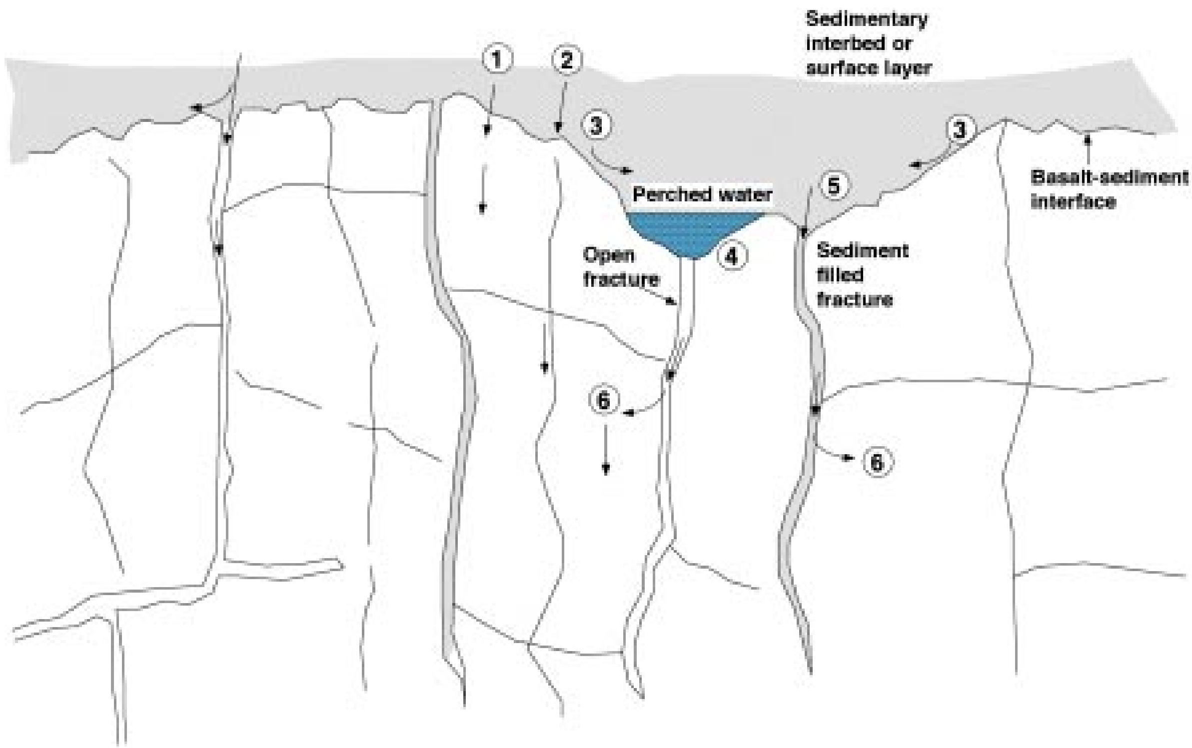

Figure 2-8 Possible mechanisms by which water can move across a sediment/basalt interface.

A brief discussion of the various processes illustrated in Figure 2-8 follows, with one or more of the processes likely to occur at the same time depending on specific conditions:

1. Water moving downward through the surficial sediment pore spaces into the pore spaces of the basalt matrix. This process will take place when the sum of the pressure and gravitational forces of the water (i.e., total water potential) in the basalt matrix is less than that in the overlying sediment. If the water flux rate in the sediment exceeds the conductance of the basalt matrix, water will either pond or move laterally at the interface between the sediment and basalt.

2. Water moving downward through the surficial sediment pore spaces into small aperture fractures in the basalt. This process will occur when the total water potential in each fracture is less than that in the overlying sediment. For this to occur, the aperture sizes must be smaller than that specified by Laplace's equation of capillarity for the fracture geometry at the prevailing capillary pressure. If the aperture is larger than this critical size, then water will not enter the fracture at the prevailing capillary pressure.

3. Water moving laterally along sediment (clay)-basalt interfaces. This process occurs when the downward water flux exceeds the hydraulic conductivity of the underlying unfractured basalt matrix or clay layers overlying the basalt surface. In general, the vertical permeability of unfractured basalt is orders of magnitude lower than that of the sediment. It is highly likely that horizontal movement occurs frequently, as evidenced at the CFA landfills (Keck et al 1995).

4. Water moving downward through the Surficial sediment pore spaces at a higher flux rate than the underlying basalt has the capacity to conduct. The result is a build up of water at the sediment-basalt interface, which may result in the formation of perched water. Water will not enter larger aperture fractures until the pressure of the water decreases to a value determined by Laplace's equation of capillarity for the fracture geometry. If air can not escape from the fracture, then water will pond.

5. Water moving downward through the surficial sediment pore spaces into sediment-filled fractures within the basalt. This process will occur when the total water potential in the sediment-filled fractures is less than that in the overlying sediment. Typically, the sediment filling the fractures is derived from the overlying sediment and has similar hydraulic characteristics which permits water to readily move into the sediment-filled fractures. Near the Subsurface Disposal Area, the sediment appears to be a low-permeability clay, probably of alluvial or lacustrine origin.

6. Water moving as thin films along fracture walls and imbibing into the basalt matrix pores. This is more likely to occur under unsaturated conditions when the total water potential in the basalt is less than that in the overlying sediments. In addition, the water pressure in the pores of the basalt matrix must be less than that in the film along the fracture walls.

As water migrates downward through the fractured basalt system, the exact mechanisms can not be determined without quantifying all of the relevant conditions including water pressures and pore/fracture sizes and locations. Furthermore, there is evidence that Darcian and non-Darcian flow may occur, which may be a function of the scale at which the processes are being described. For near saturated conditions, the flow in fractures is likely to dominate water movement through the basalt. The high fluid conductance of the fractures enhances the movement of water, as observed by Sisson and Hubbell (1998) near town facilities and by Wood and Norrell (1996) near the RWMC. Rapid downward water movement was also observed in a USGS monitoring well (USGS, 1963) and in INEEL Well 5. For unsaturated conditions, the mechanisms that dominate water movement are less clear. One possibility is the condition listed under item 6 above, i.e., with water moving as films on fracture walls and imbibing into the basalt matrix (Wang and Narasimhan, 1985). For this scenario, water movement would be largely be governed by Darcian flow in the low-permeability basalt matrix. Another possibility (not shown in Figure 2-8) is non-Darcian behavior of the film flow along the fracture walls, such as chaotic falling drips. For extremely dry conditions, the movement of water may principally occur because of vapor flow and/or diffusion, which involves the partitioning of molecules between fluid phases and possible condensation.

The extent to which water moves laterally while migrating downward through the fractured basalt is also uncertain. During the Large Scale Infiltration Test (Wood et. al., 1996), the wetting front moved vertically downward until it encountered a sedimentary interbed. Thereafter, there was considerable lateral water movement. Under INTEC, it is hypothesized that the perched water bodies under the south and north portions of the facility are hydraulically connected, although it is not clear that the sediments are laterally continuous. Lateral water migration seems to be a function of sedimentary interbed location and extent. Where sedimentary interbeds are present in the subsurface, they contribute a large permeability contrast to that of the fractured basalt system. The permeability contrast and location of clay-infilled fractures are thought to control the formation of perched water. Where perched water is found in the sediments, it is likely that the higher permeability fractured system supplies water faster than it can drain. Where perched water is found in the basalt system overlying sediments, it is likely that the fractures in the basalts are clay filled, and the basalt system forms a catch basin at the bottom. An example of the latter situation has likely been observed at the SDA in Well USGS-92. Perched water was observed in the basalts above the 200 ft interbed as the well was drilled. When the top of the interbed was penetrated, the perched water drained into the sediments. Drilling stopped and the interbed portion of the wellbore was sealed. Perched water has been recovered at that site for many years.

The spatial distribution of sediment, basalt, and fracture characteristics affect how water moves through the subsurface at INEEL. Understanding the processes by which water migrates through porous media and being able to develop parameters that capture the relevant processes as well as the effects of heterogeneities are essential for predicting water and contaminant behavior through the subsurface.

2.4 Contaminant Behavior

At the INEEL, principle contaminants include radionuclides (^{129}I, ^{137}Cs, ^{60}Co, ^{90}Sr, ^{3}H, ^{14}C, etc.), metals (Cd, Cr, Hg, As, etc), inorganic ions (NO_3, F), and chlorinated hydrocarbons (Carbon Tetrachloride (CCl_4), Trichloroethane (TCE), Dichlorethane (DCE)). Once in the environment, the contaminants are subject to advection, dispersion, interphase mass transfer and transformations. As discussed in the previous section, advection (also referred to as convection) is the transport of dissolved solute by the movement of a fluid responding to a gradient in the fluid's total potential. Dispersion represents spreading of solute about a mean position, such as the center of mass, because of variations in pore-scale fluid velocities. Interphase mass transfers, such as sorption, liquid-liquid partitioning, and volatilization, involve the transfer of matter in response to gradients in the chemical potential of the substance. Transformations include processes by which the physicochemical nature of a contaminant is altered. Examples include biotransformation, radioactive decay, and oxidation-reduction. An understanding of common assumptions made at the INEEL provides insight into observed nonideal behavior, parameter measurement, and data interpretation challenges facing investigators of the INEEL subsurface.

2.4.1 Characterizing Solute Transport

The paradigm used to understand transport of contaminants at the INEEL is based on assumptions that the porous medium is homogeneous and that interphase mass transfers and transformations are linear and instantaneous. This paradigm follows the ideal behavior model discussed by Brusseu (1999), and conforms to the standard advection-dispersion-retardation-decay model given as:

$$R\frac{\partial C}{\partial t} = -v\frac{\partial C}{\partial x} + D\frac{\partial^2 C}{\partial x^2} - \mu C \qquad (1)$$

where x is the spatial coordinate, t is time, C is the concentration of contaminant in the fluid, v is the average linear velocity of the fluid in the pores of the medium, D is the dispersion coefficient, μ is a first-order reaction coefficient, and R is the retardation factor, defined as

$$R = 1 + \frac{\rho}{\theta}K_D \qquad (2)$$

where ρ is the bulk density of the porous medium, θ is the volumetric fluid content (porosity in a saturated media), and K_D is a coefficient representing the distribution of contaminant between the solid and liquid phases (e.g., sorption). The term on the left-hand side of Equation 1 represents the change in contaminant mass with time that occurs at a specified location in response to transport and fate processes. The retardation factor represents the influence of fluid-solid transfer (sorption) on transport. The first term on the right-hand side represents advective transport, while the second term represents dispersive transport. The dispersion coefficient is derived from a dispersivity, tortuosity, advective velocity, and fluid-phase diffusion coefficient. The product of dispersivity and average linear velocity represents the contribution of mechanical mixing and axial or molecular diffusion and is represented by the ratio of the diffusion coefficient to tortuosity. The third term on the right-hand side of Equation 1 represents a loss of contaminant from the fluid due to reaction.

Primary assumptions in this approach include: a homogeneous porous medium in which an average linear velocity can be defined, and that interphase mass transfers and transformations are linear and instantaneous. Under these assumptions, solute transport would be characterized by a constant value of the retardation factor and minimal spreading about the mean velocity. Non-ideal behavior would result in increased dispersion compared to laboratory (second spatial or temporal moment) observations, and time- or distance-dependent R-values (first spatial moment). Comparison of contaminant arrival from the LSIT, Box Canyon, and Hells Half Acre experiments suggest that the advection dispersion model most commonly used at the INEEL is overly simplistic. The difficulty in selecting an appropriate model lies in distinguishing between the factors affecting transport behavior.

2.4.2 Factors Contributing to Nonideal Transport

- **Nonlinear Sorption.** Application of Equation 1 at the INEEL is based on the assumption that the distribution of solute between liquid and solid phases is a linear process described by a linear isotherm. Nonlinear sorption would result in asymmetrical breakthrough curves and concentration-dependent retardation factors. The possibility of nonlinear sorption behavior for contaminants on INEEL subsurface materials has not been evaluated. In fact, many of the K_D values used in application have been extracted from the literature, assuming that the materials and conditions are similar to those found in the INEEL subsurface. It is unknown whether the assumption inherent in the use of Kd (linear isotherm) is appropriate, conservative, or not conservative. Site specific issues are discussed in Section 3.

- **Rate-Limited Sorption/Desorption.** Selecting single K_D values from the literature assumes that the interactions between solute and sorbent are so rapid in comparison with hydrodynamic residence time that the interactions are instantaneous. The impact of rate-limited sorption/desorption on transport is manifested as asymmetrical breakthrough with early breakthrough and tailing, as well as being manifested as decelerating plumes resulting from increasing R values. Rate-limited sorption is related to the phenomena of *contaminant aging* and could affect the interpretation of breakthrough behavior at the INEEL. For example, a majority of the contaminants disposed of in burial pits and trenches at the SDA have been there for decades. Contaminant aging results in different interpretations and parameterizations of sorption behavior for a given constituent and media for different sorption histories. The causes are undecided, but may involve diffusive flux into domains from which release is greatly constrained, as well as binding of the contaminants to components of the soil. At the INEEL, diffusive transport is expected to occur from the fractures and soils into the basalt matrix, resulting in the transport of contaminants into normally inaccessible soil pores.

- **Spatially Variable Sorption**. The lithostratigraphy of the INEEL is highly heterogeneous. Sorption phenomena and parameters would also be expected to vary. Nonuniform sorption results in differential-front advancement leading to the observation of increased dispersion and multiple breakthroughs at a given observation location.

  In porous media, the hydraulic conductivity is typically negatively correlated to the sorptive capacity, and the correlation is a function of available reactive surface area. This implies that low velocity zones are associated with zones of high reactivity. In these zones, reactive solutes are accumulated, and released slowly to the advectively faster regions. Given a high enough contrast, this essentially leads to the appearance of insitu contaminant sources, or dual media (dual porosity) behavior. Environmental management decisions were made at TRA based on predicted decreases in contaminant concentrations. Recent observations suggest that the concentrations are not decreasing. The initial numerical approach was simplistic in its representation of sorption distribution, and neglected the potential influence of spatially variable sorption.

Mineralogy parallels the lithostratigraphy of the INEEL. As discussed in Section 2.1, the INEEL subsurface consists of basalt units and sediments from a variety of sources. The mineralogy of the Big Lost River alluvium is quartz (32 to 45%), plagioclase feldspar (16 to 30%), clay minerals (8 to 14%), potassium feldspar (6 to 18%), pyroxene (8 to 14%), and/or calcite or dolomite (2 to 6%) (Bartholomay 1990). The clay minerals identified in the alluvium are illite, smectite, mixed-layer illite-smectite, kaolinite, and chlorite. These clay minerals are detrital and have not been formed in place by weathering (Knobel, Bartholomay, and Orr 1997). At some locations, the gravel is lightly cemented or coated by secondary calcite. Analysis of coatings on the alluvium indicates that the composition is 45% silica, 45% calcite, 5% iron oxide, and 5% aluminum oxide (Nace et al. 1975).

The carbonate (calcite and dolomite) grains and coatings provide rapid acid neutralization and pH buffer capacity, as well as ion exchange sites for strontium. The clay minerals provide sites for adsorption of cationic contaminant species such as Sr^{+2} and PuO_2^{+2}, and the iron and aluminum oxide coatings provide a range of sites having positive, negative, and neutral charges. The clay minerals may also provide sites (e.g., along their edges) for adsorption of anions, but the extent is not known. At very low pH (i.e., pH of less than 3), the surfaces of oxides are positively charged, and cation adsorption reactions are inhibited. As the pH of the solution rises (i.e., pH range of 4 to 6), cation adsorption increases significantly. Oxide coatings also provide sites for adsorption of both cations and anionic contaminant species such as $PuO_2(CO_3)_2^{-2}$.

As discussed previously in Section 2.1, beneath the surficial alluvium lies 600 to 900 m (2,000 to 3,000 ft) of layered basalt flows and interbedded sediments (Nace et al., 1975). The basalt flows are characterized as overlapping lobes of basalt intermixed with larger basalt flows of relatively uniform thickness beneath INTEC. The sediments found between the basalt flows are often discontinuous and characterized by sequences of sand, silt, clay, and lesser amounts of gravel (Mundorf, Crosthwaite, and Kilburn 1964).

A number of studies of basalt mineralogy have been summarized by Knobel, Bartholomay, and Orr (1997). Key findings of these studies indicate that the mineralogy of the Snake River Plain basalt is remarkably uniform in composition, and that very little weathering of basalt is noted. Fractures and vesicles in basalt can contain sediments washed into the basalt after cooling. These sediments are generally fine-grained silt- and clay-sized particles consisting of quartz and clay minerals with lesser amounts of feldspar, calcite, and pyroxene.

