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Plans and Practices for Groundwater Protection at the Los Alamos National Laboratory

Committee for the Technical Assessment of Environmental Programs
at the Los Alamos National Laboratory

Nuclear and Radiation Studies Board
Division on Earth and Life Studies

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Reviewers

This report has been reviewed in draft form by persons chosen for their diverse perspectives and technical expertise in accordance with procedures approved by the National Research Council's Report Review Committee. The purposes of this review are to provide candid and critical comments that will assist the institution in making the published report as sound as possible and to ensure that the report meets institutional standards of objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following for their participation in the review of this report:

Jean M. Bahr, University of Wisconsin, Madison
Sue B. Clark, Washington State University, Pullman
David E. Daniel, University of Texas, Dallas
Michael Kavanaugh, Malcolm Pirnie, Inc., Emeryville, California
Frank J. Schuh, Drilling Technology, Inc., Plano, Texas
Bruce M. Thomson, University of New Mexico, Albuquerque
Laura Toran, Temple University, Philadelphia, Pennsylvania

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse, nor did they see the final draft of the report before its release. The review of this report was overseen by Frank Stillinger, Visiting Research Collaborator, Princeton University, and Lloyd A. Duscha, Deputy Director of Engineering and Construction, U.S. Army Corps of Engineers (retired). Appointed by the National Research Council, they were responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the National Research Council.

Preface

The Manhattan Project during World War II led to construction of the world's first atomic weapon at a site near Los Alamos, New Mexico, in 1943. Now designated as the Los Alamos National Laboratory (LANL), the site continues to play key roles in science and defense. Like other Department of Energy (DOE) sites in the nation's nuclear complex, LANL has a legacy of radioactive waste and environmental contamination that can pose a threat to groundwater.

Groundwater is a precious resource in New Mexico. While groundwater protection efforts have been ongoing throughout the site's history, a state-mandated program to ensure groundwater protection began in 1998 with a major study to characterize the site's hydrogeology. Under a Consent Order issued by the New Mexico Environment Department (NMED), the program, including remedial actions as necessary, is to be completed by 2015. At that time, groundwater protection will transition into a phase of environmental stewardship and long-term monitoring.

To help ensure the program's successful completion, the DOE National Nuclear Security Administration (NNSA) turned to the National Academies for advice on scientific and technical aspects of the program through a study funded by the DOE Office of Environmental Management. DOE asked the Academies' study committee to address a series of questions regarding the current state of the program and provide recommendations that would improve its future effectiveness. While confining itself to its task statement, the committee has been aware of citizens' concerns about the quality of the region's groundwater and LANL's ability to protect it. These concerns provided an important context for the committee's deliberations.

The committee is indebted to the many scientists, officials, and citizens who participated in its information-gathering meetings (March, May, and August 2006)[1] and other phases of the study. We would like to recognize several individuals who made special efforts to assist our work:

Mat Johansen, of the Los Alamos Site Office of NNSA, and Jean Dewart, of LANL's Environmental Programs Directorate (EPD), served as the committee's points of contact. Their work in organizing technical presentations and workshop discussions by LANL scientists was central to the committee's information gathering. Donathan Krier, EPD, helped to fulfill the committee's many document requests. Danny Katzman, EPD, organized our visit to the LANL site during our May meeting and was always willing to address our many questions.

The committee was honored to accept an invitation from Governor James Mountain to visit the Pueblo de San Ildefonso in May 2006. The Pueblo is adjacent to the LANL site and on the groundwater flowpath from the site. Neil Weber served as the committee's point of contact with the Pueblo. Marian Naranjo of the Santa Clara Pueblo assisted in the distribution of information about the study to other Pueblos and Native American organizations in New Mexico.

The Northern New Mexico Citizens' Advisory Board (NNMCAB) through its chairman, J.D. Campbell, provided valuable information, assistance, and advice to the

[1] Participants and their presentations are listed in Appendix A.

committee. The committee participated in an NNMCAB groundwater forum meeting at the Dwayne Smith Auditorium in Los Alamos in May 2006.

Robert Gilkeson, a registered geologist, provided the committee much technical material directed at LANL's groundwater monitoring program by a presentation at the committee's May meeting, participation in its August workshop, and written contributions. Joni Arends, of Concerned Citizens for Nuclear Safety, described both technical and public concerns to the committee. She and Mr. Gilkeson jointly responded to committee requests for information regarding radionuclide contamination on the site.

James Bearzi, chief of the NMED Hazardous Waste Bureau, and his staff helped the committee understand the state's role in enforcing groundwater protection regulations and the regulatory requirements set forth in the Consent Order by participating in all of the committee's information-gathering meetings. At the workshop, Richard Meyer described the U.S. Environmental Protection Agency's views and concerns about groundwater protection at LANL.

The committee would also like to thank John Till, Risk Assessment Corporation, and his staff members Justin Mohler and Bruce Jacobs for providing the committee, pro bono, some of the graphical representations of LANL groundwater monitoring data that appear in this report. The committee understands that these representations are based entirely on publicly available data supplied by LANL and that they do not imply any authentication or interpretation of the data by Risk Assessment Corporation.

Most importantly, as chair and vice chair of the committee, we would like to thank all of the committee members for freely sharing their expertise, insights, opinions, and especially their time in the preparation of this report. While never hesitant to express and defend their views, members were unanimous in their spirit of cooperation and objectivity—and in arriving at the report's findings and recommendations. The committee was ably assisted by the staff of the National Academies' Nuclear and Radiation Studies Board. John Wiley, who served as the study director, and Courtney Gibbs, senior program assistant, supported all phases of our work from the initial committee appointment, through its information gathering, report writing, review, and publication of this report. Kevin Crowley, board director, regularly attended our meetings where he shared thoughtful advice and guidance for making this report valuable for policy makers, scientists, and interested members of the public.

Larry W. Lake, Chairman

Rodney C. Ewing, Vice Chairman

Contents

Summary

The world's first nuclear bomb was developed in 1943 at a site near the town of Los Alamos, New Mexico. Designated as the Los Alamos National Laboratory (LANL) in 1981, the 40-square-mile site is today operated by Los Alamos National Security LLC[1] under contract to the National Nuclear Security Administration (NNSA) of the U.S. Department of Energy (DOE). Like other sites in the nation's nuclear weapons complex, the LANL site harbors a legacy of radioactive waste and environmental contamination. Radioactive materials and chemical contaminants have been detected in some portions of the groundwater beneath the site.

Groundwater protection is an important issue because water resources in the LANL area of north-central New Mexico are limited. Seven of Los Alamos County's twelve drinking water supply wells are located on the LANL site. Los Alamos County and the County and City of Santa Fe have water supply wells located along the projected flowpath of groundwater leaving the LANL site. The Pueblo de San Ildefonso[2] also lies on the pathways of the groundwater and the few surface streams that flow from the site to the Rio Grande, which supplies water to much of the state.

Under authority of the U.S. Environmental Protection Agency, the State of New Mexico regulates protection of its water resources through the New Mexico Environment Department (NMED). In 1995 NMED found LANL's groundwater monitoring program to be inadequate. Consequently LANL conducted a detailed workplan to characterize the site's hydrogeology in order to develop an effective monitoring program. A legally binding Consent Order[3] issued by NMED in 2005 establishes requirements and schedules for the monitoring program, which LANL is now developing, as well as a schedule for completing future remedial actions by 2015.

The study described in this report was initially requested by NNSA, which turned to the National Academies for technical advice and recommendations regarding several aspects of LANL's groundwater protection program. The DOE Office of Environmental Management funded the study. The study came approximately at the juncture between completion of LANL's hydrogeologic workplan[4] and initial development of a sitewide monitoring plan. In addressing its statement of task (given in Sidebar 1.1), the committee considered LANL's groundwater protection program to be work in progress. The committee's findings are necessarily a snapshot in time, reflecting publicly available information through about April 2007.

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[1] Los Alamos National Security LLC is a consortium of Bechtel, the University of California, BWX Technologies, and Washington Group International. After competitive bidding, the Department of Energy selected this consortium to operate LANL in December 2005, and the transition was completed in June 2006. See http://lansllc.com/.

[2] The Pueblo de San Ildefonso is a federally recognized Native American tribal government—one of nineteen pueblos still in existence in New Mexico and one of five Tewa-speaking tribes. The Pueblo's 30,271-acre reservation (i.e., Tribal Trust Lands) is located in north-central New Mexico adjacent to the LANL site (see Figure 1.1).

[3] The Order on Consent for Los Alamos National Laboratory, usually referred to as the Consent Order, was signed by NMED, DOE, and the University of California on March 1, 2005.

[4] Los Alamos National Laboratory's Hydrogeologic Studies of the Pajarito Plateau: A Synthesis of Hydrogeologic Workplan Activities (1998-2004) was issued in December 2005.

OVERARCHING FINDINGS

Successful completion of the groundwater protection program will not be easy. The program is challenged by scientific and technical problems in understanding and quantifying LANL's sources of contamination and the migration of contaminants from these sources. Because groundwater is an important resource in the area, citizens are concerned about the dangers of its pollution by LANL. Some citizens' groups seek assurances of essentially zero contamination. Reflecting citizens' concerns, state officials and regulators have imposed strict schedules and detailed regulations (e.g., the Consent Order) on the program.

Regardless of the difficulties that lie ahead, prudence and the law require that a groundwater monitoring system be established. In deliberating on the issues in its task statement, the committee came to the conclusion that it is technically feasible for LANL to establish a monitoring system that meets the groundwater protection requirements of the Consent Order. The findings and recommendations presented in this report are intended to help ensure the efficacy of LANL's work.

There are four overarching findings that arose from the committee's study and that have relevance to essentially all parts of the task statement.

Geochemistry

LANL demonstrated substantial progress in site characterization under the hydrogeologic workplan. However, LANL's work in geochemistry has not kept pace with work in hydrogeology. Geochemistry[5] is central to understanding the extent to which contaminants move with groundwater; it is a tool for better understanding hydrogeologic pathways; and it is essential for determining the degree to which groundwater monitoring samples are representative of actual groundwater.

Mass Balance

LANL needs better ways to demonstrate its considerable understanding—and eventually its mastery—of potential threats to the regional aquifer arising from site contamination. Specifically this means knowing the site's inventory of contaminants and where they are. Most contaminants are evidently still in or near their sources; a sizeable fraction of some have migrated into the vadose zone;[6] and a small fraction are in the regional aquifer. This information can be quantified and presented succinctly by the method referred to as mass balance, which is introduced in Chapter 3.

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[5] Geochemistry is the study of the chemistry of the materials of the Earth including, in this instance, how contaminants interact with these materials.

[6] The vadose zone is the unsaturated region of the Earth's crust that extends vertically from the surface to the water table, as indicated in Color Plate 2.

Uncertainty

LANL's groundwater protection program is proceeding in the face of substantial technical uncertainty—about the contamination sources themselves, pathways by which contaminants might reach potable water, and how contaminants can reliably be detected at near-background levels. Uncertainty is inherent in scientific knowledge, and work to address uncertainty can improve knowledge. LANL needs to do a better job of describing the uncertainties in its groundwater protection program to both scientific and public audiences. This includes fundamental conceptual uncertainty—things that are simply not known, such as the nature of some groundwater pathways—and measurement uncertainty, such as the variability of laboratory results for contaminants detected at very low levels.

Peer Review

The committee was not hesitant to accept LANL's motto: "The World's Best Science Protecting America" at face value. However, like many publications from DOE laboratories, LANL reports typically fall in the area of non-peer-reviewed literature. LANL has produced massive amounts of report material in its groundwater investigations. The additional step of summarizing and publishing key portions as authoritative contributions to peer-reviewed scientific journals, as done with some information from the hydrogeologic workplan (VZJ, 2005), can demonstrate the scientific merit of the program. This in turn can help allay public concerns about LANL's ability to protect their groundwater.

FINDINGS AND RECOMMENDATIONS TO ADDRESS THE TASK STATEMENT

The task statement and the outline of this report generally follow the sequence of issues one would consider in developing a groundwater protection program. The first set of questions to be addressed asked the committee to judge LANL's understanding of its major sources of groundwater contamination and whether these sources have been controlled. The second set asked the committee to judge the scientific basis and scope of LANL's current (interim) groundwater monitoring program and, in particular, if it is adequate to provide early warning and response to potential groundwater contamination from LANL operations. The third set dealt with practicalities of conducting a monitoring program, including whether LANL is using sound scientific practices in assessing the quality of its groundwater monitoring data and if the data are properly qualified so that they can be interpreted correctly.

In several instances, the committee's short answers to these questions were negative. Such findings do not necessarily indicate major deficiencies in LANL's groundwater protection program, but rather that the program is incomplete. Work remains to be done in order to satisfy completely the conditions questioned in the task statement. The committee's recommendations are intended to help LANL increase its effectiveness in completing its groundwater protection program. Chapter 6 of this report provides a complete summary of all of the committee's findings and recommendations, which are developed and described in detail in Chapters 3, 4, and 5.

Sources and Source Controls

Radioactive or chemically hazardous wastes disposed of onsite at LANL are the sources from which contaminants enter the soils, rocks, and water that comprise the hydrogeologic environment beneath the site. The Laboratory has practiced onsite disposal of its wastes since the early 1940s. Disposal methods include the discharge of liquid effluents into canyons and the emplacement of solid wastes, mainly on mesa tops.[7]

In responding to its task statement, the committee found that liquid waste discharges, which LANL considers to be sources of the contamination currently detected in groundwater, are generally eliminated or controlled. Solid wastes and contaminants deemed by LANL to have less near-term potential to impact groundwater have received much less attention—the committee found that they are not well inventoried or controlled.

> ***Recommendations:*** *LANL should complete the characterization of major contaminant disposal sites and their inventories, i.e., complete the investigation of historical information about these disposal sites with emphasis on radionuclides and chemicals likely to impact human health and the environment. Selected sites should be characterized by field analysis when historical information is insufficient to determine quantities of major contaminants disposed and to confirm the degree of transport that has occurred.*
>
> *LANL should devote greater effort to characterizing sources with significant inventories of contaminants (especially plutonium) that usually are considered to be practically immobile but still have the long-term potential to migrate in the presence of water.*

These and other findings and recommendations related to sources and their control are described in Chapter 3.

Contaminant Pathways and the Interim Monitoring Plan

LANL carried out its hydrogeologic workplan from 1998 through 2004 to better characterize the site's hydrogeology and potential pathways for contaminant transport in order to develop the basis for a sitewide groundwater monitoring plan. The committee found that the hydrogeologic workplan was effective in improving characterization of the site's hydrogeology.

The task statement directed the committee to review LANL's current (interim) monitoring plan. In doing so, the committee found that the knowledge gained through

[7] Discharges of gaseous effluents are not considered in this report.

the hydrogeologic workplan does not appear to have been used effectively in the development of the interim monitoring plan (LANL, 2006a,c). The workplan is mentioned only in the introduction of the monitoring plan, and rationale for the siting of new wells in the monitoring plan is not grounded in the scientific understanding of the site evident in the Synthesis Report (LANL, 2005a), which summarized results from the workplan.

> ***Recommendation:*** *LANL should demonstrate better use of its current understanding of contaminant transport pathways in the design of its groundwater monitoring program. Tables in the monitoring plan that give the rationale for locating monitoring wells should include at least a general linkage between the proposed locations and the site's hydrology, or a section discussing the relation between well locations and pathway conceptualization should be added.*

The committee found that LANL's current conceptualization of the site's groundwater system into alluvial, intermediate-perched, and regional components, along with the importance of these components for understanding the flow system within and below wet canyons, are major accomplishments. However, there is a lack of understanding of the *interconnectedness* of subsurface pathways between watersheds. While there is a general understanding that perched waters are probably redirecting contaminants from areas directly below canyons where they originally infiltrate to sub-mesa areas and to other nearby canyons, the detailed knowledge needed to predict subsurface flow paths does not exist.

> ***Recommendation****: LANL should add a sitewide perspective to its future groundwater monitoring plans. This would include the following:*
> - *Design additional characterization, modeling, and geochemical investigations to better understand potential fast pathways between watersheds.*
> - *Increase the area of the regional aquifer that is monitored by drilling more wells to sample the inter-canyon areas underneath the mesas as well as more wells in the canyons.*
> - *Provide additional monitoring locations in the southern area of the site and on Pueblo de San Ildefonso lands.*

These and other findings and recommendations related to contaminant pathways and LANL's current plan for monitoring are described in Chapter 4.

Monitoring and Data Quality

Implementing a monitoring plan involves the practicalities of constructing groundwater wells and analyzing samples from the wells. Any monitoring activity faces a conundrum: If little or no contamination is found, does this mean that there is in fact little or no contamination, or that the monitoring itself is flawed?

In responding to the questions asked in the statement of task, which dealt with data quality issues, the committee found that LANL is using good practices in terms of having the proper quality assurance and quality control (QA/QC) plans and documentation in place, but falls short of consistently carrying out all the procedures cited in the plans. Results of analyzing groundwater samples often do not carry the proper qualifiers according to good QA/QC practices. This especially applies to analytical results near or below the limits of practical quantitation and detection, near the natural background, or both. The difficulty here is that reported detection of contamination that is not statistically significant may be taken as real by regulators and other stakeholders—with concomitant concerns and calls for remedial actions.

> ***Recommendations:*** *LANL should ensure that measurements of contaminants at concentrations that are at or near background levels or near analytical detection limits (i.e., Method Detection Limits and Practical Quantitation Levels) are performed and reported in ways that are scientifically and statistically sound.*
>
> *The LANL site office of DOE should take steps to ensure that LANL and site regulators agree on how all such data are to be handled, compiled, and reported.*
>
> *LANL should make more effort to ensure that data uncertainties are made clear to public stakeholders.*

During this study the committee was presented with information indicating that many wells into the regional aquifer at LANL (R-wells) are flawed for the purpose of monitoring. The committee did not disagree, but rather found a lack of basic scientific understanding of the subsurface geochemistry that could help ensure future success. Evidence about the conditions prevalent around the sampling points (screens) in the compromised wells is indirect—relying on plausible but unproven chemical interactions around the screens, general literature data, analyses of surrogates, and apparent trends in sampling data that may not be statistically valid.

The committee received little scientific information—for example, on a par with LANL's publications about vadose zone pathways (VZJ, 2005)—regarding the geochemical behavior of contaminants in the subsurface or effects of non-native materials (drilling fluids, additives, construction materials) on the geologic media to be sampled. Data from scientifically vetted (peer-reviewed) studies are necessary to authoritatively address concerns and uncertainties about how drilling and well completion processes might alter the native conditions around well screens and to ensure reliable monitoring activities in the future.

> ***Recommendation:*** *LANL should plan and carry out geochemical research on the interactive behavior of contaminants, materials introduced in drilling and well completion, and the geologic media. As a part of LANL's future plans for sitewide monitoring, laboratory and field work would include:*
>
> - *Determining the nature of interactions among materials proposed for use in constructing monitoring wells and the types of geological media that LANL intends to monitor,*
> - *Quantitative measurement of sorption or precipitation of contaminants onto the natural, added, and possibly altered constituents that would constitute the sampling environment of a monitoring well, and*
> - *Publication of results in peer-reviewed literature.*

The committee is not recommending open-ended research. Rather the work would underpin plans for future monitoring of specific areas of the site: contaminants of greatest concern in the area; geologic media expected to be sampled; and drilling fluids, additives, and other materials intended to be used in constructing the monitoring well(s).

These and other findings and recommendations related to the implementation of groundwater monitoring at LANL are described in Chapter 5.

CLOSING COMMENTS

LANL's groundwater protection program is at about its temporal midpoint, continuing for another eight years until 2015. The Consent Order establishes an enforceable process and schedule for the program. The committee hopes that the assessments, findings, and recommendations presented in this report will be useful in informing future technical decisions that will be made within the Consent Order process.

1
Introduction

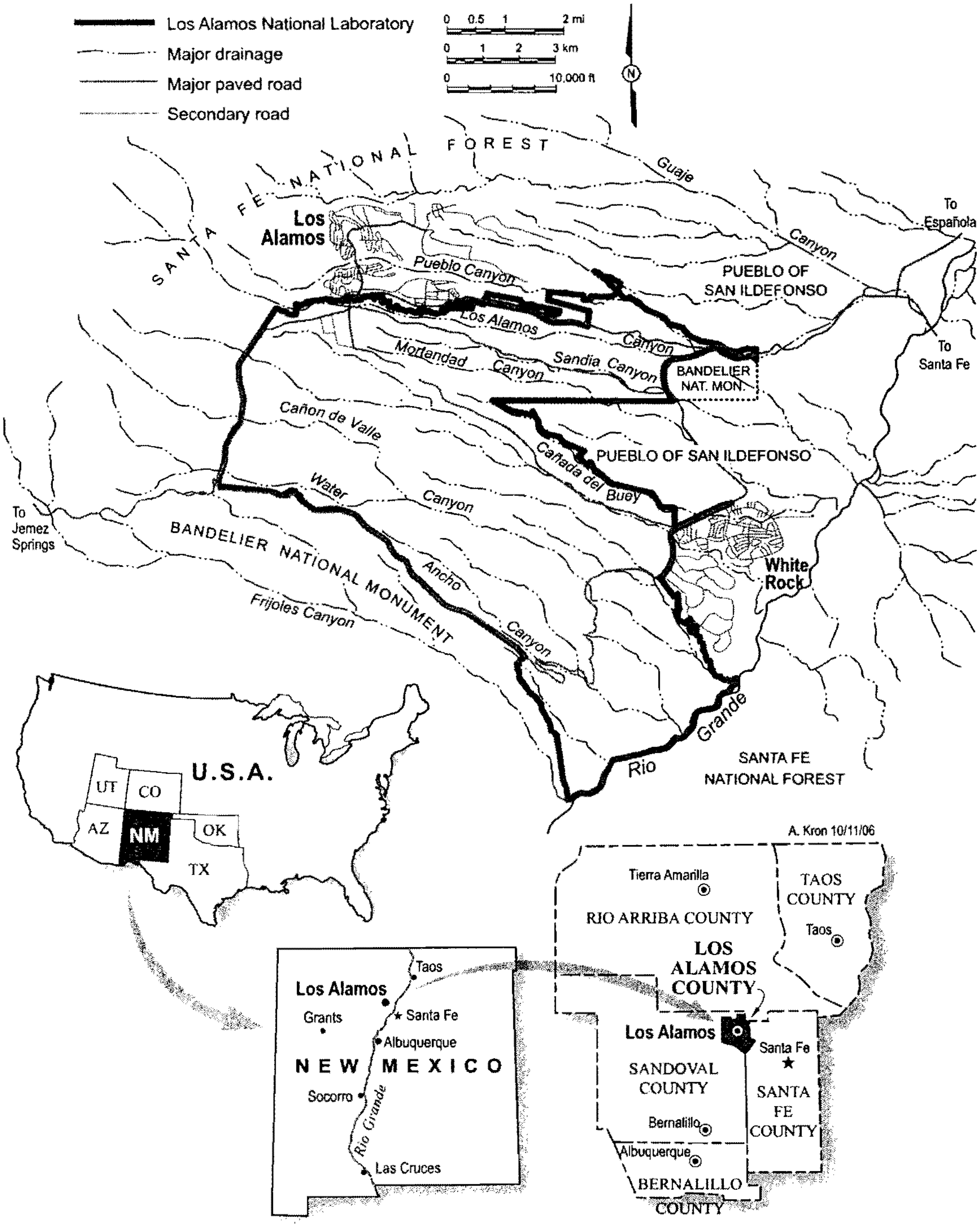
Operations at the Los Alamos site in northern New Mexico began in 1943 under the Manhattan Project. That project led to the world's first nuclear bomb, which was successfully tested in 1945. In view of its continuing missions in national security and basic research, the original Los Alamos Laboratory became the Los Alamos Scientific Laboratory in 1947. Designated as Los Alamos National Laboratory (LANL) in 1981, the site is operated by Los Alamos National Security LLC[1] under contract to the National Nuclear Security Administration (NNSA) of the U.S. Department of Energy (DOE).

Like those at other sites in the nation's nuclear weapons complex, LANL's operations created a legacy of radioactive waste and environmental contamination, which is now being addressed by DOE (DOE, 1997). At LANL, liquid wastes were generally discharged into canyons, and solid wastes were buried in several locations, mostly in high mesas. Radionuclide and chemical contamination has been detected in some portions of the groundwater beneath the site.

Under authority of the U.S. Environmental Protection Agency (EPA), the State of New Mexico regulates protection of its water resources through the New Mexico Environment Department (NMED). NMED has recently issued an Order on Consent for Los Alamos National Laboratory[2] that establishes schedules for additional investigations that will lead to a corrective action decision under the Order. New Mexico citizens and citizens' groups are also actively involved in environmental issues at LANL. The Pueblo de San Ildefonso,[3] Los Alamos County, and the County and City of Santa Fe have water supply wells located in the projected pathway of groundwater leaving the LANL site, and, as a consequence, their citizens have a long-term interest in the quality of groundwater (see Figure 1.1).

The committee's study came at an important juncture in LANL's groundwater protection program—beginning shortly after LANL completed an extensive program to characterize the site's hydrogeology[4] and continuing concurrently with LANL's initial planning for sitewide groundwater monitoring. The study was funded by the DOE Office of Environmental Management. The Los Alamos site office of NNSA requested the study and served as the DOE liaison. NNSA also requested the committee to prepare an interim status report, which described the information-gathering phase of the study but contained no findings or recommendations. The interim report was issued in fall 2006.[5]

[1] Los Alamos National Security LLC is a consortium of Bechtel, the University of California, BWX Technologies, and Washington Group International. After competitive bidding, the Department of Energy selected this consortium to operate LANL in December 2005, and the transition was completed in June 2006. See http://lansllc.com/.
[2] Usually referred to as the Consent Order. This legally binding agreement among NMED, DOE, and the University of California was signed on March 1, 2005.
[3] The Pueblo de San Ildefonso is a federally recognized Native American tribal government—one of nineteen pueblos still in existence in New Mexico and one of five Tewa-speaking tribes. The Pueblo's 30,271-acre reservation (i.e., Tribal Trust Lands) is located in north-central New Mexico adjacent to the LANL site (see Figure 1.1).
[4] Los Alamos National Laboratory's Hydrologeologic Studies of the Pajarito Plateau: A Synthesis of Hydrogeologic Workplan Activities (1998-2004), issued December 2005.
[5] See http://books.nap.edu/catalog.php?record_id=11781.



Source: Andrea Kron, LANL

FIGURE 1.1 Location of Los Alamos National Laboratory in northern New Mexico. The site is traversed by numerous canyons, such as Mortandad Canyon, which has been studied extensively. Groundwater flow is generally from west to east toward Pueblo de San Ildefonso lands and the Rio Grande.

THE COMMITTEE'S TASK

The statement of task for this study is shown in Sidebar 1.1. The first two subsets of tasks direct the committee to provide answers to questions regarding LANL's knowledge of potential sources of groundwater contamination and aspects of its monitoring program. The last subset of the task statement asks for the committee's recommendations.

During the committee's information gathering (see Appendix A), LANL representatives paraphrased portions of the task statement to emphasize issues of greatest interest to the Laboratory and to DOE, as follow (Dewart, 2006):

- Do we [LANL] understand and have we controlled our sources of groundwater contamination?
- Are we adequately addressing issues of groundwater data quality?
- Is our groundwater monitoring approach effective in identifying contaminants that may migrate at unacceptable levels to public receptor locations?

At the study's beginning the committee recognized that water is a precious resource in northern New Mexico, and citizens of that state are very concerned that their water supplies be protected. The LANL site itself is located on lands historically occupied by Native Americans and immediately adjacent to several active pueblos. While confining its deliberations to technical issues, the committee included citizens' concerns in its information gathering and kept their concerns in mind as it considered its task.

The committee also recognized that LANL is legally bound to meet milestones specified in the Consent Order with NMED, which requires the Laboratory to evaluate and remediate, as necessary, contamination in the groundwater by about 2015. The task statement does not ask the committee to address or comment on the Consent Order, and it has not done so.[6] However, meeting the Order's provisions is strongly influencing LANL's groundwater investigations, plans for monitoring, and future remediation decisions. The committee requested and received two presentations from NMED about the Order, which is described in Chapter 2.

The committee considered its task to be a review of work in progress. Findings and recommendations are provided from this perspective. At the beginning of the committee's first meeting, Mat Johansen, NNSA liaison to the committee, stated that LANL's groundwater protection program is at about its temporal midpoint (see Figure 1.2). Significant source control measures began in the late 1990s and, under the Consent Order, the program is to be completed by about 2015—with continuing long-term monitoring and site stewardship. While observing that LANL has made great progress, the committee also recognizes that considerable work remains.

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[6] The committee was also aware that radioactive materials at DOE sites, including LANL, are regulated by DOE, whereas the Environmental Protection Agency has given the State of New Mexico authority to regulate toxic and chemically hazardous materials, as described in Chapter 2. In their meetings with the committee, DOE and LANL representatives did not raise this legal distinction as an issue for the committee's delibrations.

SIDEBAR 1.1
Statement of Task

This study will focus on specific scientific and technical issues related to groundwater monitoring and contamination migration at LANL as follow:

1. General review of groundwater protection at LANL:

   What is the state of the laboratory's understanding of the major sources of groundwater contamination originating from laboratory operations and have technically sound measures to control them been implemented?

   Have potential sources of non-laboratory groundwater contamination been identified? Have the potential impacts of this contamination on corrective-action decision making been assessed?

   Does the laboratory's interim groundwater monitoring plan follow good scientific practices? Is it adequate to provide for the early identification and response to potential environmental impacts from the laboratory?

   Is the scope of groundwater monitoring at the laboratory sufficient to provide data needed for remediation decision making? If not, what data gaps remain, and how can they be filled?

2. Specific data-quality issues:

   Is the laboratory following established scientific practices in assessing the quality of its groundwater monitoring data?

   Are the data (including qualifiers that describe data precision, accuracy, detection limits, and other items that aid correct interpretation and use of the data) being used appropriately in the laboratory's remediation decision making?

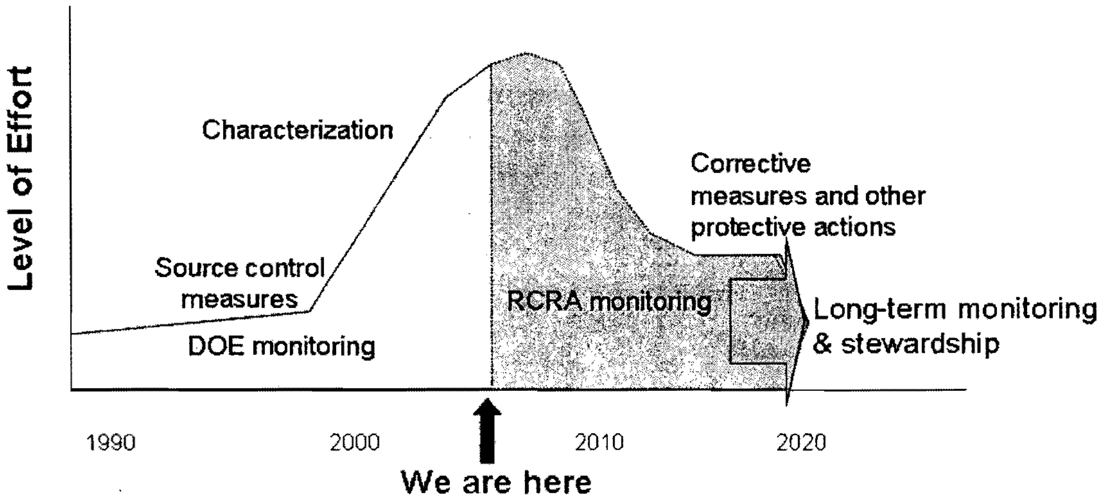
3. Recommendations to improve the future effectiveness of the laboratory's groundwater protection program with respect to:

   Potential remedial actions for the groundwater contamination, especially for radionuclide contamination for which DOE is self-regulating; and

   Monitoring for long-term stewardship.

OVERVIEW OF THIS REPORT

This report is organized according to the sequence of activities that one might consider in developing a groundwater protection program. Chapter 2 describes the technical, legal, and public issues that frame the program. Chapter 3 addresses sources of contamination and the degree to which they are accounted for and controlled. Chapter 4 describes hydrogeologic pathways along which contaminants might move from their sources eventually into a water supply and evaluates LANL's Interim Plan to monitor those pathways. Chapter 5 addresses monitoring activities themselves—well drilling, sampling, sample analysis, and data quality. Each chapter addresses parts of the task



Source: Johansen, 2006

FIGURE 1.2 LANL groundwater protection activities over time. DOE and LANL are at about the halfway point in establishing the groundwater protection program. In preparing this report, the committee considered the program to be work in progress. The committee's findings and recommendations are intended to assist DOE and LANL to complete the program by 2015 as required by the Consent Order.

statement and includes findings and recommendations. Chapter 6 summarizes all of the committee's findings and recommendations.

In the course of this study the committee developed some general observations that bear on the groundwater protection program. These observations are summarized below and presented in greater detail throughout this report.

LANL learned a great deal during its Hydrogeologic Workplan, which was carried out from 1998 through 2004 to develop sufficient information to begin site monitoring (LANL, 1998, 2005a). Work in geochemistry has not kept pace with this work in hydrogeology.[7] Geochemical studies applied to LANL's groundwater protection program would address how contaminants' interactions with natural and anthropogenic materials affect their transport by groundwater—they may move freely with the groundwater or be retained to a greater or lesser extent by materials along the groundwater pathways. Geochemical interactions affect contaminant migration from sources (Chapter 3), along groundwater pathways (Chapter 4), and in monitoring wells (Chapter 5).

A second observation is that LANL needs better ways to demonstrate its considerable knowledge of the groundwater system—ways that are both scientifically meaningful and reassuring to citizens. Introduced in Chapter 3, the use of mass balance

[7] Water is responsible for the migration of contaminants in the environment. Hydrogeology is the study of groundwater behavior in the subsurface. Geochemistry is the study of the chemical processes and reactions of materials of the Earth, and in this case would include how contaminants interact with these materials and groundwater.

and the careful representation of uncertainties are two recurring themes throughout this report. Mass balance analyses, with estimates of data uncertainties, can be used to account for contaminant sources, releases, radioactive decay, and migration through the hydrogeologic system.

More generally, there are needs and opportunities for LANL to present more of its groundwater protection work in peer-reviewed literature. Peer-reviewed publication is the standard of science. LANL has produced massive amounts of report material, and the additional step of summarizing and publishing key portions, as it did with much information from the Hydrogeologic Workplan (VZJ, 2005), can help authenticate LANL's groundwater protection program. LANL's motto—"The World's Best Science Protecting America"—is clearly applicable to groundwater protection.

2
Framework for Groundwater Protection at LANL

Los Alamos National Latoratory's (LANL's) groundwater protection program is framed by technical difficulties associated with the complex hydrogeology of the Pajarito Plateau, regulatory mandates for conducting the program, and citizens' concerns about the program's adequacy. This chapter provides an overview of these issues to provide a context for the remainder of this report.

Studies of groundwater beneath the LANL site have been ongoing throughout the site's history. The U.S. Geological Survey began this work in 1945, and in 1949 the site initiated studies to monitor and protect its groundwater quality. A court decision in 1984 extended the Environmental Protection Agency's (EPA's) authority under the Resource Conservation and Recovery Act (RCRA) to regulate chemically hazardous waste at DOE sites. In 1986 EPA clarified its jurisdiction for mixed waste (waste that contains both chemically hazardous and radioactive constituents) and determined that states must include mixed waste in RCRA authorizations.[1] The EPA and the New Mexico Environment Department (NMED) issued LANL an operating permit in 1989, which required monitoring of RCRA-regulated facilities.

In 1995 NMED notified LANL that there was insufficient information about the site's hydrogeologic setting upon which to base approval of a waiver from its groundwater monitoring requirements. LANL developed a Hydrogeologic Workplan (LANL, 1998) to refine its understanding of the site's hydrogeology in order to design an effective monitoring network. NMED approved the workplan in 1998, and it was completed on schedule in 2004. In 2005 NMED issued an Order on Consent for Los Alamos National Laboratory[2] that establishes schedules for additional investigations that will lead to a corrective action decision under the Order.

The committee's study approximately coincided with the publication of a major report (LANL, 2005a), which described LANL's site characterization activities under the Hydrogeologic Workplan, and the development of LANL's 2006 Integrated Groundwater Monitoring Plan (LANL, 2006a). LANL developed the monitoring plan according to legal requirements set forth in the Consent Order.

TECHNICAL CHALLENGES CONFRONTING LANL'S GROUNDWATER PROGRAM

The Laboratory's current understanding of the hydrogeology beneath the site is summarized in Sidebar 2.1. In brief, the site is very heterogeneous with both fast and slow pathways that may serve to transport contaminants from the surface to the groundwater. Groundwater itself occurs in three modes: near-surface groundwater in canyon alluvium, intermediate-perched groundwater in the vadose zone, and groundwater in the regional aquifer beneath the water table. Surface water, e.g., streams, runoff, can

[1] See http://www.epa.gov/radiation/mixed-waste/mw_pg4.htm
[2] Usually referred to as the Consent Order. This legally binding agreement among NMED, DOE, and the University of California was signed on March 1, 2005.

redistribute contaminants on the surface, move them into the near-surface groundwater, or transport them offsite toward the Rio Grande. Color Plates 1 and 2 illustrate these general hydrogeological features. Note that the vadose zone is the unsaturated region that extends vertically from the surface to the water table, as depicted at the back of the cross section.

SIDEBAR 2.1
Overview of the LANL Site's Geological and Hydrological Setting

Los Alamos National Laboratory occupies about 40 square miles of the Pajarito Plateau in north-central New Mexico, approximately 60 miles north-northwest of Albuquerque and 25 miles northwest of Santa Fe, as shown in Chapter 1, Figure 1.1. The Plateau is located within the Española Basin of the Rio Grande Rift, a major North American tectonic feature; see Color Plate 1. The Española Basin, as well as the Pajarito Plateau on its western edge, is filled with Miocene and Pliocene-age sediments and volcanic rocks. The topographic plateau is bounded to the west by the Pajarito fault zone. The Pajarito Plateau is formed by Pleistocene Bandelier Formation ash-flow tuffs from the Jemez volcanic field, which cover older volcanic units and the basin-fill sediments.

The Laboratory site is interlaced with finger-like mesas separated by deep west-to-east oriented canyons cut by streams. Mesa tops range in elevation from approximately 7800 feet on the flanks of the Jemez Mountains to about 6200 feet near the Rio Grande Canyon. Most of the mesas in the Los Alamos area are formed from Bandelier Tuff (Color Plate 2), which includes ash fall, ash fall pumice, and rhyolitic ash-flow tuff. Deposited by major eruptions in the Jemez Mountains' volcanic center 1.2 million to 1.6 million years ago, the tuff is more than 1000 feet thick in the western part of the plateau and thins to about 260 feet eastward above the Rio Grande.

On the western part of the Pajarito Plateau, the Bandelier Tuff overlaps onto the Tschicoma Formation, which consists of older dacitic volcanics that form the Jemez Mountains. The tuff is underlain by the fanglomerate of the Puye Formation in the central plateau. Near the Rio Grande, the Bandelier Tuff is underlain by the Cerros del Rio basalts. These formations overlie the sediments of the Santa Fe Group, which extend across the Rio Grande Valley and are more than 3300 feet thick.

