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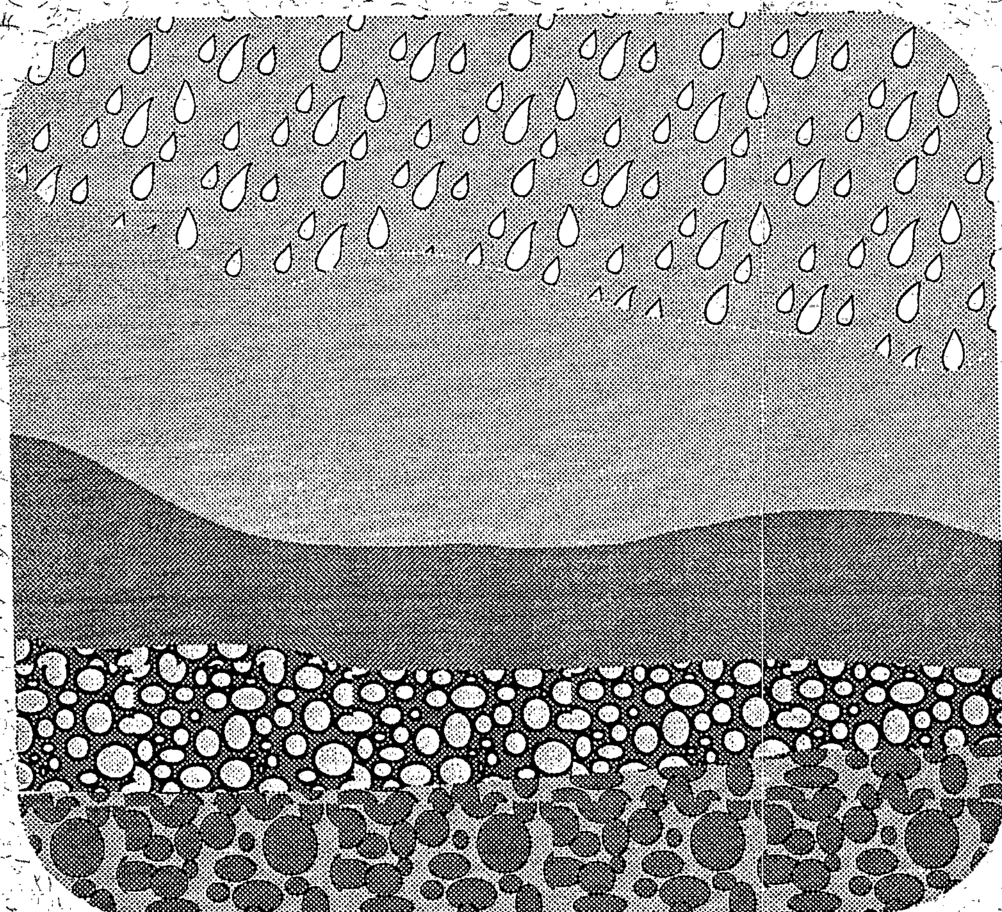
Ground-Water Research

Research Description
Third Edition



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Research Description

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Prepared for the

Office of Research and Development
Office of Technology Transfer and Regulatory Support
U.S. Environmental Protection Agency
Washington, D.C. 20460

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PREFACE

This document describes the ground-water research program conducted by EPA's Office of Research and Development (ORD). It updates the earlier *Research Program Description, Ground-Water Research* (EPA/600/9-89/088, October 1989). The research program is carried out by the Offices of Environmental Processes and Effects Research (OEPER), Modeling, Monitoring Systems, and Quality Assurance (OMMSQA), Environmental Engineering and Technology Demonstration (OEETD), and Exploratory Research (OER). Of ORD's 12 laboratories and four research groups, four laboratories have lead responsibilities and base budgets in ground water: OEPER's Robert S. Kerr Environmental Research Laboratory in Ada, Oklahoma (RSKERL-Ada); OEPER's Environmental Research Laboratory in Athens, Georgia (ERL-Athens); OMMSQA's Environmental Monitoring Systems Laboratory in Las Vegas, Nevada (EMSL-LV); and OEETD's Risk Reduction Engineering Laboratory in Cincinnati, Ohio (RREL-Cin). ORD's Center for Environmental Research Information (CERI) conducts educational seminars and prints and disseminates publications in support of the ground-water research program. The overall program is coordinated by the ORD Matrix Manager for Ground-Water Research. The current matrix manager is Peter Preuss, Director of ORD's Office of Technology Transfer and Regulatory Support. Further information may be obtained by contacting the ORD laboratories, offices, and technical experts listed in the *Ground-Water Research Technical Assistance Directory* (EPA/600/9-91/006, March 1991), which is available from CERI at FTS-684-7391 or 513-569-7391.