The sedimentary interbeds are primarily composed of sand and silt, with some small clay lenses. The majority of the interbeds are thin (0.3 to 1.5 m [1 to 5 ft]) layers of silt that were deposited in eolian or fluvial environments between the major basalt flows. The mineralogy of the interbeds is similar to that of the alluvium, and composed of quartz (18 to 39%), plagioclase and potassium feldspar (26 to 42%), clay minerals (0 to 42%), and pyroxene (0 to 41%). Dolomite is absent and the calcite percentage is variable (0 to 28%). Identified clay minerals include illite, smectite, mixed-layer illite-smectite, kaolinite, and chlorite (Knobel, Bartholomay, and Orr 1997). Clay minerals were identified as detrital and commonly have reddish coatings of ferric oxyhydroxides (Rightmire 1984; Rightmire and Lewis 1987).

Clay and iron oxide minerals provide the greatest amount of chemical-solid reaction potential, and exist primarily within the interbed portions of the groundwater flow path. Assessing effective reaction potential is made difficult because a) the percentage of these minerals varies spatially, b) the thickness of interbeds varies spatially, and c) multiple pathways exist for water infiltrating through the vadose zone, with water being deflected along interbed surfaces rather than through them, or by passing sediments altogether.

Additional complications are presented by changing moisture conditions which alters the processes determining flow regime and flow path. As a result, field-scale reaction potential is a spatially and temporally variable property that is moisture dependent.

- **Structured/Locally Heterogeneous Media and Spatially Variable Hydraulic Conductivity.** The concept of dispersion is based on variations of solute breakthrough about a mean velocity. At the INEEL, defining an average linear velocity poses a significant challenge. The existence of velocity variations caused by preferential flow, flow through basalts, and caused by local and lithostratigraphically correlated hydraulic conductivity differences all contribute to nonideal breakthrough of contaminants at depth. In addition to affecting the interpretation of macroscale dispersivity, the velocity variations present differential diffusional mass transfer opportunities between advective and nonadvective domains. This effect has been incorporated to some extent in INEEL CERCLA investigations through the use of dual porosity models. However, as discussed below, parameterizing dual porosity, heterogeneous models is difficult when the other nonideal transport factors are also considered.

- **Biogeochemical Reactions.** Biogeochemical processes occurring in the vadose zone can result in spatial and temporal variation in the interphase transfer of contaminants by fixing or modifying the local geochemical environment. Important processes such as oxidation/reduction, dissolution/precipitation, and biotransformation are governed by local pH and redox conditions, both of which can be mediated by microbial activity. In the vadose zone, microbial activity is a strong function of water availability, temperature, and soil gas composition. Aerobic microbial metabolism in the vadose zone can degrade organic matter (both natural organic matter and buried organic waste), increase the partial pressure of carbon dioxide in soils gas, and decrease the partial pressure of oxygen. In areas of high microbial activity and/or near water saturation all the oxygen in the soil gas can be consumed leading to localized reducing conditions. Carbon dioxide can be transported in soil gas and react with water to form carbonic acid. In turn, carbonic acid interacts with the vadose zone mineral matrix to control the pH of vadose zone water. The extent and nature of the coupling between hydrogeological characteristics that control fluid movement and microbial activity that mediate the local geochemical environments of contaminated vadose sites at the INEEL are largely unknown.

- **Co-Contaminant Interactions.** Vadose zone contamination (e.g., SDA) is typically composed of mixtures of metals, radionuclides, and organics. The interaction of these contaminants with each other in heterogeneous vadose zone can result in either enhanced mobility or increased retention. Processes such as complexation and cosolvation cause complex subsurface chemical behavior that is inadequately understood. It is likely that waste buried at the SDA contains complexing ligands such as ethylenediaminetetraacetic acid (EDTA), citrate, and oxalate that decrease the ability of contaminants to adsorb from solution. Evaluation of complexing agents in the waste and wastewater at the INEEL has not been done. Indicators such as anions are not always measured because they are not contaminants. In addition, to metals and radionuclides, large amounts of organic solvents were also discharged into the SDA. The extent to which these solvents have modified the behavior of co-disposed radionuclides is not known.

3 STATUS OF INEEL FACILITY INVESTIGATIONS

The purpose of this section is to establish a knowledge base of key hydrogeologic features and across the Idaho National Engineering and Environmental Laboratory (INEEL) and to document contaminant inventories and time lines for remaining investigations. The historical perspective identifies contaminant inventories, and illustrates assumptions made in past investigations. It is not the intent of this section to reproduce a detailed technical summary of INEEL contaminated sites. A bibliographic summary of references is available at the INEEL Vadose Zone Science and Technology Program Office.

3.1 Radioactive Waste Management Complex

The Radioactive Waste Management Complex (RWMC) is located in the southwest portion of the INEEL and covers approximately 144 acres. An aerial view of the RWMC is provided in Figure 3-1. The facility is divided into the Subsurface Disposal Area (SDA) and the Transuranic Storage Area (TSA). The SDA covers about 88 acres, and has been used for the disposal of radioactive and hazardous waste since 1952. The TSA has been used for the aboveground storage of transuranic waste since the 1970s. Other projects at the RWMC include investigations of shallow land burial technology, waste retrieval and processing, and the interim storage and treatment of transuranic waste awaiting transport to a permanent federal repository.

From 1954 to 1970, organic and radioactive waste was received from the Rocky Flats Plant in Colorado, and was placed into unlined pits and trenches within the 5- to 20-ft thick surficial sediments of the SDA. The waste included organic solvents, low- and high-level radioactive liquids (including transuranic elements), oils, and contaminated clothing. Prior to being transported to the RWMC, solvent

Figure 3-1 Aerial view of the Radioactive Waste Management Complex.

waste was mixed with calcium silicate to create a semi-solid, grease-like compound. Over time, waste containers developed leaks allowing waste to leach into the underlying soils and sediments. Organic vapors, primarily carbon tetrachloride, have been found in the soils and sediments beneath the SDA, throughout the 580-ft-thick vadose zone as well as in the groundwater beneath the site. Rapid rainfall and snowmelt events have flooded the disposal pits and trenches at the SDA, and may have increased the infiltration through the waste.

3.1.1 Description of Lithostratigraphy

The RWMC is located in a topographically low area acting as a regional collection basin for overland flow. Local surface ponding is enhanced by surface features including mounded buried waste, road beds with well defined barrow pits, and drainages that serve to focus infiltration. As found across the entire INEEL, the subsurface is comprised of basalt-sediment sequences. The upper basalt layer at the RWMC is covered by alluvial sediments ranging in thickness from 5 to 20 ft (Anderson, 1989). Additional sedimentary interbeds are located between land surface and the aquifer. The A-B, B-C, and C-D interbeds occur at depths of roughly 30-, 110-, and 240-ft below land surface, respectively. The top elevation of these interbeds is highly variable, with the subsurface topology serving to re-focus infiltration.

Analysis of the thickness of RWMC interbeds is interesting because it indicates that they are not laterally continuous. These variogram analysis results are given in Table 3-1., with the second column presenting the number of wells used in the analysis. Variogram models, correlation length, range, and sill are given in the third through sixth columns. It is of interest to note that the A-B interbed was not found in 40 wells of 69 wells drilled deep enough to have penetrated it. Either the A-B interbed is comprised of isolated sediment occurrences, or it has a highly variable perimeter with a relatively short interconnected sediment mass. Similar observations can be made of the B-C interbed while the C-D interbed is apparently more massive.

The distribution of sediment plays an important role controlling the direction and rate of water and vapor movement. As discussed previously, the sediments play a primary role in the formation of perched water, providing two media for contaminant sampling. The sediments also provide vapor barriers, re-directing and re-routing vapor phase contaminants. As a reactive media, the sediments comprise the highest sorptive potential for reactive contaminants. Delineation of the sediments, and determination of the hydrogeochemical properties and influence of the interbeds has not been a primary focus of subsurface investigations at the RWMC.

Table 3-1. Summary of analysis of RWMC sediment thickness.

Sediment Unit	Total # of Wells	Variogram Analysis of Thickness (m)				Thickness Range (m)	# of Zero Thickness Occurrences
		Model	Range	Sill	Nugget		
Surficial sediment	94	Spherical	172	2.6	1.3	1.5-8.0	0
A-B interbed	94	Exponential	110	0.87	0.15	0.0-6.1	55
B-C interbed	91	Exponential	160	3.5	1.6	0.0-9.8	9
C-D interbed	76	Spherical	205	8.5	0.0	0.6-10.7	7

3.1.2 Contaminant Sources and Detection at Depth

Within the SDA, individual storage and disposal areas consisting of pits, trenches, above ground storage pads, and soil vaults have received waste for 30 years. The long term release rates from the waste containers, hydrologic properties, and geochemical environment of the near source backfill enclosing the pits and trenches are unknown. It is likely that the chemical and hydrologic conditions will change over time, and because of the different radiologic half-lives and degradation rates, contaminants released from the waste containers will be subject to different near-field conditions. As an example, most significant tritium releases from buried beryllium blocks probably occur within a decade of burial, when the soil disturbance caused by auguring and backfilling still affect water and vapor movement. However, ^{14}C

releases may occur hundreds of years later after the backfill material have regained natural characteristics. Again, using the beryllium as an example, the chemistry in the near field is currently affected by the presence of $MgCl_2$, applied as dust control, which increases the potential for galvanic corrosion because of the proximity of the beryllium blocks to their carbon steel containers. As a result, near-term tritium release rates will be affected by the accumulation of beryllium corrosion products.

As a result of leakage from the various burial sites, organic and radionuclide contaminants have been detected in the vadose zone. Contaminants detected at depth include carbon tetrachloride, trichlorethylene, tricloroethane, tetrachlorothylene, and chloroform in the vapor phase, ^{14}C and ^{3}H in the gas phase, and liquid phase ^{247}Am and Pu isotopes (among others). Key detection times and locations are given below in Table 3-2.

Table 3-2. Detected contaminants at the SDA

Dates	Project	Observations
1960-69	Atomic Energy Commission Subsurface Disposal Area (SDA) surficial sediment investigation.	In wells installed in the SDA surficial sediments, perched water was found to exist for several years. Strontium-90 and Cs-137 were detected in some of the water samples. Schmalz, 1972.
1971–72	U.S. Geological Survey (USGS) SDA vadose zone investigation	Trace amounts of radionuclides were detected in the B-C and C-D interbeds at 110- and 240-ft. It was not clear whether contaminants had migrated, or if the samples had been cross-contaminated during drilling. Barraclough, et. al., 1976.
1975	Energy Research and Development Administration (ERDA) SDA vadose zone investigation	Interbed samples were obtained near the two wells of the 1971-72 USGS study. While drilling, the A-B interbed was identified at a depth of 30 ft. Techniques were developed to prevent cross contamination of cores by surface soils, airborne radionuclides, and well-bore contamination. Core samples from the A-B, B-C, and C-D interbeds were analyzed for Cs-137, Ce-144, Pu-238, Pu-239/240, Co-60, Am-241, and Sr-90. The analysis was statistically negative. Burgus et. al., 1976
1976–77	EG&G Idaho SDA vadose zone investigation	Trace levels of radioactive contaminants were found in interbed soils but were not detected in duplicate analyses. Samples from immediately beneath the waste showed very limited migration with a “halo” of adsorbed transuranic elements. Humphrey et. al., 1978.
1978	EG&G Idaho SDA vadose zone investigation	A new set of samples was obtained from the 1976-1977 cores. The study concluded that most positive results observed in core samples from all studies since 1975 were probably a result of statistical variation rather than evidence of radionuclide migration. Humphrey, 1980.
1979	EG&G Idaho SDA vadose zone investigation	Three additional wells were drilled in and around the RWMC to collect sedimentary interbed core samples. Radioactive contaminants were detected in the B-C interbed. Bergalt et. al., 1992.

Table 3-2. Detected contaminants at the SDA

Dates	Project	Observations
1983–90	SDA Subsurface Investigations Program: EG&G Idaho and the USGS.	Numerous deep and shallow boreholes were drilled at the RWMC to collect sample material for evaluation of radionuclide content in the interbeds, to determine geologic and hydrologic characteristics of the sediments, and to provide monitoring sites for moisture movement in these sediments. Suction lysimeters and heat dissipation sensors were installed in deep boreholes to collect moisture data. Moisture sensing instruments (tensiometers, thermocouple psychrometers, gypsum blocks, heat dissipation sensors, and neutron loggers) were installed in shallow sediments and monitored. Because of the large volume of collected data, the RWMC Data Management System was developed and implemented to facilitate the storage, retrieval, and manipulation of the database. Ambient air, air in boreholes, and soil gases were sampled to determine the identity, location, and relative concentrations of selected chlorinated and aromatic volatile organic compounds (VOCs) first discovered in an exhaling well in 1987. Measurable concentrations of VOCs were detected in soil gases 2,000-3,400 ft from the SDA boundary. Analyses of gases collected at various depths beneath the RWMC indicated maximum gas concentrations at around 100 ft below land surface, and measurable concentrations to depths of 576 ft. Cores recovered from the interbeds conclusively indicated migration of actinides down to the B-C interbed in at least one location within the SDA. Migration to the C-D interbed at this same location was possible but was not confirmed. Laney et. al., 1988.
1992–present	Organic Contamination in the Vadose Zone	Vadose zone monitoring network consisting of wells with gas ports and extraction wells was installed. A series of feasibility and treatability tests preceded development of a full-scale remediation system. Duncan et. al., 1993. and INEEL/EXT-99-99742, 1999.
1995–present	Tritium and C-14 monitoring	Soil gas has been monitored for tritium and ^{14}C near a beryllium reactor block burial site to determine releases from the beryllium and transport pathways. Moisture monitoring and soil water sampling also are conducted at the burial site. The burial location for this beryllium block is known, while the locations of 5 others are not. Ritter et., al. 1999.

3.1.3 Historical Measurement of Moisture Conditions

Moisture conditions were monitored in the SDA surficial sediments through two neutron access tubes (NATs) during the 1985-1989 time period, and through an expanded network of 24 NATs during the 1993-1995 time period. During the earlier period, data were collected on an infrequent basis, but were collected quarterly during the 1994-1995 time period. Using this data, infiltration and drainage rates through the surficial sediments were determined to vary from 8 to 12 cm/yr. Most of the infiltration followed spring snowmelt with lesser amounts occurring after heavy spring and summer rainfall events. The time-history of snowmelt events proved to be a controlling factor, with meltwater flowing over frozen ground ponding along roadsides and local depressions as illustrated in Figure 3-2. Subsequent thawing allowed deep infiltration of the ponded water to the sediment-basalt interface.

Figure 3-2 Ponding resulting from an average snow melt over frozen ground at the RWMC-SDA.

In addition to suction lysimeters and NATs, a network of deep wells is used for monitoring perched water. Of the 90+ wells drilled to the depth of the B-C interbed, 15% have shown evidence of perched water. Three of those indicative wells were completed to allow water level monitoring and to allow the recovery of samples for contaminant analyses. The last 3 years of quarterly sampling have yielded no water samples. The same percentage of wells drilled to the C-D have shown indications of saturated conditions. Three of the indicating 11 wells were also completed to allow sample recovery and water level monitoring. Water has been recovered consistently in only the one well drilled in 1972.

Perched water levels obtained during the 1992-1994 time period were used to provide estimates of wetting front travel times. The data suggests that recharge events generally occur in response to infiltrating spring snowmelt and to heavy precipitation events. Wetting front travel times between land surface to the first basalt contact are on the order of days, and velocities down through the 110- to 240-ft depths are on the order of tens of feet per month. Although not definitively confirmed, water levels in the vadose zone suggest that infiltration from the spreading areas west of the RWMC impacts perched water under the SDA.

Continuous monitoring of the vadose zone at the RWMC is problematic. Over time, 40 lysimeters, 25 NATs, and several advanced tensiometers have been installed throughout the surficial sediments in and around the SDA. These instruments are generally not co-located, and are not sampled at the same time. Only 75% of the lysimeters are still functional, with failures attributed to loss of hydraulic contact and tubing failure. The remaining functional lysimeters have been sampled quarterly over the last 2 years, and have yielded water samples only 14 times. Lack of recovery can be attributed to either insufficient hydraulic contact or to overly dry conditions. Had either the NATs or tensiometers been co-located with the lysimeters and sampled at the same time, the hypothesis of dry conditions could be verified. In general, reliable data is collected from the NATs when they are sampled. However, because the radioactive source cannot be left in place at the INEEL, the NATs are sampled manually, and only periodically.