Natural surface water in the Los Alamos area occurs primarily as short-lived stormwater or snowmelt runoff and in short ephemeral segments draining the uplands in the western portion of the Pajarito Plateau. Effluent from Laboratory and Los Alamos County operations also feeds the reaches of some streams. Perennial springs on the flanks of the Jemez Mountains supply base flow into the upper reaches of some canyons, but the volume is insufficient to maintain surface flows across the Laboratory site before the water is depleted by evaporation, transpiration, and infiltration.

The site can be considered as having four hydrogeologic settings, as illustrated in the foreground of Color Plate 2, and described in Table 2.1. These settings range from the normally dry mesa tops to the regional aquifer. Surface water and alluvial groundwater provide pathways for LANL-derived

SIDEBAR 2.1 continued

contaminants introduced into canyons to migrate significant lateral distances. Stormwater and snowmelt are the dominant transport mechanisms for contaminants that are adsorbed to sediment, and the natural and effluent-supported "baseflow" conditions are most important for migration of contaminants in solution. Below the surface, groundwater occurrs as: (1) water in shallow alluvium in canyons, (2) perched water (a body of groundwater above a less permeable layer that is separated from the underlying main body of groundwater by an unsaturated zone), and (3) the regional aquifer (depicted in Color Plate 2 as the saturated zone beneath the water table).

Flow and transport of water in the vadose zone varies by rock type. Most of the plateau is covered with nonwelded to moderately welded Tshirege and Otowi Member ash-flow tuffs of the Bandelier Tuff. Unsaturated flow and transport through these nonwelded to moderately welded tuffs occurs predominantly through the porous matrix. On the western edge of the plateau, both fracture and matrix- dominated flow can occur, depending on the degree of welding of the tuff. In contrast to the flow behavior in the Bandelier Tuff units, groundwater flow in basalts occurs both as porous flow through breccia zones and as fracture flow where dense flow interiors are broken by interconnected fracture systems.

Beneath the Pajarito Plateau, perched water bodies in the vadose zone may be important components of subsurface pathways. Depending on the geometry and hydrologic properties of perching layers, water within perched zones may be relatively stagnant or may flow laterally. It is postulated that saturated lateral flow along perching layers may facilitate movement of contaminated fluids toward the water table if the water is diverted laterally from an area with matrix-dominated flow (such as in porous tuff or brecciated basalt) to an area with fracture-dominated flow (such as in a dense, but fractured, basalt). Perched water is most often found in Puye fanglomerates, the Cerros del Rio basalt, and units of the Bandelier Tuff.

The regional aquifer beneath the Pajarito Plateau is part of an aquifer that extends throughout the Española Basin (an area roughly 6000 km^2). This aquifer is the primary source of water for the Laboratory; the communities of Santa Fe, Española, Los Alamos, and White Rock; and numerous pueblos. The sources of recharge to that portion of the regional aquifer beneath the Laboratory are diffuse recharge in the Sierra de los Valles and focused recharge from wet canyons on the Pajarito Plateau, as indicated in Color Plate 2. Natural discharge from the regional aquifer is primarily into the Rio Grande directly or to springs that flow into the Rio Grande. Flow modeling simulations also suggest that flow beneath the Rio Grande (west to east) may be induced by production at the Buckman wellfield just east of the Rio Grande, which supplies the city of Santa Fe. The aquifer is under water-table conditions across much of the Plateau, but exhibits more confined aquifer behavior near the Rio Grande. Hydraulic properties are highly heterogeneous and anisotropic, with vertical hydraulic conductivities much less than horizontal hydraulic conductivities, resulting in a muted response at the water table to supply-well pumping at greater depths.

SIDEBAR 2.1 continued

Imprinted on the natural variations in chemistry along flowpaths is the presence of contaminants historically released since the early 1940s when Laboratory operations began. The impacts to groundwater at the Laboratory have occurred mainly where effluent discharges have caused increased infiltration of water. The movement of groundwater contaminants is best seen through the distribution of conservative (non-sorbing) species. Under many conditions contaminants like chromate, nitrate and residues of high explosives, tritium, and perchlorate move readily with groundwater. For some compounds or contaminants (americium, barium, cesium, plutonium, strontium-90, uranium, some high-explosive compounds, and solvents), movement can be slowed considerably or their concentrations decreased by adsorption or cation exchange, precipitation or dissolution, chemical reactions like oxidation/reduction, or radioactive decay.

Sources: Excerpted and modified from LANL, 2005a, p. 1-1 and LANL, 2005b, p. 22.

Table 2.1 summarizes the site's hydrological settings beginning at the mesa tops, where most sources of contamination are located, downward to the regional aquifer. The regional aquifer, which furnishes drinking water for residents of northern New Mexico, is relatively deep (approximately 1000 feet). Under the Hydrogeologic Workplan, 25 wells into the regional aquifer and 6 intermediate-zone wells were completed for hydrogeologic characterization (LANL, 2005a, p. 1-1).

Technical and programmatic challenges encountered in drilling and completing these characterization wells are documented in a history of the drilling program that was released by LANL in December 2006 (Nylander, 2006).[3] While drilling a 1000-foot-deep well is not especially problematic—the petroleum industry routinely drills wells that are miles deep—the often conflicting requirements for data gathering at multiple depths both during drilling and after completion, drilling with little or no fluids ("muds")[4] to avoid changing the natural conditions around the borehole, and schedule and budget constraints made the work difficult. Compromise solutions to meet these requirements led to controversies about the quality and reliability of data provided by these wells (DOE, 2005; Ford et al., 2006; Ford and Acree, 2006; Gilkeson, 2006a,b).

Aware of the challenges in carrying out the Hydrogeologic Workplan, LANL sought and received independent technical advice. Early in the program, LANL commissioned Schlumberger[5] to review LANL's drilling methods and management. In general the review (Schlumberger, 2001) recommended that LANL develop better knowledge and use of industry practices.

[3] C.L. Nylander, History of Drilling and Well Construction Decision-Making for Los Alamos National Laboratory's Hydrogeologic Characterization Program and Groundwater Protection Program 1995-2006.
[4] Drilling fluids are used to lubricate the drill bit, remove cuttings, and stabilize the borehole, see Chapter 5.
[5] Schlumberger is an international oilfield and information services company. The report "Evaluation of Environmental Drilling Program at Los Alamos National Laboratory" was received by LANL in July 2001.

TABLE 2.1 Hydrogeologic Settings at the Los Alamos National Laboratory

Region	Subregion	Location	Characteristics
MESAS	Dry mesas	Bandelier Tuff, eastern part of Laboratory	1. Low rainfall, high evaporation, efficient water use by vegetation. 2. Net infiltration rates for dry mesas are less than 10 mm/yr and typically on the order of 1 mm/yr or less. 3. Enhanced air circulation through the mesas may enhance evaporation within the mesa interior, limiting downward moisture movement.
	Wet mesas	Bandelier Tuff, western part of Laboratory	1. Higher rainfall and increased welding of the tuff, compared to mesas on eastern part of Laboratory. 2. Transient zones of higher saturation, related to fractures and lithologic variations. 3. Increased potential for vertical transport of water and solutes compared to dry mesas. 4. Some evidence of fast fracture flow with slow transport through the matrix.
	Disturbed mesas	Liquid waste disposal, asphalt covers, devegetation	1. Rainfall and liquid disposal could cause leaching. 2. Investigations indicate limited vertical transport of water and solvents.
	Perched water tables	On lithologic interfaces within the unsaturated zone	1. Potential storage of water and solutes.
ALLUVIUM	NA	Unconfined, perched on underlying Bandelier Tuff, Cerros del Rio basalts, or Puye Formation	1. Historical or current anthropogenic liquid discharges combined with runoff. 2. Source of recharge to underlying intermediate, perched zones and to the regional aquifer. 3. Seasonal water tables (highest in late spring from snowmelt runoff and mid- to late summer from thunderstorms). 4. Percolation from the alluvial groundwater might occur as saturated flow, which could rapidly transport solutes to the underlying intermediate or regional groundwater.
INTERMEDIATE-PERCHED	NA	Beneath major canyons and in the western part of the Laboratory	1. Lateral extent and volumes of saturated zones uncertain. 2. May provide flow and transport paths from beneath one canyon to another.
REGIONAL AQUIFER	NA	Beneath entire site	1. Significant heterogeneity and anisotropy. 2. Receptors associated with water supply wells, springs.

Sources: LANL, 2005a, Sections 2.3 (geologic), 2.5 (alluvial), 2.6 (vadose zone), 2.7 (perched), and 2.8 (regional); LANL, 2005c; and LANL, 2006c, Appendix A, which lists (in tabular form) conceptual model elements for each watershed at LANL.

An External Advisory Group (EAG; Anderson et al., 2005) commissioned by LANL held semi-annual meetings with LANL personnel and stakeholders from 1998 to 2003 and close-out meetings in 2004 and 2005. The EAG's final report emphasized the need to develop sitewide hydrogeological models, noting that:

> "LANL will never have enough field data to 'fill the gaps' (i.e., to integrate and interpolate) or to answer the most important questions (i.e., to predict [migration]) directly through sampling" (Anderson et al., 2005, p. 7).

While the EAG judged that modeling activities conducted under the Hydrogeologic Workplan were less directed at developing a monitoring plan than initially envisioned, sufficient data currently were available to do so. The EAG suggested beginning with simpler models and integrating them.

In its final report, the EAG was generally complimentary of LANL's progress under the workplan. In remarking on LANL's accomplishments and on the complexity of the site's hydrology, the EAG stated that "the many findings help unscramble the omelet that is the Pajarito Plateau" (Anderson et al., 2005, p. 2).

In approaching this study, the committee recognized that the technical issues confronting LANL's groundwater protection program have a long history and are complex. This study is clearly not the first time that LANL has sought independent technical advice. The study, however, comes at a critical juncture as LANL moves from site characterization under the workplan to establishing its groundwater monitoring program.

STAKEHOLDERS' CONCERNS ABOUT GROUNDWATER PROTECTION AT LANL

The term "groundwater protection" is prominent in the committee's task statement (see Chapter 1, Sidebar 1.1). During the committee's early deliberations, several members raised the question of what exactly is meant by the term. It appeared that DOE, its regulators, and public stakeholders had different views of what would constitute groundwater protection at LANL.

Accordingly, for its third meeting[6] the committee organized part of its plenary session around the questions: "What constitutes groundwater protection?" and "What should be the objectives of LANL's groundwater protection program?" Representatives from six organizations were invited to give five- to seven-minute commentaries on these questions and then participate in a question and answer session, which was open to all attendees. Invited organizations were selected by the committee to reflect a variety of viewpoints, based on their participation in the earlier meetings and advice from the Northern New Mexico Citizens' Advisory Board (NNMCAB). The viewpoints presented are summarized in Sidebar 2.2.[7]

The committee considered these views on groundwater protection in approaching

[6] Appendix A gives a list of committee meetings and presentations to the committee.

[7] Sidebar 2.2 was presented in the committee's Interim Report (NRC, 2006), which summarized the committee's information-gathering meetings.

its task statement. More importantly, the committee hopes that further discussion of these fundamental questions by LANL, its regulators, and public stakeholders will help promote agreement on what LANL's groundwater protection program should accomplish.

SIDEBAR 2.2
Stakeholder Perspectives on Groundwater Protection

Concerned Citizens for Nuclear Safety (CCNS)
Groundwater protection is very basic and simple. It means:

- Protecting water supplies now and in the future;
- Collecting representative groundwater samples in compliance with the Clean Water Act and the Resource Conservation and Recovery Act;
- Imposing fines for facilities that are not in compliance with the law;
- Having answers to questions about where contaminants are going;
- Considering and including wastes buried in unlined pits, trenches, and shafts in monitoring and remediation programs; and
- Removing sources of contamination.

Department of Energy-National Nuclear Security Agency (DOE-NNSA)
Groundwater protection is achieved by meeting specific requirements that are spelled out in:

- The NMED Order on Consent for the Los Alamos National Laboratory;
- New Mexico Water Quality Control Commission (WQCC) regulations; and
- DOE Orders.

DOE requires maintaining groundwater quality adequate for its highest beneficial use, which DOE considers to be extraction of drinking water from the regional aquifer.

Environmental Protection Agency (EPA)
EPA's standards and policies for groundwater protection include the following:

- Meet appropriate cleanup standards as determined by a site-specific risk assessment. EPA standards range from one excess cancer in 10,000 exposed people to one excess cancer in 1 million exposed people (i.e., a risk range of 10^{-4} to 10^{-6}).
- Address all exposure points from groundwater, such as groundwater to surface water, groundwater to springs, or indoor inhalation of contaminants from groundwater (e.g., radon).
- Be flexible in the cleanup standards according to usage classification of the water (e.g., residential, industrial, farming) and the natural quality of the groundwater itself.

SIDEBAR 2.2 continued

New Mexico Environment Department (NMED)
What constitutes groundwater protection at LANL is specified in the:

- New Mexico Water Quality Act;
- New Mexico WQCC Regulations; and
- the Order on Consent for Los Alamos National Laboratory.

According to both the WQCC regulations and the Consent Order, "groundwater" means interstitial water that occurs in saturated earth material and which is capable of entering a well in sufficient amounts to be used as a water supply. The WQCC regulations include the notion of groundwater that can be "reasonably expected to be used in the future" and states that risk from a toxic pollutant must not exceed one cancer per 100,000 exposed persons. The Consent Order requires cleanup of groundwater when the lower of either WQCC standards or EPA maximium contaminant levels (MCLs) is exceeded.

Northern New Mexico Citizens' Advisory Board (NNMCAB)
Contamination at LANL arose in the context of ensuring the nation's nuclear security. Similar commitment and continuity in monitoring and site remediation is required, including:

- Monitoring and detecting trace-level contaminants in order to anticipate significant migrations.
- Improving flow models. (Must understand groundwater flows because the only alternative is to remove the sources, which would be very difficult.)
- Taking a very long-term perspective, perhaps 2000 years. Such long times are unique—beyond our experience. Models that can reliably predict contaminant behavior over such times are necessary. Be prepared for surprises and incorporate uncertainty in models.
- Following a risk-informed decision process.

Pueblo de San Ildefonso
Land, air, and water are sacred. They must be viewed holistically, so that groundwater cannot be separated from the others. LANL occupies the ancestral domain of San Ildefonso.

- All environmental media have been contaminated by LANL activities;
- Contamination violates the sanctity of religious and cultural resources; and therefore,
- Contamination at any level is unacceptable.

SIDEBAR 2.2 continued

Los Alamos National Laboratory
LANL summarized its goals for groundwater protection during the opening session of the plenary, as follow (Dewart, 2006):

- Demonstrate compliance with applicable standards and regulations;
- Protect the drinking water supplies of surrounding communities;
- Protect the quality of groundwater moving from LANL to offsite locations; and
- Protect the quality of water in springs and the Rio Grande.

THE REGULATORY FRAMEWORK FOR GROUNDWATER PROTECTION AT LANL—THE CONSENT ORDER

Radioactive and hazardous waste management is a complex issue, not only because of the nature of the waste, but also because of the complicated regulatory structure for dealing with it. There are a variety of stakeholders affected, and there are several regulatory entities involved. Federal government agencies involved in radioactive waste management include the Department of Energy (DOE), the Environmental Protection Agency, the Nuclear Regulatory Commission (USNRC), and the Department of Transportation.[8] In addition, these federal agencies may share or designate portions of their authorities to the states.

The Atomic Energy Act (42 U.S.C. Sect. 2011-Sect. 2259) (AEA) delegates the regulation of nuclear energy primarily to DOE, the USNRC, and the EPA. DOE authority extends to source material, special nuclear material, and byproduct material containing radioactive components. With respect to byproduct material, DOE issued a final rule [10 Code of Federal Regulations (CFR) Part 962] with a much narrower interpretation of the term as it applies to radioactive material having a hazardous waste component (i.e., mixed wastes). Under this rule DOE retains authority under AEA for the actual radionuclides in byproduct material. Any nonradioactive hazardous component of the material will be subject to regulation by EPA or an authorized state program under the Resource Conservation and Recovery Act (RCRA).

Generally speaking, EPA's role in radioactive waste management is to develop and issue radiation protection standards and to provide technical expertise during site cleanup. EPA also works with and provides assistance to other federal agencies and state and local governments on radioactive waste issues. Under the Comprehensive Environmental Resource, Compensation and Liability Act (CERCLA), EPA has the authority to respond to releases or threatened releases of hazardous substances, pollutants, and contaminants, including radionuclides.

[8] Generally speaking, the USNRC and Department of Transportation have authority over DOE radioactive wastes only when the wastes are shipped away from a DOE site, for example for disposal in a privately owned facility.

RCRA, 42 U.S.C. parts 6901 to 6992(k), authorizes regulation of hazardous waste. Under the Act, Congress specifically waived the sovereign immunity of the United States for actions brought under state laws implementing RCRA. New Mexico enacted the New Mexico Hazardous Waste Act (HWA), NMSA 1978, parts 74-4-1 to 74-4-14, as the state equivalent to RCRA, to authorize New Mexico's regulation of hazardous waste. In order to implement the statute, New Mexico promulgated the Hazardous Waste Management Regulations (HWMR) 20.4.1 NMAC.

Authority to administer and enforce the state hazardous waste program under its regulatory framework was delegated to the New Mexico Environment Department's predecessor agency by the EPA in April 1985; New Mexico received authorization for the corrective action portion of the federal program in January, 1996. Both the HWA and the HWMR require corrective action at sites, such as LANL, where hazardous waste or its constituents have been released into the environment. A Hazardous Waste Facility Permit under HWMR was issued to the University of California (UC) and DOE (DOE as owner, and both DOE and UC as co-operators of the Los Alamos National Laboratory) in November 1989. A permit addressing corrective action at LANL was issued by EPA in March 1990.

Compliance Order on Consent

Preceding and during the period of the Hydrologic Workplan (1998-2004), NMED concluded that LANL's efforts and progress in addressing the contamination at the site were insufficient. Because NMED judged a variety of technical and regulatory issues were not being fully addressed, NMED issued an Order pursuant to the New Mexico Hazardous Waste Act, NMSA 1978, § 74-4-13, on November 26, 2002, to DOE and the UC. This Order declared that the contamination at LANL constituted an imminent and substantial endangerment to human health and the environment, and directed DOE and UC to undertake certain prescribed actions to address the endangerment. DOE and UC subsequently sued the State of New Mexico. The settlement negotiations that ensued culminated in Compliance Order on Consent (Consent Order, see Sidebar 2.3) that recognized the results of previous investigation work, but mandated additional investigation as necessary and approved by NMED, to fully characterize the nature, extent, fate, and transport of contaminants that have been released to the environment, including soil, sediment, surface water, and groundwater, to determine the need for and scope of corrective action. The Consent Order replaced the substantive provisions of the LANL corrective action permit issued by EPA.

The overall goal of the Consent Order involves determining the nature and extent of releases of contaminants at or from LANL, and using that information to make informed remedy selections for LANL's contaminated sites. It seeks to establish an aggressive, transparent, and collaborative process that ensures that results will be achieved in a timely fashion. The Consent Order is intended to accelerate the pace of investigation and cleanup of the site. The Order places LANL under an enforceable schedule under the Hazardous Waste Act that requires completion of all remedial activities by 2015.

SIDEBAR 2.3
What Is a Consent Order?

Federal and state regulatory agencies may issue Orders in situations involving violations of statutes, regulations, permits, or other orders. In these orders a regulatory agency is authorized to assess penalties, require corrective or remedial actions, and modify, suspend, or revoke permits. Under RCRA (or an equivalent state law), EPA or states may also issue Orders addressing imminent and substantial endangerments to human health and the environment.

Consent Orders are a mechanism to resolve such orders through negotiation. Consent Orders memorialize such negotiations in a legally enforceable document. In this respect, Orders issued after administrative hearings and Consent Orders are quite similar to statutes and regulations in the sense that failure to obey an Order is punishable under the law. Consent Orders are designed to bridge noncomplying activities into compliance and must be limited in time and scope.

The contents of Consent Orders will vary depending upon the regulatory program involved and an agency's enforcement protocols. Such orders may include the following provisions:

1. Remedial Program—The Order may require the respondent to remedy any environmental, natural resource, or public health damage resulting from the violations.
2. Compliance Schedules—The Order may include a detailed compliance schedule that (1) provides monitorable milestone dates that correct all violations and leads to full regulatory compliance, by the soonest feasible date; and (2) requires the implementation of any other remedy, by certain dates.
3. Interim Controls—The Order may require the use of effective and feasible controls to minimize any environmental threat or damage during the interval between the execution of the Order and the date of final compliance in the compliance schedule.
4. Pentalties—The Order may include penalties consistent with an agency's policies on the subject.

The technical requirements of the Order include the following:

- The completion of investigations currently underway for several waste management units at LANL;
- Specific investigation requirements for high-priority sites including investigations of separate watersheds within LANL, and investigations of individual waste management units and technical areas (TAs) at LANL;
- General characterization requirements for sites not yet addressed underthe LANL environmental restoration program;
- Specific methodology and procedures for investigation, sampling, and analysis;

- Requirements for groundwater monitoring, drilling, and well construction;
- Requirements for identification of cleanup alternatives and corrective actions, including interim measures, to clean up contaminants in the environment and to prevent or mitigate the migration of contaminants at or from LANL;
- The implementation of cleanup measures for LANL as agreed upon and approved by NMED;
- Methods for establishing screening and cleanup levels for contaminants at LANL that meet state environmental standards;
- Reporting and submission requirements; and
- Schedules for reporting, workplan submittals, and corrective action completions.

The Consent Order contains no specific requirements for radionuclides or the radioactive portion of mixed waste at LANL because the state does not have jurisdiction over regulation of such substances. The DOE may voluntarily include information about radionuclides in any plan, report, or other document. However, such submission is not enforceable by any entity, including the state, under the Consent Order, because such information falls wholly outside the requirements of the Consent Order.

Groundwater Investigation

Under the Consent Order, LANL is to conduct investigations of groundwater in accordance with NMED-approved workplans to fully characterize the nature, vertical and lateral extent, fate, and transport of groundwater contamination originating from the Laboratory to determine the need for, and scope of, corrective action. The investigation is to include an evaluation of the physical, biological, and chemical factors influencing the transport of contaminants in groundwater. All data must be collected according to EPA and industry accepted methods and procedures. Sidebar 2.4 gives a synopsis of the 2006 Integrated Groundwater Monitoring Plans that LANL developed to meet requirements of the Consent Order. Chapters 4 and 5 deal in detail with technical issues related to monitoring at LANL.

Implementation of the Consent Order began in March 2005 just as the Hydrogeologic Workplan was completed. Implementation of the groundwater monitoring requirements of the Consent Order fulfill the groundwater monitoring requirements of the NMSA Hazardous Waste Regulations. Based on the results of groundwater investigations conducted in accordance with the Consent Order or other information, NMED may require modification of the number and location of piezometers and wells to be installed as part of the Consent Order. Groundwater monitoring wells and piezometers must be designed and constructed in a manner that will yield high-quality samples, ensure that the well will last the duration of the project, and ensure that the well will not serve as a conduit for contaminants to migrate between different stratigraphic units or aquifers.

SIDEBAR 2.4
The 2006 Integrated Groundwater Monitoring Plan

The 2006 Integrated Groundwater Monitoring Plan for Los Alamos National Laboratory (LA-UR-06-4429) issued in July 2006 is an extension of the Interim Facility-Wide Groundwater Monitoring Plan (LA-UR-06-2888) that LANL issued in April 2006. The interim plan is included as section 1 of the Integrated Plan. Section 2 of the Integrated Plan describes LANL's monitoring of water supply wells in Los Alamos County and the city of Santa Fe. This monitoring is conducted under DOE Orders. Section 3 describes LANL's monitoring of groundwater and surface water at locations within Pueblo de San Ildefonso, which is performed under a Memorandum of Understanding between the Pueblo and DOE. Section 4 describes monitoring to satisfy conditions of two groundwater discharge permits under New Mexico Water Quality Control Comission regulations.

According to the Integrated Plan, the purpose of monitoring is to:

- Determine the fate and transport of known legacy-waste contaminants;
- Detect new releases;
- Determine efficacies of remedies; and
- Validate proposed corrective measures.

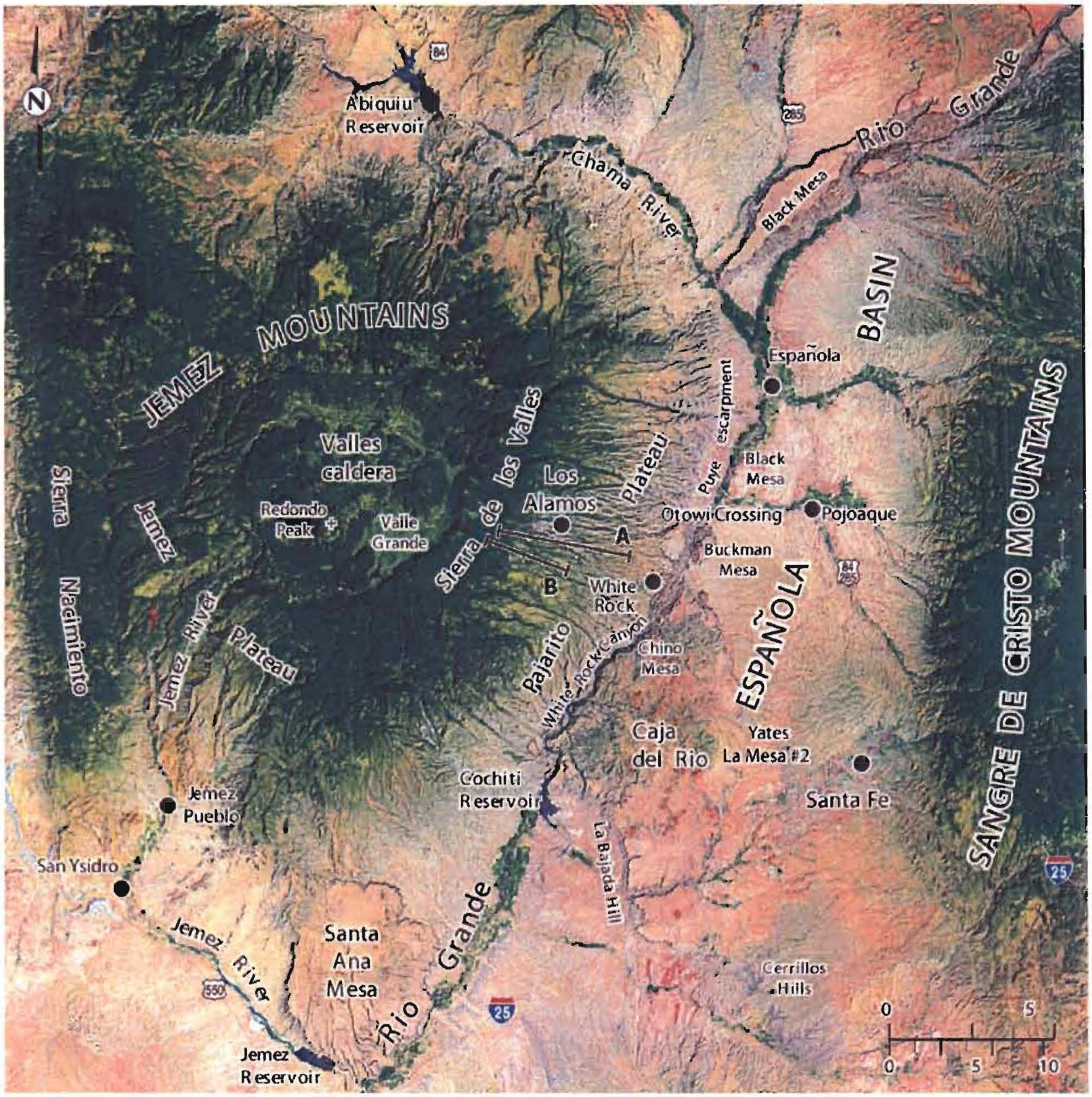
LANL intends that the work under the Integrated Plan will identify potential risks to the regional aquifer as a drinking water source and monitoring data will be used in risk-based decision making as stipulated in the Consent Order.

Groundwater Cleanup Levels

Since the eventual goal of the program is the restoration and cleanup of the environment in and around LANL, decisions must be made regarding groundwater cleanup levels and the regulatory basis for such. The Consent Order follows the principle that groundwater cleanup levels for human health should usually be developed using existing standards (e.g., drinking water standards) when they are available and should be applied to protect against current and reasonably expected exposures.

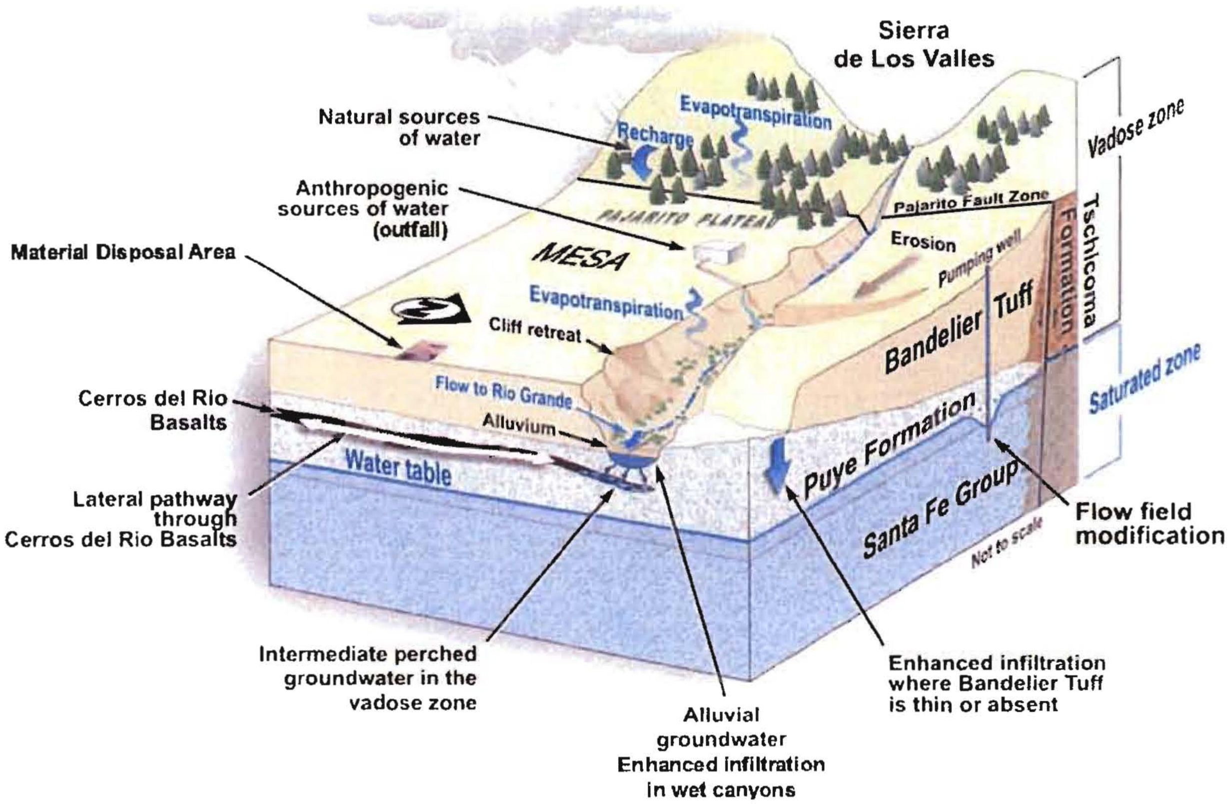
The Order establishes the process whereby NMED and LANL must refer to EPA guidance, *Handbook of Groundwater Protection and Cleanup Policies for RCRA Corrective Action* (Sept. 2002 and as it may be amended), in developing and applying groundwater cleanup levels. As provided in that guidance, states may take a more stringent approach than EPA would otherwise use for making groundwater use and cleanup decisions. The WQCC groundwater standards, including alternative abatement standards (20.6.2.4103 NMAC), and the drinking water maximum contaminant levels (MCLs) adopted by EPA under the federal Safe Drinking Water Act (42 U.S.C. §§ 300f to 300j-26) or the EIB (20.7.10 NMAC) are cleanup levels for groundwater. If both a WQCC standard and an MCL have been established for an individual substance, then the lower of the two levels will be considered the cleanup level for that substance.

Color Plates



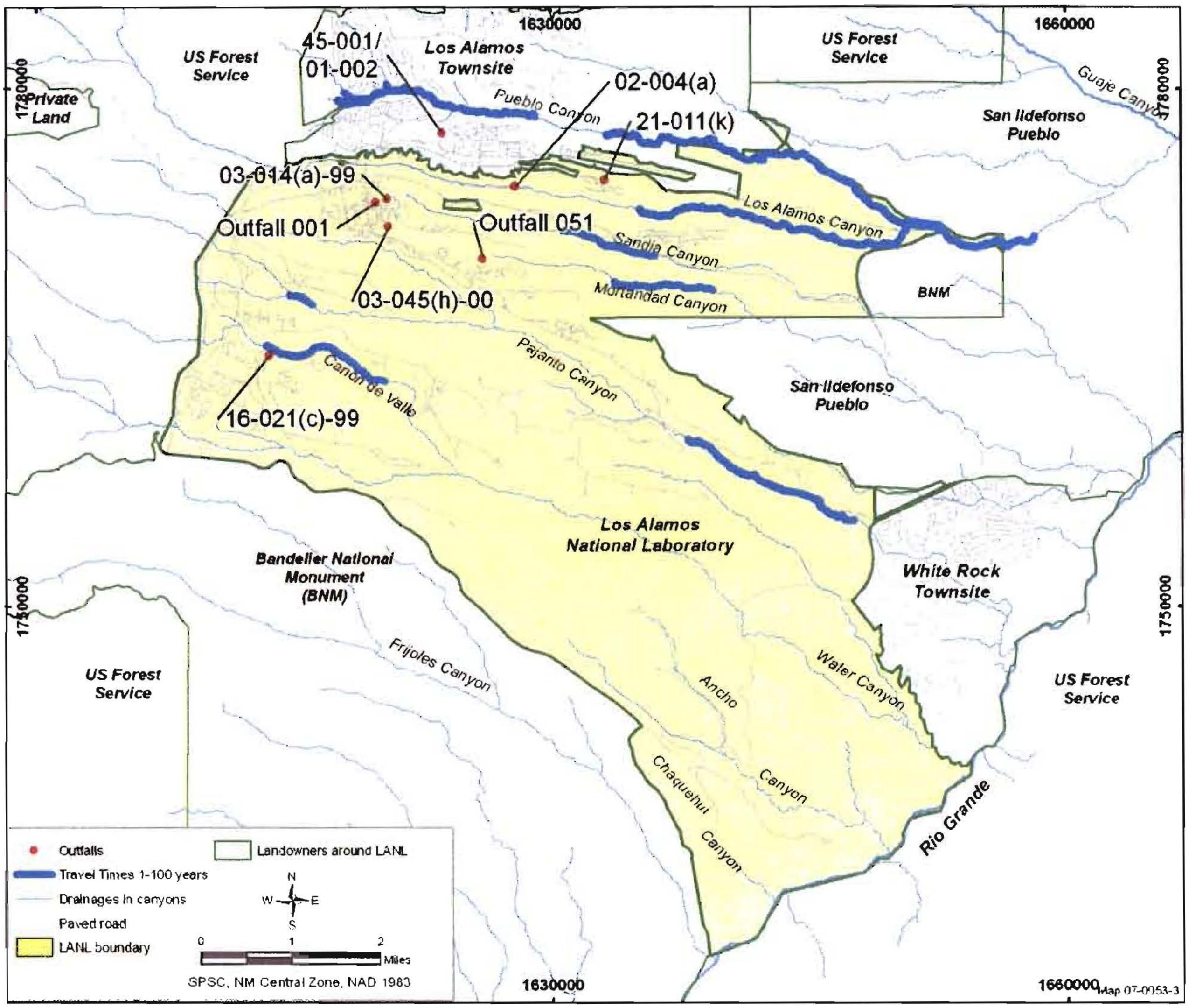
Source: Donathan Krier, LANL

COLOR PLATE 1 Satellite photograph of the Los Alamos area of the Española Basin. Green indicates areas of greater vegetation in this false-color image. For orientation, the lines running approximately west to east below Los Alamos indicate the location of the representative cross section shown in Plate 2.



Source: Donathan Krier, LANL

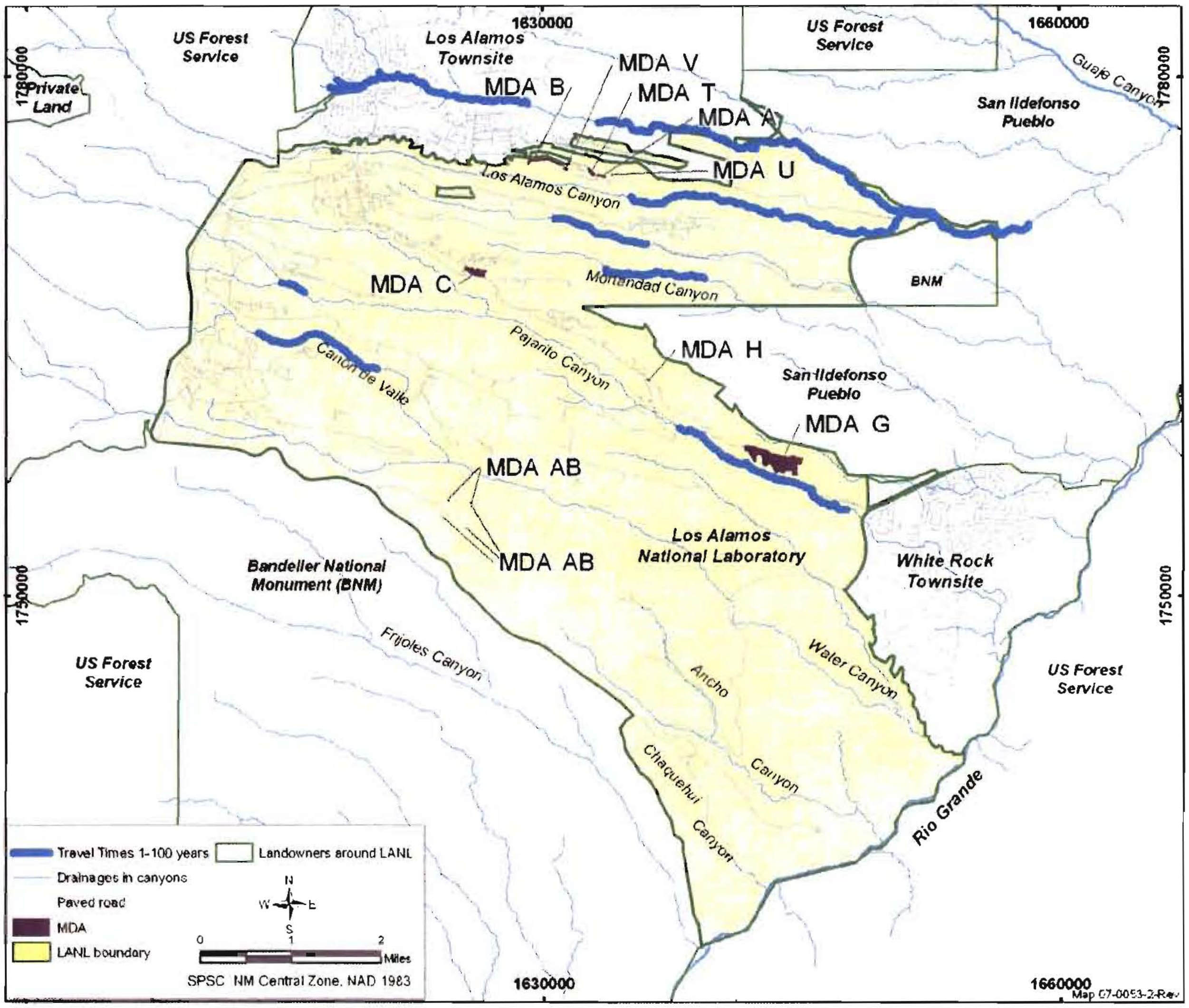
COLOR PLATE 2 Representative geological cross section of the LANL site. Note that the representative canyon cuts from the Sierra de Los Valles and surface water flows toward the Rio Grande. Alluvial material is erosional sediment, including gravels, sands, silts, and clays, that is deposited by surface water. The materials are eroded from higher elevations in the watershed.