The spatial and temporal variability of lysimeter response, NAT observations, and perched water levels suggests that water movement beneath the SDA is complex. It appears as though preferential water movement occurs through local regions adjacent to regions experiencing dry conditions. The onset of flow seems to be related to rapid recharge events and to the proximity to local topographic lows. An example is presented by Well 77-2, which prior to 1992 consistently indicated perched water at depth. However, following the addition of soil to the surface of the adjacent disposal pit in the 1980's, the well does not accumulate standing water. Presumably, formerly infiltrating water has been diverted and is now running off the sloped surface of the pit to infiltrate elsewhere.

3.1.4 Simulation

Water and contaminant movement under the RWMC have been the foci of numerous modeling studies. Initially based on pure hypotheses and assumption, as data became available, the modeling studies shifted to include more site-specific information. The simulations have, for the most part, been based on the ideal advection, dispersion, transport, and transformation equivalent porous media model discussed in Section 2.4. More recent investigations have incorporated a dual-porosity, dual-permeability media description for the fractured basalts. In all cases, the geochemical model has been extremely simplistic, and based on the linear instantaneous adsorption premises. Simulations conducted for RWMC programatic needs have included the flow and transport of contaminants transported as dilute constituent in the liquid water phase, and vapor phase organic contaminants.

Success in emulating observed behavior has been highest for volatile organic carbon (VOCs) contaminants. In addition to being able to calibrate the model to observed values, predictive simulations have been partially validated by subsequent sampling. Confidence in the VOC simulation results has allowed their use in directing and revising the subsurface VVE remediation system. The dissolved-phase transport simulation studies have been less successful, primarily because of inadequate field observations of water movement and dissolved-phase contaminant movement in the vadose zone. However, this inability to conclusively demonstrate model calibration has led to expanded characterization activities that are in progress at the RWMC focused on improving the vadose zone monitoring network.

3.1.5 Remaining Analyses

- CERCLA: Comprehensive RI for the SDA
- CERCLA: PIT 9
- CERCLA: Comprehensive FS for the SDA
- CERCLA: ROD recommendations
- RCRA: Waste Management Program

3.1.6 Quantifying Uncertainty: Remaining Issues and Unanswered Questions

There is a significant inventory of metals, organics, and radionuclides at the RWMC. Much of the contaminant inventory is contained in pits, trenches, and otherwise buried. Release, transport, and transformation mechanisms are uncertain. Actual contaminant inventories are unknown, and predictions have been based on conjecture. Waste Management and Environmental Management programs have played a large role in collecting and analyzing the information available to date. These programs in addition to the RCRA and HLW activities will make decisions on how to manage contaminants left in the environment. The decision basis will be primarily predicted contaminant behavior. To date, inherent sources of uncertainty have plagued our predictive ability. As a first step in quantifying and reducing the uncertainty, the following outstanding issues have been identified:

- Data used to infer lithostratigraphy is based on interpretation of core material extracted while drilling. Based on the available information, 50% of the wells in the shallowest interbed, and 10% of the wells in the two deep interbeds indicate that the sediments are not laterally continuous. This does not imply that 90% of the subsurface is covered areally. In fact, the areal continuity of sedimentary material presents a significant potential contributor to prediction uncertainty.

  Variability in composition of the material comprising the interbeds is known to occur. However, variable hydrogeochemical properties of the sediment material have not been incorporated into predictive transport models. Based on the few analyses performed, the material is comprised of clays, sands, and gravels. The spatial composition distributions are unknown as are the hydraulic and geochemical characteristics of the materials themselves. Additionally, the sorptive processes occurring in the interbeds have not been analyzed. The propensity for colloidal formation, parameters for adsorption isotherms, and adsorption mechanisms are unevaluated.

As a hydraulic and sorptive barrier, the sediments have been factored into many of the analyses performed thus far. This has been done based on assumptions of continuity, and based on a few isolated analyses of hydraulic characteristics. Quantifying prediction uncertainty with respect to these assumptions would require verification of continuity in regions intercepting key contaminant sources, and obtaining hydrogeochemical parameters used to describe flow, transport, and transformation processes.

- Data obtained for the purposes of elucidating water and vapor redistribution in the subsurface are collected infrequently and unreliably. This has implications on the long-term predictability of contaminant behavior. It appears as though transient infiltration events have a significant affect on the redistribution of water. Transient events are not recorded consistently or accurately. As a result, the formation of perched water, local lateral fluid migration, outflow from the spreading areas, and rapid subvertical fluid migration go undetected. The influence of transient infiltration on long-term transport predictions is unknown. Simulations have not incorporated these effects, nor have flooding events been evaluated. Similarly, the transient influence of barometric pressure and temperature effects on vapor transport are unknown and, as yet, unevaluated. In order to quantify the relative impact on overall prediction uncertainty, the cost-effective collection of data is necessary. New analysis methodology and data collection technology (including instrumentation, installation, and information retrieval) are needed.

- Chemical sampling of aquifer water and sedimentary interbeds provides an indication that a portion of contaminants originating near the surface are being transported to great depths. It is unknown whether these positive detections are indicative of transport through fast or preferential flow paths or of facilitated transport via colloids. Chemical sampling in the vadose zone is problematic given current technology, and occurs at best periodically and at isolated points in space. Simulations of contaminant transport have not been able to accurately predict observed behavior.

  In addition to transport and transformation issues, the inventory of constituents placed in the pits, trenches, and other burial locations is highly speculative. Container failure rates and transport mechanisms away from the depositories are not well determined. The hydrogeochemical environment surrounding the depositories is likely different from the natural environment through which the constituents ultimately pass. These unknowns are contributors to the overall prediction uncertainty.

- Physical processes contributing to fluid (water and air) movement are not well understood. Simulations of the vapor vacuum extraction process do not predict observed rebound. Actinides arrive at depth decades earlier than predicted. The processes contributing to fluid and contaminant migration and transformation have not been validated. Predictive models are calibrated to field data using long-term average conditions as opposed to operating in a predictive mode, minimizing the utility of available data.

At a first glance, it would seem as though increased monitoring would enable these issues to be addressed. However, the technology and analyses methodology are not currently available. The experimental protocol necessary to parameterize and validate process models is undetermined. As a result, it is not clear whether the process models currently assumed describe transport, or if new process models are necessary. In order to meet the long-term environmental management needs, addressing these issues is necessary.

3.2 Idaho Nuclear Technology and Engineering Center

The Idaho Nuclear Technology and Engineering Center (INTEC) lies on 210 acres in the southwestern portion of the INEEL, just north of Central Facilities Area (CFA). INTEC houses facilities for reprocessing government defense and research spent nuclear fuel. Facilities at INTEC include spent fuel storage and reprocessing areas, a waste solidification by calcination facility, and related waste storage bins, remote analytical laboratories, and a coal-fired steam generating plant. An aerial view of INTEC is provided in Figure 3-3.

Construction of INTEC, formerly known as the Idaho Chemical Processing Plant, began in 1950, fuel storage operations began in 1952 and the recovery of unused fissile uranium by reprocessing spent nuclear fuel (fuel recovery) for defense projects was conducted from 1953 to 1994. During the fuel dissolution and extraction process, highly radioactive (i.e., containing thousands of curies of activity) liquid waste (HLW) was created and was stored in a series of underground stainless steel tanks enclosed in underground concrete vaults (i.e., the Tank Farm).

The liquid waste in the Tank Farm was transferred to the Waste Calcining Facility (CPP-633) for calcination, converting the liquid into a more stable solid form during the 1963-1981 time period, and then to the New Waste Calcining Facility (CPP-659) during the 1981-2000 time period. The calcined solids are stored in six stainless steel binsets, the Calcined Solids Storage Facilities.

Other processes at INTEC have created sodium-bearing liquid waste which is also stored at the Tank Farm. To date, the tanks have not leaked. However, subsurface piping, valve boxes, and transfer lines

Figure 3-3 Aerial view of the Idaho Nuclear Technology and Engineering Center.

carrying the radioactive liquids have leaked, resulting in contaminated surficial sediments and soils at several INTEC locations. In 1992, the DOE announced that fuel reprocessing at the INTEC would be phased out. The current mission for the INTEC is the management and interim storage of spent nuclear fuel and treatment and interim storage of radioactive waste awaiting future disposal.

Essentially all of the high-level waste at the INEEL resulted from INTEC operations (Palmer et al., 1998). All of the high-level waste historically was stored at the INTEC Tank Farm. According to the OU 3-13 ROD, contamination from releases within the Tank Farm boundary account for approximately 95% of the known contaminant inventory, in total curies of radioactive material, at the INTEC (DOE-ID 1999, Section 4).

The fuel recovery process also generated low-level liquid waste which was discharged into a deep injection well during the 1952 to 1989 time period. This practice created a groundwater plume containing a suite of radionuclides. Of the entire inventory, ^{3}H, ^{90}Sr, and ^{129}I concentration currently exceed the MCL. At least twice during injection operations, the casing in the disposal well collapsed, discharging the radioactive liquids into the vadose zone above the aquifer. In addition, percolation ponds, leaky (non-radioactive bearing) storage tanks, pipes, and inadvertent spills have contaminated surface soils and the underlying vadose zone.

3.2.1 Description of Lithostratigraphy

Based on observations of 53 well logs, there are 14 different sedimentary units in the vadose zone underlying the INTEC as described by Anderson (1991), and summarized in Table 3-3.. These sediment units (Column 1) are relatively thin, closely grouped in depth, and difficult to correlate between wells. As denoted in Column 3, the sediment units are grouped by primary basalt flow, hence the naming convention given in Column 1. In contrast to the sediment occurrences found at the RWMC, sediment groups at INTEC (Column 3) were created during quiescent periods of a single basalt flow consisting of several flow events occurring intermittently in time. During quiescent periods, sediments infilled the depressions, and were subsequently overlain by basalt. This sequence differs significantly from that observed at the RWMC, where apparently the basalt flows were much more massive, with relatively long sediment accumulation times between flows.

Table 3-3. Stratigraphic units appearing in the INTEC vadose zone.

Stratigraphic Units in the ICPP Vadose Zone	Average Depth to the top of Sedimentary Unit	Primary Sedimentary Group
Alluvium	10	Alluvium
B BC	35	C CD
BC C	95	
C CD	110	
CD D	130	
D DE2	140	D DE2
DE2 DE3	160	
DE3 DE3-4E	195	DE3-4E DE4
DE3-4E DE4	225	
DE4 DE5	300	
DE5 DE6	365	DE5 DE6
DE6 DE7	390	
DE7 DE8	410	
DE8 E	460	

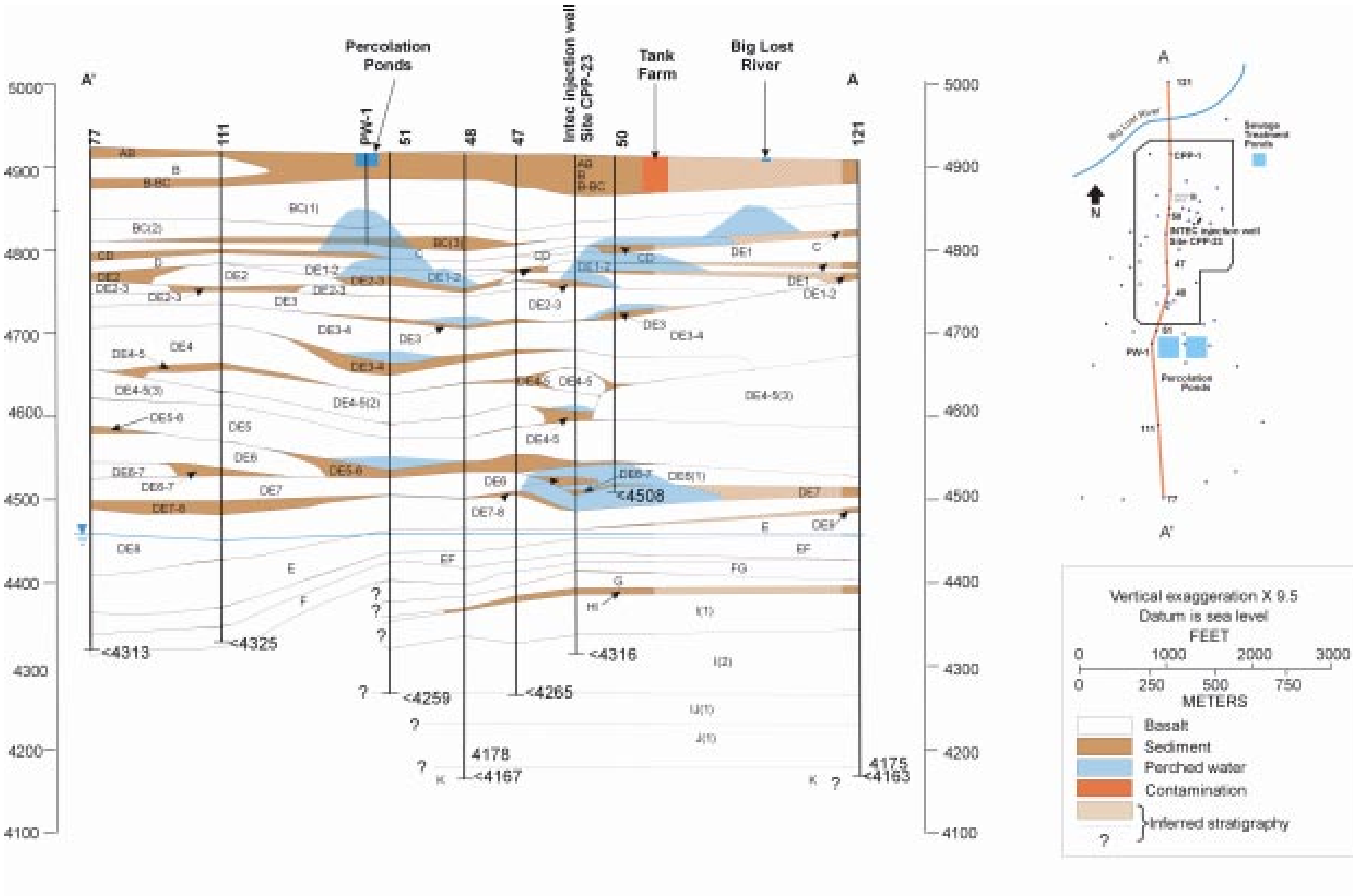

Figure 3-4 Planar view of sediment and perched water distribution at INTEC.

3.2.2 Contaminant Sources and Detection at Depth

Potential contaminants of concern (PCOCs) were identified at INTEC based on aquifer, perched water, and soil samples. PCOCs are contaminants with concentrations approaching the MCL, 10^{-6} risk for carcinogens, or hazard quotient (HQ) of one for non-carcinogens.

- Aquifer samples indicate that 31 non-radionuclides have been detected, with As, Be, Cd, Pb, NO_3, N, and Th identified as PCOCs. Additionally, 25 radionuclides have been detected, with ^{241}Am, ^{3}H, ^{129}I, ^{237}Np, ^{90}Sr, ^{99}Tc, ^{234}U, and ^{238}U approaching environmental limits.

- Perched water data indicates that in addition to the aquifer PCOC list, antimony, chloride, and Fe are non-radiologic PCOCs. Radionuclides in the perched water approaching unacceptable limits are the same as those identified through aquifer samples. Peak perched water concentrations for H-3 (6.3×10^4 pCi/L) and Sr-90 (2×10^5 pCi/L) both exceeded their acceptable environmental concentrations (671, and 0.87 pCi/L, respectively) by orders of magnitude.

- Soil samples have been used to identify 41 COPCs, with Aroclor-1260, Cr, Hg, ^{60}Co, ^{137}Cs, and ^{325}U added to the existing list of PCOCs derived through water samples.

Sources of these contaminants include known and estimated volumes of inadvertent liquid releases, the disposal of process waste water, and unknown origins of other soil contaminants. A short list follows:

- Contaminants from known or estimated liquid releases include the known leaks in the tank farm corresponding to (a) discharges from CPP-28, which are also assumed to cause the Site 79 contamination, (b) the 1986 tank farm Release, and (c) discharges from CPP-31. Known releases outside the tank farm include (a) CPP-02, which is a former french drain west of CPP-603, and (b) CPP-80, which is also known as the CPP-601 vent tunnel drain leak.