Source: Donathan Krier, LANL

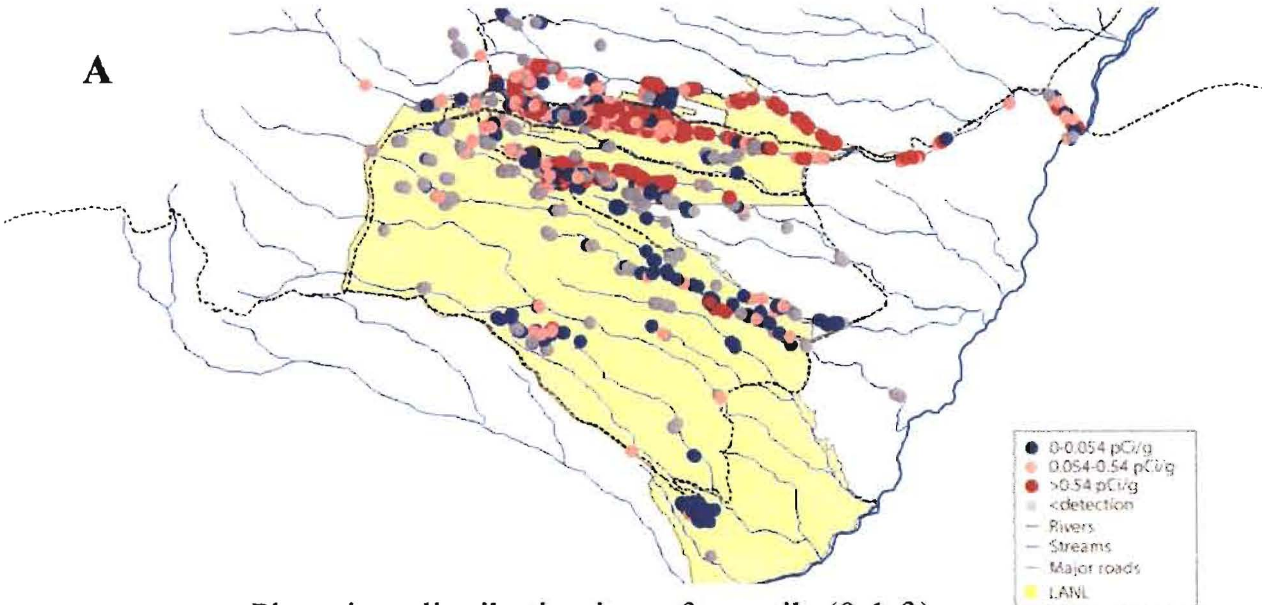
COLOR PLATE 3 Location of the key liquid waste outfalls on the LANL site. This map includes the outfalls that LANL believes to be sources of contamination that has been detected in site groundwater. In addition, the map shows regions where LANL's site characterization work indicates relatively fast travel times through the vadose zone, based largely on the detections of contamination in groundwater.

All except two of these "historic" outfalls have been closed; see Table 3.1. The Radioactive Liquid Waste Treatment Facility discharges wastes from Outfall 051 into Mortandad Canyon, and a power plant and sanitary waste facility discharge wastes from Outfall 001 into Sandia Canyon. Discharges from these two facilities and other currently operating facilities meet NPDES and DOE discharge requirements.

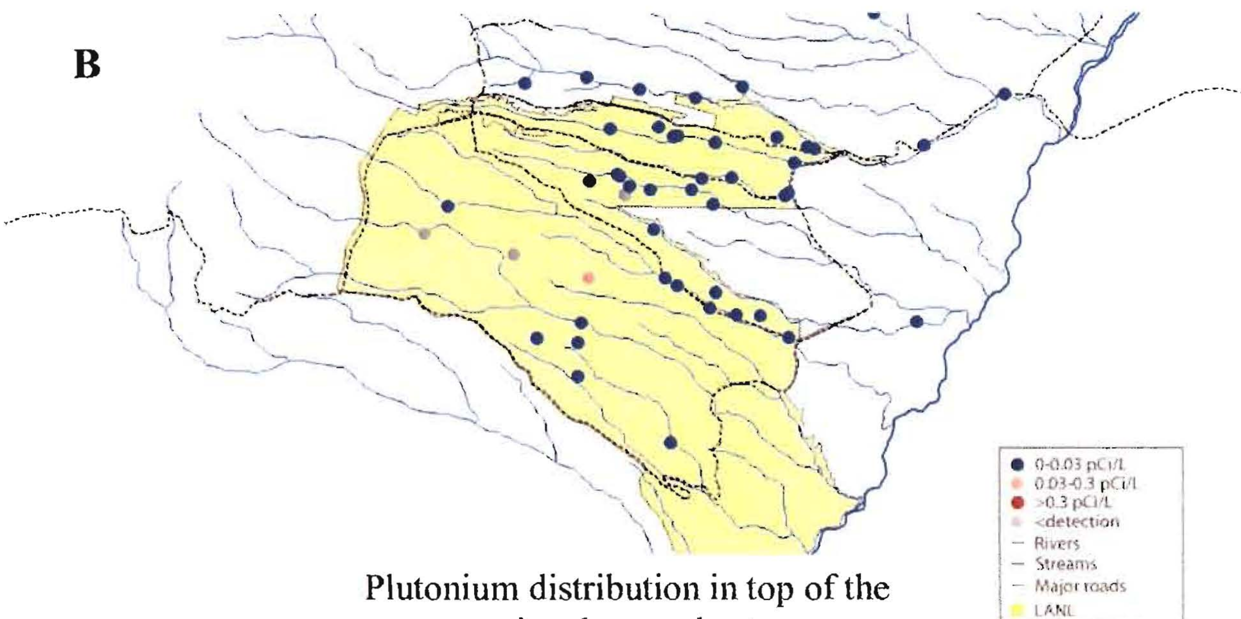


Source: Donathan Krier, LANL

COLOR PLATE 4 Location of the key material disposal areas (MDAs) on the LANL site. These nine areas contain sufficiently large inventories of solid wastes that they may pose future threats to groundwater; see Table 3.2. Most are located on meas tops that are normally dry. Some are relatively near fast vadose zone pathways identified by LANL. Thus far in LANL's groundwater protection program solid waste disposal areas have received relatively less attention than liquid outfalls.



Plutonium distribution in surface soils (0-1 ft)

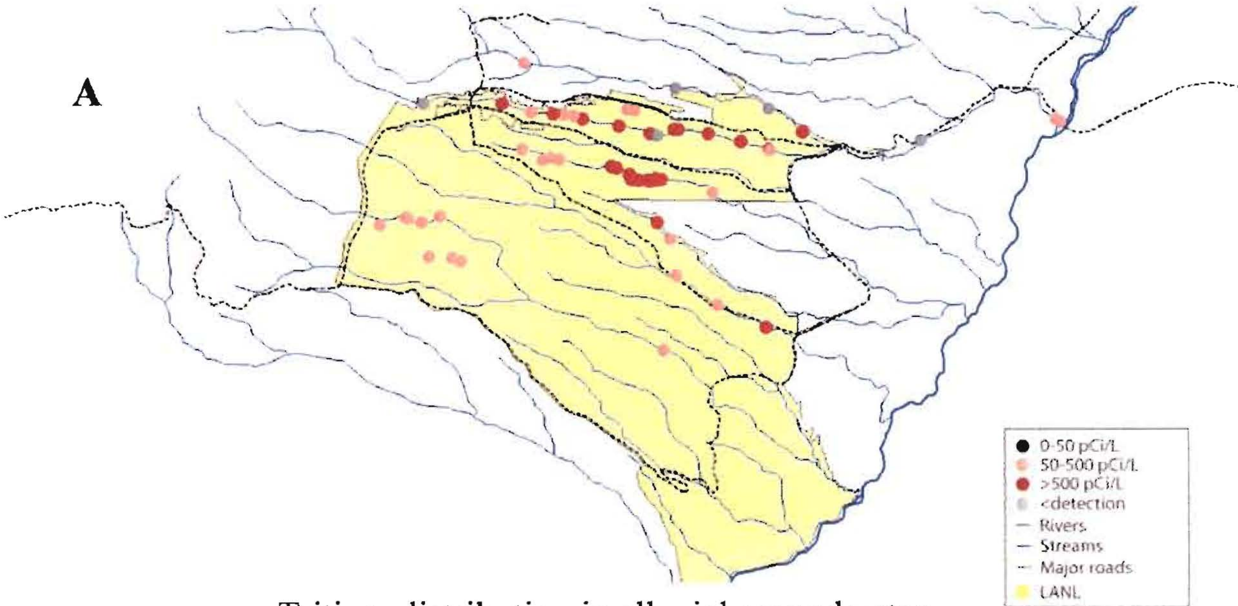


Plutonium distribution in top of the regional groundwater

Source: Risk Assessment Corporation

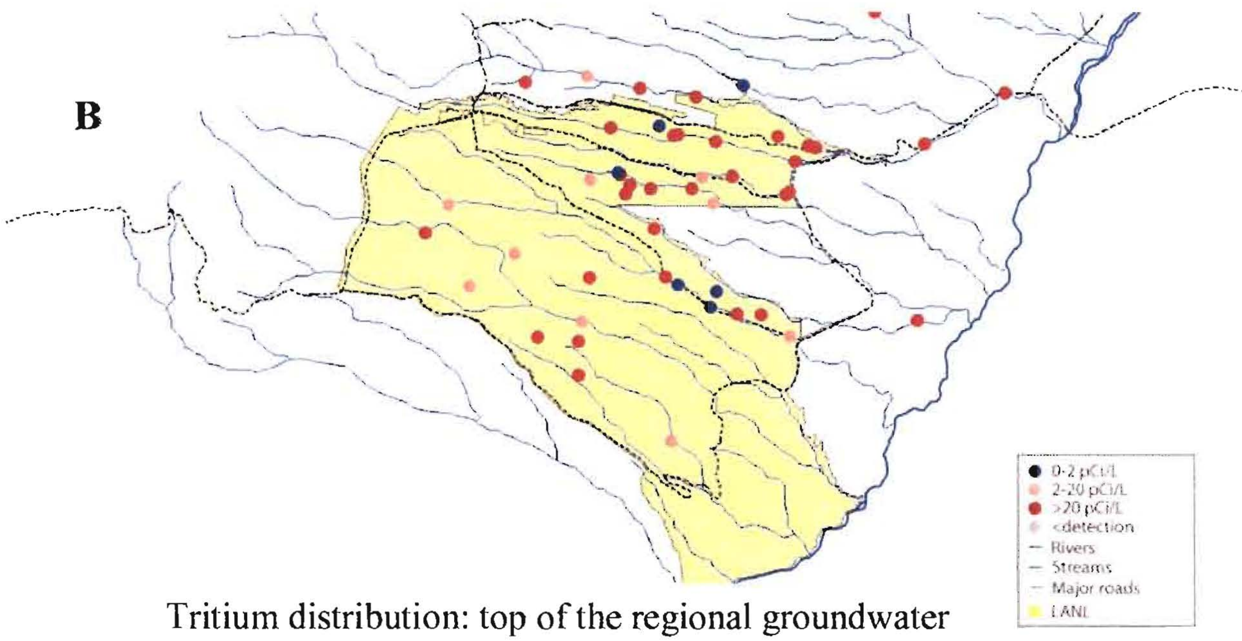
COLOR PLATES 5a,b Illustrative plots of plutonium data from site samplng. Plot A shows plutonium detected in surface soils ratioed to a chosen reference value of 0.054 pCi/g. Plot B shows the most recent plutonium analyses of regional groundwater ratioed to a chosen reference value of 0.03 pCi/L. The reference value of 0.054 pCi/g in soil is an upper tolerance limit used by LANL (LA-UR-98-4847). The reference value of 0.03 pCi/L is the average background value for plutonium detected in sediments in the Rio Grande from Graf (1994). Note: the plot will look different for different reference values chosen. All analytical values at or below the MDL (non-detects, shown in gray) are shown to illustrate where samples were collected but no plutonium was detected. Blue values show measured concentrations at or below the reference value, interpreted in these plots to be below or near atmospheric fallout levels. Red values show where plutonium was detected. Most of the plutonium is located in the shallow surface soils within the canyons. There is one analysis of plutonium in the regional groundwater that is a J value, which means a detection was reported, but the level is too low to be reported with a high degree of confidence; see sidebar 5.2. Two duplicate analyses were subsequently analyzed and both were non-detect values. Therefore, this J-value should be interpreted with caution and serves to demonstrate the difficulty of interpreting data that is near the analytical limits of detection. See discussion in Chapter 5. These plots are for illustrative purposes only as the RACER project is still being developed.

A



Tritium distribution in alluvial groundwater

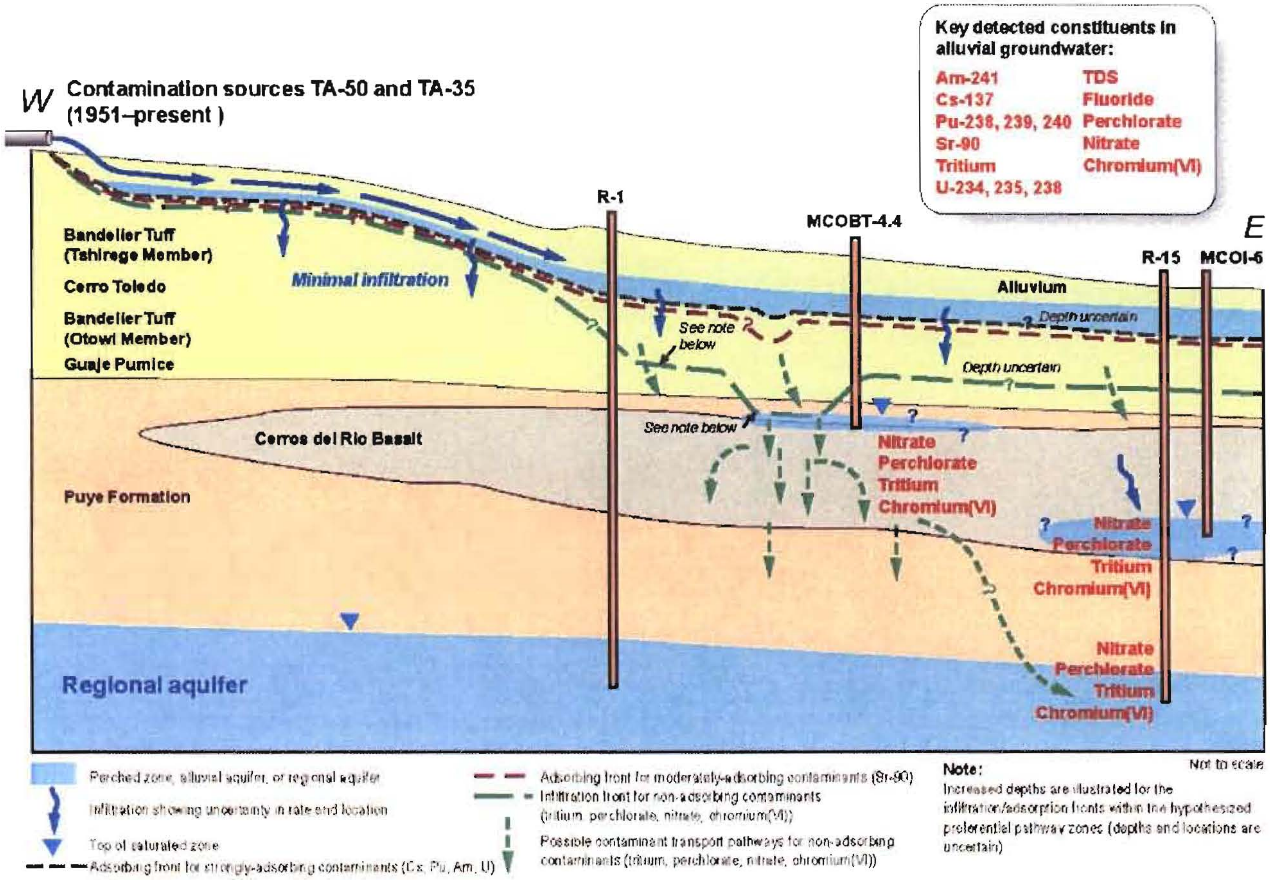
B



Tritium distribution: top of the regional groundwater

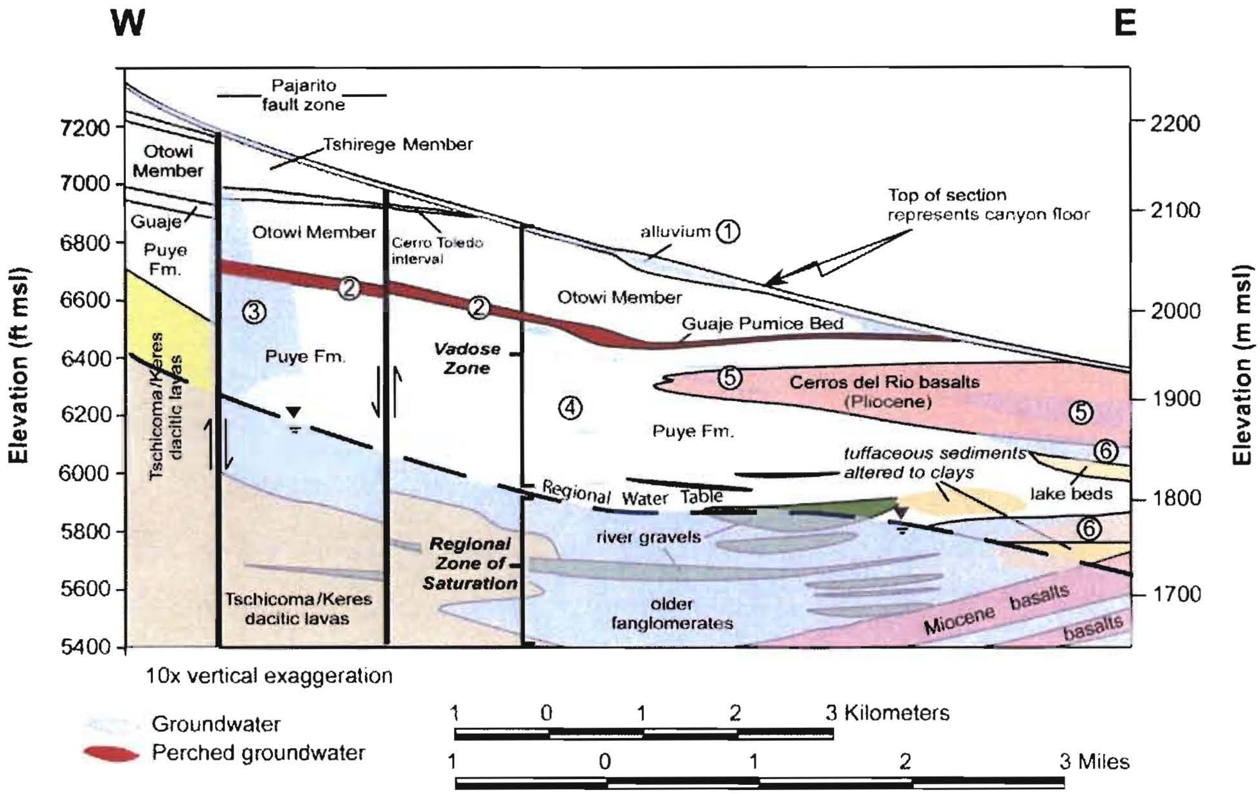
Source: Risk Assessment Corporation

COLOR PLATE 6a,b Illustrative plots of tritium data from site samplng. Plot A shows tritium detected in shallow alluvial groundwater ratioed to a chosen reference value of 50 pCi/L. Plot B shows the tritium analyses in the top of the regional groundwater ratioed to a chosen reference value of 2 pCi/L. The reference value of 50 pCi/L in the alluvial groundwater was taken as a reasonable background atmospheric fallout level (LANL, 2006b). The reference value of 2 pCi/L is the average background value for tritium detected for regional groundwaters as a result of atmospheric fallout (LANL, 2006b). Note, the plot will look different for different reference values chosen. All analytical values at or below the MDL (non-detects, shown in gray) are shown to illustrate where samples were collected but no tritium was detected. Blue values show measured concentrations at or below the reference value, interpreted in these plots to be below or near atmospheric fallout levels. Red values show where tritium was detected. Tritium has been detected in both the shallow alluvial groundwater and the regional aquifer. These plots are for illustrative purposes only as the RACER project is still being developed.



Source: Donathan Krier, LANL

COLOR PLATE 7 Conceptual model of hydrogeology and contaminant transport in Mortandad Canyon. Mortandad Canyon is located above the Mortandad watershed, which is shown on Color Plates 9 and 10. LANL considers this canyon to be a significant source of groundwater contamination. Much scientific effort has been focused on understanding the hydrogeology of wet canyons, as discussed in Chapter 4.



① Canyon-floor alluvial groundwater - most commonly found in large, wet watersheds with significant snow and storm runnoff or in smaller watershed that receive liquid effluent from wastewater treatment plants. Saturated thickness and down-canyon extent varies seasonally.

② Perched groundwater is associated with the Guaje Pumice Bed in Los Alamos Canyon. This perched water body has a lateral extent of up to 3.7 mi. Guaje Pumice Bed has a high moisture content but is not fully saturated in most other locations.

③ Canon de Valle area in the southwest part of LANL. This is the largest perched zone identified on the plateau. A deep-sounding surface-based magnetotelluric survey suggests that this perched zone is discontinuous laterally, occurring as vertical, pipe-like groundwater bodies. One interpretation of this zone is that it represents groundwater mound(s) formed in response to local recharge beneath a wet canyon floor. Recharge may be enhanced across the Pajarito fault zone where shallow, densely-welded tuffs rocks are highly fractured.

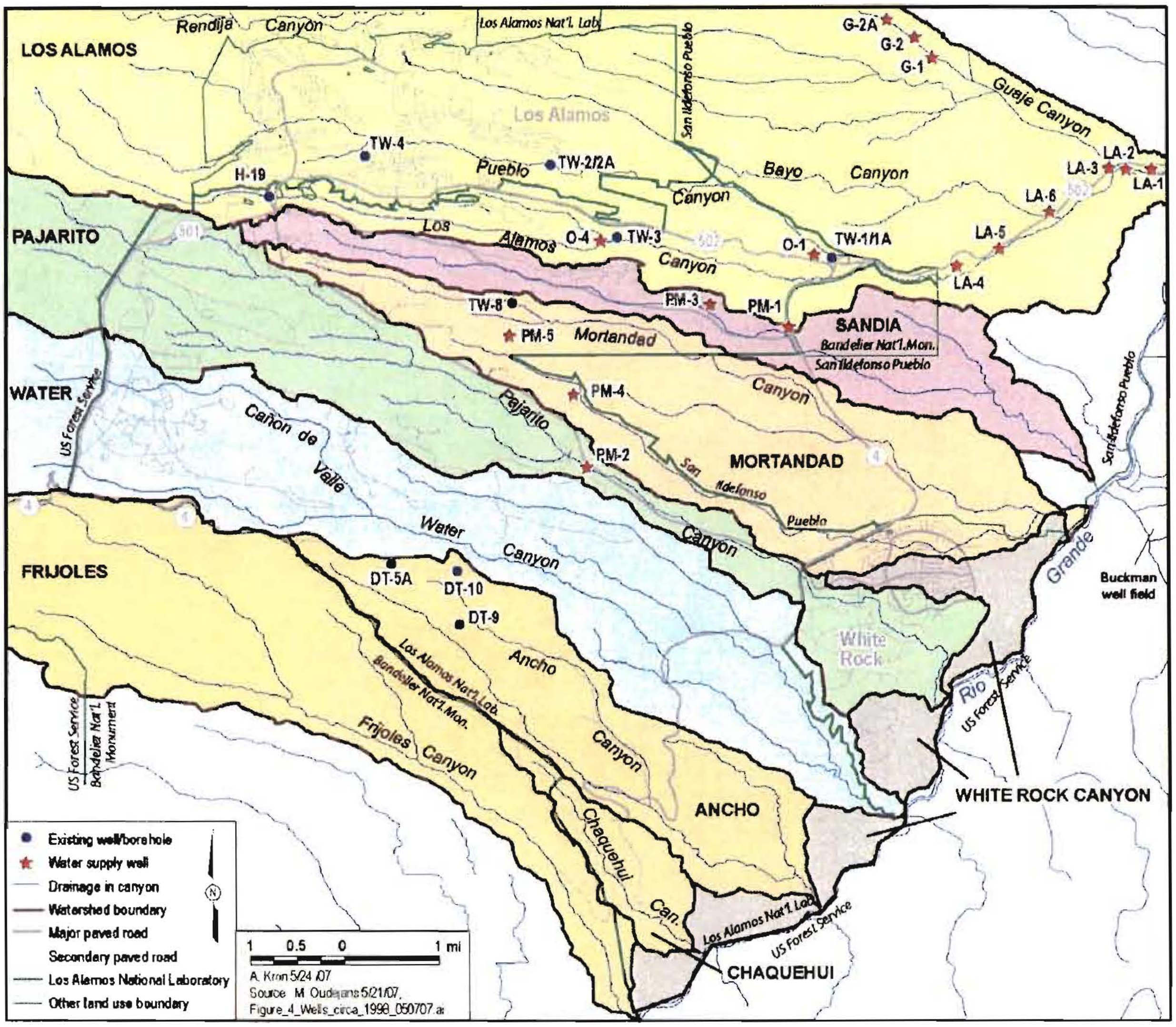
④ Small zones of perched water formed above stratigraphic traps in Puye fanglomerate. These perched zones tend to be more numerous beneath large wet canyons and less frequent beneath dry mesa tops.

⑤ Perched groundwater associated with Cerro del Rio basalt. Saturation occurs in fractured basalt flows and in interflow breccias and sediments.

⑥ Perched zones form in response to local geologic conditions on the eastern side of the plateau. These include perch zones within clay-altered tuffaceous sediments and above lake deposits.

Source: Donathan Krier, LANL

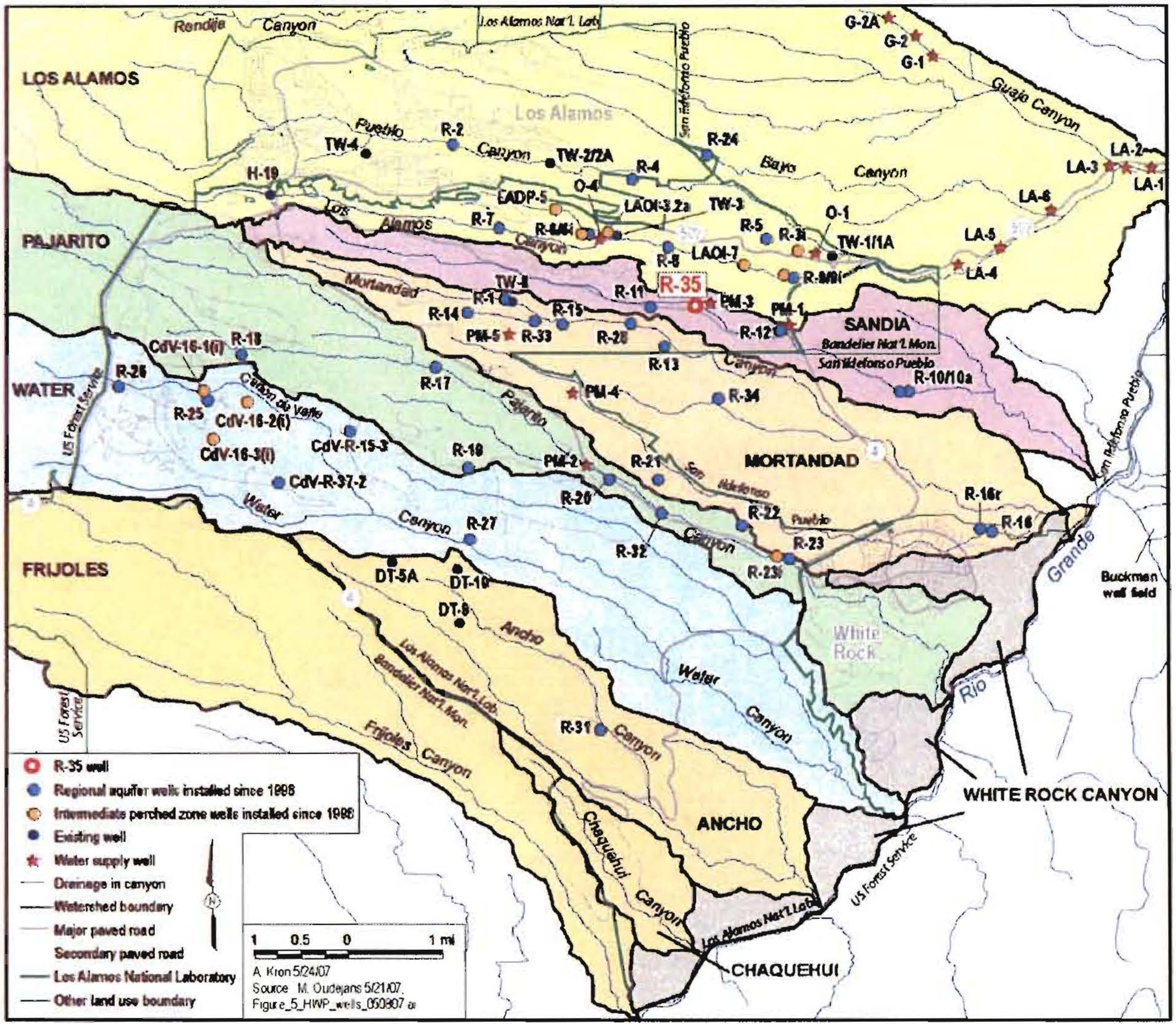
COLOR PLATE 8 Occurrences of perched water beneath the LANL site. Small zones of intermediate-depth groundwater are referred to as "perched" because they occur in the unsaturated zone above the more laterally extensive and productive regional aquifer. This west to east cross section shows the variety of occurrences of perched water found beneath the area of the site between the lines indicated on Color Plate 1. Contaminants have been found in perched water, and it is believed that the hydrogeology associated with perching can redirect contaminant transport laterally between watersheds, as discussed in Chapter 4.



Source: Broxton 2006

COLOR PLATE 9 Well and borehole emplacements at LANL in about 1997. Most wells are water supply wells, which reach the regional aquifer. These wells supply water to Los Alamos County, the Pueblo de San Ildefonso, and to the LANL site. Wells in the Buckman well field, east of the Rio Grande (on the right margin of the figure), supply water to the city of Santa Fe. Relatively few wells or boreholes had been emplaced for site characterization or monitoring.

This map as well as Color Plate 10 also show the seven watersheds or groups of watersheds on which LANL's interm plans for site monitoring are based.



Source: Broxton 2006

COLOR PLATE 10 Wells and boreholes in 2005 after completion of the Hydrogeologic Workplan. Under the workplan 25 wells (designated R) were drilled into the regional aquifer. Most of these wells provided sampling points (screens) at more than one depth. About 22 new intermediate-depth boreholes and wells were drilled to sample groundwater perched above the regional aquifer. The original intent of this work was to improve LANL's knowledge of the site's hydrogeology in order to begin planning a groundwater monitoring network. Extending the use of the R-wells for groundwater monitoring has been controversal, as discussed in Chapter 5.

3
Contamination Sources and Source Control

Radioactive or chemically hazardous wastes disposed onsite at the Los Alamos National Laboratory (LANL) constitute the sources of contamination that are the subject of this chapter. The Laboratory has conducted onsite disposal of its wastes since the early 1940s. Disposal methods include the discharge of liquid effluents into canyons and the emplacement of solid wastes, mainly on mesa tops.[1]

Identifying and controlling contamination sources is essential for groundwater protection. Controlling a source of aqueous waste (e.g., an "outfall")[2] could involve treating that waste to remove contaminants or reducing or stopping the discharges. Controlling solid waste could involve ensuring that it is emplaced in such a way that it cannot release contaminants or, if necessary, recovering the disposed waste, repackaging it, and possibly shipping it offsite.[3]

This chapter addresses three questions regarding sources that were posed in the committee's statement of task:

1. What is the state of the laboratory's understanding of the major sources of groundwater contamination originating from laboratory operations and have technically sound measures to control them been implemented?
2. Have potential sources of non-laboratory groundwater contamination been identified?
3. Have the potential impacts of this [non-laboratory] contamination on corrective-action decision making been assessed?

The committee's short answer to the first question is yes for liquid sources and no for solids. Liquid waste discharges are generally eliminated or controlled. LANL's data indicate that former liquid discharges were the sources of contamination currently found in groundwater. However, solid wastes and contaminants deemed by LANL to have less near-term potential to impact groundwater have received much less attention than the liquid sources and are not well understood, especially in terms of source inventories.

The committee's short answer to the second question is a qualified yes. The short answer to the third is no, because LANL is only beginning to determine corrective actions under the Consent Order. This aspect of decision making was not discussed with the committee.

More detailed elaborations of these answers are provided in this chapter.

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[1] Discharges of gaseous effluents are not considered in this report.

[2] An outfall is an intended point of discharge of wastewater into the environment. LANL outfalls are permitted by the state under the National Pollutant Discharge Elimination System (NPDES).

[3] The term waste package refers to the solid waste itself, its container, which may be simply a metal drum or may be more elaborately designed, and additional barrier materials inside or around the container if they are used.

LANL'S SOURCE PRIORITIZATION

LANL is systematically investigating contaminant sources and the nature and extent of migration from them under a prioritized sequence that is directed by the Consent Order (see Chapter 2 for a description of the order). These sources range from solid waste disposal sites in dry areas, to sanitary waste treatment plants, to radioactive waste treatment facilities. LANL's Site-Wide Environmental Impact Statement (SWEIS) identifies operating facilities as "key" or "non-key" depending on their potential to cause significant environmental impact (LANL, 2004a, p. 2-3).

At the committee's request, Birdsell et al. (2006) provided a summary of contaminant sources that LANL considers to be the most significant, including locations of liquid waste outfalls and disposal areas for solid wastes. LANL's criteria for selecting these as the most significant sources include the following:

- A large contaminant inventory,
- A natural or anthropogenic aqueous driver (e.g., rainfall, facility effluent, alluvial groundwater) that occurred concurrently with and/or subsequent to the contaminant release,
- Contaminants that tend to move with the aqueous driver ("mobile" contaminants), and
- Release into a canyon (as opposed to emplacement on a dry mesa top).

In addition to the Birdsell et al. (2006) summary, the types, amounts, and locations of waste releases to the subsurface are included in numerous references (LANL, 2003, Sec. 2.0; LANL, 2004a, Sec. 3.2; LANL, 2004b, Sec. 2.1 and Sec. 6.0; Del Signore and Watkins, 2005; Katzman, 2006; LANL, 2006a, Appendix; Rogers, 2006a; LANL, 2007a).

Liquid Discharges

LANL presented data indicating that the major sources of contaminants affecting the groundwater beneath the Pajarito Plateau were past ("historic") liquid discharges from radioactive treatment plants, sanitary treatment plants, high-explosives machining operations, and other outfalls; see Color Plate 3. Most of these discharges were neither treated nor regulated, and substantial amounts of contaminants were released to the environment; see Table 3.1. Recently LANL has made a significant effort to reduce its liquid discharges. From 1993 through 2006, the number of outfalls was reduced from 141 to 17. Of the 17 currently operating outfalls, LANL considers that only two, the outfall in TA-50 and the current sanitary wastewater system outfall 13S, are significant contamination sources according to the criteria listed above.

TABLE 3.1 Key LANL Outfalls and Approximate Contaminant Quantity Released

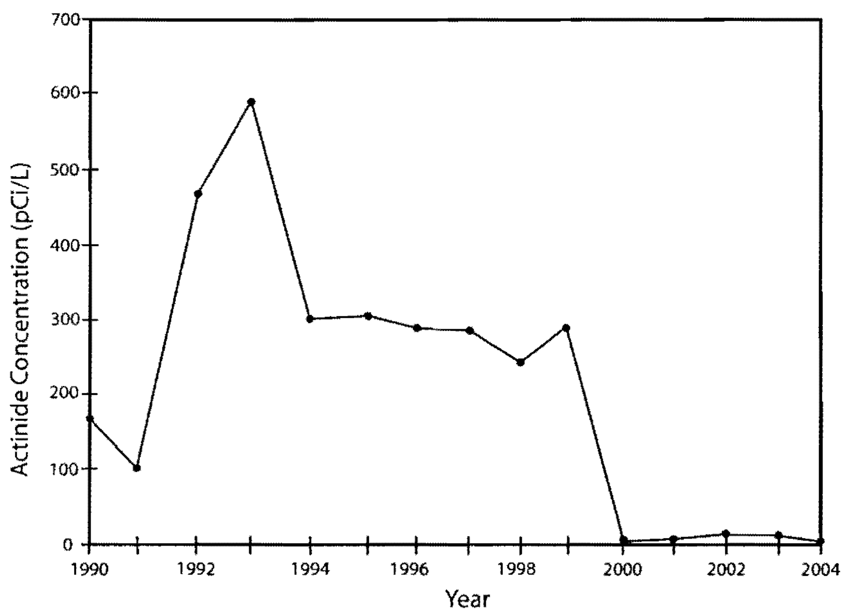
Source Number (SWMU: Solid Waste Management Unit)	Source Name	Location Canyon (Watershed)	Operation	Period of Operation	Key Mobile Constituents Detected in Deep GW	Approximate Water Volumes Released (m^3)	Approximate Contaminant Quantity Released[a]	Approximate Key Radionuclide Released
01-002 (SWMU) 45-001 (SWMU)	Combined TA-1 Outfall TA-45 Outfall	Acid Canyon (Pueblo Canyon)	Radioactive wastewater treatment	1944-1964	Tritium, perchlorate	600,000	Perchlorate—unknown Nitrate ~ 100,000 kg	Tritium ~ 58 Ci Sr-90 ~ 27 mCi Pu ~170 mCi
02-004(a) (SWMU)	Omega West Reactor	Upper Los Alamos Canyon	Research and molybdenum production	Possibly ca. 1970-1993	Tritium	2,000 to 4,000		Tritium 70 Ci (maximum)
21-011(k) (SWMU)	SWMU 21-011(k)	DP Canyon (Los Alamos Canyon)	Industrial wastewater outfall	1952-1986	Tritium, perchlorate, nitrate	200,000	Perchlorate—unknown Nitrate > 20 kg	Tritium > 55 Ci Pu ~ 36 mCi Sr-90 ~ 5 mCi Cs-137 ~ 250 mCi Am-241?
03-045(h)-00 (SWMU) 03-014(a)-99 (SWMU) Outfall 001	TA-3 Power Plant Former TA-3 Wastewater Treatment Plant Current Power Plant and Sanitary Wastewater System (SWWS)	Sandia Canyon	Cooling towers Sanitary wastewater treatment Cooling tower and sanitary wastewater treatment	1950-present	Chromium (ca. 1956-1972); accidental tritium release with sanitary waste (ca. 1969-1986)	> 10,000,000 (~150,000 to 400,000 m^3/yr continuously since 1951)	Chromium ~ 26,000 to 105,000 kg	Tritium ~ 30 Ci
16-021(c)-99 (SWMU)	260 Outfall	Canon de Valle (Water Canyon)	High explosives machining	1951-1996	High explosives (RDX)	340,000 to 1,500,000	RDX 15,000 to 64,000 kg	None
Outfall 051	TA-50	Effluent Canyon (Mortandad Canyon)	Radioactive wastewater treatment	1963-present	Tritium, nitrate, perchlorate	1,400,000	Perchlorate—800 to 1200 kg Nitrate ~ 200,000 kg	Tritium ~800 Ci Sr-90 ~ 470 mCi Pu (239,240) ~ 0.2 Ci Pu (238) ~0.1 Ci Cs-137 ~ 2.1 Ci Am-241 ~ 0.2 Ci

[a]Note that tritium releases here are reported as original releases rather than decay-corrected current radioactivity.
Source: Donathan Krier, LANL

The Radioactive Liquid Waste Treatment Facility (RLWTF) located at Technical Area-50 (TA-50) has been LANL's only source of liquid radioactive waste discharges since 1986. The facility collects and processes waste from over 1000 generating points sitewide. Liquid wastes from the RLWTF go to the TA-50 outfall, which discharges into Mortandad Canyon.

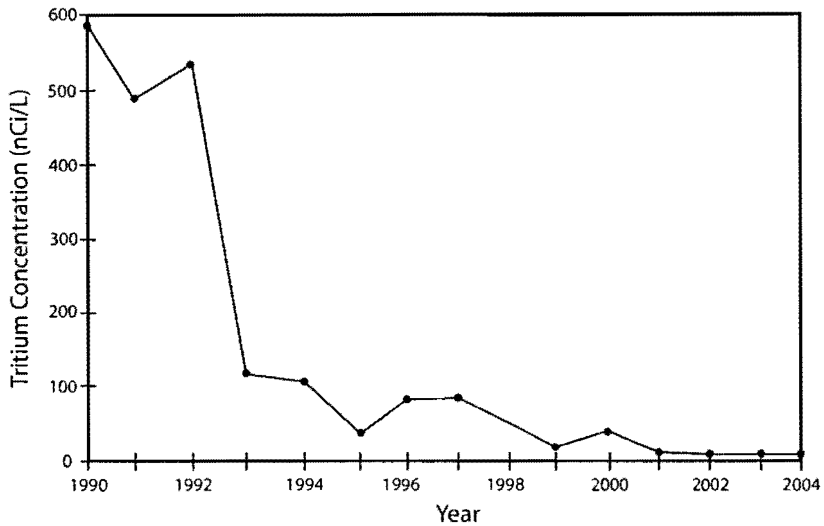
Modernizing the RLWTF in 1999 substantially reduced the concentrations of actinides released (Figure 3.1a). Tritium concentrations in the effluent were curtailed in the early 1990s (Figure 3.1b). These are real and substantial reductions because the volume of water discharged decreased from over 20 million liters per year in 1990 to just under 10 million liters per year in 2004. The release of radioactive contaminants from TA-50 continues but has been below the discharge limits stipulated by the Department of Energy (DOE; Del Signore and Watkins, 2005, p. 47). Contaminant releases into Mortandad Canyon thus appear to have been controlled.

Nonetheless, the substantial amount of water still being discharged at the TA-50 outfall may itself serve as a continuous aqueous driver to move previously released contaminants deeper into the groundwater. LANL is currently evaluating a plan to eliminate all effluent releases from the RLWTF at TA-50.



Source: Del Signore and Watkins, 2005

FIGURE 3.1a Actinide (Pu-238, Pu-239, Am-241) concentrations in effluent from the Radioactive Liquid Waste Treatment Facility. Releases of actinides have decreased significantly after upgrades to the facility in 1999. The concentration units of picocuries per liter (pCi/L) are 1000 times smaller than those in the figure for tritium below. These actinides have much longer radioactive half-lives than tritium, so they are usually of greater concern for groundwater protection.



Source: Del Signore and Watkins, 2005

FIGURE 3.1b Tritium concentrations in effluent from the Radioactive Liquid Waste Treatment Facility. The concentrations are in units of nanocuries per liter. A nanocurie is 10^{-9} curie.

Emplacements of Solid Wastes

Potential sources of groundwater contamination are not limited to liquid effluents. Solid wastes[4] include a large amount of radioactive material that is disposed of in the subsurface and present substantial uncertainties in the amount of contaminants that could eventually migrate to the groundwater. The committee encountered a number of terms applied to areas of the site where solid wastes are emplaced or that have been contaminated.

The term "solid waste management unit" (SWMU) refers to any area from which DOE determines there may be a risk of release of contaminated materials, irrespective of whether the area was intended for the management or disposal of such materials. Areas where there was only a one-time spill are not considered to be SWMUs, but rather are included in the category of "area of concern" (AOC). An AOC is any area, which is not an SWMU, that may have had a release of hazardous waste or hazardous constituents. DOE also uses the generic term "potential release site" (PRS) in referring to areas from which contaminants have the potential to migrate into the environment, but not necessarily to contaminate groundwater.

LANL uses a more restrictive term "material disposal area" (MDA) to designate specific areas used between 1945 and 1985 for the disposal of radioactive and hazardous

[4] The Resource Conservation and Recovery Act defines solid waste as any garbage, refuse, sludge from a wastewater treatment plant, water supply treatment plant, or air pollution control facility, and other discarded material, including solid, liquid, semisolid, or contained gaseous material, resulting from industrial, commercial, mining, and agricultural operations and from community activities. See http://www.epa.gov/epaoswer/hotline/training/defsw.pdf.

wastes. MDAs are generally near-surface disposal facilities located on mesa tops; see Color Plate 4. The waste is usually buried in pits or shafts.

Given the variety of nomenclature, estimates of the number of solid waste emplacements or contaminated areas appear to converge around 1000. LANL (2007a) counts 829 SWMUs and AOCs that are in the process of being investigated, need investigation, or are pending a decision from NMED. Birdsell et al. (2006) identify 25 MDAs and 902 PRSs—478 of the PRSs are confirmed or suspected radiological sites and the remaining are non-radiological. A Notice of Intent (NOI) to sue LANL for violations of the Clean Water Act (Western Environmental Law Center, 2006) refers to SWMUs, AOCs, and PRSs collectively as "stormwater sites." The NOI states that an original estimate of the number of stormwater sites was 2093. According to the NOI, 688 of these sites received No Further Action status by NMED, leaving 1405 to be dealt with.

LANL considers that 9 of its 25 MDAs have a significant potential to contaminate groundwater. Of the nine MDAs considered significant, the inventory for two is "unknown" (see Table 3.2). For MDA G, the tritium inventory according to Table 3.2 is about 3.6 million Ci, which is far larger than the tritium discharged from any of the liquid outfalls. A large amount of Pu-239, about 2300 Ci or 39 kg, is reported to be in MDA AB.

The presence of large amounts of radioactive materials in unlined pits in the MDAs is an issue. Although the mesa tops are generally considered to be dry, this is not true year-round. Standing water has been observed in unlined pits in several locations, including MDA AB (CCNS, 2007; Levitt et al., 2005). This contact of precipitation and runoff with stored waste materials implies that a fraction of the contaminants are subject to leaching and subsequent migration. The extent of this leaching is not known (CCNS, 2007).

Overall, LANL estimates 40-60 percent of the SWMUs have been sampled; however, information about the total mass of contaminants for the SWMUs has not yet been compiled (D. Katzman, personal communication, August 2006). Although LANL is still in the process of characterizing most solid waste disposal areas, the committee was not shown data to substantiate the claim that waste has not migrated from the SWMUs. Evaluation of all sites is scheduled for completion by 2015 (Birdsell et al., 2006).

LANL has given generally lower priority to understanding and controlling its solid waste emplacements than its liquid waste discharges. While LANL presented a clear rationale for doing so, dealing with these solid wastes will become technically more challenging and economically more demanding as time progresses. Over time, waste materials will degrade and become more vulnerable to leaching. Contaminants will migrate away from the wastes, thereby contaminating an increasingly large volume in the subsurface. One way of considering this issue is: If the mesa tops were proposed for disposal of these materials today, what types of assessment and engineering controls would be required? The answer to this question can help guide LANL's future efforts to manage its MDAs and SWMU contaminated areas.

TABLE 3.2 Nine out of 25 Principal Material Disposal Areas at LANL.[a]

Material Disposal Area (MDA)	Location (Technical Area)	Period of Operation	Key Radionuclide Inventory
A	21	1944-1978	Pu ~ 701 Ci Am ~ 1.5 Ci
B	21	1945-1952	Pu ~ 6.22 Ci Sr-90 ~ 0.285 Ci Cs ~ 0.005 Ci
T	21	1945-1986	Pu ~ 182 Ci Am ~ 3740 Ci U ~ 6.9 Ci
U	21	1948-1976	Unknown (Am, Cs, Pu, tritium, Sr, U)
V	21	1945-1961	Unknown (Am, Cs, Pu, Sr-90, U, tritium)
AB	49	1959-1961	Pu ~ 23,000 Ci (includes ~ 20,600 Ci of Pu-241, which has a 14.4-year half life, and ~ 2300 Ci of Pu-239, which has a 24,000-year half life) U ~ 0.246 Ci
C	50	1948-1974	Tritium ~ 20000 Ci Sr-90 ~ 21 Ci U ~ 25 Ci Pu ~ 26 Ci Am ~ 145 Ci
G	54	1957-1997 (parts remain active today)	Am ~ 2360 Ci Cs ~ 2810 Ci Tritium ~ 3,610,000 Ci Pu ~ 16,000 Ci Sr-90 ~ 3500 Ci U ~ 124 Ci
H	54	1960-1986	Tritium ~ 240 Ci Pu ~ 0.0267 Ci U ~ 75.2 Ci

[a]The Technical Area (TA) in which each is located is shown on Color Plate 4.

Source: Birdsell et al., 2006

Non-LANL Sources

Groundwater constituents that are unrelated to LANL operations include those from off-site anthropogenic sources and from the natural geologic environment (background). The Laboratory is aware of several non-LANL sources of anthropogenic groundwater contamination, including runoff from roads and paved areas in the town of Los Alamos, pesticide applications in the headwater areas of the Santa Fe National Forest and Los Alamos, and low levels of radionuclides from atmospheric fallout (LANL, 2004b). The Los Alamos County wastewater treatment facility in Pueblo Canyon is a source of nitrates and other constituents typical of treated municipal wastewater. This source releases treated effluent into alluvial sediments that were known to contain LANL-derived contaminants. LANL (2006a) lists the facility as a "key source" of deep groundwater contamination with nitrate.

LANL's Groundwater Background Investigation Report (2006b) provides a detailed description of background concentrations of chemical constituents. The report defines background as "natural groundwater occurring at springs or penetrated by wells that have not been contaminated by the Laboratory or other municipal or industrial sources and that are representative of groundwater discharging from their respective host rocks or aquifer material." Sidebar 3.1 describes typical steps in groundwater sampling and analysis. Chapter 5 gives the committee's assessment of LANL's data quality procedures.

The background report contains detailed information about the chemical analysis (inorganic, organic, stable isotope, radionuclide) of 208 groundwater samples from 12 springs and wells considered background. The major cations (calcium, magnesium, sodium, potassium) and anions (bicarbonate, chloride, fluoride, sulfate) as well as silica were detected in essentially all samples, i.e., frequencies of 98 to 100 percent of the samples, as would be expected for typical groundwater in the area. Trace metals—that would be considered "pollutants" if originating from an anthropogenic source—were detected over wide range of frequencies. For example, arsenic (in 5 percent of the samples), cadmium (3 percent), chromium (48 percent), lead (15 percent), uranium (100 percent), and zinc (44 percent).

Radionuclides at very low concentrations were detected in a relatively small percentage of the background samples, e.g., americium-241 (16 percent), plutonium-238 (5 percent), plutonium- 239/240 (5 percent). LANL attributed these results to either fallout or, since many statistical "non-detections" were reported, instrument noise (LANL, 2006b, p. 36).[5] Gross alpha-radioactivity was detected in 76 percent of the samples with very little variation in concentration among sampling locations, indicative of naturally occurring uranium. Tritium was detected in all background samples and is interpreted as global fallout. Background activities of tritium were measured in excess of 30 pCi/L in the alluvial groundwater, $<$2 pCi/L in the perched aquifer, and $<$1 pCi/L in the regional aquifer. Strontium-90 was not detected in any of the samples.

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[5] An instrument sometimes returns a reading that indicates the presence of a contaminant at a level that is near the limit of its ability to detect the contaminant. If the result cannot be corroborated by additional measurements or by other methods, it is usually considered to be a false positive or non-detection. Assessing the statistical significance of analytical data is discussed further in Chapter 5.

By presenting a detailed assessment of the background concentrations of contaminants at the site, LANL (2006b) is an important step in establishing a baseline for future remediation work at LANL. Little about non-LANL sources was presented during the committee meetings, however, indicating that LANL may not consider them especially important in its groundwater investigations. Although the Consent Order requires LANL to identify and assess non-LANL sources, it is not clear if such assessment of sources will have an effect on the corrective action decision (NMED, 2005, Section XI.F).

SIDEBAR 3.1
Description of a Typical Groundwater Analysis

LANL acquires samples from groundwater monitoring wells in alluvial, perched-intermediate, and regional aquifer zones; water supply wells; springs; and surface water base flow stations. Samples to measure contaminants from offsite sources or determine the natural background are taken from locations that are clearly up-gradient from possible areas that may contain contamination from LANL operations. Field data collection procedures generally follow guidelines of U.S. Geological Survey water sample collection methods and industrial standards common to environmental sample collection and field measurements, including the collection of field blanks and field duplicates and the use of trip blanks. Sample collection, preservation, and measurement of field parameters for groundwater are conducted according to standard operating procedures and quality procedures. For the majority of analyte suites, both filtered and unfiltered samples are collected.

Chemical analyses of water samples use commonly accepted analytical methods required under federal regulations such as the Clean Water Act and approved by the Environmental Protection Agency. Statements of work for contract analytical services include specific requirements for analyzing groundwater samples.

A typical suite of parameters measured for a groundwater monitoring sample includes parameters measured in the field and those measured in analytical laboratories. Field parameters collected are pH, turbidity, specific conductance, dissolved oxygen, temperature, and oxidation-reduction potential. Analytical laboratory suites include 25 metals, hexavalent chromium, organics (volatile and semivolatile compounds pesticides, polychlorinated biphenyls, high explosive residues, and dioxins or furans), radionuclides (gross alpha, gross beta, isotopic uranium, strontium-90, and tritium), and general inorganics (major ions, total dissolved solids, trace anions, silica, nitrogen species, total Kjehldahl nitrogen, perchlorate, and total organic carbon).

Source: Ardyth Simmons, LANL

MIGRATION FROM SOURCES: GEOCHEMISTRY

The significance of a source depends on the hazard posed by the contaminants themselves (amount, toxicity, persistence), the volume of waste disposed, the size of the disposal area, and perhaps most importantly, the likelihood that the contaminants might move from the source into the groundwater. Packaging of solid waste is usually considered a primary barrier against migration; liquid discharges have no such barrier. In either case, however, once in the geologic media (e.g., the soil or rock material surrounding the source) migration depends on the chemical interactions between the contaminants and the geologic media in the presence of water. These interactions determine if the contaminant will move freely with the water or be substantially retained by geologic media along the flow path.

Chemical and physical interactions among some contaminants and the geologic media can cause them to adhere or "sorb" onto the media; see Sidebar 3.2 and Figure 3.2. Contaminants may sorb to a greater or lesser degree depending on their chemical form (speciation) and the nature of the geologic media. The radionuclides cesium-137 and strontium-90, and the actinide elements such as plutonium, are examples of contaminants that can strongly sorb onto geologic media, and hence their migration tends to be significantly retarded in the subsurface environment. There are instances, however, when species sorb onto small particulates or colloids, which can be transported by water, as noted in Sidebar 3.2 and discussed later in this section.

Other contaminants are much more soluble in water and do not sorb as readily onto solids or other media. These contaminants are mobile and move at about the same velocity as the groundwater. Examples of non-sorbing contaminants include chromium (as chromate, CrO_4^{2-}), nitrate (NO_3^-), perchlorate (ClO_4^-), tritium (as tritiated water), and some high explosives (e.g. RDX).[6]

Contaminant Species in the Subsurface

LANL has long recognized the presence of radionuclide and chemical contamination in groundwater beneath the site. According to Birdsell et al. (2006), the combined conditions of a large, mobile inventory with a topographically focused water source are sufficient to drive non-sorbing contaminants through the thick unsaturated zone to the regional aquifer on the time scale of a few decades. While it is not surprising that the more mobile contaminants have been detected in the regional groundwater, their concentrations are much attenuated from the concentrations detected in the shallower subsurface.

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[6] Chemically 1,3,5-trinitroperhydro-1,3,5-triazine, RDX is an explosive used in military and industrial applications. This chemical and its degradation products are typical of the high-explosive residues that are found in some areas of LANL groundwater.

SIDEBAR 3.2
Chemical Factors that Affect the Migration of Contaminants in the Environment

The hydrology, geology of the surrounding environment, water chemistry, and chemical composition of the contaminants all influence the ability of contaminants to migrate in the subsurface. The geochemistry (or chemical and physical characteristics) of contaminants controls their transport behavior in the environment, determining their aqueous speciation, solubility, sorptivity, oxidation/reduction behavior, and the extent of their transport by colloids. The composition of a given groundwater is derived from its chemical interaction with the surrounding rock and can be approximately described by pH, redox potential (Eh), ionic strength, and cation/anion composition. As the groundwater flows through different subsurface media, the chemistry of the groundwater can change and the aqueous speciation, solubility, sorptivity, and oxidation state of the contaminants may also change.

Solubility

The solubility of a contaminant is the maximum amount that can dissolve in a given quantity of solution at a specified temperature and pressure. Thus, a contaminant that has a high solubility for a given groundwater composition readily dissolves and may be highly mobile. In contrast, a contaminant with a low solubility will not readily dissolve. Contaminants that have a high solubility in groundwater at the site include chromium, nitrate, perchlorate, tritium, and high explosives (e.g., RDX) (LANL, 2005a, Birdsell et al., 2006). Calcium, sodium, and bicarbonate are the dominant major ions in the groundwater beneath the site (LANL, 2005a). Dissolved carbonate forms complexes with trace metals and influences the metals' solubility and ultimately mobility in the subsurface. For example, a change in the pH or carbonate alkalinity of the groundwater will affect uranium's aqueous speciation and either increase or decrease its solubility and sorptivity.

Sorption

Sorption refers to removal of an ion or molecule from solution due to its adhering to a solid material. In general, it does not imply a mechanism for that removal. The term sorption is often used to describe a number of surface processes including adsorption, ion exchange, and co-precipitation. Adsorption implies that ions or molecules are removed from solution and deposited on the surfaces of solids by chemical or physical binding. Chemical binding (sometimes referred to as chemisorption) suggests strong binding that is often irreversible because it is the result of a chemical bond between the ion and the surface. Another sorption process, ion exchange, results from the physical interchange of ions associated with a solid and ions in solution; this reaction is generally

SIDEBAR 3.2 continued

reversible. Physical binding is much weaker and is the result of van der Waals forces. Other processes such as precipitation/co-precipitation may also play a role in the removal of ions or molecules from solution. Sorption is a convenient term to use in transport modeling because it relates to the overall process of removing contaminants from migrating fluids without addressing the underlying mechanistic reactions. If precipitation is the actual mechanism involved, using a sorptive-type retardation model would not be appropriate.

Certain minerals present in the subsurface, such as iron oxides, manganese oxides, clays, and zeolites have a high sorption capacity for contaminants. Cesium, americium, plutonium, and strontium are contaminants that strongly sorb to these minerals as well as to organic carbon present in the water and soil. Although sorption is typically considered reversible, the sorption of contaminants acts to significantly retard their movement or, at the least, disperse the contaminant into a larger volume of water.

Oxidation States

The oxidation state of an element is defined by its charge. The oxidation state of an element is important in determining its aqueous speciation and reactivity in solution. For example, solutes such as uranium, plutonium, sulfate, nitrate, and chromate tend to be mobile under oxidizing conditions but can precipitate or sorb under reducing conditions.

The water chemistry strongly determines which oxidation states dominate and which species are more prevelant. The behavior of U and Pu is strongly dependent on the redox potential of groundwater. At higher Eh values, the higher oxidation states of plutonium [Pu(V) and Pu(VI)] are more stable. Lower Eh values favor the lower oxidation state of Pu(IV). In general, contaminants in their higher oxidation states are more soluble in groundwater and, therefore, are more mobile than in their reduced state.

Complexation

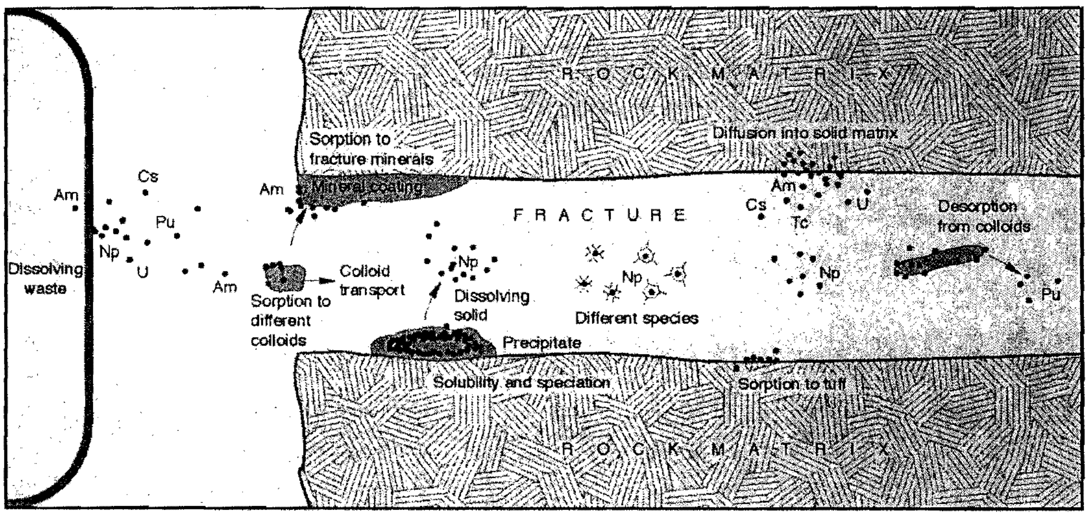
Ligands present in groundwater, such as humic and fulvic acids, CO_3^{2-}, and SO_4^{2-}, can form strong aqueous complexes with actinides. The ligands act to stabilize anions in groundwater and enhance the concentration of anions in groundwater. For example, the presence of carbonate in groundwater has been shown to complex U resulting in an increase in the solubility of U in groundwater.

Colloids

Transport of contaminants in groundwater occurs as both dissolved solutes and as colloids. Colloids are naturally occurring particles, defined as ranging in size from 0.1 to 0.001 micrometer. Colloids are found in nearly all surface water and

SIDEBAR 3.2 continued

groundwater and are formed as a result of weathering of rocks, soils, and plants.Because they are small, colloids can remain suspended and are readily transported with groundwater. Colloids are a concern as a transport mechanism because contaminants that sorb strongly to the organic or inorganic aquifer matrix can also attach to suspended organic and inorganic colloids and migrate with groundwater. At the site, colloids may include natural material (silica, clays, organic matter, and Fe and Mn oxides) and possibly solid phases associated with the treated Laboratory discharge.



Source: LANL, 2000

FIGURE 3.2 Some geochemical processes that can affect contaminant migration. A variety of chemical and/or physical processes can retard or halt the migration of contaminants along a hydrogeologic pathway, such as the fracture depicted here. While the general nature of these processes is understood, the committee received little quantitative data to confirm many of LANL's assumptions about contaminant migration. Processes similar to those depicted in this figure may also operate around sampling points in monitoring wells. Such processes involving materials introduced in drilling the monitoring wells could interfere with the sampling of contaminants in groundwater (see Chapter 5).

Table 3.3 shows the frequencies of detections of contamination in the alluvial, intermediate, and regional groundwater. The mobile contaminants chromium, nitrate, perchlorate, tritium, and RDX have moved downward from the alluvium where they were discharged from various outfalls. With the exception of tritium, there are few data to suggest that radioactive contaminants have migrated downward from the alluvial groundwater.

TABLE 3.3 Frequencies of Detections of Key Contaminants in LANL Groundwater

Analyte	Number of Analyses	Number of Detections	Frequency of Detections (percent)
Chromium Alluvial UF (UF = unfiltered)	317	176	55.5
Chromium Intermediate UF	142	105	73.9
Chromium Regional UF	603	433	71.8
Chromium Alluvial F (F = filtered)	306	113	36.9
Chromium Intermediate F	108	65	60.2
Chromium Regional F	454	244	53.7
Perchlorate Alluvial UF	257	122	47.5
Perchlorate Intermediate UF	94	37	39.4
Perchlorate Regional UF	1058	334	31.6
Perchlorate Alluvial F	301	193	64.1
Perchlorate Intermediate F	136	75	55.1
Perchlorate Regional F	375	136	36.3
Nitrate Alluvial UF	169	127	75.1
Nitrate Intermediate UF	72	60	83.3
Nitrate Regional UF	422	352	83.4
Nitrate Alluvial F	261	245	93.9
Nitrate Intermediate F	107	94	87.9
Nitrate Regional F	395	295	74.7
Tritium Alluvial UF	301	217	72.1
Tritium Intermediate UF	170	127	74.7
Tritium Regional UF	869	205	23.6
RDX Alluvial UF	172	87	50.6
RDX Intermediate UF	96	29	30.2

TABLE 3.3 continued

RDX Regional UF	615	23	3.7
Tritium, Chromium, Nitrate, Perchlorate combined Alluvial UF	1044	642	61.5
Tritium, Chromium, Nitrate, Perchlorate combined Intermediate UF	478	329	68.8
Tritium, Chromium, Nitrate, Perchlorate combined Regional UF	2952	1324	44.9
Chromium, Nitrate, Perchlorate combined Alluvial Filtered	868	551	63.5
Chromium, Nitrate, Perchlorate combined Intermediate F	351	234	66.7
Chromium, Nitrate, Perchlorate combined Regional F	1224	675	55.1
With Tritium[a]			
All Radionuclides Alluvial UF	1429	444	31.1
All Radionuclides Intermediate UF	787	137	17.4
All Radionuclides Regional UF	4158	231	5.6
Without Tritium[a]			
All Radionuclides Alluvial UF	1128	227	20.1
All Radionuclides Intermediate UF	617	10	1.6
All Radionuclides Regional UF	3289	26	0.79
Tritium is not analyzed on filtered samples			
All Radionuclides Alluvial F	871	133	15.3
All Radionuclides Intermediate F	403	5	1.2
All Radionuclides Regional F	1068	6	0.56

[a]Radionuclides include -- americium-241, cesium-137, cobalt-60, iodine-129, neptumium-237, plutonium-238, plutonium-239/240, strontium-90, technetium-99, and tritium

Source: Ardyth Symmons, LANL

Other than RDX, the non-radioactive contaminants occur naturally and have measured background values for the alluvial, intermediate, and regional groundwaters (LANL, 2007b). Some of the detections reported in the table may be below background values. For some species that occur naturally, e.g., chromium, uranium, determining the amounts added from anthropogneic sources is difficult. Measurement of isotopic ratios is a primary way of determining this difference.

Contaminant Migration

Graphical representations of LANL's sampling data for plutonium and tritium contrast the general tendencies of these contaminants to migrate with groundwater and indicate how they are distributed across the site. Color Plates 5A,B compare plutonium measured in the shallow soils versus plutonium in the deep regional groundwater. They show that most plutonium is currently located in the shallow surface soils at the canyon bottoms. LANL has attributed its few sporatic detections of plutonium in the regional groundwater to "false positives" (Phelps, 2007; also see Chapter 5).

Color Plates 6A,B compare the distribution of tritium in the shallow alluvial groundwater and the regional groundwater at the LANL site. In contrast to the current distribution of plutonium, tritium is prevalent in the groundwater system and not concentrated in surface soils. Most of the tritium is found in the shallow groundwater, with attenuated values observed in the deep regional groundwater. These observations are consistent with LANL's conceptual models of pathways for contaminant migration, which are discussed in Chapter 4.

As noted previously, water can transport contaminant species sorbed onto colloids (e.g., McCarthy and Degueldre, 1993; Ryan and Elimelech, 1996). Colloids are ubiquitous, naturally occurring or anthropogenic organic or inorganic particles, typically smaller than 1 micron in diameter, that remain suspended in water (Stumm, 1992). Studies have shown that colloids have a large range in concentration in natural waters, ranging from 0.0002 to 200 mg/L (McCarthy and Degueldre, 1993). Colloidal transport of plutonium in both surface water and groundwater has been documented at DOE sites, including Rocky Flats and the Nevada Test Site (Kersting et al., 1999; Santschi et al., 2002), and more recently iron oxide colloids were shown to transport plutonium at the Mayak site in Russia (Novikov et al., 2006). Colloidal transport of plutonium was invoked for plutonium detected in alluvial groundwater samples collected from Mortandad Canyon, but the conclusions remain controversial (Penrose et al., 1990; Marty et al., 1997).

The distribution of plutonium in shallow soils along canyons floors downgradient of the outfall locations, illustrated in Color Plate 5a, is indicative of transport by surface runoff, probably as colloidal and particulate matter. Storm events remobilize contaminated sediments and transport them downgradient. Stormwater runoff and erosion after the Cerro Grande fire in spring 2002 moved considerable amounts of soil and other materials, including contaminants, toward the Pueblo de San Ildefonso and the Rio Grande (Alvarez and Arends, 2000; LANL 2005b).

Chromium provides another example of how geochemistry can affect the mobility of important contaminants. There are two chromium species that typically exist in the environment. The hexavalent species, chromate (CrO_4^{2-}), is chemically toxic and mobile in the environment. Chromate is the prevalent form of chromium under oxidizing conditions. Under reducing conditions the trivalent oxide (Cr_2O_3), which has limited mobility and toxicity, predominates. The unexpected detection of chromium in 2005 initiated a major, ongoing effort to determine the amounts and location of the bulk of the contamination and develop plans for its remediation, as summarized in Sidebar 3.3.

Committee Views on Geochemistry and Contaminant Migration

As discussed in this section, geochemical interactions are important for contaminant migration. Like the hydrogeology, the geochemistry of the LANL site is quite complex. However, the committee received little evidence that LANL has sought to understand the geochemistry of contaminant migration at a level of detail comparable to the site investigations conducted under the Hydrogeologic Workplan. For example, the Synthesis Report (LANL, 2005a) that summarizes site characterization under the workplan is some 300 pages long but contains only a 50-page description of groundwater chemistry with no discussion of how this chemistry could affect contaminant migration. During the course of this study, few data were presented to the committee from laboratory experiments or field tests that would begin to quantify the general knowledge about geochemical effects on contaminant migration described in Sidebar 3.2 or to substantiate LANL's general observations and assumptions about the geochemical behavior of sorbing contaminants that have been described in this section.

REPRESENTATION OF SOURCE DATA

LANL has amassed a very large amount of data on contamination sources. The committee struggled to comprehend so much information in spite of well-prepared presentations at the committee's meetings and the workshop discussions. The Birdsell et al. (2006) report provided a useful initial summary of the sources LANL considers to be the most significant. Although limited in scope, the Birdsell et al. report is a good model for future reports.

In the next three parts of this section, the committee gives its views about how LANL not only can provide more comprehensible summaries of contamination sources and their importance, but also demonstrate mastery of groundwater protection fundamentals to a broad audience of stakeholders.

SIDEBAR 3.3
Chromium Contamination in Groundwater at LANL

Routine groundwater monitoring conducted in 2005 led to the identification of chromium contamination in regional groundwater at monitoring well R-28 located in Mortandad Canyon, see Color Plate 10. Chromium concentrations at that well have been between about 300 and 440 μg/L (ppb) exceeding the New Mexico Environment Department (NMED) and Environmental Protection Agency standards of 50 μg/L and 100 μg/L, respectively. Investigations are underway pursuant to the 2005 Compliance Order between LANL and the NMED. Objectives of the investigation are to:

- Characterize the present-day spatial distribution of chromium and related constituents,
- Collect data to evaluate the geochemical and physical or hydrologic processes that govern chromium transport, and
- Collect and evaluate data to help guide subsequent investigations and remedy selection.

<u>Potential Sources of Chromium Contamination</u>

Multiple potential sources of chromium contamination have been identified including electroplating, photo-processing, and use as a corrosion inhibitor in cooling-tower systems. The highest chromium usage is believed to be associated with the cooling-tower system in TA-03 at the head of Sandia Canyon, where potentially large amounts (potentially up to 37 lb/day) of chromate (Cr^{6+}, the highly soluble, mobile, and toxic form of chromium) were released along with large volumes of water.

<u>Extent of Contamination in Regional Groundwater</u>

Chromium has been detected in the regional groundwater at concentrations above the background value of 6.62 μg/L in three wells including R-28, R-11, and R-15. Studies show that the chromium is in the chromate form. Chromium in nearby water supply wells is within background. Quarterly sampling in monitoring and water-supply wells is ongoing.

Chromium occurs at relatively low concentrations (generally less than 15 μg/L) in surface water, shallow alluvial groundwater, and intermediate depth groundwater beneath Sandia Canyon. The unsaturated zone between the surface and the deep groundwater at ~700-800 feet also shows low concentrations of chromium suggesting that much of the chromium might remain bound to sediment near the surface and/or has migrated through the unsaturated zone into the regional groundwater.

The current (2007) phase of the investigation involves installation of a deep monitoring well (R-35) to further define the extent of chromium and to serve as a monitoring point relative to water supply well PM-3. A sediment investigation is also underway to determine how much chromium remains bound to sediments at the surface.

Source: Danny Katzman, LANL

Mass Balance

Mass balance is a mathematical tool used throughout science and engineering to account for materials in a system—for example in the design and operation of a chemical plant or a refinery; see Sidebar 3.4. Applied to groundwater protection, developing mass balances would demonstrate LANL's ability to account for contaminants released from its operations. LANL is aware of this and has begun to develop mass balances for contaminants around some sources (Birdsell et al., 2006). With appropriate acknowledgment of uncertainties (see the next section), mass balances would provide summary representations of LANL's source and monitoring data that would allow verification by outside experts and enhanced understanding by all stakeholders. Identifying major uncertainties in the development of a mass balance can help guide future site investigations.

As illustrated in Figure 3.3, sources are the inputs from which contaminants enter the soils, rocks, and water that constitute the hydrogeologic environment beneath the LANL site. Contaminants from a source may migrate along a pathway through the geologic media. The "control volume" enclosing the pathway is a conceptualization. In some cases where contaminants have migrated only a short distance from the source, it may represent the relatively small volume of soil or other media around the source that is contaminated. This is frequently true for solid sources disposed of in dry locations. Uncertainties in the mass balance will be due primarily to uncertainties in source inventory as discussed earlier in this chapter. In these cases, remediation options including source removal, containment, or no action can be evaluated as means to ensure groundwater protection.

In other cases, contaminants may have migrated substantial distances from their source, and the control volume may encompass an entire watershed or more. Along with uncertainties in the source inventory, a mass balance for such a large volume will reflect uncertainties in the contaminant migration pathways, discussed in Chapter 4, and in the monitoring data, discussed in Chapter 5. In cases of extended migration, source removal will probably not be practical; instead, reducing flows of water that could move the contamination deeper into the subsurface, as LANL is doing for the TA-50 discharges into Mortandad Canyon, may be more appropriate.

The simple mass balance equation in Sidebar 3.4 provides only a snapshot at a given time. In this sense, mass balance provides no predictive ability. However, successive mass balances performed as additional monitoring data are acquired can provide estimates of the rate a contaminant is migrating from its source, accumulating in the vadose zone, and entering the regional aquifer if this is the case.

Developing a mass balance for significant contaminants (those listed in the Consent Order and other regulations) is an important tool for LANL to demonstrate that contaminants from its operations are accounted for. LANL has sufficient data to begin constructing mass balances for simple systems where source quantities are reasonably well known and migration is limited, which is LANL's current approach. These limited mass balances could then be integrated to describe larger areas as more knowledge is acquired from future work on defining source inventories and monitoring. Such future work is clearly indicated if knowledge to develop the mass balance of an important contaminant, e.g., chromium, plutonium, around a given source is lacking.

SIDEBAR 3.4
The Applications of Mass Balance

Mass balance is an expression of the law of conservation of mass. It is one of several fundamental conservation laws (e.g., energy, momentum, electrical charge). Use of mass balance is ubiquitous in science and engineering to account for materials in a given system. The more important aspects and limitations of applying mass balance principles to LANL's groundwater protection program are outlined below.

The mass balance applies to essentially any material entity that can be identified and quantitatively measured, including radioactive and chemical species. Often mass balance is applied to groups of components that behave collectively as one component. The entity is chosen according to the needs of the problem.

The mass balance applies to a specific region in space or "control volume." The dimensions of the control volume are chosen according to the needs of the problem. The control volume does not have to be a single region in space, be in one phase (fluid or solid) or have a regular geometric shape. Choosing an appropriate control volume may be the most important part of the application of mass balance in accounting for contaminants at LANL, see Figure 3.3.

The mass balance applies to a specific time increment or the time difference between the *present* and *initial* terms. Formally, mass balance is described by a time-dependent non-steady-state equation. For the purpose of this discussion, the equation can be written as:

mass present in the control volume (determined by monitoring) – **initial mass in the control volume** (from the original source) = **mass from non-LANL sources** (natural or arising offsite) – **mass output** + **mass reacted** (altered or retained in the flowpath)

The terms in this expression can be described and used as follows:

1. The mass present in the control volume at any time after the initial time is determined from monitoring around the source(s) and as necessary monitoring extended pathways, which must be known from site characterization. Uncertainty in this parameter arises from uncertainty in knowledge about the pathways (Chapter 4) and uncertainty in the sampling data (Chapter 5).
2. The initial mass from original or indigenous sources is known or estimated from records of waste emplacements or discharges. This quantity can be from a single event or be a sum of events, including continuous discharge. The committee recognizes a good deal of LANL's source data are incomplete or missing, which is a major source of uncertainty discussed earlier in this chapter.
3. Mass from non-LANL sources such as naturally occurring contaminants (background) or from offsite origins is also determined by measurements discussed earlier in this chapter. This term of the equation is important because it may account for part or all of the mass of the contaminant detected in the control volume (term 2 above). There are clearly uncertainties in this term as well as the others.