  The release volume for the CPP-28/79 discharge has been estimated based on computing the maximum throughput of liquid through a 1/8” diameter transfer line hole, a total discharge volume, and a given line pressure. The duration was assumed to begin at the time of construction in 1956 and to have lasted through the discovery date in 10/74. During this time period, the process waste stream at INTEC has spanned a considerable range of possibilities. The release volumes and duration dates for the CPP-31, 1986, CPP-02, and CPP-80 discharges are known and documented. However, discharged liquid originated from several fuel reprocessing campaigns.

  The released activity for each of the CP-28/79 and 1986 discharges are unknown, but were estimated based on approximate volumes and representative process chemistry for the time frame. The total activity released in the CPP-31, CPP-02, and CPP-80 discharges are documented. In both cases, the specific composition of the waste streams are not known, but were reconstructed based on radionuclide ratios. In all of these discharges, the actual released inventory is estimated, and presents an enormous source of uncertainty.

- Waste or process water that is currently disposed of in the sewage treatment system or the percolation ponds and process water that was disposed of directly in the aquifer via the CPP injection well.

- Alluvium contaminant inventories estimated based on a few soil concentrations and approximate contaminated soil volumes.

The perched water contamination is a result of near-surface contaminant releases, and the aquifer contaminants are a combined result of direct injection and transport from the vadose zone. The vadose zone contributions include transport from the surface in addition to releases into the vadose zone caused by injection well casing failures. Table 3-4. (Rodriguez, et. al., 1997) summarizes the total amount of mass or activity for each of the COPCs, from each of these sources. The tank farm known releases provide the vast majority of the ^{241}Am, ^{137}Cs, ^{129}I, Total Pu, ^{90}Sr, and ^{99}Tc, with the ^{237}Np and ^{3}H having been injected directly into the aquifer. Arsenic, mercury, and ^{60}Co is primarily contained in the contaminated soils. Compared to TRA sources, the INTEC chromium and ^{3}H sources much smaller. Overall, the tank farm releases account for the majority of the environmental contamination.

Table 3-4. Summary of the INTEC contamination sources.

COPCs	Units	Known Release		Service Waste[1]		Soils	TRA	Total
		Tank Farm	Other	Injection Well	Sewage Waste Ponds			
Arsenic	kg	0	0	0	0	4.57E+02	0	4.57E+02
Cr	kg	1.60E+01	0	0	0	1.20E+02	21000	2.17E+04
Mercury	kg	2.81E+01	0	4.00E+02	0	5.96E+02	0	1.02E+03
^{241}Am	Ci	1.10E+02	0	1.23E-01	0	9.05E-01	0	1.11E+02
^{60}Co	Ci	6.84E+01	0	1.24E+00	1.12E-02	1.06E+02	0	1.76E+02
^{147}Cs	Ci	2.68E+04	309	2.58E+01	5.34E-01	2.68E+03	0	2.98E+04
^{3}H	Ci	1.85E+01	378	2.01E+04	9.99E+02	0	8900	3.04E+04
^{129}I	Ci	7.05E-03	0	1.39E+00	8.20E-02	3.89E-02	0	1.52E+00
^{237}Np	Ci	2.16E-01	0	1.07E+00	0	1.33E-01	0	1.42E+00
Total Pu	Ci	1.18E+03	0	8.22E-01	6.92E-02	1.02E+01	0	1.19E+03
^{90}Sr	Ci	1.80E+04	309	2.43E+01	2.95E-01	1.11E+03	0	1.94E+04
^{99}Tc	Ci	2.58E+00	0	0	0	1.06E-01	0	2.69E+00
Total U	Ci	7.47E-01	0	2.69E-01	7.01E-02	9.40E-01	0	2.03E+00

1. Time period over which the estimates are available (from RWMIS) varies by contaminant.

3.2.3 Water Sources and Moisture Conditions

Contaminant migration is facilitated by underflow from the Big Lost River flowing across the North end of the INTEC, an addition to surface recharge from precipitation and various anthropogenic sources. Losses from the Big Lost River and process water discharges account for the majority of infiltration. Table 3-5. (Rodriguez et. al., 1997) summarizes the annual volumetric rate of recharge within the INTEC. Water sources include precipitation, fire-water system leaks, irrigation, steam injection condensate, infiltration from the basins at CPP-603, infiltration from the sewage treatment ponds, and the water disposed of at the percolation ponds (listed in Column 1). Column 2 lists the annual volumetric rate of water infiltrating into the northern portion of the ICPP in gal/yr. Source rates for the entire facility are given in Column 3. The total annual influx 712 Mgal, excluding precipitation and the Big Lost River contributions. Although not indicated in this table, the recharge occurs as a combination of point, line, and areal sources.

Table 3-5. Estimated volume of water recharging the perched water bodies at INTEC

Source	Recharge Volume in the Northern region (gal/yr)	Total Recharge Volume Across the Facility (gal/yr)
Precipitation infiltration (180 acres, 4.1cm/yr)	3,800,000 (northern most 87 of 180 acres)	8,000,000
Water system leaks	3,980,000	3,980,000
Landscape irrigation	1,568,000	1,568,000
Steam Condensate	1,300,000	1,700,000
CPP-603 Basins	None	49,275
Sewage treatment ponds	15,000,000	15,000,000
Service waste water (perc ponds)	None	690,000,000
Big Lost River (9820 Acre ft/yr) (between the INEEL Diversion and Lincoln Blvd.)	3,200,000,000	
Subtotal (excludes precipitation and the Big Lost River)	25,648,000	712,297,275

Estimate based on past leaks and irrigation practices. Actual loss from piping leaks is unknown.
Although shown as an average value, the Big Lost River intermittently flows to the northwest of the INTEC facility. In the late 1980s and early 1990s, the Big Lost rarely flowed, but beginning in 1996, flow in the river has been nearly continuous.

Perched water regions under the INTEC are maintained by the constant influx of anthropogenic water, transient recharge from the Big Lost River, and natural precipitation. The perched water occurs at roughly 110 and 380 ft below ground surface. However, the perched zones are not laterally continuous as indicated by 46 monitoring ports completed in 36 wells throughout the vadose zone. Only 58% of the wells show evidence of perched water, and 41% are dry. These monitoring wells are primarily clustered in the northern and southern regions of INTEC, with very few wells between the two regions. Two different interpretations of the shallow (110 to 150-ft depth) data suggest that (1) two distinct perched water bodies exist, one underlying the northern part, and one underlying the southern part of INTEC), and (2) that numerous small discontinuous perched water bodies are present. The former interpretation is consistent with a laterally continuous sediment or dense basalt region allowing accumulation, while the latter is consistent with the interpretation of isolated sediment packages. The interpretation of sediments used in the OU 3-13 RI/BRA analysis was based on sediment groups rather than sediment units, resulting in laterally continuous effective interbeds. Given the available surface recharge, the sedimentary interbeds were predicted to be relatively wet (greater than 90% saturated) everywhere with some locations achieving saturated conditions. The alternate hypothesis was not evaluated because of the computational and parameterization requirements.

There are no wells located directly beneath either the Tank Farm or other primary contaminated surficial sediments. Additionally, there are no actively monitored NATs, advanced tensiometers, or lysimeters in the vadose zone at INTEC.

3.2.4 Simulation

Simulation of transport beneath the INTEC facility was done as part of the INTEC remedial investigation/feasibility study (comprehensive OU 3-13 RI/FS) (Rodriguez et al. 1997; DOE-ID 1997). The following discussion is derived from, and the references are contained in, that document. The TETRAD code was used to evaluate contaminant transport through the subsurface pathway, and the simulation results were accepted by the U.S. Department of Energy, Idaho Operations Office (DOE-ID), EPA, and the Idaho Department of Health and Welfare (IDHW). Through that effort, a substantial effort was expended to create a working model of the INTEC to directly support the OU 3-14 RI/BRA, the OU 3-13 remedial action evaluations, and the INTEC HLW-EIS. Based on model predictions, the remedial options were predicted to be extremely costly, given the level of underlying uncertainty. Realizing that limited data were available for the Tank Farm area, and that predicted costs and technical challenges were prohibitive, the decision was made to reevaluate the contaminant sources and groundwater pathway affected by the Tank Farm area. The primary assumptions, incorporated data, observations, and simulation difficulties underlying that decision are discussed below.

The paradigm employed for the OU 3-13 RI/BRA simulations was based on assumptions of equivalent 3-dimensional porous media, effective-latterally continuous interbeds, steady-state recharge from all water sources, and conventional advection-dispersion- and decay processes. Key assumptions and issues are reviewed below.

- A three-dimensional conceptual model was used to allow spatially variable surface recharge sources to be incorporated. Previous attempts to reproduce perched water conditions through the use of 1- and 2-dimensional simulations had failed.

- The vadose zone was represented as an equivalent porous media comprised of an alluvium, upper- middle- and lower-interbeds, and interlayered basalts. As discussed above, the lithostratigraphy is very complex, consisting of multiple sediment units within each sediment group. The use of lumped, or effective, interbeds and the contribution to uncertainty were not evaluated.

- Hydraulic characteristics for sediments and basalts originated from several sources. In many cases, the perched zones under the INTEC had been evaluated for saturated hydraulic conductivity. However, unsaturated characteristics were unavailable, and were assumed to correspond to data collected at the RWMC. Characteristic parameters for the INTEC basalts were also unavailable, and were derived from the results of the LSIT, also obtained near the RWMC. Given the differences in lithostratigraphy between the RWMC and INTEC, it is not clear that the sediment and basalt characteristics should be similar.

- Percolation pond discharges were known with a fair degree of accuracy. However, other water losses were estimated as were their locations. Steam injection rates are not monitored, nor were their temperature effects incorporated. Losses along the Big Lost River were assumed to be steady-state, and were represented by an annual average. Flow in the Big Lost River is highly variable, with no recharge occurring for years, and high flows occurring over months. Annual average precipitation infiltration was assigned based on previous RWMC analyses. Although both areas are comprised of a combination of backfill material and natural sediments, the surface topology is quite different. Much of the INTEC surface is relatively flat and is either paved or covered with packed sand/gravel, while the surface topology at the RWMC is more variable and covered with a higher percentage of native material. Neglecting transient nature of infiltration from all of the water sources presents another potential source of uncertainty.

- Average observations of water levels were used to match predicted perched water formation as a point of calibration. Calibration to the perched water levels was achieved after local grid refinement, inclusion of all water sources, increasing the infiltration rates, and reducing the sediment permeability. This suggests that the alluvium at INTEC is more permissive. Reducing the permeability of the unsaturated sediments to achieve a match suggests that the actual interlayered basalt-sediment sequence presents a capillary fringe effect that is not incorporated by the effective interbed approach. Given insufficient data, the relative contributions to uncertainty cannot be evaluated.

- Observed chloride concentration in the vicinity of the percolation ponds were used to calibrate the transport model. The breakthrough or arrival of chloride discharged as part of the process stream at all wells was not available. As a result, only part of the arrival and long-term concentrations were available for comparison to model predictions. Data from more distant wells were not available for calibration. Given the lack of monitoring data between the southern and northern regions of the INTEC, it is not clear that the resultant porosity is representative of conditions under the Tank Farm.

- Dispersivity assigned to the transport simulations was derived from simulation results of the LSIT experiment. As discussed above, dispersion is a mechanism to account for velocities deviating from ideal behavior. Given the differences in lithostratigraphy between the RWMC and INTEC facilities and differences in the way it was incorporated into the predictive approach, it is not clear that the dispersion values should be the same because the *ideal model* was not. Additional dispersion is introduced through numerical gridding. It is not clear that the combined influence adequately represents reality.

- Ideal sorption behavior was assumed. Parameters for sorption coefficients (Kds) were, for the most part, obtained from literature values. Not only is it unclear that linear-instantaneous adsorption is a valid way of representing processes ongoing in fractured media, it is unclear that the specific parameters used are representative of the soils and basalts at the INTEC facility. It was assumed that contaminants would not adsorb to the Tank Farm alluvium based on the very low pH (-1 to 1) of tank liquids. The sorption coefficients for the basalt units were 1/25th those of the sediment material. This assumes that the adsorption to fracture infill, fracture coatings, and basalt material is relative to the sediment material.

The OU 3-13 RI/BRA (Rodriguez et al. 1997) vadose zone model predicted easily detectable concentrations (greater than 100 pCi/L) of plutonium and high concentrations of Sr-90 in the upper interbed (approximately 130 ft bgs) by the 1990s. These concentrations were predicted to exist over much of the Tank Farm area. However, plutonium has not been measured in the limited number of analyses of perched water from the upper interbeds and although large Sr-90 concentrations have been found, they are in relatively isolated portions of the INTEC compared with the model predictions. These discrepancies are indicative of the uncertainty discussed above.

3.2.5 Remaining Analyses

- The OU 3-14 ROD has recommended placing a second cover over the Tank Farm. This may prohibit collection of any data in that area, and will prohibit collection of data representative of past infiltration. Emplacement of the new cover may enhance flow under the tanks as a result of temperature gradients, condensation, focused recharge, and reduced evapotranspiration. The effect on the subsurface transport of contaminants already in the vadose zone have not been evaluated. Additionally, diverting precipitation, and the potential to result in focused recharge in areas adjacent to the tank farm has not been evaluated.

- The OU 3-13 ROD has recommended development of the INEEL CERCLA Disposal Facility, or ICDF. Determining the waste acceptance criteria (WAC) for the facility will require evaluation of subsurface contaminant transport and ultimate groundwater impact. The facility will require monitoring to ensure permanent containment, and will ultimately require a cover to prohibit long-term infiltration.

- The INTEC High Level Waste- Environmental Impact Statement (HLW-EIS) is analyzing facility dispensation alternatives including how to handle the High Level Waste liquids in the INTEC Tanks, the calcine in the binsets, and other contaminated facilities.

- Additional operations will require licenses as they occur which will probably require an EIS.

- Spent Nuclear Fuel Program activities will have to be assessed.

3.2.6 Quantifying Uncertainty: Remaining Issues and Unanswered Questions

In addition to the sources of uncertainty discussed above, remaining issues include:

- Assessing the subsurface influence of Big Lost River infiltration. Volumetrically, losses along the Big Lost River are significant. However, the lateral extent to which the infiltration contributes to perched water is unknown. If flow in the river stops for the time period during which INTEC and Tank Farm investigations occur, the impact of flow in the river on perched water formation and recharge will be difficult to access. A long-term program of characterization monitoring is required to quantify this ephemeral water source.

- Sampling sites have been established by feasibility and are limited to the few locations where underground structures, subsurface piping and electrical conduits are known not to exist. As a result, accurate inventories of contaminated soils and an evaluation of the soil chemical environment are not available. The assumption that contaminated tank farm soils are the source of perched water contamination has not been validated through exhaustive field characterization and monitoring activities.

  Current water, contaminant, and soil samples are based on opportunity rather than being technically justified. It is not clear how to obtain subsurface water and contaminant samples that are statistically representative of subsurface conditions. As a result, the possibility of biased soil samples exists, and water sample locations have not been optimized. Expanding the soil moisture, contaminant, and perched water sampling network; delineation of contaminated soil extent and inventory, and detection of as-yet unknown contaminant sources all pose significant technical challenges.

- The effect of drilling, sampling, and steam discharges on subsurface water distributions are unknown, as are the effects of barometric pressure changes. Local changes in temperature, vibration, and pressure may affect water and contaminant redistribution.

- Perched water level data collected from wells around the tank farm suggest that changes in barometric pressure have a pronounced effect. This limits the usefulness of the small changes in water level data in delineating the individual contributors to the perched water. Removing barometric pressure signals from the water level data is required to accomplish water source distinction. Given the importance to sampling, understanding the mechanisms determining the formation of perched water and the transport to them from the surface is paramount.

In general, it is not clear how to obtain field measurements from the limited sampling opportunities that are representative of contaminant distributions. Obtaining representative chemical concentrations in the highly variable material underlying the Tank Farm is, at best, problematic. Predictive simulation allowing testing of process-discrete hypotheses and uncertainty analyses presents a tremendous computational challenge, and obtaining data of sufficient quality and quantity to make scientifically based management decisions provides a significant technical challenge.

3.3 Central Facilities Area

The Central Facilities Area (CFA) is located in the south-central portion of the INEEL, approximately 93 km (50 mi) west of Idaho Falls, Idaho (see Figure 3-5). The original facilities at the CFA were built in the 1940s to house U.S. Navy gunnery range personnel, and have been modified over the years to fit the changing needs and now provides craft, office, service, and laboratory space.

Figure 3-5 Aerial view of the Central Facilities Area.