SIDEBAR 3.4 continued

4. Mass reacted is the amount of the contaminant that is transformed along the flowpath. Some radioactive contaminants with relatively short half-lives may simply decay away at the source or along the pathway. For example, tritium has a half-life ($t_{1/2}$) of about 12.5 years; for plutonium-241, $t_{1/2}$ is about 14.4 years; and for strontium-90 and cesium-137 $t_{1/2}$ is about 30 years. Geochemical, or in some cases biochemical, processes may immobilize or nearly immobilize a contaminant or change it to a non-hazardous form.
5. The mass output represents migration of a contaminant out of the control volume into a previously uncontaminated area.

If all the terms in the mass balance require estimation, which is clearly the case described here, the equation is used to check the consistency of the estimates. If the equation is satisfied, the mass balance is said to be *closed* for that entity and control volume. This application of mass balance, essentially a means by which LANL can succinctly display its knowledge and uncertainties of the amounts and locations of contaminants on the site, is the use envisioned by the committee. Reducing uncertainties identified in performing mass balance can help guide future work in LANL's groundwater protection program.

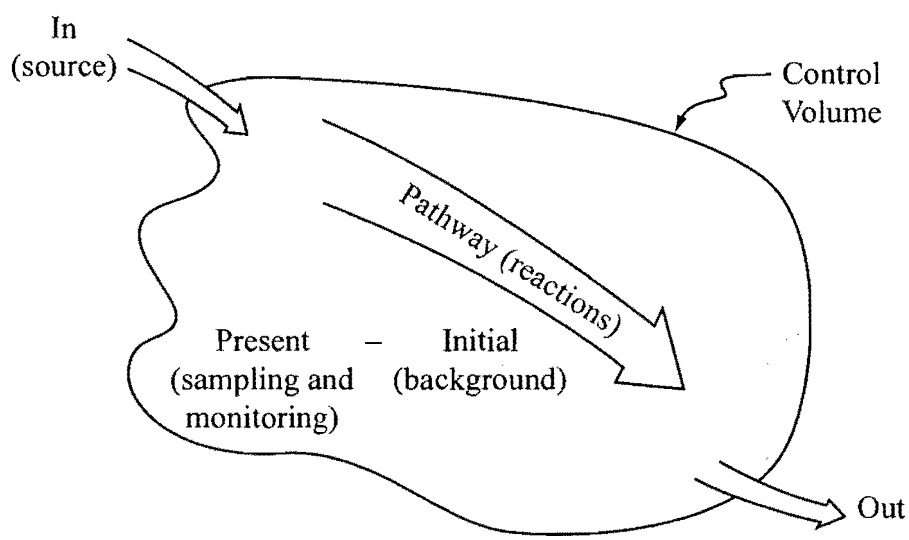


FIGURE 3.3 Conceptualization of the migration of contaminants from their source through the hydrogeologic environment. In principle, one can use source inventories, release data, and sampling to determine, or estimate, a mass balance that accounts for the inventory of a contaminant that may reach an important water supply at some future time. The pathway represents all of the ways that a contaminant can more from input to output.

By accounting for contaminants, mass balance is an important tool in planning remediation. While remediation by controlling or removing the source is typically the simplest, quantifying the buildup of contaminants that have moved outside their source into the vadose zone and intermediate aquifers can inform decisions for continued monitoring or active remediation along a pathway.

Uncertainty

Beginning with uncertainties in LANL's source inventories described in this chapter, concepts of uncertainty reappear throughout this report. According to IAEA (1989) and NCRP (2005) nomenclature, uncertainty can be divided into Type A and Type B. Type A uncertainty reflects how well a property can be determined by measuring it. This type of uncertainty is generally estimated by repeated measurements of the property under investigation—repeated field or laboratory measurements of the hydraulic conductivity of intact rock would be an example of this kind of uncertainty. In technical terms, this type of uncertainty analysis deals with the variability about a mean estimate of a parameter or some other measurable feature of the system (stochastic variation), which is typically indicated with error bars or a plus/minus interval bounding the measurement. Addressing Type A uncertainty is central to all data collection and is usually addressed by a well-functioning quality assurance program and sample analysis plans. Chapter 5 provides the committee's assessment of LANL's data quality program.

A second type of uncertainty is due to lack of knowledge about the system or a component of the system. Type B uncertainty is equally or perhaps more important than Type A at this stage of LANL's groundwater protection program. Two examples of Type B uncertainty at LANL are the following:

- Source inventories—the radionuclide inventories for two (of nine) key MDAs listed in Table 3.2 are "unknown." The currently unknown quantity of radionuclides in those MDAs includes Am, Cs, Pu, tritium, Sr, and U.
- Pathways for contaminant migration—there are alternative conceptual models that can account for currently available characterization data, as discussed in Chapter 4.

These Type B uncertainties are difficult to express with error bars or bounding intervals.

Type B uncertainties (based on lack of knowledge) usually dominate Type A uncertainties in environmental decision making, for example, for making a regulatory decision about the level of cleanup or the type of characterization that might be required. Type B sources of uncertainty led to the "surprise" discovery of chromium in the regional aquifer; see Sidebar 3.3.

The committee does not mean to imply that Type B uncertainties cannot be addressed or reduced. LANL scientists have made significant progress in understanding the major features and components of past waste disposal practices and the geologic system. Characterizing contamination sources and the hydrogeologic system cannot eliminate Type B uncertainty, but it can help both to reduce the uncertainty and to better estimate the level of uncertainty that remains.

Uncertainty is a fundamental component of scientific knowledge. For LANL, the problem is not removed simply by acquiring additional data. Progress in the groundwater protection program will be an iterative process, for which increased knowledge may reduce uncertainty in some cases or increase the uncertainty in other cases. Better communication of uncertainty with the public and stakeholders could help support consensus-building efforts as the program advances.

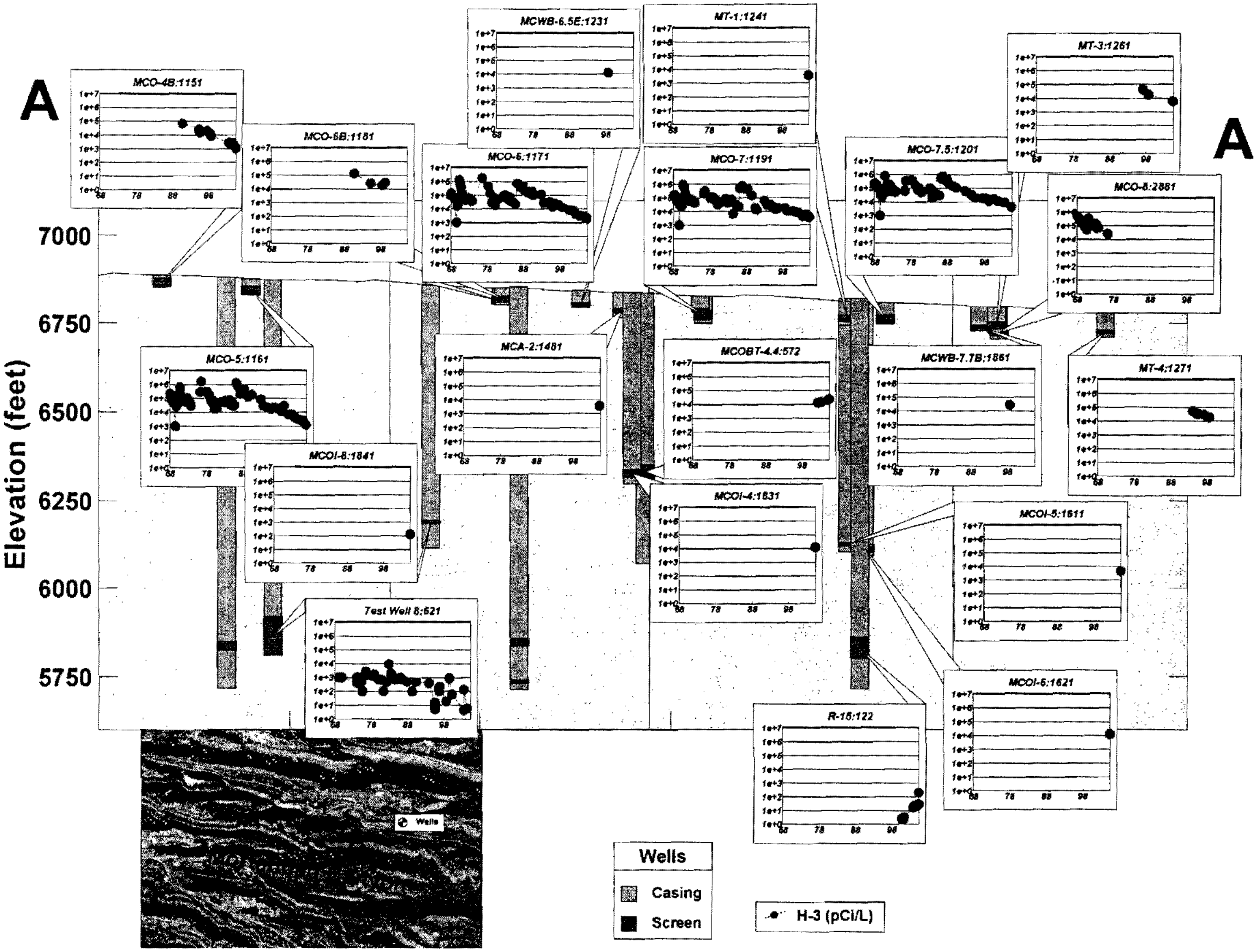
Relational Databases and Data Visualization

LANL gave the committee a tremendous amount of analytical data in a variety of presentations and discussions, figures, and reports. Finding the most informative ways to use these data, for example to show source locations or the locations of contaminants detected in site characterization, is challenging. LANL could not readily display data to address questions that came up during the committee's workshop discussions regarding sources. Based on this experience, LANL appears to have the need—and the opportunity—to find better ways to describe its accumulated knowledge.

Relational databases allow one to more easily store and retrieve data, and can be very useful for managing data for analysis and visualization. The term relational database refers to the storage of data in a set of tables that are linked by a set of logical relations; this is different from the storage of data in a single spreadsheet or table, which can be inefficient. Results of interrogating a relational database can be displayed visually to provide an efficient means of conveying information.

One such database is a part of the RACER program, a DOE-funded interactive relational database that allows easy visualization and analysis of large datasets.[7] Produced by the RACER program, Figure 3.4 summarizes a large amount of tritium data in a way that is relatively easy to understand. The diagram shows the location of wells located along an A-A' transect in Mortandad canyon, number of wells, location of the screened intervals and a plot of tritium concentrations for each well at a given date. Tritium data for each well are plotted as concentration (pCi/L) (y-axis) versus time (1968-2000) (x-axis). Lower inset shows the location of A-A' transect. Such graphical relational databases are useful for making very large amounts of data understandable to both scientists and interested citizens. For example, the plots show that higher concentrations of tritium were detected in the shallow groundwater compared to groundwater collected from the regional aquifer. Data analyses that were below the detection limit (below MDL and designated as U, see Sidebar 5.2) were not plotted. This plot is for illustrative purposes only as the RACER project is still being developed.

[7] Information contained in the RACER database was provided by LANL, and it is publicly available in LANL's Water Quality Data Base accessible at http://wqdbworld.lanl.gov.



Source: Risk Assessment Corporation

FIGURE 3.4 Visualization of tritium detected in wells along Mortandad Canyon. Tritium concentrations are graphed as a function of time at each sampling point. The diagram gives a sense of the location of sampling wells, the number of wells, and the depth at which tritium has been detected Such visual aids are important for making very large amounts of sampling data understandable to both scientists and interested citizens.

FINDINGS AND RECOMMENDATIONS ON SOURCES

General Findings

The committee found that LANL has controlled its liquid waste discharges. According to information presented to the committee, contamination now found in groundwater, including the regional aquifer, most likely came from previous discharges of liquid wastes. Solid wastes and contaminants deemed by LANL to have less near-term potential to impact groundwater have received much less attention than the liquid sources and are not well characterized, especially in terms of source inventories. Remediation of these solid wastes (e.g., the MDAs) under the Consent Order has only recently begun and was not discussed with the committee.

Based on LANL's written reports, the committee judged that the Laboratory has a good understanding of non-LANL sources of contamination. Offsite anthropogenic sources are identified in the Integrated Groundwater Monitoring Plan for Los Alamos National Laboratory (LANL, 2006a, 2007b). The LANL Groundwater Background Investigation Report (LANL, 2006b) provides comprehensive data on naturally occurring contamination in the site's groundwater.

Detailed Findings and Recommendations

The committee offers the following findings and recommendations to assist LANL in future work to understand and control its contamination sources, with emphasis on longer-term concerns that have not been addressed during the first portion of the groundwater protection program.

Solid wastes (e.g., the 25 MDAs) and certain contaminants deemed by LANL to be essentially immobile (e.g., Pu) have the potential for impacting groundwater in the future. MDA AB in TA-49, which contains some 2300 Ci of Pu-239, is an example. The committee received little information that would provide assurance that these sources are well understood or well controlled.

> ***Recommendation:*** *LANL should complete the characterization of major contaminant disposal sites and their inventories, i.e., complete the investigation of historical information about these disposal sites with emphasis on radionuclides and chemicals likely to impact human health and the environment. Selected sites should be characterized by field analysis when historical information is insufficient to determine quantities of major contaminants disposed and to confirm the degree of migration that has occurred.*
>
> *LANL should devote greater effort to characterizing sources with significant inventories of contaminants (especially plutonium) that usually are strongly sorbing but still have the long-term potential to migrate in the presence of water.*

Priority for investigating sources is established by the Consent Order. This recommendation emphasizes the need to confirm assumptions that underpin the assignment of lower priority to "immobile" wastes.

There are still large uncertainties in LANL's estimates of the inventories of principal contaminant sources and their locations. Similarly, analyses are lacking to approximate the current locations of contaminants (which may have migrated from these sources) in the various hydrogeological units that constitute the LANL site and surrounding areas.

> ***Recommendation:*** *For the major disposal sites, LANL should develop mass balance estimates of the quantities of disposed chemicals and radionuclides remaining in the surface soil and/or residing in the shallow alluvium, the vadose zone, and the regional aquifer.*
>
> *Sitewide, LANL should perform a mass balance for hazardous and radioactive substances by assessing the types, quantities, and volumes of individual hazardous materials that have entered the site over the years.*[8]

These analyses, with estimates of data uncertainties, should help LANL account for contaminant sources, releases, radioactive decay, and migration through the hydrogeologic system in a way that is transparent and understandable to all of its stakeholders.

Surface water is an important pathway for transport of contaminants to the groundwater. Stormwater can re-mobilize contaminants that have been deposited in canyons and transport them downstream. The contaminants can enter the shallow groundwater away from their original source or be transported offsite.

> ***Recommendation:*** *LANL needs to quantify the inventories of contaminants released in the canyons in order to understand their potential threat to groundwater. The sitewide mass balance of inventories of hazardous and radioactive substances should include the surface water transport pathway.*
>
> *LANL should continue to develop surface water and sediment monitoring programs. LANL should continue, and improve, its control of contaminants moving down the canyons to prevent further surface transport and redistribution offsite of both mobile and sorbing contaminants. Measures to control surface transport down canyons, including further reduction of aqueous discharges, removal of contaminated media, and appropriate use of barriers, are needed.*

The geochemistry of contaminant migration has not been studied at a level of detail comparable to the site investigations conducted under the Hydrogeologic Workplan. This is a gap in LANL's current groundwater protection program.

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[8] When taking mass loss mechanisms into account (e.g., radioactive decay rates), this will identify the upper boundary of pollutant mass that may still exist at the site today.

> ***Recommendation:*** *LANL needs to better integrate geochemistry into its conceptual modeling. Laboratory experiments and field tests, in addition to literature data, are necessary to substantiate LANL's general observations and assumptions about the geochemical behavior of contaminants.*

LANL will continue to be an active DOE site with the potential for release of contaminants from its ongoing operations. Discharges and releases have been cut substantially at TA-50, the location of the site's radioactive liquid waste treatment facility. Yet, its discharges will continue to provide a flow of water that will tend to remobilize contaminants already deposited in the canyons.

> ***Recommendation:*** *LANL should continue to review all operations and reduce discharges and releases to the greatest extent practical. This includes efforts to minimize the disposal of solid wastes on mesa tops because waste disposal in those areas can pose a long-term threat to the regional groundwater.*

4
Pathways for Contaminant Transport

Los Alamos National Laboratory (LANL) carried out its Hydrogeologic Workplan activities from 1998 through 2004 to better characterize potential pathways for contaminant transport. The purpose of the workplan was to develop the basis for a sitewide groundwater monitoring plan—to be effective, monitoring wells must intercept the contaminant pathways. As noted earlier in this report, the committee's study came at the juncture between completion of the workplan activities and development of the sitewide monitoring plan. The committee was asked to review the Interim Facility-wide Groundwater Monitoring Plan that LANL issued during the study period.

This chapter first summarizes LANL's current understanding of hydrogeologic pathways that may transport contaminants from the sources described in Chapter 3 into the regional groundwater. After this summary, the chapter addresses two sets of questions in the committee's task statement:

1. Does the laboratory's interim groundwater monitoring plan[1] follow good scientific practices? Is it adequate to provide for the early identification and response to potential environmental impacts from the laboratory?
2. Is the scope of groundwater monitoring at the laboratory sufficient to provide data needed for remediation decision making? If not, what data gaps remain, and how can they be filled?

The committee found the short answers to item 1 are a qualified yes and no, respectively. While the interim groundwater monitoring plan generally follows good scientific practices, there are opportunities for improving it. The plan is not adequate to provide early identification of potential contaminant migration with high confidence because LANL's understanding of pathways for contaminant transport, especially inter-watershed pathways, is not yet adequate to support such confidence. The committee's short answer to item 2 is a qualified no. Gaps remaining in LANL's pathway conceptualizations and in the scope of groundwater monitoring at the laboratory are discussed in this chapter.

CONTAMINANT PATHWAYS AND MONITORING

Understanding pathways for aqueous transport of contaminants is necessary for determining the location and mass of contaminants at a given time, predicting their migration throughout the site's hydrogeologic system, and estimating if and when there

[1] LANL issued its Interim Facility-wide Groundwater Monitoring Plan (LANL, 2006c) in April 2006. Subsequently, LANL issued its 2006 Integrated Groundwater Monitoring Plan for Los Alamos National Laboratory (LANL, 2006a). The Interim Plan is incorporated entirely as Section 1 in the Integrated Plan. In addition the Integrated Plan includes monitoring of water supply wells in Los Alamos County and in the City of Santa Fe (Section 2); monitoring of groundwater and surface water at locations within the Pueblo de San Ildefonso (Section 3); and monitoring to satisfy conditions of two groundwater discharge permits under New Mexico Water Quality Control Commission regulations (Section 4). These additions did not affect the committee's review or its findings and recommendations, which are given in this chapter.

might be impacts on regional groundwater. Toward developing a monitoring program, LANL's understanding of pathways is essential for:

- Planning the locations of wells to sample the alluvial groundwater, perched-intermediate groundwater, and the regional aquifer so that the wells are most likely to intercept a contaminant plume;
- Determining the well-sampling frequency and types of analyses needed; and
- Providing a rationale or model for interpreting the sample results.

As summarized in Chapter 2 and described in this chapter, LANL has developed a broad understanding of the main features of the hydrogeologic environment beneath the Pajarito Plateau. LANL (2005a, referred to as the "Synthesis Report") is a comprehensive summary of the geologic and hydrologic properties of the site and potentially affected regions nearby. This chapter provides the committee's perspective and assessment of LANL's current state-of-understanding of pathways and ways to build on this understanding to establish a scientifically sound groundwater monitoring program.

VADOSE ZONE FLOW PATHWAYS

LANL has concentrated its efforts on understanding vadose zone pathways that its scientists believe have the greatest potential to impact the regional aquifer in the near term. In addition to presentations to the committee and the Synthesis Report, LANL scientists have published details about the site's vadose zone pathways in a special edition of the *Vadose Zone Journal* (VZJ, 2005). Such peer reviewed publication is the standard of sound science and illustrates the quality of scientific effort LANL has brought to bear on understanding these pathways.

The stratigraphic units of primary interest for vadose zone flow are the Bandelier Tuff, Cerros del Rio basalt and Puye Formation, see Color Plate 2. Water content distributions in the unsaturated zone, major ion and contaminant transport measurements, numerical models, field measurements at an instrumented site in basalt (Stauffer and Stone, 2005), and field injection tests in the Bandelier Tuff (Robinson et al., 2005a) form the basis for the LANL flow and transport conceptualizations.

Birdsell et al. (2005) summarize LANL's understanding of vadose zone flow in terms of conceptual models for the four hydrologic regions at the site:

- Wet canyons,
- Dry canyons,
- Dry and disturbed mesas, and
- Mountain-front mesas.

Wet canyons, believed to be the origin of most current groundwater contamination, have received by far the greatest amount of study. Other pathways assumed to present lesser or longer-term threats to regional groundwater have received less attention.

Wet Canyon Conceptual Model

Wet canyons are either naturally wet with their headwaters in the mountains (e.g. Cañon de Valle, Los Alamos, and Pueblo Canyons) or anthropogenically wet by discharges from cooling towers or wastewater treatment plants (e.g. Mortandad Canyon, Sandia Canyon).[2] The wet canyon conceptual model is the one most developed by the LANL staff, and as such the wet canyons are the focus of most of the groundwater modeling and monitoring efforts. In the committee's workshop, LANL scientists expressed a consistently high level of confidence in the wet canyon conceptualization.

Mortandad Canyon has been extensively studied, and, in large part, these studies form the basis for the conceptualization applied to all wet canyons at LANL; see Color Plate 7. Mortandad Canyon starts on the dry plateau but is considered a wet canyon because of anthropogenic discharges into the canyon. The radioactive liquid waste treatment facility (RLWTF) at Technical Area-50 (TA-50) released treated effluent in excess of 10^7 L/yr via a small side canyon emptying into the larger Mortandad Canyon. The discharge volume and contaminant mass in the effluent are well documented and, thus, have proved useful for validation of the wet canyon conceptualization.

A key component of the wet canyon conceptual model is relatively large surface water flow volumes, whether natural or anthropogenic. In Mortandad Canyon, treated wastewater effluent is discharged into the canyon, where it mixes with uncontaminated surface water runoff from other locations. The nonsorbing contaminants[3] are assumed to be well mixed with the water. To a first approximation, LANL considers this mixture to be a uniform source ("line source") of water and contaminants to the deeper unsaturated zones (LANL, 2005c). While the assumption of a uniform line source to the deeper zones is a reasonable approximation for its intended purpose, other conceptualizations could include more complicated flowpaths through the intermediate zone.

According to the conceptual model (illustrated by Color Plate 7), surface water, shown as stream runoff, percolates through the alluvium until downward movement is slowed by less permeable Bandelier Tuff, maintaining shallow bodies of perched groundwater within the intermediate zone. Under portions of Pueblo, Los Alamos, Mortandad, and Sandia Canyons, intermediate-perched groundwater occurs in the lower part of the Bandelier Tuff and within the underlying Puye Formations and Cerros del Rio basalt. Two conceptualizations are hypothesized by LANL for infiltration from the canyon bottoms to the regional groundwater. In Mortandad Canyon, it is assumed that infiltration through the tuff units is by matrix flow.[4] In contrast, near Otowi-1, at the confluence of Los Alamos and Pueblo Canyons, little or no tuff is present and rapid fracture flow is assumed through the basalts (Birdsell et al. 2005).[5]

Flow through the fractured basalts can be both vertical and horizontal. In general, the interiors of thick basalts have a high percentage of high-angle (near-vertical) fractures

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[2] The locations of these canyons are shown in Chapter 1, Figure 1.1, and several of the color plates following Chapter 2.

[3] Some other important contaminants that tend to sorb onto solid materials, such as rocks and soils, are attenuated but are still transported down-canyon, albeit at lower concentrations, see Chapter 3.

[4] Matrix flow refers to uniform flow through a porous medium, as opposed to non-uniform flow for example through cracks or fractures in consolidated rock.

[5] Otowi-1 is indicated by O-1 near the upper right corner of Color Plates 9 and 10. Otowi-1 is one of the water supply wells for Los Alamos County that is located on the LANL site.

related to columnar fracture patterns that formed when the basalt cooled at the time of its geologic origin. Fractures of all orientations, including high-angle and low-angle types, frequently occur near the upper and lower margins of the basalts. The basalts are commonly stacked in thick sequences containing a dozen or more flow units. The individual flow units are commonly separated subhorizontal zones of highly porous interflow breccia. Under unsaturated conditions, the rapid transport is thought to occur predominantly as gravity flow through the high-angle fractures and vertically across the interflow breccias. Near-saturated conditions may occur locally in regions with low effective porosities that allow the fractures to carry the groundwater and bypass lower-porosity regions within the basalt.

If surface water does not infiltrate through the alluvium, it will continue to carry contaminants down the canyons. Stormwater can remobilize considerable amounts of sediments and transport both mobile and sorbing species. The inventory of contaminants in the canyons is subject to transport by storm flow toward the Rio Grande. Surface runoff, which is an important pathway by which contaminants can be redistributed or transported offsite, is discussed later in this chapter.

Travel time of liquids from waste sources in the wet canyons to the regional groundwater is predicted to be relatively short (LANL, 2003; Nylander et al., 2003). The presence of anthropogenic contaminants in regional groundwater confirms that beneath wet canyons at least some vadose zone pathways have travel times on the order of a few decades (Birdsell et al., 2005; Robinson et al., 2005c). Data suggest vertical transport velocities of up to 9 m/yr (30 ft/yr) in Mortandad Canyon. Laboratory-derived contaminants (tritium, perchlorate) released in liquid effluents in Los Alamos and Pueblo Canyon have reached the regional aquifer and are present in Otowi-1.

In Sandia Canyon a sizeable wetland has flourished downstream of the cooling tower discharge. The sediments are retaining contaminants, such as some metals. The downstream end of the wetland contacts a visible fault, and it is likely that this wetland is providing an aqueous driver to encourage vertical movement of nonsorbing contaminants downward through the mechanisms and pathways described above.

The pathway conceptualization for the wet canyons is the most developed of the conceptualizations presented by LANL, and the interim groundwater monitoring plan relies heavily on this conceptualization. Wells have been sited to monitor the alluvium, and the perched intermediate zone is also monitored to provide early indication of potential regional aquifer contamination. However, the lateral extent and hydrogeologic continuity of intermediate, perched groundwater have not yet been established, and it is not clear where the contamination will impact the regional aquifer. This need for additional information relates directly to LANL's plans for future site monitoring.

Dry Canyon Conceptual Model

In contrast to wet canyons, dry canyons have smaller catchment areas, infrequent surface flow, and limited or no saturated alluvial aquifers. Anthropogenic sources of water (if present at all) are considered to be small (Birdsell et al., 2005). Travel times from the surface to the regional aquifer are expected to be from hundreds to several thousands of years (Nylander et al., 2003; Birdsell et al., 2005) based primarily on the analysis of chloride data. This assumes that chloride, derived from atmospheric deposition, is concentrated in shallow vadose zone pore water by evapotranspiration (Walvoord and Scanlon, 2004). While relatively little scientific effort has been applied to dry canyons, the committee is in agreement with LANL that the dry canyon conceptualization is adequate under current dry, undisturbed conditions. However, disruptive events such as the Cerro Grande fire and its aftermath of severe stormwater runoff, can lead to significant mobilization and redistribution of contaminants as noted in Sidebar 4.1 (also see Alvarez and Arends, 2000; LANL, 2005b).

Dry and Disturbed Mesas

Dry mesas are assumed to have annual net infiltration rates ranging from less than 1 mm/yr to 10 mm/yr, with travel times for contaminants migrating from the mesas to the regional aquifer—which lies some 300 meters (1000 feet) beneath the mesa tops in the central part of the plateau—on the order of several hundred to thousands of years (Newman, 1996; Newman et al., 1997; Birdsell et al., 2000; Nylander et al., 2003). The assumed infiltration rates are based on the conceptualization of dry mesas being generally composed of non-welded to moderately welded tuffs with low water content and, thus, matrix-dominated flow. These assumptions may not always be true if the mesa is disturbed, for example by human activities or other geophysical circumstances.

Birdsell et al. (2005) gave several examples that show focusing surface runoff on disturbed mesa tops can result in flux increases up to hundreds of millimeters per year. One example was focused runoff on Mesita del Buey caused by an asphalt pad. A second example is from Frijoles Mesa, where surface water was concentrated when an elevated asphalt pad trapped surface water along its edge. The higher infiltration rates that occurred under these disturbed conditions were estimated to range from 60 to 388 mm/yr. Another potential water source on dry mesas mentioned in public meetings by the State of New Mexico and stakeholders is ponding of precipitation and runoff in disposal pits during the period of time that they remain open.

In the committee's public meeting in May 2006, LANL presented the concept of a "breathing mesa." According to this concept, changes in atmospheric pressure move air in and out of the mesas. Drying is attributed to convective air circulation within the mesas. For liquid phase transport, the hydraulic conductivity of an unsaturated soil is a strong function of water content. Drying of a soil due to the mesa's "breathing" would result in lower unsaturated hydraulic conductivity and a reduced downward migration rate of contaminants compared to wetter soil. Capillary suction also serves to draw water from wetter to drier soils if the liquid source is persistent. These same conditions will enhance vapor transport of volatile species. The importance of vapor transport in deep vadose profiles varies and strongly depends on soil texture and water content. Because the water contents in the dry mesas are low, vapor transport may be significant.

LANL's conceptualization of contaminant transport from dry mesas is not as well developed as that for wet canyons. Given the large inventory of wastes disposed of on the mesas, assumptions that underpin the view that contaminants will be relatively immobile need more field and laboratory confirmation. Vapor transport deserves greater study. Wastes disposed of near surface on the mesas can be affected by disruptive events that might occur either by human activities or through natural causes. They can also be affected by anthropogenic activities that lead to ponding or focused runoff.

Mountain-Front Mesas

Mountain-front mesas are classified as naturally wet mesas, with greater precipitation, runoff, and infiltration than the dry mesas. The wet mountain-front mesas have numerous springs, which are rare in the dry mesas or the eastern part of the plateau except where the regional aquifer discharges near the Rio Grande. Mountain-front mesas are likely the dominant recharge zone for the plateau. The upper tuff units along the mountain front are often moderately to strongly welded, resulting in fracturing and minor faulting. Thus, fracturing appears to control spring locations and contaminant distributions in the subsurface near outfalls and wastewater lagoons.

LANL's conceptual model for contaminant movement on mountain-front mesas includes rapid movement along fractures, but assumes most of the mass is transported through the soil matrix. Very rapid vadose zone flow and transport were shown to occur during a bromide tracer test performed in 1997 in a former high explosives outfall pond at TA-16, although the majority of the contaminant mass remains close to TA-16 (LANL, 1998b).

While it is generally not feasible to directly monitor fracture flow on a routine basis, additional sampling of the matrix could be used to confirm that the expected mass of contaminants in the matrix can be accounted for. Natural tracers such as chloride and bromide and radioactive species (especially those associated with atmospheric testing of nuclear weapons such as tritium and Cl-36) have been used to identify rapid transport in fractures or faults at some sites. For example, bomb-pulse Cl-36 was used to identify rapid transport in parts of the Department of Energy's (DOE's) proposed Yucca Mountain repository for spent fuels and high-level radioactive waste (Wolfsberg et al., 2000).

Potentially Fast Vadose Zone Pathways

From most locations on the LANL site, water percolates slowly through the porous and permeable matrix of most subunits of the Bandelier Tuff. The exceptions are fractures, perched water, and the combination of both that can lead to fast pathways. LANL scientists have identified several sites where fracture flow is evident. The complex geology of the site also suggests that funnel flow or perched flow may be important processes in redirecting the groundwater.

When water percolates through the unsaturated soil matrix, predictions of flow and transport are based on Darcy's law and Richards' equation and, generally, slow transport is predicted from the typically low values of recharge and unsaturated hydraulic conductivity in the vadose zones of arid and semi-arid regions. However, there is evidence at LANL that preferential pathways are occurring in the vadose zone. Preferential flow may transport water and contaminants horizontally beyond the watershed in which they were discharged or transport them vertically to the aquifer far sooner than might be predicted based on bulk-media properties and Richards' equation.

Preferential flow in the vadose zone refers to flow that is locally concentrated with fluxes higher than predicted by Richards' equation for unsaturated matrix flow. Preferential flow paths include macropore flow (resulting from soil fissures, cracks, and fractures, e.g.), unstable flow, and funnel flow (NRC, 2001). Because the term funnel flow is often associated with redirection of unsaturated flow by capillary barriers, one can distinguish between funnel flow and preferential flow resulting from perching of water on finer geologic strata. The complex geology of the site also suggests that funnel flow or perched flow may be important processes in redirecting flow.

Fractures in the Shallow Vadose Zone

Fractures are macropores that are obvious *potential* pathways for flow and transport but the presence of fractures, in itself, does not imply that they are always active as transport pathways. Near the surface, the characteristics of the source affect the tendency of fractures to transport contaminants away from the source. If the source zone is ponded water and the fractures are exposed at the surface, fracture flow would be expected to occur. If on the other hand, fractures do not reach the surface or the source is not ponded, fracture flow may not occur.

Fracture flow can occur as film flow, which exhibits behavior not expected in capillary flow (NRC, 2001). Intermittent flow in fractures can also influence the travel depth of a contaminant from the surface. Fractures may increase the depth that liquids penetrate during cyclic infiltration events (Soll and Birdsell, 1998). In this scenario, fractures would fill and liquid would flow to depth during times of heavy infiltration, followed by flow out of the fracture into the matrix afterward. This process then leaves a high water content in the matrix and less capillary drive from the fracture to the matrix. The next large infiltration event would substantially bypass the moist matrix and move deeper before imbibing into the matrix. LANL's climate consists of high-intensity, seasonal thunderstorms, which could possibly cause this behavior.

Funnel Flow

Funnel flow occurs in connection with contrasting stratigraphic layers or lenses that are discontinuous; see Figure 4.1. Funnel flow occurs when unsaturated flow is deflected by sloping coarser lenses that act as capillary barriers (Kung, 1993; Ju and Kung, 1997). Water and contaminants are redirected, resulting in preferential flow paths, local increases in water content and therefore local increases in hydraulic conductivity, and higher downward flux of the percolating water. The pollution potential of sorbing contaminants is higher for funneled flow because percolation rates increase, the time available for degradation is reduced, and the soil matrix in contact with the contaminant is limited, reducing retardation of the contaminant.

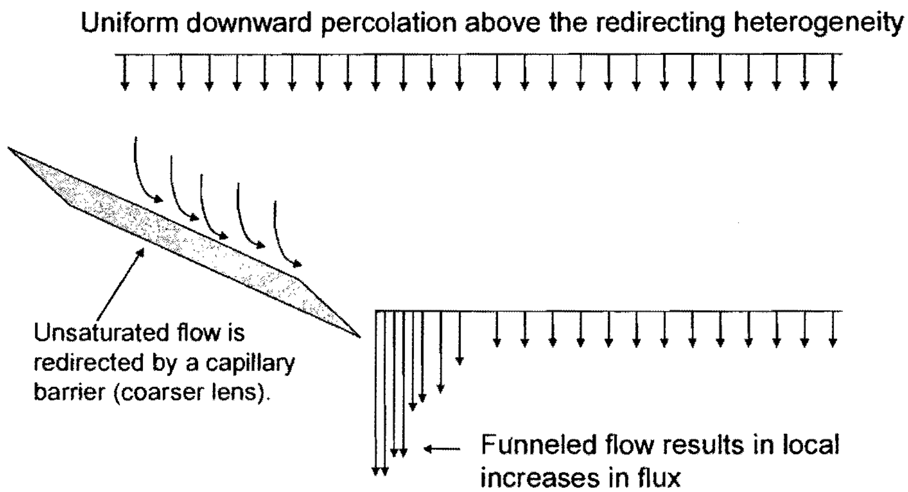

FIGURE 4.1 Funnel Flow. For unsaturated flow, an increase in water content and hydraulic conductivity occurs if downward percolating water is "funneled" into a smaller area. Water and contaminants then move more quickly and in difficult-to-predict pathways compared to uniform percolation.

Perched Groundwater

Perched groundwater refers to a zone of saturation within an unsaturated region, typically occurring when downward percolation is slowed by a low-permeability barrier. Color Plate 8 illustrates the variety of perched water occurrences on the LANL site, and Color Plates 9 and 10 indicate locations of wells that have encountered perched water. Perched groundwater tends to occur more frequently beneath large, wet canyons (Pueblo, Los Alamos, Mortandad, Sandia) beneath dry mesa tops.

In some cases, perching can slow downward transport if the low-permeability layer is extensive. However, it is as likely that perched water will move contaminants to the regional water table faster and in difficult-to-predict pathways. Perched water that spreads on finer horizontal or sloping layers may move contaminants beyond the boundaries of the watershed where they were originally discharged. The geologic units that lead to the formation of perched water are often discontinuous horizontally. Where a perching horizon ends, water pressures can build up above the perching layer, potentially resulting in preferential fingers moving into and through the underlying finer geologic unit, increasing transport rates to the regional aquifer, as illustrated in Figure 4.2.

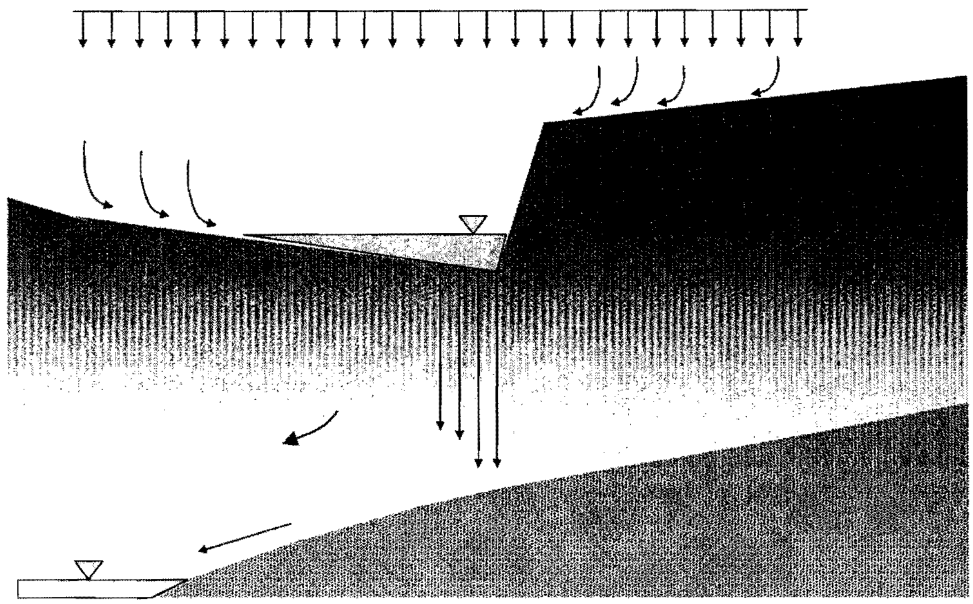

FIGURE 4.2 Perched flow is redirected by a finer geologic strata. When the percolating water ponds at a geologic heterogeneity, preferential flow may occur in the underlying formation. The complicated hydrology beneath LANL could make flowpaths exceptionally complex.

When perching occurs on a fractured geologic formation at intermediate depths, the fractures can become active pathways for fast transport. Perched water may result in complex pathways through the intermediate zones between canyons. The recent discoveries of elevated chromium concentrations in wells R-28 in Mortandad Canyon and R-11 in Sandia Canyon (LANL, 2006d) indicate the possibility of lateral movement between canyons facilitated by perched-intermediate groundwater. Although there are several possible sources of the chromium found in well R-28, a likely source is the cooling tower discharge at TA-03 in Sandia Canyon, one canyon to the north, as shown in Color Plate 10. The plate also shows that there has been limited drilling in Sandia Canyon, so relatively little is known about the possible flow directions or perching that could occur there. This demonstrates the importance of identifying potential pathways between watersheds, which may include perched water zones, and of further investigating them in the intermediate zone. These potential canyon-to-canyon flow pathways are important for the design of a monitoring program.

Fast Contaminant Transport by Surface Water

Surface water is a fast pathway for contaminants released from liquid disposal outfalls to migrate downgradient and either infiltrate the alluvial groundwater at a location that may be distant from its origin or migrate off-site toward the Rio Grande.

Storms generate large volumes of runoff water that can transport soils and contaminants along the canyons as a result of soil erosion and runoff, see Sidebar 4.1.

Graff (1994) has shown that the plutonium concentrations measured in bedload sediments collected in streams east of the LANL boundary but above the confluence with Pueblo Canyon are two to three orders of magnitude higher (0.19-3.3 pCi/g) than the average background levels of river sediments in the regional river system (0.002 pCi/g). Surface water from Acid, Pueblo, DP, and upper Los Alamos Canyons drains into Pueblo Canyon. Graff calculated that about 10 percent of plutonium deposited in Los Alamos canyon has been transported into the Rio Grande. Yet Graff estimates that the contributions of plutonium from LANL sources to the total annual plutonium flux for the entire river system is small compared to global fallout. Approximately 10 percent of the total annual plutonium flux sediment is from LANL operations.

SIDEBAR 4.1
Contaminant Transport by Surface Water

Natural surface water in the Los Alamos area occurs primarily as short-lived stormwater or snowmelt runoff and in short ephemeral streams draining the uplands along the western portion of the Pajarito Plateau. Effluent from LANL and Los Alamos County operations also forms effluent-supported reaches. Natural and effluent-supported "base flow" conditions are the most important for downstream migration of aqueous-phase (dissolved) contaminants. LANL (2004b) describes investigations conducted in Los Alamos and Pueblo canyons of surface water processes that transport contaminants across the site. The report documents observations that historical transport of soluble constituents in surface-water base flow was rapid and may have at times reached the Rio Grande, especially during periods of extended snowmelt runoff or associated with high-volume and persistent effluent releases.

For contaminants that are sorbed to sediment, stormwater and snowmelt runoff are the dominant mechanisms for migration along the canyons. The sediment and sorbed contaminants are entrained in surface-water flow via erosion of channel bed and bank sediments. A pronounced increase in stormwater runoff occurred following the May, 2000, Cerro Grande fire due to the burning and widespread elimination of the thick organic layer (duff) on the forest floor. The increase in runoff caused erosion and deposition of a large amount of sediment derived from the burned uplands as well as within canyons on Laboratory property. This hydrologic perturbation is now largely diminished (LANL, 2004c).

Source: Danny Katzman, LANL

Slow Transport Pathways

Fast pathways and mobile contaminants are the focus of most transport studies because early detections in groundwater are presumed to provide early warning of future groundwater contamination. However, mass balances to discern contaminants currently in the vadose zone are at least as important in forewarning of deeper groundwater contamination, especially when considering long-term monitoring for site stewardship. Although mass balances are inherently difficult to perform for highly heterogeneous media with preferential flowpaths, they can serve to test the validity of adopted conceptual models even when carrying a broad margin of error.

Modeling studies by Robinson et al. (2005c) show that tritium is likely in the vadose zone en route from its source to the regional aquifer. Hexavalent chromium detected near several drinking water supply wells provides another example of the importance of a mass balance to address monitoring and remediation decisions. Estimates of the amount of chromium released range up to 328,000 pounds (LANL, 2006d, p. 3), much of which is probably in the vadose zone. This situation could hold for many, if not most, other potential groundwater contaminants.

Estimating the mass of contaminants along the entire pathway from source to groundwater from available monitoring data is an important step in ensuring groundwater protection. Additional characterization and monitoring work are clearly indicated in situations where a substantial amount of a contaminant is known to have been released but cannot be accounted for using available data.

REGIONAL AQUIFER PATHWAY CONCEPTUALIZATIONS

The complexity of the regional aquifer is demonstrated by the difficulty in interpreting the results of two tests to measure changes in the level of the regional aquifer (water table) in response to pumping from water supply wells PM-2 and PM-4 (LANL, 2005a, p. 2-111). These wells are shown near the center of Color Plate 10. A 25-day test was conducted at water supply well PM-2 at a constant discharge rate of about 4700 L/min (1250 gpm). A number of observation wells (R-wells) installed as part of the hydrogeologic work plan were monitored during the 25-day pumping period and for 25 days thereafter. A second long-term aquifer test was conducted at supply well PM-4 at a constant discharge rate of approximately 5700 L/min (1500 gpm). The pumping interval was 21 days. Water levels were monitored for the 21-day pumping period and an additional 21 days during recovery.

The data from these aquifer tests suggested two competing conceptual models (LANL, 2005a). First, the regional aquifer may be a leaky confined aquifer with leaky units located above a highly conductive layer that is about 260 meters (850 feet) thick.[6] A second possible conceptualization is that the regional aquifer *appears* to behave like a

[6] An aquifer that is confined is bounded by low permeability layers above and below the aquifer. When a confined aquifer is pumped, all the water pumped is from within the aquifer. If the aquifer is leaky some of the water may come from water-bearing formations above or below the aquifer being pumped. This complicates the analysis of the data.

leaky confined system because it contains interbedded layers of alternating high and low hydraulic conductivities that are sandwiched together into a high-yielding zone.

These two conceptualizations lead to very different pictures of how contaminants in the regional aquifer might behave. If there is low connectivity between layers within the aquifer, the contaminants might remain near the top of the regional aquifer and most likely discharge in the springs near the Rio Grande. On the other hand, higher connectivity could result in the contaminants spreading vertically and more likely entering the deep screened intervals of the regional water supply wells.

LANL scientists are aware of the importance of the conceptual model and that the regional aquifer conceptualization will have important implications for the groundwater monitoring program. Even though planned three-dimensional model simulations to further examine aquifer heterogeneity should provide a better interpretation of the aquifer test data, additional hydrogeologic characterization of the regional aquifer is warranted. Geochemical information could also be used to corroborate the aquifer test data. Effective design of a groundwater monitoring system will require an accurate and complete conceptual model of the regional aquifer.

NUMERICAL MODELS

Numerical models combine information on geology, geochemistry, infiltration, regional groundwater fluxes and waste discharges in a manner that quantifies understanding of the physical/chemical processes and interactions involved in the transport of contaminants. Information gained during the process of model development provides valuable insight on the validity of the conceptualization implemented in the numerical model. Though many "solutions" are possible, comparison of predicted results to actual measurements provides an estimate of the level of understanding of the flow and transport processes moving contaminants away from their initial disposal locations.

Central to the numerical model is the conceptual model. The numerical model quantifies the meaning of the conceptual model, indicates where refinement to the current conceptualization is necessary, and helps to identify where more information could most likely reduce the level of uncertainty in numerical estimates of future conditions.

Chapter 3 introduced the two types of uncertainty (parametric and conceptual) that must be dealt with in any attempt to understand the site's geohydrology. Handling these uncertainties is one of the biggest challenges in numerical modeling. Explicit evaluations of uncertainty in relation to an important model output, such as estimated concentration or expected travel time, are the most difficult yet the most important elements of scientifically sound modeling practice.

Numerical modeling of the regional aquifer at LANL is fairly recent. The model FEHM, a finite element heat and mass transfer code used to model unsaturated and saturated flow and contaminant transport in porous and fractured media (Zyvoloski et al., 1997), was first applied to regional aquifer modeling in 1998, and a number of related models have been developed since then (LANL, 2005a). Key features of the LANL modeling work include expanded model boundaries to better incorporate regional flow and recharge locations, which, in turn, better accommodate the simulation of the aquifer system under the LANL site. Slightly earlier regional models used for water supply were developed by the U.S. Geological Survey. LANL (2005a) gives a summary of the numerical models used for site modeling. Some of these models have estimated travel times through the vadose zone. Vadose zone predictive model results are typically most sensitive to assumptions regarding infiltration and waste inventory. Alternative conceptual models and infiltration rates are considered.

The committee recognizes that the vadose zone is complex and the exact pathways from source zones to the regional groundwater are unpredictable. However, the more information that LANL can bring to bear on the vadose zone transport pathways, and the spatial and temporal knowledge of contaminant waste sites, the better LANL can evaluate the effectiveness of a groundwater monitoring system and improve its design.

An example of a good start for the process is in Robinson et al. (2005c). Two- and three-dimensional vadose zone models were developed to incorporate Los Alamos Canyon, DP canyon, Well R-9, and facilities such as the Omega West Reactor. A variety of contaminants, mostly radionuclides, were suspected to have been released into the canyon with a primary source being the Omega West Reactor. The tritium model predicted that, for locations near well Otowi-4, most of the tritium is likely still present in the vadose zone with a small but non-zero concentration predicted to have reached the regional aquifer. Well R-7, located downstream of the tritium contaminants but further upstream of the Los Alamos-DP canyon confluence, was predicted to have no tritium arriving at the water table. The most rapid transport to the water table was predicted at R-9, where the peak concentration of tritium already reached the water table.

Model results show that, within this portion of the Pajarito Plateau, the regional aquifer is most at risk for contamination at locations near or below the confluence of Los Alamos and Pueblo Canyons. Model results showed further that, even for a nonsorbing contaminant such as tritium, the majority of the released mass is still in the vadose zone. A small fraction of the released mass has reached the water table, primarily in locations in the canyon with high infiltration rates or where the Bandelier Tuff is absent. An update to the regional aquifer model is provided by Keating et al. (2005) who state that "predicted flux through older basalts in the aquifer can vary by a factor of three. . . . the true uncertainty of our predictions, including the impact of possible conceptual errors, is likely to be larger and is difficult to quantify."

The modeling by Robinson et al. (2005c) and Keating et al. (2005) demonstrates that a comprehensive understanding of vadose zone transport processes depends on integrating data from geologic, hydrologic, and site characterization studies with uncertainty analyses. More generally, these LANL scientists have demonstrated that modeling and site characterization studies are important to selecting well locations and sampling frequency as part of the design of an effective monitoring system.

In the August committee meeting, Vesselinov and Birdsell described a stepped coupled modeling approach that will be applied to the wet canyons. Point sources are simplified into uniformly distributed unit sources along alluvial canyon bottoms, consistent with LANL's wet canyon conceptual model. Twenty-one potential source configurations have been studied so far, with the travel time through the intermediate zones assumed to be instantaneous. These types of modeling exercises have the potential to directly link the wet canyon conceptual model with the regional groundwater monitoring program.

Modeling at LANL is appropriately incorporating important features of the vadose and saturated zone: matrix flow, fracture flow, varying stratigraphy, and hydrogeologic properties. Important to this effort will be to maintain a balance in the level of modeling sophistication already available and the understanding of the actual site hydrology. This will be particularly important in incorporation of uncertainty where it quite often happens that the non-modeled uncertainty (conceptual uncertainties about the actual site conditions not reflected in the model's equations) can outweigh the uncertainty in parameters included in the model. Overlooking conceptual, non-modeled, uncertainties can lead to results that give an overly optimistic perception of the current state of knowledge about present and future groundwater contamination.

EVALUATION OF THE INTERIM GROUNDWATER MONITORING PLAN

The committee was asked to evaluate the interim groundwater monitoring plan developed by LANL. Specifically, two questions were posed in the committee's task statement: Does the plan follow good scientific practices; and is it adequate to provide for the early identification and response to potential environmental impacts from the laboratory? As noted previously, the short answer to the first question is a qualified yes, while the answer to the second question is no.

The Interim Facility-wide Groundwater Monitoring Plan (LANL, 2006c) states that the purpose of monitoring is to:

- Determine the fate and transport of known legacy-waste contaminants,
- Detect new releases,
- Determine efficacies of remedies, and
- Validate proposed corrective measures.

The Interim Plan notes that groundwater monitoring at the site was started in 1945 by the U.S. Geological Survey. The first monitoring network consisted of water supply wells, observation wells, and springs. Early monitoring was primarily from shallow alluvial groundwater. Twenty-five deep wells into the regional aquifer and six intermediate-zone wells were added under the Hydrogeologic Workplan between 1998 and 2004 (LANL, 2005a).

The Interim Plan is intended to monitor the seven main watersheds on the site: Los Alamos, Sandia, Mortandad, Pajarito, Water/Cañon de Valle, Ancho/Chaquehui/Frijoles, and White Rock. The major canyons that define these watersheds are shown in Color Plates 9 and 10.

In the Interim Plan, a table for each watershed presents the rationale for each well in that watershed. The design of the interim monitoring network is stated to be "based on conceptual models of potential sources, hydrogeologic pathways, and receptors" (LANL, 2006c, p. 1-2). The division of monitoring into the following four modes is consistent with LANL's pathways conceptualizations:

- Base flow—persistent surface water that is maintained by precipitation, snowmelt, effluent, and other sources;
- Alluvial groundwater—water within the alluvium in the bottoms of the canyons;

- Intermediate perched groundwater—localized saturated zones within the vadose zone; and
- Regional groundwater—the deep, laterally continuous groundwater beneath the Pajarito Plateau.

The Interim Plan is responsive to the Consent Order (see Chapter 2), which is the regulatory driver that the plan addresses, and which specifies much of the structure, choice of locations, and sampling frequency set forth in the Interim Plan. For example, Table XII-5 of the Consent Order includes a listing of wells that must be included in the Interim Plan. The Interim Plan also states that it was based in part on guidance for monitoring network design published by the Environmental Protection Agency (EPA), and in particular, on Office of Solid Waste and Emergency Response (OSWER) Directive No. 9355.4-28, "Guidance for Monitoring at Hazardous Waste Sites: Framework for Monitoring Plan Development and Implementation" (EPA, 2004b).

The committee found that the Interim Plan follows good scientific practice in several respects. The report includes discussion of potential sources and the media being monitored under the plan, i.e., stream base flows, alluvial groundwater, intermediate (perched) groundwater, and the regional groundwater aquifer. The choice of monitoring locations by LANL appears to have been made using the hydrogeologic approach (Minsker, 2003), based on the use of expert judgment for selection. The reasons for those choices are presented in the monitoring plan tables provided for each watershed. This is especially important when the choice of sampling locations or frequency differs from the locations or frequency specified in the Consent Order.

However, there are areas where the Interim Plan does not appear to follow good scientific practice. The most important of these is the focus on a watershed approach, where the monitoring plan for each watershed within LANL is developed and laid out individually in the Interim Plan. This structure, which is specified in the Consent Order, works quite well for monitoring surface base flows and alluvial groundwater that are confined to the canyons. However, it does not work well for the intermediate aquifers and even less for the regional aquifer. For example, in the discussion of the monitoring plan for Mortandad Canyon in Part 4 of the Interim Plan, the potential contaminant sources that are discussed are only those that fall within the Mortandad Canyon watershed.

As pointed out in the chromium workplan[7] (LANL, 2006d) the source of high concentrations of chromium recently found in Mortandad Canyon does not appear to be within that canyon, but from the use of chromium in large amounts as a corrosion inhibitor at power plants in Sandia and Los Alamos Canyons, one or two canyons to the north. This finding suggests that a canyon-based approach to development of monitoring plans for the intermediate and regional aquifers is not sound.

Minsker (2003) and EPA (2006, EPA 542-R-05-003) document quantitative methods for optimizing a monitoring network, which might be used by LANL and NMED for improving future monitoring plans to (1) optimize the monitoring network and (2) better incorporate uncertainty into its design. Approaches that incorporate

[7] The chromium workplan was developed following the discovery of unexpectedly high levels of chromium in some wells in Mortandad Canyon, see Sidebar 3.3. The chromium workplan lays out further investigations to determine the extent of contamination for planning possible remediation actions.

uncertainty are published (e.g., Neuman and Wierenga, 2003) and may also prove useful for application at LANL. The selection and application of any approach should be balanced by the level of knowledge and quality of data available. The main elements of an uncertainty analysis would involve the development and evaluation of alternative conceptual models for the transport of contaminants from identified sources to receptors. The alternative conceptual models might include differences in assumed transport pathways (i.e., alternative models of the hydrogeology and geochemistry), forcing conditions (e.g., input and boundary conditions), and numerical modeling approaches (Neuman and Wierenga, 2003).

For LANL, these alternative conceptual models might be used to address uncertainty in the source terms and the uncertainty in flowpaths from the sources to the regional aquifer. The alternative conceptual models can be evaluated by their ability to reproduce system behavior, e.g., contaminant plume concentrations, using calibration and inverse analysis. Predicted plumes resulting from those alternative conceptual models could then be used to evaluate the probability that the plumes would be intercepted by monitoring wells before moving off the LANL site or reaching a municipal well. Optimization approaches (e.g., Reed et al., 2000) could be used with alternative plume models to design the regional aquifer monitoring network to minimize the probability that a plume would be missed.

Plans for such an approach were identified in the Decision Analysis for Addressing Groundwater Contaminants from the Radioactive Liquid Waste Treatment Facility Released into Mortandad Canyon (LANL, 2005c). That analysis incorporated alternative conceptual models and uncertainty analysis. However, as the report points out, the current version of the decision analysis approach developed by LANL cannot be used for groundwater monitoring network design (LANL, 2005c, Section 5.2.2). The presentation on the LANL Decision Support Program (LDSP) by Chris EchoHawk at the committee's August meeting suggested that one of the goals of the LDSP is to continue to develop the approach so that it could be used for monitoring network design (EchoHawk, 2006). The use of such an approach would require negotiation with NMED.

Even without a quantitative analysis of the sample locations in the intermediate and regional aquifers, the committee noted several modifications that could be made to the current monitoring network. Given the tendency for regional aquifer monitoring wells to be located in canyon bottoms, large portions of the intermediate and regional aquifers are not monitored given the current monitoring plans and approach. This makes it far more likely that the current monitoring plan will not provide early identification and response to potential environmental impacts from the laboratory. Although the committee understands that there are strong economic and drilling incentives to locate regional monitoring wells below the canyons, and a number of additional monitoring locations could be placed in canyon bottoms that would contribute significantly to the existing network, eventually a way must be found to increase the area of the intermediate and regional aquifers that are monitored. This may require locating some deep monitoring wells below mesa tops, and/or the drilling of slant holes from canyon bottoms to monitor the regional aquifer below the mesas.

In looking at the regional monitoring network, the committee found that the southern portion of LANL is one area of the regional aquifer that is currently very sparsely monitored (see Color Plate 10). The committee assumes that this is mostly due to the general southward progression of the canyon investigation plans, and that the area will receive additional deep monitoring wells when the canyon investigation process advances to the southern canyons (Ancho, Chaquehui, and Frijoles Canyons). Another area that appears to be undersampled is the Pueblo de San Ildefonso to the east of LANL, which is generally downgradient from the site. Plans to install monitoring wells on Pueblo lands under the Memorandum of Understanding[8] described in Section 3 of LANL (2006a) are a step in the right direction. Additional monitoring to ensure early detection of contaminant plumes beneath these Pueblo lands will likely be required.

There were other parts of the Interim Plan where the committee deemed that additional information is needed. One suggestion would be to broaden the overview of geology and hydrogeology in the main text of the Interim Plan (Section 1.10). The current overview is brief and does not include any graphics to orient the reader to the geology. A good example of what might be provided can be found in Section 5.B of LANL's Environmental Surveillance Report (LANL, 2006, LA-14304-ENV).

Regarding revisions of the monitoring plan, the section on integration (Section 1.6) states:

> *The Interim Plan will be updated annually to incorporate new information collected within a watershed. Locations, analytes, and sampling frequencies will be evaluated and updated appropriately to ensure adequate monitoring and avoid unreasonable budgetary expenditures. Information gained through characterization efforts, aquifer test results, optimization iteration models, and water quality data will be used to refine a long-term monitoring plan for each watershed.*

However, no information is provided in the Interim Plan on how this aspect of the integration and revision of the monitoring plan is accomplished. A brief summary in Section 1.6 could describe the ways in which the information from related studies is used for updating the monitoring plan. More importantly, a discussion could be included in the individual watershed sections and the section on the regional aquifer that summarizes the findings of related investigations and specifically calls out the changes that were made to the monitoring plan in response to investigations (e.g., additional drilling, sampling, aquifer testing) that were completed in the previous year.

There is little to no information provided in Appendix A of the Interim Plan, or in the body of the plan, on pathways by which the contaminants are moving, which is a critical part of a conceptual model. Inclusion of graphics documenting the conceptual models would also be useful. For example, a cross section along each canyon (or the main canyon when multiple canyons are addressed) would help provide some perspective on the geology of the canyons; see Color Plate 7. The cross section could be used to highlight some of the potential flow paths.

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[8] To determine the potential impact of LANL operations on lands belonging to the Pueblo de San Ildefonso, DOE entered into a Memorandum of Understanding with the Pueblo in 1987 that establishes requirements for environmental sampling on Pueblo lands. Locations to be monitored are determined annually by representatives of the Pueblo, LANL, and DOE.

GEOPHYSICAL METHODS FOR SITE CHARACTERIZATION AND MONITORING

Challenges in LANL's groundwater protection program include understanding hydrogeological pathways in the vadose zone and monitoring large areas of the site, as described in this chapter. Well emplacements, as described in Chapter 5, are expensive and sample only limited areas around the borehole. Modern geophysical methods can at least supplement characterization and monitoring data obtained directly from well emplacements.

A previous National Academies study (NRC, 2005) described environmental monitoring at DOE sites as relying heavily on sampling and analyzing groundwater and noted that this practice provides data primarily for the individual locations that are sampled. Geophysical methods are able to provide continuous measurements in both time and space that can help fill gaps in understanding the subsurface hydrogeology between well locations and enable mapping of large subsurface areas. The report suggested that modern, noninvasive geophysical sensor techniques such as electromagnetic and electrical resistivity methods, seismic reflectivity, and ground-penetrating radar can substantially improve on direct sampling and lead to cost-effective long-term monitoring after site closure.

LANL's presentations focused on well emplacements for characterization and monitoring; geophysical methods were not discussed. However, work at other DOE sites has shown that these methods are promising and improving rapidly, largely due to refined signal processing techniques and statistical methods for data analysis. An evaluation of geophysical technologies applicable to Hanford site characterization was recently completed (Fluor, 2006). Geophysical sensor technology developed at the Idaho National Laboratory is being used to monitor a waste storage area located at the Gilt Edge Mine Superfund site in South Dakota (Versteeg et al., 2004; Versteeg, 2005).

Development and greater use of geophysical methods are fertile opportunities for applying new science and technology to improve the effectiveness of LANL's groundwater protection program and for increasing cooperation among DOE sites to address common site cleanup and remediation challenges.

FINDINGS AND RECOMMENDATIONS ON PATHWAYS

General Findings

The committee found that the Laboratory's current (i.e., interim) monitoring plan generally follows good scientific practices, but there are opportunities for improving it. The plan is not adequate to provide early identification of potential contaminant migration with high confidence because LANL's understanding of pathways for contaminant transport, especially inter-watershed pathways, is not yet adequate to support such confidence.

The committee concurs with LANL's approach, which is to characterize and understand potential pathways for contaminant transport in order to support the planning and implementation of a long-term sitewide monitoring program. The committee judged LANL's current understanding of transport pathways adequate to begin this planning and implementation process. This current understanding can, and should, be improved to ensure groundwater protection in the coming decades and centuries.

The scientific framework used by LANL to categorize the main features of mesas and canyons important to understanding groundwater flow and transport processes is well reasoned and is commended by the committee. Conceptual models for vadose and groundwater flows currently go beyond simple conceptualizations of a qualitative nature. LANL scientists show a good understanding of the suite of possible conceptualizations for various scenarios, depending on source location, contaminant properties, contaminant loading, and source type. The committee encourages continuation of this line of investigation as it is an excellent example of the creativity required to address the Type B uncertainty described in Chapter 3. This framework represents an excellent *start* to establishing a sitewide monitoring plan that will provide early identification of contaminant migration, support remediation decisions, and eventually transition into long-term monitoring for stewardship.

Detailed Findings and Recommendations

Findings and recommendations to assist LANL in addressing remaining gaps in pathway conceptualizations and improve its monitoring plans are as follows:

The current conceptualization of the LANL flow system into alluvial, intermediate-perched, and regional components, along with their importance to understanding the flow system within and below wet canyons, are major accomplishments by the LANL scientists. However, there is a lack of understanding of the *interconnectedness* of pathways between basins. While there is a general understanding that perched waters are probably redirecting contaminants from areas directly below canyons where they originally infiltrate, to sub-mesa areas and to other nearby canyons, the detailed knowledge needed to predict subsurface flowpaths does not exist. Lack of understanding of these phenomena, coupled with rapid flow in the alluvium and apparent rapid flow facilitated by perched waters, were central to the surprise over detection of chromium near the water supply wells. An improved knowledge of these interwatershed processes is needed to design an effective, early warning monitoring program.

> ***Recommendation:*** *LANL should add a sitewide perspective to its future groundwater monitoring plans. This perspective would include the following:*
>
> - *Design additional characterization, modeling, and geochemical investigations to better understand potential fast pathways between watersheds.*
> - *Increase the area of the regional aquifer that is monitored by sampling inter-canyon areas from mesas or using directional wells from canyon bottoms.*
> - *Provide additional monitoring locations in the southern area of the site and on Pueblo de San Ildefonso lands.*

- *Develop more applications of geophysical techniques to supplement information provided by well drilling and sampling, especially for understanding vadose zone pathways.*
- *As LANL's site characterization and monitoring programs mature, well locations should be derived from a quantitative spatial analysis of monitoring well locations to identify areas with the greatest uncertainty in plume concentrations, using geostatistics or other methods, possibly coupled with flow and transport modeling.*

Mathematical models are essential tools for both codifying current knowledge and identifying knowledge gaps. Although LANL is using a numerically sophisticated multiphase model for vadose and regional groundwater modeling, it is not yet possible to predict with confidence when, where, or if a contaminant might appear in the regional aquifer. This is due largely to an exceptionally complex vadose zone. Studies show that most of the mass of many contaminants is likely still in the vadose zone on the way down from the release location to the regional aquifer.

Recommendation: *LANL should increase its efforts to develop and use quantitative methods to describe contaminant pathways through the vadose zone and into the regional aquifer, as follows:*

- *Mathematical models that incorporate the uncertainties from alternative conceptual models should underpin plans for design and operation of the sitewide monitoring system. Characterization of the vadose zone begun under the Hydrogeologic Workplan should continue with emphasis on new results from characterization and monitoring being used to test and improve the mathematical models.*
- *To support an evaluation of the effectiveness of the monitoring system to provide early warning of potential impacts on the regional aquifer, LANL should quantify, to the extent possible, the inventory and current location of the contaminants disposed of in the major waste sites.*

Large waste disposal sites in the dry canyons and on dry mesas have not received as much attention as wet canyons and wet mesas because they presumably lack an aqueous driver to move contamination. The presumed dry locations have received minimal characterization with regards to the presence, strength and potential impact of aqueous drivers. In some of these, surface disturbances have led to unexpected increased infiltration rates. LANL provided few data to justify assumptions about the relative immobility of wastes at these sites.

Recommendations: *LANL should confirm the integrity (lack of surface disturbances or conditions leading to increased infiltration) of the major disposal sites in the dry canyons and mesas.*

LANL should schedule regular subsurface surveillance beneath disposed wastes on dry mesas and in dry canyons.

LANL's present conceptualizations of the regional aquifer lead to very different pictures of how contaminants in the aquifer might behave. If there is low

connectivity between layers within the aquifer, the contaminants might remain near the top of the regional aquifer and most likely discharge in the springs near the Rio Grande. On the other hand, higher connectivity could result in the contaminants spreading vertically and more likely entering the deep screened intervals of regional water supply wells.

> ***Recommendation:*** *LANL should continue efforts begun under the Hydrogeologic Workplan to characterize the regional aquifer. More large-scale pumping tests and improved analyses of the drawdown data are needed to establish a scientifically defensible conceptual model of the aquifer, i.e., leaky-confined, unconfined, or layered.*

LANL's efforts to understand the role of geochemistry in contaminant migration have not kept pace with efforts to understand hydrology. The committee found a lack of basic, site-specific geochemical data to support LANL's assumptions about the relative immobility of important contaminants—especially radionuclides—along transport pathways and judged that LANL underestimated the value of both field and laboratory geochemical measurements.

> ***Recommendation:*** *LANL should increase its attention to geochemistry within the context of its site characterization work. LANL scientists should conduct more field and laboratory studies to measure basic geochemical parameters such as sorption coefficients with the goal of testing and verifying their conceptualizations of subsurface hydrogeochemical processes.*

The following finding and recommendations reflect the committee's evaluation of the Interim Facility-wide Groundwater Monitoring Plan (LANL 2006c), which was requested in the Statement of Task.[9]

The Hydrogeologic Workplan has been effective in improving characterization of the site's hydrogeology. However, the knowledge gained through the workplan does not appear to have been used effectively in the development of the interim plan. The workplan is mentioned only in the introduction of the interim plan, and rationale for the siting of new wells in the interim plan is not grounded in the scientific understanding of the site evident in the Synthesis Report and other publications such as the *Vadose Zone Journal* (VZJ, 2005).

> ***Recommendations:*** *LANL should demonstrate better use of its current understanding of contaminant transport pathways in the design of its groundwater monitoring program. Tables in the monitoring plan that give the rationale for locating monitoring wells should at least provide a general linkage between the proposed locations and the site's hydrology, or a section discussing the relation between well locations and pathway conceptualizations should be added.*

[9] LANL's 2006 Integrated Groundwater Monitoring Plan (LANL, 2006a) included the Interim Plan in its first section. Plans for monitoring additional, mainly offsite, areas described in the Integrated Plan did not affect the committee's finding or recommendations.

LANL should take a sitewide approach to monitoring of the intermediate and regional aquifers. Furthermore, the itnerim plan should summarize (e.g., in Section 1.6) the ways in which the information from related studies will be used for updating the interim plan. The current description of the conceptual models (in Appendix A of the plan) is useful, but it should be improved. First and foremost would be a description of potential pathways, both surface and subsurface, that connect the sources (listed in Appendix A) with the groundwater that is being monitored.

LANL should examine the potential for approaches (Minsker, 2003; EPA, 2006) that both optimize the monitoring network and incorporate uncertainty into its design.

5
Monitoring and Data Quality

Implementing a groundwater monitoring plan includes four elements: drilling wells, completing the wells, obtaining groundwater samples from the wells, and analyzing the samples. Monitoring is done to measure the extent of contaminant migration along expected pathways or to determine that the water is free of contamination. Monitoring is the only direct means to confirm models and predictions about subsurface contaminant transport and to provide early warning of potential contamination in drinking water supplies.

This chapter deals with the actual practices of conducting monitoring—in particular ensuring that the Los Alamos National Laboratory's (LANL's) groundwater monitoring data are reliable. The first part of the chapter deals with LANL's well construction work. The second deals with the specific data-quality questions presented in the committee's task statement. LANL's understanding of contaminant pathways, which is essential for developing a monitoring plan, is discussed in Chapter 4.

The data-quality questions raised in the committee's task statement are:

1. Is the laboratory following established scientific practices in assessing the quality of its groundwater monitoring data?
2. Are the data (including qualifiers that describe data precision, accuracy, detection limits, and other items that aid correct interpretation and use of the data) being used appropriately in the laboratory's remediation decision making?

The short answer to the first item is a qualified yes. LANL is using good practices in terms of having the proper quality assurance and quality control (QA/QC) plans and documentation in place, but falls short of consistently carrying out all the procedures cited in the plans. Well drilling and completion methods are continuing to evolve, and the site is only beginning to implement its groundwater monitoring program under the Consent Order. Many if not all of the wells drilled into the regional aquifer under the Hydrogeologic Workplan appear to be compromised in their ability to produce water samples that are representative of ambient groundwater for the purpose of monitoring.

The short answer to the second question, as it is written, is no. Although LANL appears to be generating sound analytical data, the results reported in databases and LANL reports often do not carry the proper qualifiers according to good QA/QC practices. This especially applies to analytical results near or below the limits of practical quantitation and detection, near the natural background, or both. The difficulty here is that reported detection of contamination that is not statistically significant may be taken as real by regulators and other stakeholders—with concomitant concerns and calls for remedial actions.

WELL CONSTRUCTION

LANL will continue to construct water wells for at least three purposes. Each purpose has implications for the drilling and completion methods selected, as follow:

1. Characterization: Characterization of the site's hydrogeology and subsurface contamination in soil and groundwater at LANL is far from complete. Drilling for characterization can be relatively quick and inexpensive to survey hydrogeologic conditions over large areas. However, characterization can also become slower and more expensive if data needs include, for example, detailed identification of perched water zones, collecting core or cuttings for chemical analyses, and performing geophysics. The latter was more generally the case for characterization wells under the Hydrogeologic Workplan (LANL, 1998). Further, the drilling efforts shifted from primarily characterization toward a multiple use approach that included using a single borehole for both characterization and monitoring (Nylander, 2006).
2. Monitoring: Monitoring wells are designed and constructed to minimize their own effects on the groundwater that they are intended to monitor, and hence to provide samples that are truly representative of the actual groundwater. Monitoring wells include wells upgradient of disposal locations to establish a baseline composition of the natural groundwater, downgradient wells for early detection of migration toward receptors or compliance boundaries, and near-source wells to monitor known contaminant movement or demonstrate the effects of remediation strategies.
3. Remediation—for example, wells to pump contaminated groundwater out of an aquifer so that the water can be treated and, often, returned to the aquifer. This application was not discussed by LANL during the committee's study period.

In meetings with the committee, LANL emphasized that well design, drilling methods, and well development—particularly for the approximately 1000-foot-deep wells that reach the regional aquifer—are evolving (Broxton, 2006). The committee considers this evolution an important and essential part of the program.

Drilling Methods

Drilling is the means of penetrating into the Earth's surface to access the underlying geological formations for study and/or to physically sample groundwater. LANL's drilling program under the Hydrogeologic Workplan considerably expanded LANL's ability to sample and characterize the Pajarito Plateau; see Color Plates 9 and 10. The drilling work itself, however, had a long and difficult evolution, including technical problems, unexpected high cost, and inconsistent objectives. LANL sought and received external review and advice during the course of this work as noted in Chapter 2.

The very act of drilling always damages to varying degrees the geologic formation penetrated by the borehole. This can lead to temporary or sometimes permanent changes in the hydrogeologic and geochemical properties of the formation and the nearby groundwater. Drilling a groundwater monitoring well to 1000 feet while inflicting as little permanent damage to the formation as possible is a technical challenge. Successful drilling is very site specific with heavy reliance on the expertise of the drilling personnel. Although there are many drilling methods, see Table 5.1, the use of rotary drilling (i.e., drilling with a rotating drill bit) is the most common.

All rotary drilling methods require the use of a fluid to clear the drill bit of cuttings, to cool the bit to prolong its usefulness, and sometimes to keep the formation around the hole from collapsing before the well is completed. There are many types of drilling fluids—including air, water, and "muds," which may be clays and/or synthetic materials—and additives to improve properties of some fluids. Depending on the formation, purpose of the well, and available drilling equipment, drillers may use a variety of fluids and additives.

Broxton (2006) and Nylander (2006) describe efforts by LANL, the Department of Energy (DOE), and their drilling contractors to install the approximately 1000-feet-deep wells into the regional aquifer (R-wells) required by the Hydrogeologic Workplan. Air and/or water were found to be inadequate as drilling fluids due largely to the depth to be drilled and the instability of some formations to be drilled through, although procedural errors have also been cited (Gilkeson, 2007). Lack of lubrication and the tendency of the boreholes to collapse resulted in slow progress and instances of stuck drill pipe and bits. Broxton (2006) lists a total of over 2600 feet of stuck drill pipe abandoned in place in 8 R-wells. As a result of these experiences, more traditional fluids—municipal water with organic chemical additives (EZ Mud® and Quik Foam®)—were used in most of the 34 R-wells.[1] In eight of the R-wells, bentonite mud was used as the drilling fluid for at least part of the well depth (Table B-3, LANL 2005).

Completion Methods

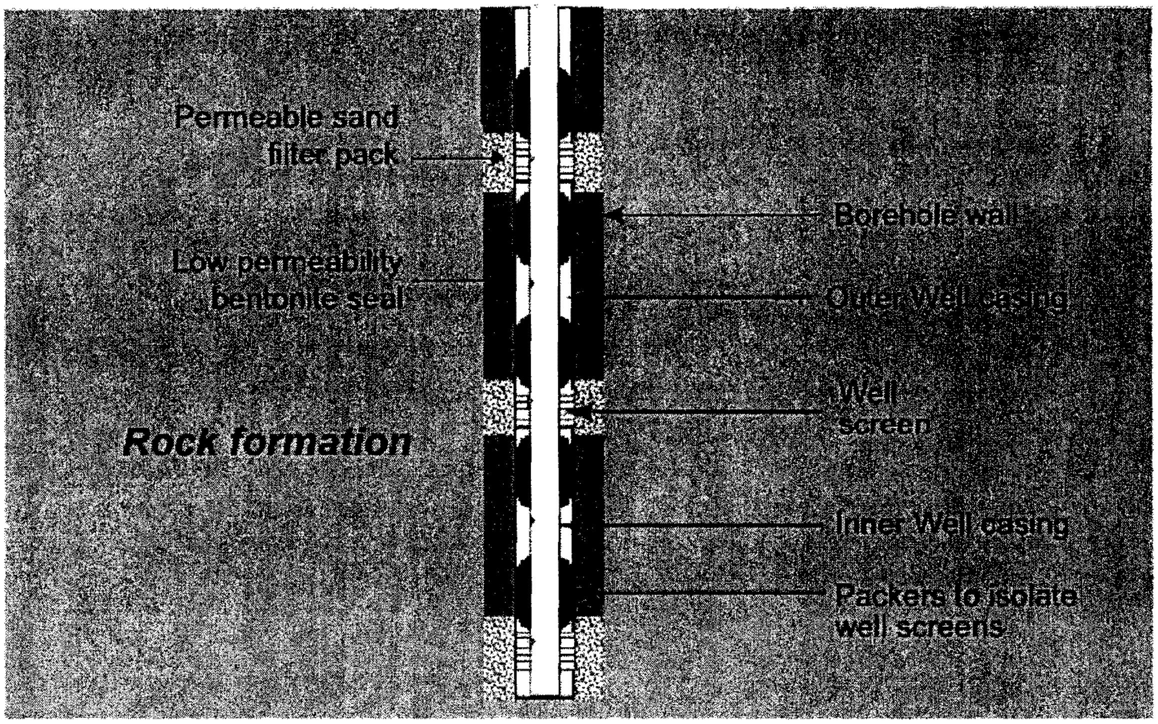
Completion refers to steps that convert a borehole to a well. Once the borehole is drilled to its planned depth, the drilling tools are removed, and the screen and casing are lowered into the hole. If an outer casing has been used to keep the borehole open as the drill bit advanced, that outer casing is carefully removed as the screen and well casing are installed. The screen allows groundwater to enter the well from the saturated aquifer material that the screen contacts (see Figure 5.1). The length of the screen and the depth at which it is placed are selected to best fulfill the intended purpose of the well, given existing knowledge of the site's hydrogeology and borehole information collected during drilling. Placement of the screen can be considered part of the three-dimensional challenge of locating the well on the surface and then placing the screen at an appropriate depth to sample the groundwater of interest.