3.3.1 Description of Lithostratigraphy

The lithostratigraphy beneath the Central Facilities Area has been evaluated as part of a RI/FS study (INEL-94/0124), and has elements similar to those found at RWMC and INTEC. Drilling and core analysis of eight boreholes for the RI/FS study indicated that 4 sedimentary interbeds are relatively continuous (i.e., are correlated between boreholes spaced several thousand feet apart), however there are many additional interbeds that are thin and discontinuous, confounding subsurface correlations between boreholes. This basalt/sediment structural heterogeneity is further compounded by spatial variability within the interbeds. Physical properties measurements (e.g., CEC, carbon content, particle size distribution) of the interbed materials (INEL-94/0124, Table 3-3) suggest variability in physical and chemical properties of samples collected near each other.

3.3.2 Contaminant Sources and Detection

The CFA vadose zone contamination issues concern the leaching (1) of landfill waste from three landfills, (2) of mercury, nitrate, and other metals from a dry pond, and (3) of nitrate from the former sewage plant drainfield. The landfill covers present infiltration and long-term performance concerns, soils from the dry pond have been removed, and an investigation is in progress to assess the extent of nitrate contamination.

The CFA Landfills I, II, and III are located approximately 0.8 km north of CFA. The predominant waste types consist of construction, office, and cafeteria waste. Lesser amounts of potentially hazardous waste, including waste oil, solvents, chemicals, and paint were also disposed of in the landfills. The Record of Decision for all three landfills requires vadose zone monitoring, and monitoring of water infiltration into the soil covers placed over the landfills (DOE-ID 1995).

To comply, soil-gas monitoring was conducted at the CFA landfills to evaluate production and migration of contaminated soil gases. Soil gas samples were collected and analyzed from approximately 11 to 107 ft below ground surface. Nine contaminants were detected including four constituents that are typically contained in solvents and degreasers, two that are degradation products of solvents, two that are freons, and one that is generated by waste degradation. Soil-gas contaminants have reached the deepest soil gas sampling ports at depths of 94 to 107.5 ft. The organic vapors, primarily chlorinated solvents, are probably migrating through preferential vertical and horizontal flow paths in the fractured basalt. The total depth the contaminants have reached is unknown, but groundwater does not appear to be impacted at the present time.

The CFA Experimental Calcining Waste Pond (CFA-04) consists of a shallow pond formerly used for the disposal of waste from operations at CFA-674. Three waste generation processes have discharged contaminants to the waste pond including:

- The calcine development work conducted in CFA-674. From 1953-1965 mercury-contaminated waste was generated and discharged to the pond.

- Laboratory activities conducted in the Chemical Engineering Laboratory. From 1953 to 1969, liquid and solid waste were discharged to the pond. These chemicals may have included simulated calcine, sodium nitrate, nitric acid, tributyl phosphate, uranyl nitrate, high grade kerosene, aluminum nitrate, hydrochloric and chromic acid, di-chromate solutions, terphenyls, heating oil, zirconium, hydrofluoric acid, trichlorethylene, and acetone.

- Construction activities across the INEEL. For an unknown period of time, construction generated bulk waste including asbestos-containing roofing material have been placed in the ponds.

Sampling activities at the CFA-04 dry pond indicated that the surface and subsurface soil are contaminated with low levels of arsenic, Cs-137, U-234, U-235, and U-238 above background concentrations. Mercury was found at concentrations up to 650 mg/kg. A time critical removal action was initiated in 1994 to remove contaminated soils from the pond. Approximately 3,066 yd^3 of soils were removed from the ground containing mercury, calcine, and a small amount of asbestos. Nonfriable asbestos and roofing material were not disturbed and remained buried in the pond berm.

During the process of renewing the Wastewater Land Application Permit (WLAP) for the sewage treatment facility at the CFA and completing the Operable Unit (OU) 4-12 Post-Record of Decision monitoring program, nitrate concentrations in the CFA-MON-A-002 and CFA-MON-A-003 wells exceeded the EPA MCL of 10 mg/L. Concerns about the potential source of elevated nitrate in the CFA monitoring wells were subsequently raised. An evaluation of possible sources indicates that the former sewage treatment plant (CFA-08) was the most probable source.

3.3.3 Historical Measurement of Moisture Conditions

Moisture conditions have been monitored at the CFA landfills to determine whether precipitation has infiltrated through the soil covers, has percolated through the buried waste. The primary concern is whether infiltration has been enhanced by rip-rap covered soil barriers, increasing the rate at which contaminants would migrate. As at the RWMC, time-domain reflectrometry (TDR) and neutron probe data indicate that most of the recharge occurs in April and May, coinciding with the spring snowmelt. Neutron probe data also suggest that precipitation recharge occurs sporadically (LMITCO 1999). Neither the TDR or NATs are monitored continuously.

3.3.4 Simulation

Relative to the RWMC and INTEC evaluations, the contaminant sources at CFA have not warranted the development and implementation of complex subsurface transport simulations. There have only been two CFA studies conducted. The first study used the hydrologic evaluation of landfill performance (HELP) model to evaluate infiltration rates through the CFA landfills (Sorenson 1996), primarily to assist in cover design.

The second study attempted to determine the most probable source location for nitrate found in the CFA facility monitoring wells (Bukowski et al. 1999). GWSCREEN, a one-dimensional semi-analytic model, was used to evaluate the propensity for the nitrate to have originated in the new sewage treatment plant (STP), the old sewage treatment plant (CFA-08), and the dry pond (CFA-04). Based on soil concentrations at CFA-04 and GWSCREEN results, CFA-04 was determined to be the most likely source of nitrate detected in the groundwater well CFA-MON-A-002. However, nitrogen isotope data indicated that the former sewage treatment drainfield was the actual nitrate source.

This latter analysis suggests that simple models can lead to erroneous results, and that a large number of uncertainties are introduced when all of the processes and parameters are not included. Key features not included in the GWSCREEN approach are associated with source concentrations, infiltration rates, stratigraphy influences such as sloping interbeds, local groundwater flow directions, and vadose zone transport parameters.

3.3.5 Remaining Analyses

- CERCLA: 5 year review of landfill performance

3.3.6 Quantifying Uncertainty: Remaining Issues and Unanswered Questions

Evaluation of the data from the two-year intensive monitoring program at the CFA landfills identified the following deficiencies (LMITCO 1999):

- Time-domain reflectrometry and NAT monitoring have not been conducted sufficiently over time to determine the effectiveness of the landfill cover designs. The frequency of NAT monitoring in late winter and early spring needs to be increased to ensure that any infiltration event is captured. The timing of the NAT measurements could be based on the TDR data.

- A defensible means for calibrating TDR and NAT data to soil moisture contents has not been developed.

- The ability to monitor the infiltration under the landfill covers has not been developed. The current TDR system only monitors to a depth of 2 ft. Time-domain reflectrometry probes should be installed below the E-T depth in Landfill I, II, and III. The infiltration estimates obtained from this automated TDR system need to be compared with infiltration rate estimates from the neutron probe measurements to determine the most effective means of monitoring infiltration.

- A means has not been developed to model soil gas data to determine an action level concentration that could lead to aquifer contamination approaching an MCL. The modeling would enable the establishment of action levels to evaluate whether groundwater will be impacted and whether some preventive action is required.

- A cost-effective means has not been developed to determine representative field soil moisture and unsaturated hydraulic conductivity.

- A comparison has not been made of TDR and NAT data to determine the most effective means of monitoring infiltration on a data quality and cost basis.

- Measurements have not been made with adequate frequency of soil moisture during spring thaw events.
- The precision of TDR measurements is not adequate.
- Neutron probe calibration in waste material is inadequate or uncertain.

3.4 Test Reactor Area

The Test Reactor Area (TRA) located in the southwestern portion of the INEEL contains high neutron flux test reactors that have been used to conduct engineering and materials tests since 1952. Water has been discharged into the sanitary sewage and process waste streams since the facility was built in 1952. The discharge locations for these waste streams has varied over the years, and includes the sewage lagoons, a retention basin, a warm waste pond, a chemical waste pond, a cold waste pond, Well USGS-53, and a disposal well. The primary contaminants of concern at the TRA are tritium and chromium. An aerial view of the TRA is provided in Figure 3-6.

Figure 3-6 Aerial view of the Test Reactor Area.

As at the INTEC, process waters and proximity to the Big Lost River contribute to perched water under the facility. The CERCLA environmental assessment of the contaminated perched water system (Dames & Moore 1992) concluded that no adverse impacts would occur from contaminants in the perched water if the surface sources of recharge were removed, allowing the perched water zones to dry out. The CERCLA actions stopped disposal to the warm waste ponds, the chemical waste pond, and the sewage lagoon, and capped these former discharge areas. However, water is still discharged to the cold waste ponds, and a lined evaporation pond was constructed to the east of the facility to replace the closed discharge areas. In 1998, a monitoring program was initiated to assess the effectiveness of the CERCLA actions (Parsons, 1998).

3.4.1 Description of Lithostratigraphy

The TRA is located just north of the INTEC facility, and has similar lithostratigraphy.

3.4.2 Contaminant Sources and Detection

Contaminant releases at the TRA have been as a result of process waste water discharges to the seepage ponds and into a deep aquifer injection well. The injection well was in operation during the 1964-1982 time period, and primarily received cold liquid waste consisting of cooling tower blowdown. Historically, water discharged to the surface ponds at the TRA (~0.75 Mgal/day) percolated downward through the surficial sediments and basalts. Infiltrating water from the seepage ponds formed two perched zones in the subsurface. The first was within the surficial alluvium at depths of up to 50 ft, and as at INTEC, the second exists at a depth of roughly 150 ft. The lateral extent of the deeper perched water body is about 400 acres in size. The rate of recharge facilitates vertical migration through the vadose zone, and the travel time from land surface has been estimated to be on the order of 7 to 8 months (Hull 1989).

3.4.3 Historical Measurement of Moisture Conditions

Perched water was initially monitoring at the TRA by the USGS in the early 1960s, and continues to be so today. The existing deep perched water monitoring system consists of 24 wells (six emplaced by the Environmental Restoration Program, and 18 by the USGS). Five wells in the aquifer are used for downgradient monitoring. This long monitoring history has provided a rich database from which trends in water elevations and contaminant concentrations can be easily distinguished and used as a basis for model calibration. There are no other vadose zone monitoring capabilities emplaced at TRA.

3.4.4 Simulation

Three modeling studies have been conducted to assess the movement of water and contaminants in the vadose zone at the TRA. The first was by Robertson (1977) who constructed a series of models representing: vertical saturated flow from beneath the ponds to the deep perched zone; two-dimensional radial flow within the perched water; and vertical water movement from beneath the perched zone to the aquifer. The models were considered to be successful in that predicted concentrations agreed with field observations. The model predicted that only low-partitioning solutes with low-partitioning coefficients and relatively long half-lives would enter the aquifer in detectable quantities.

A second modeling study by Dames & Moore (1992) was conducted in support of a CERCLA assessment of the contaminated deep perched water system beneath the TRA. A vertical two-dimensional slice oriented with the general groundwater flow direction was used for the simulation. Alternating fractured basalt layers and sedimentary interbeds were represented as equivalent porous media. The model was calibrated to observed perched water levels and to the observed breakthrough and historical monitoring data for tritium and chromium. This calibration was deemed successful and predictive simulations of future transport with this model were used to support a no action decision about the perched water.

Several years of monitoring have been conducted since use of the chemical waste pond and warm waste pond was discontinued. However, recent field observations suggests that tritium concentrations are behaving as predicted, but chromium concentrations are not following the same pattern. Overall, concentrations in the perched water have been decreasing slightly, but not as fast as the modeling had predicted.

The assumptions underlying the Dames & Moore modeling study imply that the source term and representation of hydraulic gradients were more important than matching observed perched water levels. They argued that from a risk perspective, this approach was valid as long as predicted risks were not unacceptable, and if unacceptable risks had been predicted, then a more thorough knowledge of the controls on water movement through the vadose zone would be necessary. Current deviations from field data to model predictions suggests that the formation of perched water might be more important than initially thought. Perched water is typically associated with a combination of sediment occurrences and flow contrasts. If the perched water forming mechanisms were not included, reactive transport would not be adequately accounted for. The non-reactive contaminants might behave in an ideal manner, corresponding to the simplistic effective porous media assumptions, but chromium, and other reactive contaminants would not.

The third modeling study (Arnett, 1996) was conducted to provide contaminant flux estimates for the Site-Wide Environmental Impact Study. Velocities from the Dames & Moore (1992) model were used to parameterize a simplistic vertical one-dimensional model of transport through the vadose zone. This simplistic model was used with TRA waste disposal histories and a large dispersivity in the vadose zone to estimate the contaminant mass fluxes to the aquifer.

3.4.5 Remaining Analyses

- CERCLA: a review of the technical RI basis is underway. Predicted chromium concentrations are much lower than observed values, and the rate of predicted decline is unsubstantiated by field data.

3.4.6 Quantifying Uncertainty: Remaining Issues and Unanswered Questions

Several aquifer wells downgradient of TRA show high, fairly constant chromium concentrations; however, the cause is unknown because the perched water source has been eliminated. Possibilities include the following:

- Undiscovered sources in the vadose zone or other undiscovered surface sources
- Incorrect model parameters or boundary conditions; therefore, predictions do not match observations
- A lithostratigraphic conceptual model, unrepresentative of the TRA system

Additionally, perched water well PW-13, has measurable free product organics floating in it. The source of the diesel and extent are both unknown.

3.5 Boiling Water Reactor Experiment I and Stationary Low-Power Reactor No. 1

The Boiling Water Reactor Experiment I (BORAX-I) site northwest of EBR-I is a radioactive subsurface disposal area containing radionuclide contaminated debris and reactor components. These contaminated materials were buried in place after BORAX-I was damaged during a steam explosion occurring during a planned power excursion in July 1954. Cleanup and burial of the reactor was completed approximately 1 year after the excursion.

The Stationary Low-Power Reactor No. 1 (SL-1) Burial Ground contains radionuclide contaminated debris buried in two shallow pits and a single trench northeast of Auxiliary Reactor Area (ARA)-I and ARA-II. In January 1961, an excursion involving the SL-1 reactor took place. The core, fuel, pressure vessel and miscellaneous parts needed for the post-accident investigation were removed to the Hot Shop at Test Area North (TAN), and the remainder was placed in the SL-1 burial ground, constructed 1,600 ft northeast of the SL-1 reactor site. During cleanup, surface soils were contaminated along a corridor from the reactor site to the burial ground. Over time, wind has dispersed the contamination over an area roughly 100 ha (240 acres) in size.

Both burial grounds were evaluated as CERCLA sites as part of the FFA/CO (DOE-ID 1991) for the INEEL. The RI/FS analysis (Holdren, Filemyr, and Vetter 1995) did not indicate groundwater pathway risks for either of these sites. However, predicted surface exposure risks resulted in the emplacement of basalt rip-rap covers at each site.

3.5.1 Contaminant Sources and Detection

There are contaminated surface sediments in the immediate areas around each facility. These contaminated areas resulted from the excursions, cleanup activities after the excursions, and from windblown deposition. The excursion of SL-1 was “contained” by the reactor building, and surface contamination had not occurred until the D&D&D activity started. The contaminants of concern are primarily fission and activation products, and although no vadose zone monitoring is associated with either site, aquifer monitoring wells at each facility have shown no indication of contaminants impacting water quality from these facilities.

3.5.2 Simulation

Groundwater concentrations resulting from burial grounds were predicted using a simplistic conceptual model (Holdren, Filemyr and Vetter 1995). This model considered contaminant first-order leaching, vertical one-dimensional transport through the vadose zone, and three-dimensional dispersion in a uniform flow field within the aquifer. The fractured basalt portions of the vadose zone were conservatively neglected. Retardation and transport were considered through an effective interbed, assumed to be laterally continuous and uniform. The thickness was estimated from wells in the area and total sediment thickness was confirmed as new aquifer monitoring wells around ARA-I and ARA-II were drilled as part of the CERCLA investigation. The approach predicted negligible groundwater pathway risks. Because the model was conservatively parameterized and because no vadose zone monitoring exists at either facility, no calibration was attempted.

A sensitivity study was conducted (Holdren et. al.,1999) using the same model, investigating the effect on simulated risk of increasing the inventory 2-3 factors and of increasing the infiltration rate to 22 cm/year (the annual INEEL precipitation rate). With simultaneous upper-bound inventory and infiltration rates, the predicted risks still were marginally above 10^{-6}. Based on the sensitivity analysis, the groundwater pathway was determined not to be a concern for the BORAX or SL-1 facilities. This increased infiltration was evaluated to assess the effect of contaminant concentrations resulting from increased infiltration above that allowed by a capillary barrier. As a result of the analysis, rip-rap was placed over both burial grounds to reduce risks associated with surface exposure pathways.