[1]EZ-Mud and BARAFOS are registered trademarks of the Baroid company

Table 5.1 Drilling methods that are potentially applicable to well construction at LANL

Method	Advantages	Disadvantages for Monitoring
Rotary with air as the drilling fluid to bring cutting to the surface	Relatively fast, moderately expensive, no added liquids or additives. Best for hard rock formations.	Air injection may strip volatile organic compounds (VOCs), change redox potential, and induce biodegradation. Well development is critical. Difficulty with sloughing unconsolidated sediments.
Rotary with air as the drilling fluid plus outer casing advance (lowered by its own weight or percussion-hammered) Also known as Dual Wall Reverse Circulation with air	Over-reaming bit allows casing to follow bit downhole to prevent unconsolidated materials from sloughing. Casing can be removed slowly during well construction to facilitate screen and sand/gravel pack location. With sufficient air pressure, may avoid additives.	Expensive, relatively slow. Air injection may strip VOCs, change redox potential, and induce biodegradation. Well development is critical.
Rotary with water as the drilling fluid to bring cuttings to the surface	Fast, relatively inexpensive. Can also employ dual wall reverse circulation equipment.	Water in borehole complicates identification of water-bearing layers and can change hydrologic and geochemical properties near borehole. May lose circulation in unconsolidated materials. Well development is critical.
Rotary with drilling muds made from slurry of water and mud additives to bring cuttings to the surface and to keep the borehole open in unconsolidated zones	Same as water rotary except with mud additives to prevent lost circulation and stabilize borehole wall. Fast and moderately expensive. Established practice for potable water production wells.	Additives may be reactive with chemicals of potential concern (COPC). Requires aggressive well development to reduce mudcake on borehole walls. Typically inappropriate for monitor wells for reactive COPCs.
Rotary with cold nitrogen rather than air as drilling fluid (cryogenic rotary)	Cold nitrogen gas in standard air rotary process can freeze borehole wall in wet unconsolidated zone. Non-reactive nitrogen gas cannot change geochemistry.	Like air rotary, gas injection at high pressure can affect local hydrologic characteristics near borehole. Tested at DOE facilities but not readily available. Likely expensive.
Boring into the Earth with a hollow-stemed auger bit	Fast, inexpensive, good geologic samples, no added fluids required.	Limited to shallow depths, cohesive sediments.
Cable-tool drilling by raising and dropping a heavy bit into borehole, and removing cuttings with bailers	Can be done without added fluids if unconsolidated materials in saturated layers do not slough into borehole. Geologic samples are relatively undisturbed. Samples can be collected ahead of the hole with conventional geotechnical samplers. Usually requires stepped-down borehole diameter as hole deepens.	Slow, moderately expensive. Few vendors for environmental applications.
Drilling with resonant high frequency vibration to drive drill pipe into the subsurface (sonic drilling)	No drilling fluids required, can penetrate all formations at any angle, no cuttings. Provides continuous core in drill pipe.	High cost, few vendors. Geologic sampling could require additional equipment.

Source: Committee. List based on Consent Order Section X.B



Source: Broxton, 2006

FIGURE 5.1 Components of a water sampling well. This illustration shows a well with three screened intervals (near top, center, and bottom of figure) for sampling water at three different elevations. As depicted in the illustration, each screen is surrounded by permeable sand or gravel pack to allow water to enter the well. Installing multiple screens, ensuring that each is hydraulically isolated by the use of mechanical devices called "packers," and developing multi-screen wells are difficult.

Screening

There is no universal technically correct length or position in an aquifer for placing the well screen, although guidelines can be agreed to beforehand. For example, the Consent Order suggests placing a single, relatively short (5 to 10 foot) screen in zones of relatively high hydraulic conductivity to monitor so-called fast paths for lateral flow. The Environmental Protection Agency (Aller et al., 1991) and the American Society for Testing and materials (ASTM D5092, 1995) recommend screened intervals of 2 to 10 feet. EPA (1992) acknowledges the need to design the screen length to meet the objectives of the well.

As part of the Hydrogeologic Workplan, LANL contractors did geophysical testing in both open and cased hole conditions in order to determine the high-conductivity fast-pathway zones in the formations around the borehole; see Sidebar 5.1. This geophysical testing provided information to establish locations of the higher-permeability zones by characterizing the subsurface lithologic units in terms of their moisture content (including perched groundwater), capacity for flow, and stratigraphy and mineralogy.

SIDEBAR 5.1 Geophysical Testing to Position Well Screens

Downhole geophysical tools are often applied in hydrogeologic characterization programs to identify changes in lithology indicated by mineralogical, permeability, and porosity variations. The extensive suite of geophysical testing done on most R-wells included nearly continuous measurements along the length of the borehole to measure the following:[a]

- Total and effective water-filled porosity and pore size distribution, for estimation of hydraulic conductivity,
- Bulk density considering both water- and air-filled porosity,
- Bulk electrical resistivity at multiple depths,
- Bulk concentrations of selected mineral-forming elements,
- Spectral natural gamma ray emissions,
- Bedding orientation and geologic texture,
- Acoustic compressional wave velocity,
- Borehole azimuth and inclination, and
- Borehole diameter.

In addition to helping establish higher-permeability zones for the purpose of well screening, the geophysical testing provided data to correlate variations in seismic velocity versus depth in order to calibrate surface seismic surveys and to evaluate borehole conditions including borehole diameter, vertical deviation, and degree of drilling fluid invasion.

[a]Schlumberger (2003), which was compiled for well R-20, is an example of a typical geophysical report.

Previous problems in installing well screens at LANL have been reported to include excessively long screens, screens installed at the wrong depths to intercept contaminants, too many screens per well, and screen materials that corrode in groundwater (Gilkeson, 2006b). The use of overly long screens can cause dilution of sampled contaminants. Multiple screens, on occasion as many as nine screens in some LANL wells, can cause dilution or possibly cross-contamination of samples if there is leakage between screens. Nylander (2006) reported differing technical views on screen length throughout the period of the Hydrogeologic Workplan.

Development

After the screens are in place, the well is developed (ASTM D 5092 1995, ASTM D 5521 1994). This final step of the well construction process is intended to remove drilling fluids and repair damage done to the formation adjacent to the borehole wall by the well drilling. For monitoring wells, the goal is to restore the properties of the original formation around the screened interval, especially with respect to chemical conditions, porosity, and permeability in order that water samples taken from the well are actually representative of the native aquifer. (Broxton, 2006).

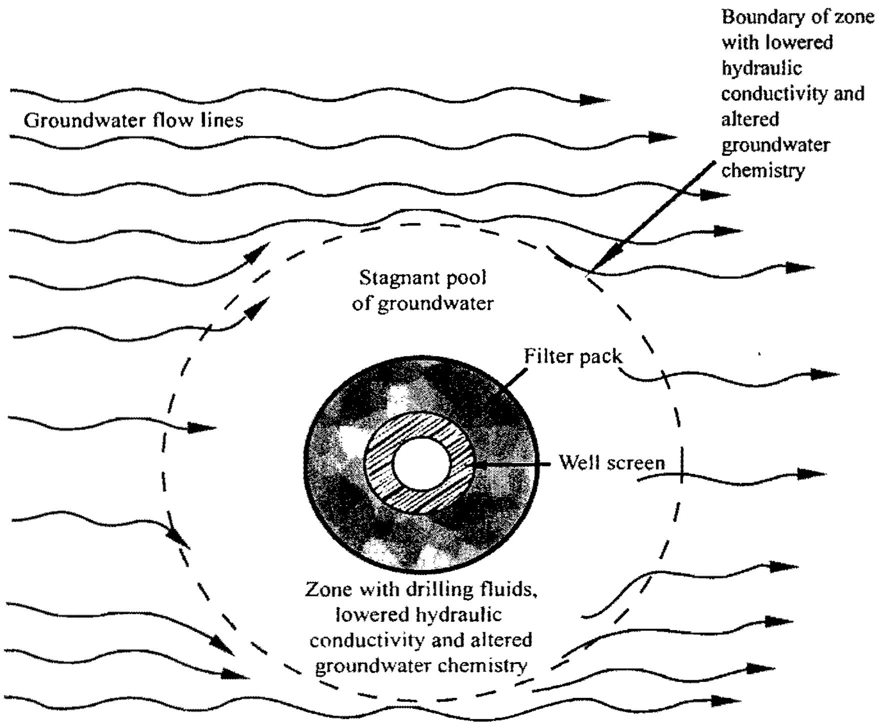
There is general agreement that the use of bentonite clay and organic additives has compromised the ability of at least some groundwater wells to yield water samples that are truly representative of the ambient, undisturbed groundwater conditions (LANL, 2005d; Ford et al., 2006; Ford and Acree, 2006; NMED, 2006). Robert Gilkeson, a registered geologist and former advisor to LANL, stated that bentonite clay and/or organic drilling additives had invaded the screened intervals in all of the LANL characterization wells (Gilkeson, 2006a,b). He illustrated a conceptual model of how these materials can set up a "reactive capture barrier" that would tend to remove contaminants from sampled groundwater; see Figure 5.2 (also see Chapter 3, Figure 3.2).

LANL's groundwater analyses typically show the presence of naturally occurring cations and anions indicating that, if it is occurring, reactive capture probably does not function as an absolute barrier. However, the degree to which contaminants might be attenuated is uncertain. LANL has acknowledged that residual drilling fluids have affected the multi-screen R-wells. In terms of providing samples representative of regional groundwater, LANL found that "single-screen wells generally provide the most defensible data" (LANL, 2005d, p. v).

Because the construction of these wells was expensive, some $1 million to $2 million for each well (Broxton, 2006), LANL began work in 2006 to try to recover some of the compromised screened intervals (LANL, 2005d, 2006e). This rehabilitation effort is itself controversial (Gilkeson, 2006a,b). The New Mexico Environment Department's (NMED's) notice of disapproval of the Well Screen Analysis Report (letter dated September 18, 2006) indicated continued disagreement on a number of important issues regarding the rehabilitation work.

After this report entered review, the New Mexico Environment Department accepted LANL's approach to identifying the impacts of drilling fluids (NMED, 2007b) via the Well Screen Analysis Report, Revision 2 (LANL, 2007c). According to LANL, a key component of the accepted methodology is the acknowledgment that a well screen at a particular location needs to provide reliable data only for potential chemicals of concern at that location.

In addition, NMED responded to the Laboratory's report on preliminary results of the pilot well rehabilitation study at three of the impacted characterization wells (LANL, 2007d) by requesting a revised well rehabilitation plan (NMED, 2007c). NMED has also requested assessments of the current groundwater monitoring network by area (e.g. TA-54, Mortandad Canyon, TA-21). According to the request, these network area assessments will evaluate the location of wells, the reliability of data from the wells, and well construction in relationship to the contaminants of concern at these areas. The area assessments will make recommendations on the specific wells to be rehabilitated or replaced. The revised well rehabilitation plan describes approaches to redeveloping wells that are determined by area assessments to be critical for monitoring. The area assessment is to be completed by December 2007, while well rehabilitation and/or replacement is expected to be completed by the end of FY09.



- In the inner region of the anaerobic zone coatings of carbonates and sulfides have formed on the aquifer strata.
- Sulfur and iron-oxidizing bacteria flourish at the interface between the anaerobic and the normal aerobic groundwater.
- The bacteria form coatings on the aquifer strata of iron oxides, manganese oxides, and high volume hydrous ferric oxides.
- The coatings have exceptional properties for removing contaminants from water produced from the well. The oxide coatings are stable as the zone returns to an aerobic chemistry.
- The coatings greatly lower the permeability of the strata to create a stagnant zone of groundwater surrounding the well screen that will be present for the 50 year life of the well.

Source: Adapted from Gilkeson, 2006a.

FIGURE 5.2 Reactive contaminant capture barrier. Geologist Robert Gilkeson described concepts of how drilling fluids could form a zone that removes contaminants from sampled groundwater. This would invalidate affected well screens as sampling points.

LANL's Plans for Well R-35

LANL will drill new monitoring wells under the Consent Order (see Table 5.2). R-35 is the first regional well being drilled during 2007. This well has the primary objective of monitoring for chromium in the upper portion of the regional aquifer, particularly relative to the PM-3 water supply well, see Color Plate 10.

Plans for drilling R-35 evolved during the committee's study period. The June 2006 workplan for drilling this well described a graded approach of using air as the drilling fluid for the first tens of feet, then water, foam, and finally muds as necessary to reach the target depth. In a March 2007 letter to the New Mexico Environment Department, LANL amended this approach and announced its intention to drill R-35 to depth using air as the only drilling fluid:

> The revised approach is to drill using casing-advance air-rotary with intent to maximize the potential for success of the air rotary method to accomplish the objectives. Each borehole will initially be drilled open hole with air-rotary foam-assist through the vadose zone to a depth above the regional aquifer. Casing will be set to hold back any perched water encountered and to prevent caving of the borehole wall. Casing will then be advanced while drilling the remainder of the borehole using conventional air-rotary to total depth. (Mangeng and Rael, 2007)

Well R-35 will actually consist of two adjacent boreholes. The shallower, R-35b, with a target depth of about 900 feet, will be screened in the most transmissive zone about 50 feet below the top of the regional aquifer (the water table). The deeper, R-35a, will be screened about 300 feet below the water table. This will be in the most transmissive zone that corresponds to the upper portion of the screen in PM-3. R-35 will thus consist of two single-screen wells.

The Mangeng and Rael (2007) letter noted that the amended approach is consistent with input from the Northern New Mexico Citizens' Advisory Board and other knowledgeable stakeholders. However, it is a significant change from LANL's presentations to the committee, which emphasized problems with air-rotary casing advance drilling encountered with the equipment and procedures used during the Hydrogeologic Workplan.

Mat Johansen, National Nuclear Security Administration liaison to the committee, informed the committee that the key to the expected success of using air-rotary with casing advance as needed for R-35 was agreement with NMED on the target zones for the two wells (Johansen, 2007). According to Johansen, with the target zones identified, the objectives of the drilling are much more focused than for the wells drilled from 1998 through 2004 under the Hydrogeologic Workplan. Those wells included objectives such as detailed geologic and hydrologic characterization of the approximately 800 to 1000 feet of vadose zone, and characterization at greater depths within the regional aquifer. Those general characterization objectives influenced the choice of drilling approaches used in past wells. Johansen noted that most of the characterization data needed to plan R-35 were available from three nearby R-wells that were drilled under the workplan.

TABLE 5.2 Current LANL Estimate of Numbers of Monitoring Wells to be Drilled

Location	Groundwater Sampled		
	Alluvial	Intermediate	Regional
Los Alamos/Pueblo Canyons Watershed[a]	1	2	3[a]
Mortandad Canyon Watershed[a]			
Water Canyon/Cañon de Valle Watershed[a]	2	3	2[a]
Pajarito Canyon Watershed[b]	11	1	2
Sandia Canyon Watershed[a]		2	2[a]
MDA G , L, H[a]			4-6[a]
MDA A, B, T, U, V (TA-21)[a]			4[a]
MDA C[a]			1[a]
MDA AB			1
Totals [a]	14	8	19-21

[a]NMED approval of area specific monitoring network assessments letter will finalize the number of wells required (NMED 2007).
[b]Per NMED approved Investigation Workplan for Pajarito Canyon

- Water Canyon/Canon de Valle assessment submitted to NMED 4/30/07
- Mortandad Canyon and Area C assessment due to NMED 6/28/07
- TA-54 assessment due to NMED 7/31/07
- Sandia Canyon assessment due to NMED 9/14/07
- TA-21 & LA/Pueblo Canyon assessment due to NMED 12/30/07

Source: Adapted by LANL from NMED, 2007a

Committee Observations on Well Construction

LANL's well construction practices (drilling, screening, development) changed significantly during the Hydrogeologic Workplan to meet changing objectives and constraints (time, money). Plans for constructing new wells continued to change during the committee's study. Changes will continue to be driven by technology, project objectives, and constraints. For example, the plans being made for R-35 seem appropriate given its objectives, but the objectives are narrow and the hydrogeological environment of the site has already been characterized by previous drilling. Future drilling under the Consent Order may encounter challenges similar to those of the Hydrogeologic Workplan.

Table 5.1 provides a description of standard drilling techniques, along with their probable advantages and disadvantages for application at LANL. It is unlikely that any single one of these techniques will satisfy all of the site's future needs for characterization, monitoring, and eventually remediation. Recognizing that decisions made over the course of the Hydrogeologic Workplan cannot be changed, it is important to incorporate lessons learned into future drilling. In this context, the committee made general observations that may be useful to LANL in constructing new wells during the remainder of its groundwater protection program.

Drilling

Test holes are often used in water well drilling programs to help identify the most productive zones and locations in heterogeneous aquifers prior to drilling and construction of the intended well. When drilled primary for geologic information through collection of cuttings and occasional core samples, test holes can be relatively inexpensive and fast. Additives can be used to expedite the drilling because the hole will not be used for quantitative water or soil analyses. In complex conditions such as the LANL subsurface, test holes can allow identification of multiple water bearing zones and application of downhole geophysical tools. The information from test holes can then be used to plan the drilling procedures and develop construction specifications for the desired monitoring or production well(s). Considering the very high cost of constructing wells to meet multiple objectives under the Hydrogeologic Workplan, and the clear need to have characterization information available before installing a monitoring well, it would appear that drilling one or more simple test holes near a planned monitoring well location could help ensure successful installation of the well.

For monitoring wells, given the uncertainties about effects of drilling muds and additives and the importance of minimizing alterations in the groundwater environment around screened intervals, the portion of the borehole to be sampled should be drilled to the extent possible with air or water as the circulating fluid. Advancing an outer casing to keep the borehole open can reduce or prevent the need for more complex drilling fluids. Mud or other additives are a last resort, but it may not be possible to completely avoid them, for example to keep boreholes from collapsing during drilling and well construction. The Consent Order allows mud rotary drilling while providing cautions about changes in the near-borehole environment that can be caused by bentonite and ionic or organic polymer fluids. In addition, the Consent Order recognizes that a polyacrylamide mud, such as EZ-Mud®, can be used appropriately if it is followed with a dispersant, such as BARAFOS®, to facilitate the breakdown and removal of the polymer. If the appropriate dispersant is applied, there should be reasonable success in recovering the dispersed and degraded EZ-Mud®.

There are other options for drilling fluids. Xanthan gum, also used in enhanced oil recovery, is far less anionic that EZ-Mud® and should offer fewer sorption sites. Starch is an option also. Combinations of bentonite and organic polymer to form a "low fluid loss" mud that reduces the amount of drilling fluid that is pushed into the formation offer another approach. Most of these options are not new (Nylander, 2006), but there is no evidence that their potential to alter the geochemical environment around LANL well screens has been evaluated.

Screening and Purging the Screens

In some instances, multiple screens in one borehole are desirable for measuring vertical gradients in pressure ("head") and groundwater composition. However, EPA (1991) and field experiences indicate that multiple screens in deep wells are prone to problems. LANL's experiences during the Hydrogeologic Workplan indicated that construction of multi-screen wells is difficult and problematic. Disadvantages of multiple screens for well construction at LANL usually outweigh their possible advantages.

Hydraulic separation of multiple screens is difficult under the simplest geologic conditions. Multiple screens, such as used in most of the compromised wells at LANL, are hard to develop individually, requiring "packers" to isolate each screen from its neighbors; see Figure 5.1. The relatively thin saturated zones contacted by each screen may not sustain great enough pressure changes (induced by pumping or "surging") to move water in and out of the screened areas to clear out the drilling fluids. The only way to completely avoid the possibility of cross-contamination between zones is to use single-screened monitoring wells.

If sampling pumps are installed in each screen, the combination of materials used in the casing, screen, pump, and discharge piping must be selected to prevent galvanic corrosion, which can result in spurious detections of metal corrosion products. Construction requires careful selection of casing and screen materials to have required strength for deep holes. Material failures have occurred at LANL, e.g., at R-25 (Nylander, 2006).

Generally screens are placed in the most permeable zone of the aquifer they are intended to sample. Geophysical logs, even as complete a suite as those used by LANL, infer permeability, but they do not of themselves measure it. The practice of inferring permeability from geophysical measurements is, nevertheless, widespread and accepted. Absent a nearby test hole, taking a side wall core during drilling of the monitoring well could be a partial solution here. This core could also be used to evaluate the correspondence between geophysical measurements and hydrologic properties. Borehole flow meters to sense flow directions and velocities within the saturated zone offer another possibility. This type of data can be useful to establish local flow directions that are affected by local heterogeneity or anisotropy, and may not be discernable by inferred flow lines from head contour maps.

Given that drilling and well construction inevitably causes disturbance of the subsurface formation, industry experience is that typically the native geochemical and hydrological conditions tend to re-establish as groundwater flows around and through the well screen. To help ensure this re-equilibration, application of proper purging techniques in both well development and groundwater sampling is necessary for collection of representative groundwater samples, especially in the regional aquifer. The most trustworthy sampling technique includes purging three or more well volumes from the monitoring well before sample collection (ASTM D 4448, 1992). While this method requires containment and potential treatment of much more water that the minimum-purge techniques, it better ensures that samples from the developed wells represent the conditions in the nearby aquifer. Purging is much easier to control and complete with single-screened monitoring wells, as noted earlier.

The uncertainty in determining the elevation of the more permeable zones is part of the larger issue of sampling along the contaminant pathways that were described in Chapter 4. The screen is intended to sample a particular pathway, which requires having a good estimate of that pathway in three dimensions. If the pathway is different than that presumed, a migrating contaminant would be missed. The issue here is one of robustness of the sampling and monitoring plan since knowledge of the pathways is always uncertain.

Concluding Comments on Well Construction

The changes and evolution of LANL's drilling program are in keeping with the development of any major scientific undertaking; indeed such evolution is essential. One cannot know all the answers at the outset and learns as the program progresses.

However in following the drilling program, the committee concluded that the program has evolved more from an operational approach—try and see what works—rather than from using careful analysis of past results to inform future planning. LANL scientists expressed concerns with drilling muds early in the Hydrogeologic Workplan, but their concerns were essentially laid aside when initial efforts to use air-rotary drilling failed to meet programmatic requirements, and the use of bentonite mud and additives was deemed the only way to proceed. Should air-rotary prove unsatisfactory for R-35 or any future well, the committee is concerned that LANL could not present a scientific rationale for switching to another drilling fluid or additive. Without a scientific basis to underpin such a change of plans, the concerns and issues raised with the existing R-wells could be repeated.

SAMPLING PROTOCOL

As noted at the beginning of this chapter, the committee answered the question: "Is the laboratory following established scientific practices in assessing the quality of its groundwater monitoring data?" with a qualified yes. The committee found that LANL has in place the proper data quality procedures to generate sound data from groundwater monitoring—with the caveat that water samples are indeed representative of the actual groundwater. However, it is not clear how such procedures are actually carried through in LANL's use and reporting of sampling data and its uncertainties, as will be discussed in this section.

In reviewing LANL's data quality program, the committee used the following working definitions:

- **Quality:** The totality of features and characteristics of a product or service that bear on its ability to meet the stated or implied needs and expectations of the user.
- **Quality assurance (QA):** An integrated system of management activities involving planning, implementation, assessment, reporting, and quality improvement to ensure that a process, item, or service is of the type and quality needed and expected by the customer.

- **Quality control (QC):** The overall system of technical activities that measure the attributes and performance of a process, item, or service against defined standards to verify that they meet stated requirements established by the customer; operational techniques that are used to fulfill requirements for quality.
- **Quality Assurance Project Plan (QAPP):** A formal document describing in comprehensive detail the necessary QA, QC, and other technical activities that must be implemented to ensure that the results of the work performed will satisfy the stated performance criteria. As defined for Superfund in the Code of Federal Regulations (40 CFR 300.430), the Quality Assurance Project Plan describes policy, organization, and functional activities, along with the data quality objectives and measures necessary to achieve adequate data for use in selecting the appropriate remedy. The QAPP is a plan that provides a process for obtaining data of sufficient quality and quantity to satisfy data needs.

Table 5.3 lists documents reviewed by the committee to better understand LANL's sampling and analytical methods, data review and compilation, data documentation, and record keeping. Section 10 of LANL's QAPP, requires independent assessment of how all data are generated, reviewed, statistically compiled, and made public with specific focus on and how specific quality assurance and quality control (QA/QC) procedures are used.

TABLE 5.3 Quality Assurance Documents Reviewed

Subject Area	**Plans Reviewed**	
Quality Assurance and Quality Control (QA/QC) procedures	Quality Management Plan for Los Alamos National Laboratory Risk Reduction and Environmental Stewardship-Remediation Services Project (RRES-QMP,R3;ER2004-012; April 15, 2004	Quality Assurance Project Plan (QAPP) for the Groundwater and Persistent Surface Water Monitoring Project (ENV-WQH-QAPP-GWSW, RO, Controlled Document signed May 8, 2006
Specific sampling and analytical procedures	2006 Integrated Groundwater Monitoring Plan for Los Alamos National Laboratory (LANL, 2006a).	Interim Measures Work Plan for Chromium Contamination in Groundwater (LANL, 2006d).
Sampling and analytical procedures, along with data review and statistical compilation approaches	LANL Groundwater Background Investigation Report, Rev. 1 (LANL, 2006b).	

Committee members compared data from analyses of groundwater samples posted on LANL's Water Quality Database (WQDB) website[2] to these data quality procedures. The WQDB is a public website, which provides real-time access to the results of chemical analyses of LANL's groundwater samples. Compilations of these data support LANL's annual Environmental Surveillance Reports and other compliance and decision-making documents. The website notes that its data are in various stages of review and are flagged to give an indication of their current status.

As one example of the results of the committee's comparison, it is unclear how QA/QC procedures were used in the sample analyses and what the specific criteria for acceptance or rejection of analytical results were. Chromium was reported in well R-32 at concentrations between 0.5 and 3 μg/L, but these are at or below the MDLs cited (<0.503 to <7.4 μg/L). In other cases, sampling results fall within the cited MDL-PQL range, yet they are not identified as J-values, as described in Sidebar 5.2.

The committee encountered instances of inconsistency in data reporting. Table C-4 (Appendix C) in the Integrated Groundwater Monitoring Plan (LANL, 2006a) gives the MDL for total chromium as 1 μg/L and the PQL as 5 μg/L. The indicates a more precise knowledge of the MDL than the range of <0.503 to <7.4 μg/L reported on the WQDB:. While the Integrated Plan reports both total chromium (Cr) and hexavalent chromium (Cr^{6+}), it gives the analytical method only for total Cr. One does not know the analytical method used for Cr^{6+} nor the MDL and PQL values for the method. Explaining how data are obtained is as important as reporting the data themselves.

In addition, LANL reports MDL and PQL values that are not appropriately rounded, and thus give an impression of accuracy and precision that do not truly exist. For example, the MDL for Cr of 0.503 μg/L on the WQDB should be rounded to 0.5 μg/L. In the Integrated Plan (Table 4.2-4a) the background chromium concentration in regional groundwater reported as 4.083 μg/L should be rounded to 4.0 or 4.1 μg/L.

While the above discussion assumes that representative groundwater samples are collected for subsequent analysis, it is essential to remember that there is debate regarding this assumption, especially related to multi-screen wells. Thus, as part of a sound QAPP, results from these suspect wells should be flagged as such. A good deal of misinformation can result if publicly available databases or compilations of LANL monitoring data do not identify the soundness of all data reported according to the data quality objectives that are clearly spelled out in the QAPP.

[2] See http://wqdbworld.lanl.gov.

SIDEBAR 5.2
Limits of Contaminant Detection and Quantitation

To be able to clearly differentiate waters impacted by LANL site activities from non-impacted waters (i.e., background), as well as to determine when an impacted water exceeds a regulatory guideline and/or standard and may require active remediation, it must be documented that such determinations are based on statistically sound analytical data. In this regard, the Method Detection Limit (MDL) and the Practical Quantitation Level (PQL) are the two measures of analytical capability used for this purpose.

- The MDL is a measure of method sensitivity. It is defined in 40 CFR Part 136 Appendix B, pp. 554-555 as “the minimum concentration of a substance that can be reported with 99% confidence that the analyte concentration is greater than zero.” MDLs can be operator, method, laboratory, and matrix specific. Due to normal day-to-day and run-to-run analytical variability, MDLs may not be reproducible within a laboratory or between laboratories. The regulatory significance of the MDL is that EPA uses the MDL to determine when a contaminant is deemed to be detected and it can be used to calculate a PQL for that contaminant.
- In the preamble to a November 13, 1985, rulemaking (50 FR 46906), the PQL was defined as "the lowest concentration of an analyte that can be reliably measured within specified limits of precision and accuracy during routine laboratory operating conditions." The EPA has used the PQL to estimate or evaluate the minimum concentration at which most laboratories can be expected to reliably measure a specific chemical contaminant during day-to-day analyses of drinking water samples. A PQL is determined either through the use of inter-laboratory study data or, in the absence of sufficient information, through the use of a multiplier of 5 to 10 times the MDL.

In practical terms, ASTM (ASTM Standard D 596-01, Standard Guide for Reporting Results of Analysis of Water) defines the MDL as the concentration below which a chemical cannot be said to be present with any confidence. Furthermore, a sample concentration detected between the MDL and PQL implies that the respective chemical is present but cannot be quantified. Concentrations of chemicals below an MDL are generally identified as “<#” or “#U” values with the # being the chemical-specific MDL. A chemical concentration between the MDL and PQL is estimated with the indicator “J” and is referred to as a “J-value.”

DATA QUALITY FOR REMEDIATION DECISIONS

The committee was asked, "Are the data (including qualifiers that describe data precision, accuracy, detection limits, and other items that aid correct interpretation and use of the data) being used appropriately in the laboratory's remediation decision making?" The committee's short answer is no, for several reasons. Formally, LANL had not begun remediation activities during the committee's study period (Dewart, 2006) and the committee heard no presentations about this aspect of its remediation decision making. More to the point, however, the committee became concerned about LANL's use of results from measurements near or below the limits of practical quantitation and detection, near the natural background, or both, in some of its key documents; see Sidebar 5.3).

In terms of supporting future remediation decision making, data in LANL's Groundwater Background Investigation Report (LANL, 2006b) appear to be derived from sound sampling and analysis. The report clearly lays out how data were collected and also pays adaquate attention to QA/QC procedures as well as how MDL concentration levels were handled. By setting up this background information for all three groundwater regimes (i.e., alluvial groundwater, intermediate-perched groundwater, and the regional aquifer groundwater), LANL is in a good position to statistically determine any future increases above background concentrations.

While the Background Investigation Report shows good statistical data compilation focused on well-documented QA/QC approaches, gaps remain. The report is not clear on how the QAPP procedures were actually followed and implemented, and in fact it does not reference the QAPP. The report also contains discrepancies in terms of documenting the actual analytical methods used and the respective MDL and PQL for the analyses. One example is for Cs-137. The background investigation report (Table 4.2-4a) gives a Cs-137 concentration of 1.1 pCi/L without specifying the MDL or PQL. Notably, 1.1 pCi/L is below the PQL for Cs-137 that LANL cites elsewhere—8 pCi/L in the Integrated Groundwater Monitoring Plan (Table C-4).

In another important example, the mean Cr concentration in a filtered sample representative of the background in the regional aquifer is given as 4.083 μg/L with a standard deviation of 5.948 μg/L (Table 4.2-4a). The same report (Table 4.1-2) cites the MDL as being either 2 or 10 μg/L depending on the particular analytical method used. Thus the actual mean Cr background concentration is not established. All that can be inferred is that the true background level is somewhere in the 1-10 μg/L range.

On this basis, it appears that the majority of the Cr concentrations cited in Figure 3-3 of the Interim Measures Work Plan for Chromium Contamination in Groundwater (LANL, 2006d) are *background levels* and that only the Cr concentrations cited for wells R-28 and R-11 can be attributed to the LANL operations. Yet without this clarification, one can infer that all the levels cited in that figure are significant (i.e., greater than background).

The Consent Order specifies that remediation meet State of New Mexico water quality standards as well as any other applicable regulations (Table B.2 of the Integrated Groundwater Monitoring Plan). For some contaminants, however, current analytical methods appear to be inadequate to ensure compliance with these requirements. That is, some MDL and PQL concentrations cited in Table C-4 of the Integrated Monitoring Plan are above the regulatory limits cited in Table B.2. For example, the cleanup requirement (Table B.2) for As is 0.45 μg/L, but the analytical MDL is 6 μg/L and the PQL is 15 μg/L (Table C-4). Likewise, for different Aroclors the cleanup criterion is 0.00064 μg/L while the MDL range is 0.0875-0.4165 μg/L and the PQL is 0.5 μg/L.

SIDEBAR 5.3
Citizens' Concern for Radionuclides Reported in Drinking Water

Near the end of this study, the non-governmental organization Concerned Citizens for Nuclear Safety (CCNS) and Robert H. Gilkeson, a registered geologist, brought to the committee's attention data in LANL's Draft Site-Wide Environmental Impact Statement (SWEIS; DOE, 2006), which indicated contamination of drinking water supply wells by neptunium and other radionuclides, including plutonium, americium, strontium and cesium. CCNS and Gilkeson pointed out that data tables in the draft SWEIS showed, for example, that neptunium (Np-237) was detected in 4 of 13 samples from Los Alamos County supply wells and in 2 of 3 samples from the Buckman well field that supplies over 40% of the drinking water for residents of the City of Santa Fe. Mean concentrations of Np-237 were 10.6 and 10.3 pCi/L, respectively. These reported concentrations approach the EPA limit of 15 pCi/L for Np-237 in drinking water.

In its memorandum to the committee, CCNS and Gilkeson stated: "We are surprised at the high levels of neptunium. This contamination may be because of the poor precision of the gamma spectroscopy analytical method. The LANL scientists claim the neptunium contamination doesn't exist and the detects are 'false positives.' *Nevertheless, the contamination is presented as valid detections in the data tables in the draft LANL SWEIS*" *[italics added]*. Gilkeson and Arends, 2007, p. 5.

In responding to CCNS, LANL did in in fact attribute the reported data to "false positives," stating: "Detections of LANL-derived contaminants, such as plutonium, americium, and strontium, have occurred sporadically in water supply wells. . . . Because the overall frequency of detection is low, we believe that these sporadic detections are false positives or caused by problems at the analytical laboratory. This conclusion is supported by numerous reanalyses of these samples and by lack of consistent detections in paired samples" (Phelps, 2007, p. 2).

This exchange between CCNS and LANL is a good example of why the committee is concerned about LANL's representations of groundwater sampling data. Whether or not the data were statistically significant, and the committee takes no position on this, the data were reported by LANL in its draft SWEIS and, reasonably, taken as real concerns by public stakeholders.

FINDINGS AND RECOMMENDATIONS ON MONITORING AND DATA QUALITY

General Findings

Any monitoring activity faces a conundrum: If little or no contamination is found, does it mean that there is in fact little or no contamination, or that the monitoring itself is flawed? During this study the committee was presented a good deal of information indicating that most or all wells into the regional aquifer at LANL (R-wells) are flawed for the purpose of monitoring. The committee did not disagree, but rather found a lack of basic scientific knowledge that could help ensure future success. Evidence about the conditions prevalent around the screens in the compromised wells is indirect—relying on plausible but unproven[3] chemical interactions, general literature data, analyses of surrogates, and apparent trends in sampling data that may not be statistically valid.

LANL is using good practices in terms of having the proper quality assurance and quality control (QA/QC) plans and documentation in place, but falls short of consistently carrying out all the procedures cited in the plans. Although LANL appears to be generating sound analytical data, the results reported in databases and LANL reports often do not carry the proper qualifiers according to good QA/QC practices. This especially applies to analytical results near or below the limits of practical quantitation and detection, near the natural background, or both.

Detailed Findings and Recommendations

Data from scientifically vetted (peer-reviewed) studies are necessary to authoritatively address concerns and uncertainties about how drilling and well completion processes might alter the native conditions around well screens and to ensure reliable monitoring activities in the future. The committee received little scientific information—for example, on a par with LANL's publications about vadose zone pathways (VZJ, 2005)—regarding the geochemical behavior of contaminants in the subsurface or effects of non-native materials (drilling fluids, additives, construction materials) on the geologic media to be sampled.

> ***Recommendation:*** *LANL should plan and carry out geochemical research to ascertain the interactive behavior of contaminants, materials introduced in drilling and well completion, and the geologic media. As a part of LANL's future plans for sitewide monitoring, this work would include:*
>
> - *Determining the nature of interactions among materials proposed for use in constructing monitoring wells and the types of geological media that LANL intends to monitor,*
> - *Quantitative measurement of sorption of contaminants onto the natural, added, and possibly altered constituents that constitute the sampling environment of a monitoring well, and*

[3] Not directly observed and measured under LANL site conditions.

- *Publication of results in peer-reviewed literature.*

The committee is not recommending open-ended research. Rather, targeted investigations would underpin plans for future monitoring of specific areas of the site: contaminants of greatest concern in the area, geologic media expected to be sampled (known from previous site characterization), and drilling fluids, additives, and other materials intended to be used in constructing the monitoring well(s). Screening tests envisioned by the committee would include simple batch equilibrium tests to measure solubilities and sorption coefficients (K_d) and to determine what, if any, interactions actually occur among drilling materials and the geologic media—and whether alterations are permanent or temporary. More detailed column tests can simulate and measure effects of flow rate and surface area (mass transfer) around the well screens. Planning, conducting, and interpreting the results will require the high quality of science one would expect of a national laboratory.

LANL's work under the Hydrogeologic Workplan significantly enhanced understanding of the hydrological characteristics of the site, and lessons learned during during the program can improve future drilling efforts. Wells constructed under the Hydrogeologic Workplan were intended for characterization. LANL later attempted to use the characterization wells that reached the regional aquifer for monitoring. As noted earlier, their use for monitoring was evidently compromised by drilling and well development procedures.

> ***Recommendation:*** *LANL should plan and conduct future characterization drilling and monitoring well drilling as separate tasks. For monitoring locations where characterization data are unavailable, LANL should consider drilling simple test holes to obtain this data before attempting to install the monitoring well(s).*

With the more complete hydrogeologic characterization that is now available (see Chapter 4), LANL can design and construct future monitoring wells more confidently. LANL's plans to obtain geologic and geophysical logs during drilling further increase confidence that well screens can be installed to intercept a contaminant pathway.

> ***Recommendation:*** *LANL should design and install new monitoring wells with the following attributes:*
>
> - *A borehole drilled through the monitoring zone without the introduction of drilling muds or additives (i.e., use air or water),*
> - *One screened interval that targets a single saturated zone, and*
> - *A carefully planned design (length and depth) of the well screen, which is confirmed with information collected in the drilling process.*

Drilling under specific conditions and sampling requirements can lead to exceptions to the above, and adapting to circumstances will be necessary.