3.5.3 Quantifying Uncertainty: Remaining Issues and Unanswered Questions

- A simple one-dimensional model based on ideal assumptions was used to predict contaminant behavior in the vadose zone. As with the RWMC and INTEC facilities, the validity of the process model, assumed biogeochemical parameters, assumed hydraulic behavior are untested. Although a sensitivity study was performed for infiltration rates, transient and hysteretic effects on contaminant transport were not assessed.

- Simulation assumptions, and deviation from analyses conducted at the RWMC and INTEC further illustrates a lack of integration, field data and common approach.

3.6 Organic Moderated Reactor Experiment

The Organic Moderated Reactor Experiment (OMRE) was a 12-MW thermal reactor located 6.25 km (2 mi) east of the CFA. While operating during the 1957-1963 time period, the OMRE leach pond received reactor effluent contaminated with organic coolant and decomposition waste. Discharges to the pond could have amounted to 211,960 L (56,000 gal) of radioactive aqueous waste and 3.8 million L (1 million gal) of reactor cooling water (EG&G 1986). Three xylene releases, likely carrying radionuclides and organic compounds, to the pond were reported totaling 1,300 L (355 gal). Additional aqueous radioactive discharges in 1959, including xylene particulate, were made to a ditch outside the OMRE (Chapin 1979). The expected contaminants include ^{137}Cs, ^{60}Co, ^{90}Sr, 1,1,1-trichloroethane (1,1,1-TCA), and other organic compounds.

3.6.1 OMRE-1 Vadose Zone Investigations

Passive soil-gas sampling at the OMRE site was conducted to identify and delineate organic contamination within the vicinity of the old leach pond. Several contaminants were detected at the OMRE leach pond including 1,1,1-TCA, 1,2-dichloroethane (1,2-DCA), 1,1-dichloroethene (1,1-DCE), and trichloroethene (TCE). The 1,1,1-TCA values are considered "very high" (a relative measurement level), while the levels of 1,2-DCA and 1,1-DCE are substantially less. The distributions of those organics were similar. In contrast, the levels of TCE in the pond were low, but the distribution pattern suggests that higher levels of TCE may exist in the ditch southeast of the pond. The soil-gas data is being used to motivate additional site characterization, with the objectives of:

- delineating and quantifying the extent of the organic vapor plume
- characterizing the nature and extent of stained soil in the OMRE ditch
- determining whether the stained soil is co-located with radionuclide-contaminated soil

The first objective can be met with field screening data and will be addressed by an active soil-gas survey. The second objective requires field screening and definitive analytical data. Physical information such as strong odors, evidence of anthropogenic debris, and stained soil will be used during field activities to detect areas of potential contamination requiring additional characterization.

3.6.2 Quantifying Uncertainty: Remaining Issues and Unanswered Questions

- the proposed field screening methods for detection of organics illustrates the need for field chemical analyses capabilities.
- real-time spatial analyses of field data would assist in locating contaminant distributions.
- real-time data analyses could be used to optimize collection of field samples for laboratory analyses.

4 SUMMARY OF OUTSTANDING ISSUES AND UNRESOLVED QUESTIONS

This section reviews the outstanding issues and unresolved questions affecting the predictability of fluid movement, contaminant transport, and chemical transformation processes in the vadose zone at the INEEL. Development of this list was obtained through documented meetings with DOE and INEEL managers and scientists as presented in INEEL/EXT-99-00984. The meetings were conducted to identify areas with remaining issues in understanding and predicting vadose zone processes, and to make recommendations for addressing these issues. The "Deficiencies in Vadose Zone Understanding at the Idaho National Engineering and Environmental Laboratory (INEEL/EXT-99-00984) document has identified more than 100 specific outstanding issues, forming the basis for the Vadose Zone Deficiencies Workshop conducted in Idaho Falls, Idaho, on October 20 and 21, 1999. Based on consensus reached at the workshop, the final version of the vadose zone deficiencies document was prepared.

Workshop participants reviewed the draft Vadose Zone Deficiencies document, ranked the identified deficiencies, grouped the deficiencies into subject areas, and made recommendations to address the deficiencies. These subject areas by section are:

4.1 Predicting Physical Transport

4.2 Transformation Processes: Geochemical and Microbial

4.3 Simulating and Estimating Contaminant Source Terms

4.4 Monitoring, Characterization, Instrumentation, and Data Analysis

4.5 Integration

with each section presenting a review of the outstanding issues and unresolved questions. From these, science needs were developed and are presented in Section 5. Recommendations and science needs collectively will serve as a basis from which to develop science plan.

4.1 Predicting Physical Transport

Available field data are of insufficient quality and quantity for use in predictive simulation. In general, the data are:

- Inconsistent - suggesting that transport occurs at one location and not at others with insufficient information limiting interpolation or extrapolation of processes or state variables

- Insufficient - and do not provide consistent spatial or temporal trends that can be used in the model calibration process, or to discriminate between processes and parameters

- Inadequate - and do not provide the necessary parameter distributions to allow uncertainty to be quantified or bounded; uncertainty in hydrologic parameters (e.g., permeability and moisture characteristic curves) and in boundary conditions (e.g., infiltration history and spatial variability) limits the applicability of predictions for environmental-decision making

- Incomplete - parameters including: matrix-fracture diffusion, microscale dispersivity, geochemical adsorption parameters, microbial activity (and indicators), unsaturated characteristic relationships for INEEL geomedia, have been obtained via literature review or guessed rather than measured. State variable and boundary condition distributions (water content, water potential, infiltration rates, evapotranspiration rates, temperature, and barometric pressure) are not recorded consistently, nor are the data interpretable when they are recorded.

Models are inadequate and have not incorporated physical and biogeochemical processes:

- Definitive mechanisms describing water movement through the unsaturated fractured basalts have not been identified for the wide range of moisture conditions experienced at the INEEL. Simulation paradigms are based on ideal processes and do not represent observed behavior. Equivalent porous media approaches are used without basis, neglecting fracture-matrix interactions. Preferential flow, (water bypassing the majority of the subsurface medium), probably occurs throughout the INEEL, and is not represented in existing models. There are no generally accepted mathematical representations of advective processes occurring in variably saturated fractured media.

- Mechanisms describing transformation and reaction processes incorporated into predictive models are overly simplistic. Facilitated transport mechanisms (including the formation of colloids) are not incorporated, and the underlying mechanisms have not been identified. Linear equilibrium adsorption assumptions have formed the basis of all predictive simulations without consideration of rate-limitations, solubility-limitations, effect of pH, redox state, temperature effects, or specific INEEL mineralogy. Vapor phase contaminant behavior has not been well represented, based in part on assumptions of single water-phase rather than two- (mobile water and air) and three-phase (oil, water and air) flow considerations. The latter would require developing site-specific consitutive parameters describing the relative permeability-saturation relationships for 2- and 3- phases. Modeling done in support of predicting TCE and CCl_4 transport have not been based on constitutive relationships for INEEL media.

- Biogeochemical mechanisms and parameters are not incorporated, and historical studies have neglected degradation and transformational processes.

- Evaluations of several sites have been made on “presumably overly conservative parameterizations” without adequate process and parameter knowledge to confirm the hypotheses. Data requirements and experimental protocol for testing process model hypotheses are undefined.

Nonlinear governing equations for multiphase flow require iterative solution schemes resulting in:

- Excessively long elapsed time for forward simulations

- Limited discretization and insufficient incorporation of spatially variable lithostratigraphy and associated hydrogeochemical transport properties

- Assumptions of steady-state flow conditions, neglecting analyses and incorporation of highly variable transient recharge events

- Limited use of probabilistic sensitivity and uncertainty analysis. Predictions of contaminant concentrations are based on single pass forward simulations without consideration of new data, and without incorporating a model-data feedback mechanism.

Various sources of uncertainty and their relative impact on the predictability of transport is unknown and currently unquantified.

- Impacts of temporally and spatially variable parameters, boundary conditions, and initial conditions have not been addressed as they contribute to uncertainty
- Data quality and bias, as they contribute to uncertainty, have not been addressed
- Methodology for assessing uncertainty - as opposed to sensitivity - has not been formalized.

New simulators require justification, review, and presentation prior to use in regulatory environmental applications. These codes must undergo evaluation when supported by the three-party code selection criteria matched to the problem at hand. As a result of the review process,

- There is a tendency to use an accepted simulation code, regardless of system characteristics (i.e., the one-d rather simple GWSCREEN code vs a more complex two- or three-dimensional simulator)
- There is a tendency to prefer public domain simulators over proprietary (and possibly more robust) codes
- Acceptance of different codes for vadose zone simulation requires excessive time, e.g., the recent introduction of the TETRAD simulator required a year to obtain concurrence from DOE, EPA, and the Idaho Department of Health and Welfare (IDHW) prior to use in CERCLA evaluations.

4.2 Transformation Processes: Geochemical and Microbial

Mechanisms and parameters describing adsorption of contaminants onto INEEL materials have not been developed or measured.

- The ideal transformation paradigm assuming linear-equilibrium-reversible adsorption, has not been tested or validated for INEEL geomedia, relevant solution chemistry, and contaminants
- Adsorption mechanisms and parameters have not been established for INEEL materials (i.e., Kds are assumed to be correct, and literature derived values are assigned)
- Correlations between substrate properties, solution chemistry, and measured K_d values have not been determined
- Interphase mass transfer reaction rates have not been evaluated for INEEL contaminants and media. Volatilization rates and release mechanisms from contaminated sediments and buried waste at the INEEL have not been established. The propensity of contaminants to travel in liquid and vapor phases (organic and water) has not been evaluated.

Effects of solution chemistry and contaminant redox states have not been evaluated.

- Redox states for contaminants and the effect on transport has not been evaluated. However, conditions are likely to vary between oxidizing in the native environment to reducing in the buried waste
- Organic complexing agents have not been evaluated in either soil or water, and anions are not always measured because they are not considered contaminants. The presence of complexing agents in waste and wastewater at the INEEL has not been evaluated, even though

decontamination solutions containing complexing agents such as citrate, oxalate, and EDTA were used and disposed of by injection wells, released through spills, and buried in waste. These were co-disposed of with inorganic anions such as fluoride, carbonate, and phosphate that could be forming aqueous complexes with contaminants, but the propensity has not been evaluated.

- pH effects on the adsorption behavior of contaminants discharged in extremely low pH solutions has not been evaluated.

Conditions leading to facilitated transport are unknown.

- Facilitated transport of actinides has not been evaluated although migration of Am-247 and Pu has apparently occurred at rates much faster than could be predicted by solute transport processes; it is unclear whether or not colloids exist in the SRPA waters and the conditions of formation are unknown
- Geochemical conditions required for development of colloids have not been demonstrated
- Combinations of K_d values have not been shown to be able to represent facilitated transport within K_d based simulators. Event driven transport (i.e., with a short duration and a large water flux) of dissolved-phase contaminants could account for the discrepancies. Computer codes currently in use at INEEL do not explicitly account for facilitated transport.

Microbial effects on transport rates and mechanisms in the vadose zone have not been addressed.

- Insufficient data are available to allow meaningful conclusions to be drawn about basic issues such as: which physiologies are present/active, how the organisms are distributed, and which physical and chemical factors control their distribution and activity
- Study locations are inaccessible and remote, making detection of microbial activity difficult
- Accessibility constraints force the requirement of costly sampling methods
- Low levels of biomass in the vadose zone will require discrimination of low signals (i.e., autochthonous biomass) against a much larger background of potential contaminant organisms
- Many organisms are unculturable, making estimation of in situ activity more difficult; assays must integrate molecular methods to evaluate microbial presence, potential, and activity.

4.3 Simulating and Estimating Contaminant Source Terms

Near-field hydraulic conditions and their influence on contaminant release and migration are unknown. In general, the variability of water flow on the scale of individual waste containers is expected to be more significant because:

- Container and backfill materials are relatively non-uniform; soil porosity and permeability of the near-field environment differ from that of the general vadose zone environment because of the structural disturbance of the soil caused by excavation and backfilling, altering the hydrology and vapor transport characteristics of the near-field environment
- Modifications to the near-field hydrology by proposed remediation technologies (grouting, vitrification etc.) will only increase the contrasts.

Chemistry of the near-field environment (e.g., the oxidation-reduction potential and solubility effects) may significantly affect the rate of migration:

- Oxidation-reduction potential and solubility effects are unknown, but may significantly affect the rate of migration to the general vadose zone

- Changes in the near-field chemistry resulting from in situ waste treatment options have not been evaluated. For example, grouting mechanically stabilizes waste but also can cause a nearly complete alteration of the chemical environment for release of contaminants.

Temporal behavior of contaminants near waste forms are unknown:

- Release rates of volatile contaminants by diffusion and advection processes from partially failed containers are unknown. Contaminant release rates (particularly ^{3}H, ^{14}C, and volatile organic compounds) to the atmosphere are currently unmonitored.

- Kinetics and spatial characteristics of container failure processes are unknown

- Inventories of contaminants within the containers, and the fractions existing in mobile forms are unknown.

Analysis methodologies are limited:

- Current source term models treat water flow through the near-field environment as a spatially uniform process, although it is more likely to be non-uniform, event driven, and episodic.

Historical leaks have contaminated the subsurface requiring determination of composition and magnitude.

- Source delineation requires obtaining soil borings which: is potentially hazardous, brings contaminated materials to the surface, and is expensive.

- Techniques for in situ speciation of contaminants have not been developed, and non-intrusive methods to detect contaminant distributions are not available.

- Geophysical techniques for contaminant mapping are subject to interference presented by surface and subsurface structural features, and have not been tied to specific contaminants of interest.

4.4 Monitoring, Characterization, Instrumentation, and Data Analysis

Temporally varying fluid saturations and pressures, precipitation, evapotranspiration, temperature, barometric pressure, etc., are collected sporadically.

- Transient infiltration events are not captured through relatively short-term, discontinuous monitoring activities
- Insufficient record lengths do not span the range of infiltration conditions, and contribute to the long-term prediction uncertainty
- Moisture content, pressure head, and contaminant concentrations are obtained at specific points in space and time. However, these state variables could very well be discontinuous in the heterogeneous environment, and values may not be representative of local vadose zone conditions. Secondary detection techniques are unavailable for confirmation of observed data.
- Correlation between measurements and indicators of hydrologic conditions (i.e., saturation and electrical resistivity) in the complex basalt-sediment materials have not been developed
- Collecting and analyzing data is currently cost-, time-, and man-power intensive

Spatially variable parameters have been measured for very few of the geomedia existing at the INEEL.

- Few ex situ laboratory estimates of unsaturated hydrologic properties (on small samples), and fewer in situ hydrologic property measurements have been made
- Few analyses of sorptive properties, chemical composition, and mineralogic makeup of sediments, basalts, and fracture surfaces are available
- Instruments and field tests allowing determination of unsaturated hydraulic characteristics in situ are not available. Instruments and testing methods sample relatively close to boreholes, and the representativeness of the vadose zone environment is in question.
- Sorptive processes and parameters have not been established for the suite of geomedia found at the INEEL. Lacking representative mechanisms, Kds are assumed rather than obtained for specific conditions found at the individual disposal sites.
- Basalt characteristics (rubble zones, dense units, and fractured units) have not been mapped across the INEEL
- Fracture characteristics (e.g., density, aperture, length, and orientation) have not been quantified.

Relationships between extracted concentrations, biologic indicators, and state variables to those of the larger vadose zone environment are unknown.

- Colloids have been retrieved using suction lysimeters beneath the SDA, but it is not known if colloidal concentrations are represent the pore fluid in the vadose zone. Discrepancies can be introduced through the adsorptive and filtration properties of the lysimeters.
- Numerous organic contaminants have been detected in soil gas and groundwater samples, indicative of biodegradation processes. Direct in situ measurements of biologic activity are not available, as are correlations between soil gas and water samples to biologic activity.

Preferred pathways are not detected or monitored, and there is relatively little information available:

- Describing three-dimensional distribution of basalts and sediments and their hydrogeochemical characteristics
- Delineation of interrelationship and interconnectivity of various fracture sets
- Quantifying effective hydraulic characteristics of unsaturated fractured media
- Describing surface topology and local ponding conditions.

Contaminant source terms (history and magnitude) are not currently quantifiable:

- Release rates of contaminants from discharge locations are not measurable, and are derived through the application of parameter estimation
- Advective fluid velocities are not currently measured
- Transport parameters including tortuosity, effective porosity, dispersivity, and permeability are not available
- Correlation between geophysical measurements and hydrologic characteristics for basalts and sediments have not been developed
- In situ inventories of contaminants and contaminant distributions have not been detectable.

Instrument bias and accuracy are often unknown:

- Current installation procedures are based on methodology developed for the agricultural and porous media applications. Installation procedures and their impact on measurements obtained in fractured media are unknown.
- Potential bias of (and the specific parameters represented for) instruments installed at fracture-well bore intersections have not been evaluated. Relative placement of instruments in dense basalt and fracture intersections can be determined via downhole video logs, but it is unclear whether water potential is reflective of that existing in the fractures or of that existing in the basalt matrix.
- Interaction and affect of porous media backfill with the fracture-matrix medium are unknown and the potential hysteretic effects involved are unquantified.

Quantifying the relative contributions to non-ideal behavior will require advances in detection and discriminatory analysis capabilities. For example:

- Current instruments and methodology cannot measure flow in single fractures or delineate fluid movement at fracture-matrix interfaces, verifying research hypotheses will require instrument development, advances in data analysis, and development of experimental protocol.

Spatially distributed estimates of state variables, lithostratigraphy, and hydrogeochemical parameters, and the techniques to obtain them, are currently not available.

- Volume averaged, or effective, properties are process and objective dependent
- Parameterizing simulation models using effective parameters (based on calibration) rather than process level values assumes that the system state is invariant
- Alterations in the system state (i.e., removal of anthropogenic water) requires alternate parameterizations.

The representativeness of in situ small-volume measurements of vadose zone parameters are unknown:

- Spatial averaging of properties and processes may provide nonrepresentative integration of point measurements
- Known lithostratigraphic variability requires an alternative to simply interpolating traditional borehole characterization data
- Inverse models incorporating the relevant processes should be developed to assist in creating a consistent picture across all scales.

Laboratory-determined properties have not been related to field-scale values and conditions.

- Methodology for translating laboratory-scale constitutive relationships to obtain field-scale properties for fractured media are not available
- General scaling relationships have been developed for porous media that might be applicable to alluvial and sedimentary facies, but scaling relationships based on site-specific data have not been developed
- Scaling relationships for fractured media have not been developed - and are probably objective dependent
- Laboratory analyses of soil & rock cores collected insitu yield a wide range of values. The use of ex situ assessment of properties and the associated measurement scale have not been evaluated.
- Appropriate scales of observation have not been defined, and are process dependent. For example, measuring the basalt-matrix permeability is of secondary importance if the fluid flow is primarily in the fractures of a larger system. Instrumentation and observation scale must be commensurate.

4.5 Integration

Across the INEEL, there have been inconsistent vadose zone characterization, monitoring, and simulation activities across the INEEL. Data is being collected on a project level with the transfer of knowledge, data, and technologies between projects being largely by informal communication. The impact of insufficient coordination has resulted in data collection duration and frequency being determined by individual projects without regard to the impact on other projects, leading to discontinuous data despite monitoring capabilities. Inconsistent contaminant transport and transformation simulation assumptions make it extremely difficult to assess site-wide impacts. Currently, there is not an mechanism for tracking programmatic needs for all vadose zone research and site assessment activities.

5 RESEARCH NEEDS AND SIGNIFICANCE

In the previous sections, the limitations in historical analyses of INEEL sites leading to unquantified uncertainty in management decisions were reviewed. The limitations were grouped into four areas: Predicting Advective and Transport Processes, Geochemical and Microbial Transformation Processes, Simulating and Measuring Contaminant Source Terms, and Monitoring, Characterization, Instrumentation, and Data Analysis. These limitations were presented from a practitioner's perspective, and lead to the development of needs from the perspective of science and technology. The themes that appear repeatedly within the specific limitations listed in Section 3 include:

- Physical flow and transport of fluids and contaminants, and the mechanisms by which they should be described
- Biogeochemical transformations that occur as the contaminants migrate through the vadose zone
- Characterization and monitoring technologies and data interpretation techniques required to quantify the transport and transformation processes
- Prediction of processes, quantification of uncertainty, and simulation capabilities forming the basis of environmental management decisions

The science and technology developments needed to address these historical limitations are discussed below. In addition, integration of scientific and end-user communities will be key to achieving defensible and cost effective management across the INEEL. The significance of integration, and an example of successful implementation is also presented in this section.

Understanding physical processes controlling the distribution of fluids in the subsurface is the first step in quantifying the uncertainty currently underlying environmental management decisions. Physical processes controlling fluid movement determine the distribution of contaminants, microbial nutrients, and the propensity for geochemical interaction of contaminants with the subsurface media. This research area is important because physical processes, and the methods by which they are described, determine the state variables and parameters that must be characterized and monitored. They also suggest appropriate data requirements (e.g., density in space and time) and associated analysis techniques. Understanding the processes that control fluid and contaminant movement will result in improved predictions of contaminant migration, in the quantification of prediction uncertainty, and will lead to the design of monitoring and characterization strategies aimed at reducing the uncertainty.

Understanding biogeochemical transformation processes is important because they can modify the transport rate and aqueous concentrations of contaminants through sorption/desorption and precipitation/dissolution reactions, in addition to modifying the toxicity of contaminants through biodegradation and redox transformations. A better understanding of biogeochemical processes, and the scale at which they occur in the heterogeneous fractured INEEL subsurface, will allow correct parameterization of transport models. This area will require development of conceptual models for all of the media underlying the INEEL. More accurate models and site specific parameterization will result in reduced prediction uncertainty, and will provide the scientific basis for improved containment and stabilization strategies.

Improved characterization and monitoring technologies are needed to increase our understanding of the previous two areas (flow, transport, and transformational processes) in addition to supporting long-term stewardship. This research area is interdisciplinary, and is needed to provide the data necessary at all stages of environmental management. Characterization and monitoring are needed for the delineation of contaminants, moisture, and lithostratigraphy representative of the volumes and time-frames dictated by process descriptions. Long-term stewardship requires the development of robust, reliable, and automated data recovery and instrumentation that can be easily modified as new technologies become available. This area must be developed in order to support the other two research areas, leading to better prediction, quantification of uncertainty, as well as detection and long-term monitoring of contaminant migration.

Enabling the assessment of uncertainty in model predictions is the primary objective of improving vadose zone science at the INEEL. This will require expansion of the current modeling paradigm to consider nonideal behavior, additional physical and biogeochemical processes, and new monitoring and characterization techniques. In addition, it will require a change in modeling philosophy. Historically, models accounting for limited sources of nonideal behavior have been applied to predict contaminant transport at the INEEL. These models have been calibrated to field data based on few observations of moisture conditions and contaminant concentrations, assumptions of steady state infiltration, flow through equivalent porous media, and instantaneous linear-equilibrium adsorption. The application of ideal models that have not accounted for all sources of nonideality, when the INEEL is affected by more than those factors, has resulted in the use of lumped parameters. Values for the lumped parameters have been obtained through calibration, and are only valid under the specific set of conditions for which they were obtained. This historical approach cannot supply process-discrete information and, thus, cannot be used to elucidate the relative contributions of various nonideality factors to overall uncertainty. Nor can they be used under changing hydrologic conditions occurring through time or after facility closure. Only through the application of models explicitly accounting for the existence of multiple nonideality factors can uncertainty be assessed and the processes quantified.

The development of more complete models will require independent values for the parameters. Obtaining parameter values through predictive mode simulation, vs through calibration, will reduce the overall uncertainty, but will require data to be obtained through system manipulation. During the experimental (manipulative) process, the means of elucidating parameters, and processes will be developed, and will ultimately result in the ability to quantify uncertainty at the field scale.

Improvements in simulation capabilities are needed to allow the integration of characterization and monitoring data with developments in process level understanding. Development of simulators that account for processes occurring in the highly heterogeneous subsurface and for the influence of seasonal variations in climatic conditions is necessary in order to fully test process level hypotheses at the laboratory- and field-scale. Implementation of advanced theories into simulators will be necessary in order to keep pace with the increasing complexity of process models and data collection capabilities. At the same time, improved data collection capabilities will require advances in interpretive techniques, and in data handling technologies. Transferring and understanding simulation results and data will require the ability to represent transient processes in three dimensions, and a means of presenting the results to decision makers, to the public, and to the regulators. Thus, simulation provides the glue to link the other three research areas together.

Integration of scientific and end-user communities will be key to achieving defensible and cost effective management across the INEEL. The scientific community should recognize that the operating budget and time constraints placed by schedule and regulation have resulted in the primarily limited analyses to date. The purpose of making advances in vadose zone science is to translate this understanding to have positive affects in that environment. This translation will ultimately minimize costs associated with INEEL cleanup and enable long-term stewardship while simultaneously providing optimized environmental protection.

5.1 Relationships Between Existing Limitations and Necessary Scientific Advances

Section 3 presented an overview of remaining issues and unanswered questions arising as a result of individual INEEL investigations. From that review, and consultation with scientists and managers during the development of the INEEL Deficiencies Document, the bases for Section 4 was compiled. In Section 4, the environmental management issues and questions were reviewed. In both of those sections of this document these limitations were stated from a practitioners perspective as opposed to presenting scientific issues or approaches to overcoming the limitations. Below, the limitations are restated to fall within the scientific study areas.

5.1.1 Physical Flow and Transport of Fluids and Contaminants

Physical processes controlling the distribution of fluids are largely unknown at the INEEL, and in all previous analyses (presented in Sections 3.1.6, 3.2.6, 3.3.6, 3.4.6, 3.5.3 and 3.6.2 for RWMC, INTEC, CPP, TRA, BORAX-1, and OMRE-1, respectively) have been treated very simply compared to the possible physical processes discussed in Section 2.3. Definitive mechanisms describing water movement through the unsaturated fractured basalt-sediment sequences have not been identified for the wide range of moisture conditions at the INEEL (implications of recharge is discussed in Section 2.2, and relevance to the INEEL is reviewed in Sections 3.1.3, 3.2.3, 3.3.3, and 3.4.3 for RWMC, INTEC, CPP, and TRA, respectively). Previous analyses have been based on assumptions of equivalent porous media, and neglect preferential flow, hysteresis, and fracture-matrix interactions. Vapor phase contaminant behavior has not been well represented (e.g., at the RWMC described in Sections 3.1.4 and 3.1.6) and has been based on assumptions of single-phase rather than two- and three-phase flow considerations, or has been based on two-phase flow with assumed constitutive relationships. Process model assumptions and their relative impact on the predictability of transport is unknown and currently unquantified. Impacts of temporally and spatially variable parameters, boundary conditions, and initial conditions have not been addressed.

Improved understanding of the processes governing fluid migration requires scientific advances in several areas including the formulation of appropriate transport approaches and equations for the INEEL fractured basalt and sedimentary interbed subsurfaces subjected to extremes in transient infiltration. To support these new approaches, better representations of the constitutive relationships for variably saturated systems will need to be developed and the role of thermal and barometric pressure effects will need to be elucidated. Processes to be examined are discussed in Section 2.3. Scientific challenges in addressing these issues include:

- Developing physical paradigms incorporating the nonideal processes that represent the interaction between, and flow through, fractures, matrix, and sediment with a focus on predicting bypass (preferential) flow (relevance to lithostrategraphy at the INEEL is presented in Sections 3.1.1, 3.2.1, 3.3.1, and 3.4.1 for the RWMC, INTEC, CPP, TRA, and the implications of not considering lithostratigraphy are discussed sections 3.5.3 and 3.6.2 for BORAX-1 and OMRE-1 investigations)

- Determining the appropriate variables to describe fluid movement over distances representative of long-term transport, and over distances representative of short-term infiltration events and possible remedial actions (see above for relevance)

- Collecting data at spatial and temporal resolutions that adequately capture significant recharge and infiltration events at the field-scale in sediments, fractured basalts, and along the interfaces between them (e.g., see Sections 3.1.3 and 3.2.3 for this need relevant to RWMC and INTEC).

- Obtaining parameter estimates representative of in situ conditions (e.g., moisture distributions, flux rates, water potential, and chemical concentrations) for the processes being investigated at the contaminated sites and in the presence of structural surface features (e.g., see Sections 3.1.2 and 3.2.2 for relevance of concentration detection at RWMC and INTEC)

- Developing and quantifying the hysteretic constitutive relationships in layered fractured basalt-sediment sequences over the range of moisture conditions found at the INEEL

- Developing the physical transport and constitutive theories representative of multi-phase transport

- Developing sparse data interpolation techniques, including the ability to infer state variables and constitutive relationships from more easily collected information

- Developing technologies that enable better representations of the INEEL subsurface lithostratigraphy
- Developing improved computational methods that allow joint use of multiple sources of data
- Developing experimental protocols to assess the validity of process descriptions and measurement techniques.

5.1.2 Biogeochemical Transformation

Biogeochemical transformational processes have not been widely incorporated into analyses of INEEL sites (for discussion, see Sections 3.1.1, 3.2.1, 3.3.1, 3.4.1, 3.5.3 and 3.6.2 for investigations of the RWMC, INTEC, CPP, TRA, BORAX-1 and OMRE-1). Mechanisms describing transformation and reaction processes incorporated into predictive models are overly simplistic compared to the range of probable reactions presented in Section 2.4. Facilitated transport mechanisms (including the formation of colloids) are not incorporated, and the underlying mechanisms have not been identified. Linear equilibrium adsorption assumptions have formed the basis of all predictive simulations without consideration of rate-limitations, solubility-limitations, effect of pH, redox state, temperature effects, or specific INEEL mineralogy. Biogeochemical mechanisms and parameters are not incorporated, and historical studies have neglected degradation and transformational processes. Evaluations of several sites have been made on "presumably overly conservative parameterizations" without adequate process and parameter knowledge to confirm the hypotheses. Data requirements and experimental protocol for testing transformation model hypotheses are undefined.

Improving scientific understanding of transformation processes occurring in the vadose zone will require advances in our ability to describe the biogeochemical interactions at a scale relevant to specific INEEL contaminants and sites. It will have to be determined whether or not the ideal transformation paradigm assuming linear-equilibrium-reversible adsorption is valid for INEEL geomedia, relevant solution chemistry, contaminants, and hydrologic conditions. The influence of forward and reverse reaction kinetics, and the irreversibility of some reactions will have to be assessed. The challenge in making these assessments will be in:

- Designing representative experiments that allow determination of reaction kinetics in an environment that simulates the highly transient flow conditions at the INEEL (relevant to all sites)
- Developing theory accounting for hysteretic availability of reaction surfaces as a result of time-varying moisture distributions (relevant to all sites)
- Optimizing and automating data collection capabilities necessary to assess in situ transformation rates and mechanisms (relevant to all sites and all time frames)
- Developing and applying the computational tools necessary to interpret experimental data in the context of the fluid flow and biogeochemical transformation processes, to assess the presence of specific metabolisms, their distributions, and the controlling physical and chemical factors (relevant to all sites)
- Developing an understanding of the relationships between laboratory and field-scale transport parameters and mechanisms (necessary to apply laboratory data field investigations)
- Developing the experimental protocol for determining in situ distributions of biogeochemical heterogeneity (perhaps through the use of chemical and biologically reactive tracers), and the effects of changing moisture conditions (especially relevant to RWMC and INTEC)

- Determining the geochemical conditions leading to the facilitated transport of actinides (e.g., formation of colloids), and incorporation into predictive simulators (relevant to RWMC and INTEC)

- Development of monitoring and characterization methods for determining in situ solution chemistry (relevant to all sites).

5.1.3 Characterization and Monitoring Technologies and Data Analysis Methods

Characterization and monitoring technologies are not currently capable of capturing the temporally varying state variables used to describe fluid distributions (e.g., saturations, pressures, temperature), biogeochemical environment (e.g., contaminant concentrations, solution chemistry, biologic activity), or external driving forces (e.g., precipitation, evapotranspiration, barometric pressure) at the INEEL. Instrumentation used for these purposes are largely unreliable, and difficult to maintain or replace as discussed in Sections 3.1.3 and 3.2.3 (RWMC and INTEC). Current instrumentation often requires manual data collection which results in sporadic data availability at high cost. In general, available data is representative of a wide sample support volume, and is often used to infer state variables rather than a direct measurement. Methods of relating measurements to hydrologic or biogeochemical conditions are not available for the INEEL subsurface.