With regard to LANL's practices in assessing the quality of its groundwater sampling data, the committee found that good data quality procedures are in place, but there is a lack of follow-through in how the data are reported.

> ***Recommendation:*** *LANL should ensure that there is consistency and clarity of all related sampling and analytical procedures with documented follow-through and appropriate action. This especially relates to:*
>
> - *having clear data quality objectives;*
> - *documenting how samples are to be collected;*
> - *documenting how data are handled, statistically compiled, and reported;*
> - *clear documentation of the quality of the data; and*
> - *identification of all suspect data.*

Interpreting data at or near analytical detection limits is an area of growing scientific interest. LANL can benefit from scientific exchanges with other groups and organizations that are actively working in this area (e.g., the Environmental Protection Agency, American Society for Testing and Materials). Lack of agreement between LANL, regulators, and concerned citizens as to what constitutes the appropriate representation of groundwater contamination data is a source of confusion and distrust.

> ***Recommendation:*** *LANL should ensure that measurements at or near background levels or near analytical detection limits (i.e., MDLs and PQLs levels) are scientifically and statistically sound and are reported appropriately.*
>
> *The LANL site office of DOE should take steps to ensure that LANL and site regulators agree on how all such data are to be handled, compiled, and reported. LANL should make more effort to ensure that data uncertainties are made clear to public stakeholders.*

LANL's Groundwater Background Investigation Report (LANL, 2006b) is an important step in establishing levels of naturally occurring contamination in the regional aquifer, although some gaps were identified by the committee. The Integrated Groundwater Monitoring Plan (LANL, 2006c) lists non-LANL sources of groundwater contamination. Such data are important to support future remediation decision making.

> ***Recommendation:*** *LANL should continue to track regional groundwater monitoring wells and water supply wells routinely to improve the statistical basis for reporting any increases above background.*
>
> *LANL's Quality Assurance Program Plan should enforce the documentation of any and all instances where it is believed that chemicals or radionuclides detected in groundwater are not the result of LANL operations, e.g., naturally occurring or anthropogenic contaminants or the result of sampling artifacts.*

6
Findings and Recommendations

This chapter summarizes the committee's findings and recommendations developed in Chapters 3, 4, and 5 of this report. Los Alamos National Laboratory's (LANL's) current groundwater protection program began under mandate from the New Mexico Environment Department (NMED) in 1998, and it is to be completed by 2015 according a Consent Order issued by NMED. To help ensure a timely and successful completion, the Department of Energy (DOE) requested the National Academies to provide technical advice on certain technical aspects of the program. The committee's statement of task is given in Sidebar 1.1.

Because the groundwater protection program is at about its midpoint, the committee viewed it as a work in progress, and this report is necessarily a snapshot in time. The committee's findings are based on information presented by LANL and other stakeholders through about April 2007. The committee's recommendations are directed toward improving the effectiveness of the program and providing a sound scientific basis for LANL's future remedial actions and long-term monitoring.

OVERARCHING FINDINGS

LANL's groundwater protection program faces substantial technical challenges. There is considerable uncertainty about the contamination sources themselves, and the pathways for transport of contaminants from their sources include four different hydrologic regimes: (1) surface streams and runoff; (2) near-surface groundwater in the canyon alluvium; (3) intermediate perched groundwater in the unsaturated (vadose) zone; and (4) a deep, regional aquifer. Each of these regimes adds considerable uncertainty to the understanding of the overall system. Even with best efforts to understand contaminant sources and pathways, the uncertainty will always be great. Nevertheless, LANL has no other options except to advance its program in the face of uncertainty. Surprises will be inevitable in this learning process.

On the positive side, LANL scientists learned a good deal through the Hydrogeologic Workplan, which was conducted from 1998 to 2005 (LANL, 2005a). While the thickness of the vadose zone, some 800 feet, and the depth of the regional aquifer, some 1000 feet, make their scientific study difficult, these features are assets for groundwater protection. The substantial relief provided by the canyons that cut through the volcanic sequence provides a good conceptual picture of the site's geology. The direction of surface and groundwater flow is generally known, even if the identification of the specific pathways is problematic.

Regardless of the difficulties that lie ahead, prudence and the law require that a groundwater monitoring system be established. The recommendations in this report support the proposition that it is technically feasible to monitor the groundwater. The efficacy of the monitoring system will have to be determined based on the analysis of the future data that will be obtained as the system is developed.

There are four overarching findings that arose from the committee's study and that have relevance to essentially all parts of the task statement.

Geochemistry

LANL demonstrated substantial progress in site characterization under the Hydrogeologic Workplan. However, LANL's work in geochemistry has not kept pace with work in hydrogeology.[1] Geochemistry is central to understanding the extent to which contaminants move with groundwater; it is a tool for better understanding hydrogeologic pathways; and it is essential for determining the degree to which monitoring data are representative of actual groundwater. The specific need is to understand how contaminant migration caused by groundwater is affected by geologic or anthropogenic media that are encountered along the groundwater's flowpath. The committee saw few fundamental, site-specific studies that quantitatively address this need. Conducting such studies in the laboratory is not difficult, but it requires dedicated scientific effort to plan and conduct appropriate tests and to interpret their results.

Mass Balance

LANL needs better ways to demonstrate its considerable understanding—and eventually its mastery—of potential threats to the regional aquifer. Specifically this means knowing the site's inventory of contaminants and where they are.[2] Most contaminants are evidently still in or near their sources; a sizeable fraction of some have migrated into the vadose zone; and a small fraction are in the regional aquifer. This information needs to be quantified and presented succinctly. The committee judged that mass balance is an appropriate tool for this purpose.[3] Mass balances, which LANL has begun developing for a few disposal areas (Birdsell, 2006), could be developed for other high-inventory areas and integrated to eventually account for contaminants sitewide. Such accounting for contaminants is the essence of groundwater protection, and it can help foster trust between LANL and its regulators and public stakeholders.

Uncertainty

Uncertainty is inherent in scientific knowledge, and work to address uncertainty leads to improved knowledge. LANL needs to do a better job of describing uncertainties in its groundwater protection program to both scientific and public audiences. This

[1] Water is primarily responsible for the migration of contaminants. Hydrogeology is the study of groundwater behavior in the subsurface. Geochemistry is the study of the chemical properties of the solid materials of the Earth, and in this case would include how contaminants interact with these materials and groundwater.
[2] LANL does not need a detailed inventory of each and every possible contaminant. Based on information presented to the committee, chromium, nitrates and high-explosive residues, perchlorate, and radionuclides appear to be most important. Others are listed in the Consent Order and DOE regulations.
[3] The elements of mass balance are discussed in Chapter 3.

includes describing fundamental conceptual uncertainty—things that are simply not known, such as the nature of some groundwater pathways—and measurement uncertainty, such as the variability of laboratory results for contaminants detected at very low levels. The committee judged that greater openness about uncertainty—on the parts of LANL and its stakeholders—could improve the quality and transparency of LANL's groundwater protection program.

Peer Review

Peer review is the standard of science. The committee is not hesitant to take LANL's motto: "The World's Best Science Protecting America" at face value. However, like many publications from DOE laboratories, LANL reports typically fall in the area of non-peer-reviewed literature. LANL has produced massive amounts of report material, and the additional step of summarizing and publishing key portions, as it did with some information from the Hydrogeologic Workplan (VZJ, 2005), can help authenticate LANL's groundwater protection program. This is not to discount LANL's other peer-reviewed publications from the program, but rather to encourage more. Besides peer-reviewed literature, other venues are available for peer review of important work that is not amenable to journal publication.[4] Demonstrations of sound science through peer review will go a long way toward ensuring the effectiveness of LANL's groundwater protection program and enhancing confidence among stakeholders.

FINDINGS AND RECOMMENDATIONS TO ADDRESS THE TASK STATEMENT

This section gives the detailed findings and recommendations developed in the main text of this report according to the task statement.

Findings and Recommendations on Sources of Contamination and Source Controls

Radioactive or chemically hazardous wastes disposed onsite at LANL constitute the sources of contamination that the committee considered in addressing its statement of task. These sources are the inputs from which contaminants enter the soils, rocks, and water that comprise the hydrogeologic environment beneath the LANL site. The

[4] It may not always be the case that detailed, site-specific groundwater protection work will rise to the level of novel methods or results of broad interest (outside of the communities affected by LANL or DOE practices) that is often a prerequisite for journal publication, or the work might simply be too detailed or lengthy for a typical journal article of 4-12 published pages. However, even routine aspects of this work would benefit from some type of outside peer review. There are alternatives for peer review. For example, the Española Basin Technical Advisory Group includes 12 organizations (including LANL) that consider the Española Basin a primary groundwater resource. This advisory group has objectives of developing strategies for integration and coordination of technical studies and information transfer. Such an organization is an example of an appropriate venue for peer review of groundwater protection studies that would not lend themselves to peer-reviewed journal articles. See http://esp.cr.usgs.gov/ebtag/About.html.

Laboratory has practiced onsite disposal of its wastes since the early 1940s. Disposal methods include the discharge of liquid effluents into canyons and the emplacement of solid wastes, mainly on mesa tops.[5]

The committee's statement of task posed three questions regarding sources:

> What is the state of the laboratory's understanding of the major sources of groundwater contamination originating from laboratory operations and have technically sound measures to control them been implemented?
>
> Have potential sources of non-laboratory groundwater contamination been identified?
>
> Have the potential impacts of this [non-laboratory] contamination on corrective-action decision making been assessed?

The committee's short answer to the first question is yes for liquid sources and no for solids. Liquid waste discharges are generally eliminated or controlled. LANL's data indicate that previous liquid discharges were the sources of contamination currently found in groundwater. However, solid wastes and contaminants deemed by LANL to have less near-term potential to impact groundwater have received much less attention than the liquid sources and are not well understood, especially in terms of source inventories.

The short answer to the second question is a qualified yes. The answer to the third has to be no because LANL is only beginning to determine corrective actions under the Consent Order. This aspect of decision making was not discussed with the committee.

The committee offers the following findings and recommendations to assist LANL in future work to understand and control its contamination sources, with emphasis on longer-term concerns than have not been addressed during the first portion of the groundwater protection program.

Solid wastes, e.g., the 25 material disposal areas (MDAs), and certain contaminants deemed by LANL to be essentially immobile (e.g., Pu) have the potential for impacting groundwater in the future. MDA AB in Technical Area-49 (TA-49), which contains some 2300 Ci of Pu-239, is an example. The committee received little information that would provide assurance that these sources are well understood or well controlled.

> ***Recommendation:*** *LANL should complete the characterization of major contaminant disposal sites and their inventories, i.e., complete the investigation of historical information about these disposal sites with emphasis on radionuclides and chemicals likely to impact human health and the environment. Selected sites should be characterized by field analysis when historical information is insufficient to determine quantities of major contaminants disposed and to confirm the degree of transport that has occurred.*

[5] Discharges of gaseous effluents are not considered in this report.

LANL should devote greater effort to characterizing sources with significant inventories of contaminants (especially plutonium) that usually are strongly sorbing but still have the long-term potential to migrate in the presence of water.

Priority for investigating sources is established by the Consent Order. This recommendation emphasizes the need to confirm assumptions that underpin the assignment of lower priority to "immobile" wastes.

There are still large uncertainties in LANL's estimates of the inventories of principal contaminant sources and their locations. Similarly, analyses are lacking to approximate the current locations of contaminants (which may have migrated from these sources) in the various hydrogeological units that constitute the LANL site and surrounding areas.

Recommendation: *For the major disposal sites, LANL should develop mass balance estimates of the quantities of disposed chemicals and radionuclides remaining in the surface soil and/or residing in the shallow alluvium, the vadose zone, and the regional aquifer.*

Sitewide, LANL should perform a mass balance for hazardous and radioactive substances by assessing the types, quantities, and volumes of individual hazardous materials that have entered the site over the years.[6]

These analyses, with estimates of data uncertainties, should help LANL account for contaminant sources, releases, radioactive decay, and migration through the hydrogeologic system in a way that is transparent and understandable to all of its stakeholders.

Surface water is an important pathway for transport of contaminants to the groundwater. Stormwater can remobilize contaminants that have been deposited in canyons and transport them downstream. The contaminants can enter the shallow groundwater away from their original source or be transported offsite.

Recommendation: *LANL needs to quantify the inventories of contaminants released in the canyons in order to understand their potential threat to groundwater. The sitewide mass balance of inventories of hazardous and radioactive substances should include the surface water transport pathway.*

LANL should continue to develop surface water and sediment monitoring programs. LANL should continue, and improve, its control of contaminants moving down the canyons to prevent further surface transport and redistribution offsite of both mobile and sorbing contaminants. Measures to control surface transport down canyons, including further reduction of aqueous discharges, removal of contaminated media, and appropriate use of barriers, are needed.

[6] When taking mass loss mechanisms into account (e.g., radioactive decay rates), this will identify the upper boundary of pollutant mass that may still exist at the site today.

The geochemistry of contaminant migration has not been studied at a level of detail comparable to the site investigations conducted under the Hydrogeologic Workplan. This is a gap in LANL's current groundwater protection program.

> ***Recommendation:*** *LANL needs to better integrate geochemistry into its conceptual modeling. Laboratory experiments and field tests, in addition to literature data, are necessary to substantiate LANL's general observations and assumptions about the geochemical behavior of contaminants.*

LANL will continue to be an active DOE site with the potential for release of contaminants from its ongoing operations. Discharges and releases have been cut substantially at TA-50, the location of the site's radioactive liquid waste treatment facility. Yet, its discharges will continue to provide a flow of water that will tend to remobilize contaminants already deposited in the canyons.

> ***Recommendation:*** *LANL should continue to review all operations and reduce discharges and releases to the greatest extent practical. This includes efforts to minimize the disposal of solid wastes on mesa tops because waste disposal in those areas can pose a long-term threat to the regional groundwater.*

Findings and Recommendations on Contaminant Pathways and the Interim Monitoring Plan

LANL carried out its Hydrogeologic Workplan from 1998 through 2004 to better characterize the site's hydrogeology and the potential pathways for contaminant transport. The purpose of the characterization program was to develop the scientific basis for a sitewide groundwater monitoring plan.

The committee's statement of task posed two questions regarding LANL's current (interim) monitoring program:

> Does the laboratory's interim groundwater monitoring plan follow good scientific practices? Is it adequate to provide for the early identification and response to potential environmental impacts from the laboratory?
>
> Is the scope of groundwater monitoring at the laboratory sufficient to provide data needed for remediation decision making? If not, what data gaps remain, and how can they be filled?

After reviewing LANL's Interim Facility-wide Monitoring Plan[7] the committee answered the two parts of item 1 with a qualified yes and no, respectively. While the Interim Plan generally follows good scientific practices, there are opportunities for improving it. The plan is not adequate to provide early identification of potential contaminant migration with high confidence because LANL's understanding of pathways

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[7]The Interim Monitoring Plan was subsequently included as section 1 in LANL's 2006 Integrated Sitewide Monitoring Plan (LANL, 2006a). Three additional sections dealt with offsite monitoring and monitoring to satisfy the conditions of two discharge permits. These additions did not affect the committee's review or its findings or recommendations.

for contaminant transport, especially inter-watershed pathways, is not yet adequate to support such confidence. The committee answered item 2 with a qualified no.

Findings and recommendations to assist LANL address remaining gaps in pathway conceptualizations and improve its monitoring plans are as follows:

The current conceptualization of the LANL flow system into alluvial, intermediate-perched, and regional components, along with their importance to understanding the flow system within and below wet canyons, are major accomplishments by the LANL scientists. However, there is a lack of understanding of the *interconnectedness* of pathways between basins. While there is a general understanding that perched waters are probably redirecting contaminants from areas directly below canyons where they originally infiltrate, to sub-mesa areas and to other nearby canyons, the detailed knowledge needed to predict subsurface flowpaths does not exist. Lack of understanding of these phenomena, coupled with rapid flow in the alluvium and apparent rapid flow facilitated by perched waters, were central to the surprise over detection of chromium near the water supply wells. An improved knowledge of these interwatershed processes is needed to design an effective, early warning monitoring program.

Recommendation: *LANL should add a sitewide perspective to its future groundwater monitoring plans. This perspective would include the following:*

- *Design additional characterization, modeling, and geochemical investigations to better understand potential fast pathways between watersheds.*
- *Increase the area of the regional aquifer that is monitored by sampling inter-canyon areas from mesas or using directional wells from canyon bottoms.*
- *Provide additional monitoring locations in the southern area of the site and on Pueblo de San Ildefonso lands.*
- *Develop more applications of geophysical techniques to supplement information provided by well drilling and sampling, especially for understanding vadose zone pathways.*
- *As LANL's site characterization and monitoring programs mature, well locations should be derived from a quantitative spatial analysis of monitoring well locations to identify areas with the greatest uncertainty in plume concentrations, using geostatistics or other methods, possibly coupled with flow and transport modeling.*

Mathematical models are essential tools for both codifying current knowledge and identifying knowledge gaps. Although LANL is using a numerically sophisticated multiphase model for vadose and regional groundwater modeling, it is not yet possible to predict with confidence when, where, or if a contaminant might appear in the regional aquifer. This is due largely to an exceptionally complex vadose zone. Studies show that most of the mass of many contaminants is likely still in the vadose zone on the way down from the release location to the regional aquifer.

> ***Recommendation:*** *LANL should increase its efforts to develop and use quantitative methods to describe contaminant pathways through the vadose zone and into the regional aquifer, as follows:*
>
> - *Mathematical models that incorporate the uncertainties from alternative conceptual models should underpin plans for design and operation of the sitewide monitoring system. Characterization of the vadose zone begun under the Hydrogeologic Workplan should continue with emphasis on new results from characterization and monitoring being used to test and improve the mathematical models.*
> - *To support an evaluation of the effectiveness of the monitoring system to provide early warning of potential impacts on the regional aquifer, LANL should quantify, to the extent possible, the inventory and current location of the contaminants disposed of in the major waste sites.*

Large waste disposal sites in the dry canyons and on dry mesas have not received as much attention as wet canyons and wet mesas because they presumably lack an aqueous driver to move contamination. The presumed dry locations have received minimal characterization with regards to the presence, strength and potential impact of aqueous drivers. In some of these, surface disturbances have led to unexpected increased infiltration rates. LANL provided few data to justify assumptions about the relative immobility of wastes at these sites.

> ***Recommendation:*** *LANL should confirm the integrity (lack of surface disturbances or conditions leading to increased infiltration) of the major disposal sites in the dry canyons and mesas.*
>
> *LANL should schedule regular subsurface surveillance beneath disposed wastes on dry mesas and in dry canyons.*

LANL's present conceptualizations of the regional aquifer lead to very different pictures of how contaminants in the aquifer might behave. If there is low connectivity between layers within the aquifer, the contaminants might remain near the top of the regional aquifer and most likely discharge in the springs near the Rio Grande. On the other hand, higher connectivity could result in the contaminants spreading vertically and more likely entering the deep screened intervals of regional water supply wells.

> ***Recommendation:*** *LANL should continue efforts begun under the Hydrogeologic Workplan to characterize the regional aquifer. More large-scale pumping tests and improved analyses of the drawdown data are needed to establish a scientifically defensible conceptual model of the aquifer, i.e., leaky-confined, unconfined, or layered.*

LANL's efforts to understand the role of geochemistry in contaminant migration have not kept pace with efforts to understand hydrology. The committee found a lack of basic, site-specific geochemical data to support LANL's assumptions about the relative immobility of important contaminants—especially radionuclides—along

transport pathways and judged that LANL underestimated the value of both field and laboratory geochemical measurements.

> ***Recommendation:*** *LANL should increase its attention to geochemistry within the context of its site characterization work. LANL scientists should conduct more field and laboratory studies to measure basic geochemical parameters such as sorption coefficients with the goal of testing and verifying their conceptualizations of subsurface hydrogeochemical processes.*

The following finding and recommendations reflect the committee's evaluation of the Interim Facility-wide Groundwater Monitoring Plan (LANL 2006c), which was requested in the Statement of Task.

The Hydrogeologic Workplan has been effective in improving characterization of the site's hydrogeology. However, the knowledge gained through the workplan does not appear to have been used effectively in the development of the interim monitoring plan. The workplan is mentioned only in the introduction of the interim plan, and rationale for the siting of new wells in the interim plan is not grounded in the scientific understanding of the site evident in the Synthesis Report and other publications such as the *Vadose Zone Journal* (VZJ, 2005).

> ***Recommendations:*** *LANL should demonstrate better use of its current understanding of contaminant transport pathways in the design of its groundwater monitoring program. Tables in the monitoring plan that give the rationale for locating monitoring wells should at least provide a general linkage between the proposed locations and the site's hydrology, or a section discussing the relation between well locations and pathway conceptualizations should be added.*
>
> *LANL should take a sitewide approach to monitoring the intermediate and regional aquifers. Furthermore, the interim plan should summarize (e.g., in Section 1.6) the ways in which the information from related studies will be used for updating the plan. The current description of the conceptual models (in Appendix A of the plan) is useful, but it should be improved. First and foremost would be a description of potential pathways, both surface and subsurface, that connect the sources (listed in Appendix A) with the groundwater that is being monitored.*
>
> *LANL should examine the potential for approaches that both optimize the monitoring network and incorporate uncertainty into its design (Minsker, 2003; EPA, 2006).*

Findings and Recommendations on Monitoring and Data Quality

Implementing a monitoring plan involves the practicalities of constructing groundwater wells and analyzing samples from the wells. Any monitoring activity faces a conundrum: If little or no contamination is found, does this mean that there is in fact little or no contamination, or that the monitoring itself is flawed?

During this study the committee was presented a good deal of information indicating that most or all wells into the regional aquifer at LANL (R-wells) are flawed for the purpose of monitoring. The committee did not disagree, but rather found a lack of basic scientific knowledge that could help ensure future success. Evidence about the conditions prevalent around the screens in the compromised wells is indirect—relying on plausible but unproven[8] chemical interactions, general literature data, analyses of surrogates, and apparent trends in sampling data that may not be statistically valid.

The committee's statement of task posed two questions regarding the reliability of data produced in LANL's current monitoring program:

> Is the laboratory following established scientific practices in assessing the quality of its groundwater monitoring data?
>
> Are the data (including qualifiers that describe data precision, accuracy, detection limits, and other items that aid correct interpretation and use of the data) being used appropriately in the laboratory's remediation decision making?

The short answer to the first item is a qualified yes. LANL is using good practices in terms of having the proper quality assurance and quality control (QA/QC) plans and documentation in place, but falls short of consistently carrying out all the procedures cited in the plans. Well drilling and completion methods are continuing to evolve, and the site is only beginning to implement its groundwater monitoring program under the Consent Order.

The answer to the second item as written was judged as no. Although LANL appears to be generating sound analytical data, the results presented in databases and LANL reports often do not carry the proper qualifiers according to good QA/QC practices. This especially applies to analytical results near or below the limits of practical quantitation and detection, near the natural background, or both. The difficulty here is that reported detection of contamination that is not statistically significant may be taken as real by regulators and other stakeholders—with concomitant concerns and calls for remedial actions.

The following findings and recommendations are intended to strengthen LANL's well drilling and sample analyses for site monitoring.

Data from scientifically vetted (peer-reviewed) studies are necessary to authoritatively address concerns and uncertainties about how drilling and well completion processes might alter the native conditions around well screens and to ensure reliable monitoring activities in the future. The committee received little scientific information—for example, on a par with LANL's publications about vadose zone pathways (VZJ, 2005)—regarding the geochemical behavior of contaminants in the subsurface or effects of non-native materials (drilling fluids, additives, construction materials) on the geologic media to be sampled.

> ***Recommendation:*** *LANL should plan and carry out geochemical research to ascertain the interactive behavior of contaminants, materials introduced in*

[8] Not directly observed and measured under LANL site conditions.

drilling and well completion, and the geologic media. As a part of LANL's future plans for sitewide monitoring, this work would include:

- *Determining the nature of interactions among materials proposed for use in constructing monitoring wells and the types of geological media that LANL intends to monitor,*
- *Quantitative measurement of sorption of contaminants onto the natural, added, and possibly altered constituents that constitute the sampling environment of a monitoring well, and*
- *Publication of results in peer-reviewed literature.*

The committee is not recommending open-ended research. Rather, targeted investigations would underpin plans for future monitoring of specific areas of the site: contaminants of greatest concern in the area, geologic media expected to be sampled (known from previous site characterization), and drilling fluids, additives, and other materials intended to be used in constructing the monitoring well(s). Screening tests envisioned by the committee would include simple batch equilibrium tests to measure solubilities and sorption coefficients (K_d) and to determine what, if any, interactions actually occur among drilling materials and the geologic media—and whether alterations are permanent or temporary. More detailed column tests can simulate and measure effects of flow rate and surface area (mass transfer) around the well screens. Planning, conducting, and interpreting the results will require the high quality of science one would expect of a national laboratory.

LANL's work under the Hydrogeologic Workplan significantly enhanced understanding of the hydrological characteristics of the site, and lessons learned during during the program can improve future drilling efforts. Wells constructed under the Hydrogeologic Workplan were intended for characterization. LANL later attempted to use the characterization wells that reached the regional aquifer for monitoring. As noted earlier, their use for monitoring was evidently compromised by drilling and well development procedures.

> ***Recommendation:*** *LANL should plan and conduct future characterization drilling and monitoring well drilling as separate tasks. For monitoring locations where characterization data are unavailable, LANL should consider drilling simple test holes to obtain this data before attempting to drill the monitoring well(s).*

With the more complete hydrogeologic characterization that is now available (see Chapter 4), LANL can design and construct future monitoring wells more confidently. LANL's plans to obtain geologic and geophysical logs during drilling further increase confidence that well screens can be installed to intercept a contaminant pathway.

> ***Recommendation:*** *LANL should design and install new monitoring wells with the following attributes:*
>
> - *A borehole drilled through the monitoring zone without the introduction of drilling muds or additives (i.e., use air or water),*

- *One screened interval that targets a single saturated zone, and*
- *A carefully planned design (length and depth) of the well screen, which is confirmed with information collected in the drilling process.*

Drilling under specific conditions and sampling requirements can lead to exceptions to the above, and adapting to circumstances will be necessary.

With regard to LANL's practices in assessing the quality of its groundwater sampling data, the committee found that good data quality procedures are in place, but there is a lack of follow-through in how the data are reported.

> ***Recommendation:*** *LANL should ensure that there is consistency and clarity of all related sampling and analytical procedures with documented follow-through and appropriate action. This especially relates to:*
> - *having clear data quality objectives;*
> - *documenting how samples are to be collected;*
> - *documenting how data are handled, statistically compiled, and reported;*
> - *clear documentation of the quality of the data; and*
> - *identification of all suspect data.*

Interpreting data at or near analytical detection limits is an area of growing scientific interest. LANL can benefit from scientific exchanges with other groups and organizations that are actively working in this area (e.g., the Environmental Protection Agency, American Society for Testing and Materials). Lack of agreement between LANL, regulators, and concerned citizens as to what constitutes the appropriate representation of groundwater contamination data is a source of confusion and distrust.

> ***Recommendation:*** *LANL should ensure that measurements at or near background levels or near analytical detection limits (i.e., MDLs and PQLs levels) are scientifically and statistically sound and are reported appropriately.*
>
> *The LANL site office of DOE should take steps to ensure that LANL and site regulators agree on how all such data are to be handled, compiled, and reported. LANL should make more effort to ensure that data uncertainties are made clear to public stakeholders.*

LANL's Groundwater Background Investigation Report (LANL, 2006b) is an important step in establishing levels of naturally occurring contamination in the regional aquifer, although some data quality gaps were identified by the committee. The Integrated Groundwater Monitoring Plan (LANL, 2006c) lists non-LANL sources of groundwater contamination. Such data are important to support future remediation decision making.

> ***Recommendations:*** *LANL should continue to track regional groundwater monitoring wells and water supply wells routinely to improve the statistical basis for reporting any increases above background.*

LANL's Quality Assurance Program Plan should enforce the documentation of any and all instances where it is believed that chemicals or radionuclides detected in groundwater are not the result of LANL operations, e.g., naturally occurring or anthropogenic contaminants or the result of sampling artifacts.

CONCLUDING REMARKS

LANL's groundwater protection program is at about its temporal midpoint, continuing for another eight years until 2015. The Consent Order establishes an enforceable process and schedule for the program. The committee hopes that the assessments, findings, and recommendations presented in this report will be useful in informing future technical decisions that will be made within the Consent Order process.

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Appendix A
Presentations to the Committee

Santa Fe, New Mexico, March 23-24, 2006

Welcome, Mat Johansen, NNSA Los Alamos Site Office

History of LANL, John Rhoades, Bradbury Science Museum

Sitewide Geology of Los Alamos National Laboratory, David Vaniman, LANL

Sitewide Hydrology, Bruce Robinson, LANL-ENV

LANL Groundwater Contaminants: Sources and Transport, David Rogers, LANL-ENV

DOE Request for Specific Questions to Be Addressed by NAS, Mat Johansen, NNSA Los Alamos Site Office

Public comments

Groundwater Monitoring at Los Alamos National Laboratory, Armand Groffman, LANL

Groundwater Data Adequacy Project, Ardyth Simmons, LANL-ENV

Control of Groundwater Contamination Sources, David Rogers, LANL-ENV

Evaluation and Decision Making for Radionuclides at Environmental Restoration Sites, Danny Katzman, LANL

Perspectives on this Study from the Northern New Mexico Citizens' Advisory Board, J.D. Campbell, NNMCAB

Perspectives on this Study from the San Ildefonso Pueblo, Neil Weber, San Ildefonso Pueblo

Perspectives on this Study from the New Mexico Environment Department, James Bearzi, NMED

Public comments

May 16-18, 2006

Improving LANL's Groundwater Monitoring and Analysis Program, Robert Gilkeson, Registered Geologist

Overview of the LANL Consent Order, James Bearzi, NMED

Summary of LANL Groundwater Issues of Regulatory Importance, James Bearzi, NMED

A Brief History of Drilling for the Hydrogeologic Workplan at LANL, Dave Broxton, LANL

Vadose Zone Hydrology of the Pajarito Plateau, Brent Newman and Kay Birdsell, LANL

Sources of Deep Groundwater Contamination, Danny Katzman, LANL

Review of documents to be provided to the NAS panel, DOE/LANL Staff

Comments from the Northern New Mexico Citizens' Advisory Board, J.D. Campbell, NNMCAB

Public comments

San Ildefonso Pueblo Site Visit

LANL Site Visit

Groundwater forum poster session at Dwayne Smith Auditorium in Los Alamos

Santa Fe, New Mexico, August 14-16, 2006

LANL's Environmental Programs: Overview and Objectives, Andy Phelps, LANL

Current Knowledge and Status of Groundwater Protection at LANL: A Framework and Definitions for the Workshop Sessions, Jean Dewart, LANL

Public comments

RACER: Tools and a Process to Guide Decisions Made About Risk Reduction at Los Alamos National Laboratory, John Till, Risk Assessment Corporation

LANL Decision Support Process (LDSP) Description for Groundwater Contaminants, Chris EchoHawk, LANL

Invited Perspectives from Northern New Mexico Citizen's Advisory Board, J.D. Campbell, NNMCAB

Invited Perspectives from Pueblo de San Ildefonso, Neil Weber, Pueblo de San Ildefonso

Invited Perspectives from Concerned Citizens for Nuclear Safety, Joni Arends, CCNS

Invited Perspectives from Department of Energy, Mat Johansen, DOE

Invited Perspectives from Environmental Protection Agency, Richard Mayer, EPA

Invited Perspectives from New Mexico Environment Department, James Bearzi, NMED

Public comments

Appendix B
Committee Biographies

CHAIRMAN

Larry W. Lake (NAE) holds the W.A. Moncrief Centennial Endowed Chair in petroleum and geosystems engineering at the University of Texas, Austin. Dr. Lake is an expert in modeling flow in porous media. He chaired the Department of Petroleum Engineering at the University of Texas, Austin, from 1989 to 1997 and from 2006 to the present. His approximately 200 publications deal with the permeability characteristics of near-surface as well as deep geological formations and include uranium leaching. In addition to his research, he has served as a consultant to major national and international companies and taught specialized short courses throughout the United States and abroad. He served on committees of the National Research Council's Board on Earth Sciences and Resources and Board on Energy and Environmental Systems. Dr. Lake was elected to the National Academy of Engineering in 1997. He received a B.S.E. degree from Arizona State University and a Ph.D. degree from Rice University, both in chemical engineering.

VICE CHAIRMAN

Rodney C. Ewing is the Donald R. Peacor Collegiate Professor in the Department of Geological Sciences with joint appointments in the Departments of Nuclear Engineering and Radiological Sciences and Materials Science and Engineering at the University of Michigan. Dr. Ewing is an expert in geology and geochemistry, and he has a broad knowledge of radioactive waste issues. Prior to his appointment at Michigan, he was Regents' Professor in the Department of Earth and Planetary Sciences at the University of New Mexico. Dr. Ewing has served on several National Research Council committees and was a member of the Nuclear and Radiation Studies Board (formerly Board on Radioactive Waste Management) from 2001 through 2006. He is a fellow of the American Association for the Advancement of Science, the American Geophysical Union, the Geological Society of America, and the Mineralogical Society of America. Dr. Ewing received M.S. and Ph.D. degrees in geology from Stanford University.

COMMITTEE MEMBERS

Deanna S. Durnford is a professor in the Department of Civil Engineering at Colorado State University. Dr. Durnford is an expert in groundwater contaminant hydrology, mechanics of unsaturated and multiphase flow, and movement of water and contaminants. She has done consulting work for several major corporations and has an extensive list of publications. She is a fellow of the American Society of Civil Engineers, and a member of the American Geophysical Union and the National Groundwater Association. Dr. Durnford received a B.S. degree in mathematics from the University of Wisconsin, Platteville, and M.S. and Ph.D. degrees in civil engineering from Colorado State University.

Rolf U. Halden is an assistant professor in the Johns Hopkins Bloomberg School of Public Health, Department of Environmental Health Sciences. Dr. Halden is an expert in analyzing pollutants in water, determining their source, and estimating their health risks. In his research, Dr. Halden uses a variety of advanced methods for sampling and analysis of organic and inorganic pollutants, along with mass balance calculations, to track pollutants from their point of release to a given receptor. He served on the Maryland State Water Quality Advisory Committee from 2003 to 2005 and was an invited delegate to the Congress on Emerging Contaminants held in Washington, D.C., in 2005. Dr. Halden received an M.S. degree in biology from the Technical University, Braunschweig, Germany, and M.S. and Ph.D. degrees in civil engineering from the University of Minnesota.

Inez Hua is an associate professor of civil engineering and the founding interim head of the Division of Environmental and Ecological Engineering at Purdue University. Dr. Hua is an expert in water treatment, fate and transport of chemical contaminants, inorganic and organic environmental chemistry, and groundwater and soil remediation. Three of her current research projects deal with contaminant detection and remediation. She has held temporary appointments with the Environmental Protection Agency and the National Aeronautics and Space Administration. Dr. Hua received a B.A. degree in biochemistry from the University of California, Berkeley, and M.S. and Ph.D. degrees in environmental science and engineering from the California Institute of Technology.

Annie B. Kersting is director of the Glenn T. Seaborg Institute at Lawrence Livermore National Laboratory. Dr. Kersting is an expert in isotope geochemistry and environmental chemistry. Her current research focuses on geochemical mechanisms that control actinide transport in the soil and groundwater, with special interest in how nanoparticles facilitate transport of contaminants in both saturated and unsaturated systems. She served as a scientific adviser on the Actinide Migration Committee for Rocky Flats from 2000 to 2003. She received a B.A. degree in geology from the University of California, Berkeley, and M.S. and Ph.D. degrees from the University of Michigan, both in geochemistry.

Anthony J. Knepp is a senior engineer and project manager at YAHSGS LLC, a technology management consulting firm located in Richland, Washington. Before joining YAHSGS in 2004, he had more than 20 years of experience at the Department of Energy's Hanford site. Mr. Knepp is an expert in regulatory documentation and negotiations for both federal and state environmental statutes and their implementing regulations. He also has extensive experience with hazardous, radioactive, and mixed waste cleanups; site characterization; and groundwater investigations and remediation (with DOE from 1985 to 1989 and subsequently with Hanford site contractors). Mr. Knepp received a B.S. degree in engineering from Johns Hopkins University and an M.S. degree in environmental engineering from Clemson University.

Christopher J. Murray is a staff scientist in the Applied Geology and Geochemistry Group at Pacific Northwest National Laboratory where he leads a group of geostatisticians. Dr. Murray is an expert in applying statistics to problems of assessing subsurface contamination. His work focuses on resolving two questions: "Does a network of monitoring wells provide adequate sampling capability to understand and account for the heterogeneity in the subsurface hydrogeology?" and "Are the well-sampling data statistically valid?" Most of his work has involved the Hanford site; in addition, he has done work applied to mapping contaminated sediments off the coast of Southern California. Dr. Murray has more than 20 peer-reviewed publications and has given numerous lectures on his research. He received his B.A. and M.S. degrees in geology from the University of Montana and a Ph.D. degree in applied earth sciences from Stanford University.

Kenneth A. Rainwater is a professor of civil engineering, with a joint appointment in geosciences, and director of the Water Resources Center at Texas Tech University. Dr. Rainwater is an expert in groundwater sampling and well construction and groundwater modeling and monitoring. He has been an expert witness on environmental contamination, water rights issues, and groundwater well field design and management, and he has peer-reviewed groundwater modeling and risk assessment at the Pantex nuclear weapons site near Amarillo, Texas. He is a member of the American Society of Civil Engineers, the American Geophysical Union, and the Universities Council on Water Resources. Dr. Rainwater received a B.S. degree in civil engineering from Rice University and M.S. and Ph.D. degrees in water resources from the University of Texas, Austin.

Arthur W. Ray has his own consulting firm, Wiley Environmental Strategies, specializing in development of proposed public policy, standards, legislation, and regulations; promotion of innovative technologies; and environmental justice, brownfields, and sustainability. Mr. Ray is an expert in the aforementioned areas. Before starting his own firm in 2003, he was Exelon Generation Corporation's assistant general counsel for environmental matters. From 1995 to 2001, he was deputy secretary of the Maryland Department of the Environment. He has done pro bono work for community groups and environmental organizations in New Mexico, including the Southwest Organizing Project and the Southwest Network for Economic and Environmental Justice, and has served as a guest lecturer at the University of New Mexico. Mr. Ray received a B.A. degree in psychology from Brown University and a J.D. degree from George Washington University.

John R. Smith is section head of Sustainable Production Technology at Alcoa, Incorporated and an adjunct associate professor in civil and environmental engineering at Carnegie-Mellon University. At Alcoa his responsibilities include early application of cost-effective and innovative solutions to address sustainability issues throughout Alcoa worldwide. Dr. Smith is an expert in remediation of both operating and closed facilities, including environmental fate and transport, application of innovative remedial technologies, and risk-based remedial approaches. Dr. Smith received a B.S. degree in civil engineering and an M.S. degree in civil and environmental engineering from the

State University of New York, Buffalo, and a Ph.D. degree in civil and environmental engineering from Carnegie-Mellon University.