Supporting advances in physical and transformational processes will require scientific advances in our ability to quantify the hydrogeologic and biogeochemical interactions at a scale relevant to a range of investigative methods. Characterization and monitoring paradigms will have to be expanded to enable cost effective field-scale data collection to support experimental activities, will need to be developed to support meso-scale laboratory investigations, and will need to evolve as new technologies become available and as process paradigms shift. Quantification of uncertainty will require collection of data beyond that necessary for simple forward prediction, and long-term stewardship will require highly robust data. Specific scientific challenges include the following:

- Determining:
  - State variable data density (in time and space) requirements for predictive model parameterization
  - State variable quality needs (how much measurement uncertainty is acceptable)
  - The set of state variables to be consistently monitored that can serve as indicators of processes and consideration of surrogate parameters
  - The appropriate spatial density, sample size, and monitoring strategy to represent flow and transport processes.
  - An optimal data collection strategy for temporally-dependant spatially-variable state variables.

- Evaluation and minimization of:
  - Potential bias introduced through instrumentation installation, specifically for instruments installed at fracture and sediment-borehole intercepts
  - Potential bias introduced by installing instrumentation in non-native (infilled) porous media
  - Bias introduced in collecting (colloidally transported) contaminants.

- Development of sensors and instrumentation to:
  - Quantify liquid, gas, and contaminant source composition and release rates in situ

- Evaluate in situ biological activity
- Measure fluid flux
- Quantify state variable distributions over volumes represented in simulators, and to provide the distribution of state variables between access locations (boreholes)
- Provide in situ chemical and mineralogic analyses and sorptive properties of sediments and basalts
- Allow in situ determination of hysteretic hydraulic constitutive relationships under the wide range of infiltration and lithostratigraphic conditions observed at the INEEL
- Delineate and monitor preferential flow paths, and to predict the large-scale effects of preferential pathways.

• Development of methods enabling:

  - The assessment of effective in situ hydrologic properties
  - The collection of large, undisturbed samples (~1 m^3) of sediments and basalts for ex situ physical and chemical property tests and measurements
  - Better interpolation of lithologic information.

• Development of:

  - Improved, low impact methods of in situ sensor emplacement and maintenance
  - A standard for instrumentation, installation, calibration, and data collection to allow calibration, and a means of calibrating existing soil moisture content probes in situ to minimize error introduced by converting in situ count rates, velocities, elapsed time, etc. to state variables based on disturbed sample calibrations
  - A means of monitoring remediated sites to assess simulation predictions and remediation effectiveness

• Development of techniques for:

  - Installing instrumentation and networking of sensors resulting in measurements representative of the processes being investigated
  - Correlating biological activity indicators to location and rates of contaminant degradation
  - Enhancing the contrast of biological heterogeneity enabling geophysical characterization
  - Testing the instruments and data collection strategies.

• Design laboratory- and field-scale tests together to identify the relationships between laboratory- and field-scale observations to:

  - Assess how, and at what level, spatial variability affects transport over the infiltration conditions observed at the INEEL
  - Determine mechanisms and properties contributing to preferential flow

- Determine scaling relationships between point measurements and model values
- Evaluate scales of heterogeneity and their impact on prediction.

5.1.4 Prediction of Processes, Quantification of Uncertainty, and Simulation Capabilities

Current simulation capabilities do not allow the assessment of uncertainty, optimal design of characterization or monitoring strategies, optimal selection of parameters, integration of different data sources, and do not include relevant hydrologic or biogeochemical processes. Different simulators, input structures, and post processing routines must be used for every hydrologic and biogeochemical process included. The lack of a common input and output framework results in excessive model development, parameter input, and transition time between models. The time required for data analysis, for model parameterization, for forward simulation, and to process simulation results is excessive, and leads to non-optimal parameterization and presentation of results. Simulators used for the purposes of source term characterization do not adequately account for near-field hydrologic or chemical environments, and for the changes between the near-field conditions and larger vadose zone environment. Container, tank, transfer line, and waste encapsulation models do not account for INEEL specific contaminants or solution chemistry.

Advances in simulation capabilities are necessary to support research in the areas of physical and transformational processes, to support advances in characterization and monitoring, and to enable quantification of uncertainty. New simulators will need to be developed to account for different process models, and to allow interpretation of the data used to drive them. Faster implementations of existing process models will be necessary to incorporate increased spatial resolution of lithostratigraphy, and transient recharge conditions. More robust numerical algorithms will be required to enable Monte Carlo (or other) statistical simulation required to assess uncertainty. Specific challenges include the following:

- Development of computationally efficient simulators allowing fine discretization and statistical application with an expanded paradigm including:
  - Easily modified process descriptions for hypothesis testing
  - Biogeochemical interactions including kinetic reactive transport
  - Facilitated transport and the controlling mechanisms
  - Alternative conceptual models to equivalent continuum descriptions of water and contaminant movement in fractured basalt and sedimentary interbeds (e.g., dual-porosity dual-permeability media, effective media, and other physical models)
  - Efficient visual postprocessing
  - Geostatistically based input of spatially varying properties, accounting explicitly for aggregation of uncertainties
  - Inverse parameter estimation techniques.
- Development and formalization of methodologies for assessing uncertainty and the development of algorithms enabling assessment of the various sources of uncertainty including those resulting from:
  - Uncertain process models
  - Temporally and spatially variable parameters, boundary conditions, and initial conditions
  - Data quality and bias
  - Data interpretation models.

- Development of simulation strategies focused on testing hypotheses to elucidate mechanisms governing fluid redistribution to support:
  - Laboratory scale experiments
  - Meso scale experiments, and
  - Field scale experiments.
- Development of models for the purposes of assessing near-field impacts of contaminant releases from:
  - Containment vessels (e.g., tanks, piping) with the relevant solution chemistry to evaluate the effect on the subsurface environment
  - Buried waste and the container failure process
  - Encapsulated waste (e.g., grouted waste, buried in landfills, vitrification) and the release from containment.
- Implementation of simulators that:
  - Generate a range of conceptual models to assist process evaluation by scientists from various disciplines
  - Are visually accessible to the public and to the regulators.

5.1.5 Integration

Integration of scientific and end-user communities will be key to achieving defensible and cost effective management across the INEEL. The scientific community must recognize that the operating budget and time constraints placed by schedule and regulation have resulted in the primarily limited analyses to date. The purpose of making advances in vadose zone science is to translate this understanding into improved monitoring and simulation tools. This translation will ultimately minimize costs associated with INEEL cleanup and enable long-term stewardship while simultaneously providing optimized environmental protection.

6 TECHNICAL APPROACH

Predictions of transport and transformation of contaminants through INEEL's vadose zone are currently limited by inaccurate and incomplete source term estimates, an incomplete understanding of the mechanisms by which fluids and contaminants are transported and transformed within the heterogeneous subsurface, an inability to characterize parameters representative of the processes, and the use of models that do not include all of the salient processes. Prediction uncertainty is increased by the strong dependence of the transport regime on moisture conditions, and by the occurrence of highly variable and transient infiltration across the INEEL. The dependence of transport processes on infiltration rate and history implies that specific transformation reactions and rates will take place, and that they will be hysteretic and moisture dependant. The mechanisms by which these coupled processes occur determine the ultimate arrival of contaminants in the SRPA and the associated health risk. Understanding the role of heterogeneity, the coupling between processes, and the influence of transient recharge is a necessary first step in enabling sound environmental management decisions.

Addressing the research and development needs (given in Section 5) to enable more accurate prediction of contaminant behavior will require a multi-scale, interdisciplinary approach centered around defining coupled vadose zone processes at the field-scale (i.e., the scale of the problems). Development of new paradigms to describe the nonideal physical transport and transformation occurring at the INEEL will require observation of discrete and coupled processes in the field. Enabling the field-scale observations will require advances in characterization and monitoring techniques, the development of joint data analysis techniques and new data management tools. These observations will form the basis for alternate conceptual models of contaminant behavior at INEEL sites. The differentiation of competing conceptual models will require experimentation and testing. These experiments range from obtaining better definitions of contaminant sorption parameters developed through traditional laboratory scale experiments through complex coupled process meso-scale experiments with heterogeneity and nonuniform unsaturated flows representative of environmental conditions to field scale manipulations. Advances in numerical simulators and visualization techniques are needed to develop a comprehensive understanding of the coupled processes, to interpret experiments, and to transfer results to field-scale applications. New simulation approaches will link together data from advanced field characterization and monitoring tools obtained through experimentation to yield an integrated representation of the vadose zone and its processes. These simulation approaches can be used to design effective long-term monitoring strategies that ensure that imposed environmental solutions are performing as expected or can identify early deviation from design criteria for prompt and effective remedies.

Predicting transport through INEEL's vadose zone presents extreme challenges in the areas of heterogeneity, process coupling, and extremes in transient infiltration. Lithostratigraphic units at the INEEL include dense, porous, and fractured basalts, rubble zones, and sedimentary materials. Associated with these components are hydraulic properties, mineralogy and microbial populations. In addition to property variation across stratigraphic units, the properties are spatially variable within stratigraphic units. Developing a process based predictive transport model through these media must begin with understanding the role of each of these heterogeneities, and of the behavior of the ensemble at the scale over which transport occurs. The vadose zone at the INEEL is on the order of hundreds of feet thick, and is comprised of many reoccurrent lithostratigraphic sequences. From a purely hydrologic perspective, characterizing these units poses a significant challenge. Viewed as an equivalent porous media, this characterization would at least include saturated hydraulic conductivity, hydraulic constitutive relationships, and porosity in addition to dispersivity and tortuosity. Each of these properties would be representative over a specific volume of geologic media, or representative elementary volume (REV). Viewed at a more fundamental level, the hydraulic transport of fluids is governed by interactions at the pore scale which are characterized by surface tension, pore geometry, and fluid pressure gradients. Hydraulic properties at media interfaces (e.g., between dense basalts and sediments, or sediments and fractured basalts) present another level of interaction, and it is not clear that the interface can be represented as a volume averaged process.

In addition to the heterogeneities affecting fluid migration, variations in lithostratigraphy give rise to variability in geochemical characteristics, and presumably to microbial distributions. The alluvial-, fluvial-, and eolian-derived sedimentary materials are characterized by different mineralogies, as are the materials comprising the basalts, and coatings on fracture faces. Solution chemistry, and available reactive surface area play significant roles in determining the in situ reactions that take place at the mineral surfaces. The solution chemistry is a function of microbial action and specific contaminants. We can hypothesize that the available reactive surface area is directly related to fluid flow paths, and that it would be highly variable depending on recharge conditions. These interactions take place at the pore-scale, or below. Determining the specific reactions can be done at the microscopic scale for each of the media-contaminant combinations, but developing an understanding of the hydraulic controls will require a larger REV. As with the hydraulic properties, defining the appropriate REV has yet to be accomplished.

Infiltration sources and volumes across the INEEL are highly variable and seasonally dependent. Rainfall, snowmelt, streamflows, discharges to spreading areas, and facility waters all contribute to vadose zone transport. The spatial and temporal distributions of recharge across the INEEL have not been well characterized, as a result, the properties that vary as a function of saturation have also not been well characterized. Used to describe volume averaged processes, hydraulic characteristics are nonlinear functions of water saturation, and exhibit hysteretic behavior. Determining hydraulic characteristic parameters for porous media has posed significant investigative challenges to petroleum, geothermal, and environmental scientists for decades. Relationships for fractured media are difficult to obtain, and developing an understanding of the hydraulic constitutive relationships at media interfaces poses an even larger scientific question. Although the hydraulic conductivity is known to be a non-linear function of capillary pressure, and that capillary pressure-saturation relationships are non-linear and hysteretic, their influence on geochemical reactions have not been widely acknowledged. In the highly heterogeneous media underlying the INEEL, the flow of water through fractures, sediments, and basalts is thought to be determined by moisture regime. This implies that the media contacted by contaminants will also depend on water infiltration, and more importantly, on infiltration history. Understanding the role of heterogeneity on contaminant transport, thus, requires a commensurate understanding of the role of infiltration rates and history. The overall complexity of INEEL's vadose zone suggests that physical flow processes and microbial and geochemical processes cannot be viewed independently, and that they should be viewed as coupled.

Developing an understanding of contaminant transport, and the ability to predict it will require investigation at a variety of scales. Investigations include laboratory analyses to determine specific reactions at mineral surfaces, studies to examine processes at media interfaces, and larger volume studies to examine ensemble behavior. Conducting these investigations in a controlled laboratory setting will allow examination of individual and decoupled behaviors, without the sampling and characterization challenges presented by field-scale experiments. Additionally, smaller scale investigation presents the opportunity to develop and test instrumentation for the purposes of characterization and monitoring. The repeatability of carefully controlled experiments will allow the development and testing of process based simulators, and the development of methodologies to obtain process-discrete information for model parameterization. Prior to embarking on field-scale experiments, an understanding of the limits imposed by characterization and monitoring techniques, a means of optimizing data collection and processing, and accurate numerical simulators will be developed. As these tools become available, they will be transferred to the field.

Effective integration of new vadose zone scientific advances into the environmental decision making process requires early and continual involvement of problem holders, regulators, and other stakeholders. Their participation is critical in ensuring that the vadose zone science needs are prioritized relative to their impact on the cost and/or effectiveness of proposed environmental management options. In addition, the relative importance of environmental problems across the various INEEL programs need to be clearly articulated and understood (e.g., the relative importance of contaminant movement at WAG 7 vs. anticipating HLW tank closure at INTEC) to ensure that science resources are focused on high priority needs. Finally, the timing of scientific advances is critically important to their impact. Scientific and technological advances that impact the selection of treatment or stewardship options ideally should be available before the selection is made.

Effective integration of scientific advances into the environmental management process has been demonstrated at the INEEL for the TCE plume in TAN groundwater where the integrated use of science and outside research has resulted in the replacement of the baseline pump and treat solution with more effective in situ approaches. The process developed for TAN can be used as a model for solving problems in the vadose zone at INEEL. This process includes the early involvement of the research community and cleanup managers through open workshops to help translate specific cleanup needs into prioritized science questions. Regularly coordinated meetings and annual stocktaking meetings between scientists and end users at TAN have ensured the timely transfer of results. The environmental managers have served as the interface between responsible agencies and the science community. Furthermore, they have called upon members of the scientific community to support public outreach activities. This advocate role has allowed researchers funded through DOE science programs, such as EMSP, to simultaneously meet the science objectives of the EMSP and provide the high impact results needed to meet the remedial objectives at TAN. Enabling the effective integration of the scientific and end-user communities is the final objective of this plan.

7 NEAR-TERM AGENDA

Across the INEEL, there are many vadose zone sites requiring environmental management. These sites are diverse in terms of lithostratigraphy, hydraulic conditions, and potential contaminants. Management decisions for these facilities will be made over the next several years, and will affect the public for generations. The agenda for these decisions, the complexity of the sites, and regulatory concerns will underly the schedule. Specific short-term agenda items are:

- Prioritization of exiting contaminated sites, future closures, and other environmental management decisions by risk through time. The diversity across the sites, specific regulatory time-frames and requirements will necessitate that the sites be prioritized. Prioritization will allow focusing scientific advances, and will maximize the integration between end-users and the scientific community. Thus, the first step in completing the technical plan will be the review of historical and future decision points and the ranking of sites by risk over time. This is expected to occur during FY 2001-2002.

- Workshops to bring environmental problem holders, stakeholders, regulators, and practitioners together. As stated above, it is imparative that the end-user communities be involved from the beginning to successfully integrate the scientific advances into the management process. The purpose of these workshops will be to initiate open communication, to complete the assessment of analyses limitations and to ensure that the proposed path forward is acceptable to all involved. This is expected to occur during FY 2001-throughout the duration of the project.

- Development of the research agenda. In order for the proposed experimental approach to succeed, the scientific advances must be mutually supportive. Given the overall complexity of vadose zone transport at INEEL, the research agenda will initially focus on the development and testing of instrumentation, sensors, data handling capabilities, and data analyses required to support laboratory-scale investigations. These investigations will include micro-scale determination of geochemical reactions on native materials, and meso-scale experiments to elucidate flow and transport processes through representative INEEL media. Concurrent numerical simulators will be developed and tested to facilitate the use of new information, develop and test research hypotheses, and optimize the simulation process. These controlled experiments and technology development will occur throughout the next five years.

- Field-scale implementation of scientific advances will be required to address the contaminant management issues facing the INEEL. As research tools become available, they will be migrated to the field. The initial developments will occur as sensors are developed and as lithostratigraphic and chemical characterization technologies become available. As these tools collect sufficient data, field-scale experiments will be performed to elucidate flow and transport conditions and to test the hypotheses developed at the meso-scale at field conditions. This is expected to occur throughout the next 10 years, with most of the field-scale manipulative experiments occurring during the second 5 years.

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