Further information may be obtained by contacting the directors of the following ORD facilities:

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INTRODUCTION

Ground-water quality has a major impact on human health and the environment. The importance of ground water for consumption and agricultural and industrial uses, as well as the role of ground water as part of the hydrologic cycle and consequent interaction with the environment, has become increasingly apparent in a number of EPA programs. Research is needed to support EPA programs that require increasingly sophisticated knowledge and greater technical assistance to develop and implement human health and environmental protection programs. While significant strides have been made in understanding various aspects of ground-water science and technology, the scope of ground-water research needs has been broadened by greater concern for ground-water quality, new legislation and regulations, better problem identification, and a tendency for investigations to uncover ever greater variability in the chemistry, physics, and biology of the subsurface.

Background

While EPA has no single authority under which it is charged to protect ground water, most statutes that govern the Agency's mission address the need to protect ground water. Some of the most significant include: the Resource Conservation and Recovery Act (RCRA); Comprehensive Environmental Response; Compensation, and Liability Act (CERCLA or Superfund); Safe Drinking Water Act (SDWA); Clean Water Act (CWA); and Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA). This broad spectrum of statutory authority within the Agency has contributed to a variety of ground-water issues, priorities, regulations, and research needs.

EPA ground-water research reflects the diverse priorities among seven program office clients: Office of Ground Water and Drinking Water (OGWDW); Office of Solid Waste (OSW); Office of Emergency and Remedial Response (OERR); Office of Waste Programs Enforcement (OWPE); Office of Underground Storage Tanks (OUST); Office of Pesticide Programs (OPP); and Office of Radiation Programs. The research program also supports EPA's ten Regions and a number of cross-media offices and task forces. Because States and EPA policy delegate many ground-water protection responsibilities to the states and regional variations in hydrogeology, EPA is increasing its emphasis on providing information and direct technical assistance to state and local agencies that must apply new knowledge and technologies to local problems.

The overall research and technology transfer program is guided by three EPA research committees and four Office of Research and Development (ORD) offices. The research committees—Water, Hazardous Waste/Superfund, and Pesticides—are joint ORD/program office/Regional committees responsible for reviewing research programs, ranking research needs, and recommending allocations of research funds to ORD's Assistant Administrator. ORD's research offices—Modeling, Monitoring Systems, and Quality Assurance (OMMSQA), Environmental Processes and Effects Research (OEPER), Environmental Engineering and Technology Demonstration (OEETD), and Exploratory Research (OER)—are responsible for coordinating ground-water research programs and overseeing the operations of the research laboratories within their program areas.

Responding in part to a recommendation by the Science Advisory Board, in 1986 ORD's Assistant Administrator created a matrix manager for ground-water research to be responsible for cross-office, cross-research-committee coordination among competing priorities. Program office and ORD technical specialists and managers participate in periodic reviews, led by the matrix manager, of ground-water research priorities and outputs. The reviews serve to refine research priorities based on the evolving knowledge of ground-water science and needs of the program offices. They form the basis for defining and communicating ORD's direction in ground-water research.

In 1989, EPA's Administrator established a Ground-Water Task Force to review the Agency's ground-water protection program and to develop concrete principles and objectives to ensure effective and consistent decision-making in all Agency decisions affecting ground water. The outcome of this effort is policy and implementation principles that are intended to set forth an aggressive approach to protecting the Nation's ground-water resources and direct the course of the Agency's ground-water program.

EPA's responsibilities in ground water include providing technical and financial assistance to guide state and local governments in the development of their ground-water protection and management programs, and developing policies to ensure integration and consistency of approach for federal programs focused on ground-water protection. To support EPA responsibilities, ORD offices and laboratories conduct their own research as well as fund research at other institutions, including universities and colleges, state and other federal laboratories, associations, and consulting and engineering firms. ORD research provides tools for decision-making at all government levels to improve the protection of ground-water resources from man-made contamination. In addition to designing a research program to satisfy multiple needs, ORD coordinates with other federal agencies concerned with ground-water problems.

The objectives of ORD's ground-water research programs are the development of methods, data, and guidance for detecting and monitoring various point and nonpoint sources of contamination, predicting subsurface transport and fate processes to better assess human and environmental exposure to ground-water contamination, controlling contamination from numerous possible sources, and restoring contaminated aquifers to a point where human health and the environment are no longer at risk. Research into predicting the distribution, movement, and fate of man-made contaminants in ground water is basic to ground-water protection and sets the pace for progress in controlling contamination sources and remedial action. To ensure that the latest science and technology advances are applied to ground-water problems by government and private sector decision makers, ORD has implemented technology transfer and technical assistance programs.

EPA Program Office Responsibilities

This section summarizes the responsibilities of EPA Program Offices, Regional Offices, and the states and the resulting information needs to which ORD's ground-water research program responds. Although research results have broad applicability, in practice, research activities are supported by, and performed in support of, individual EPA programs.

RCRA Hazardous Waste

The management of regulatory programs under RCRA and the Hazardous and Solid Waste Amendments of 1984 (HSWA) is the responsibility of OSW, OUST, and OWPE. RCRA and its amendments allow states to take over responsibility for program implementation and enforcement and provides for oversight by EPA's Regions. Because the hazardous waste program is what most people think of when RCRA is mentioned, the terms "hazardous waste" and "RCRA" are used interchangeably to refer to research in support of hazardous waste (RCRA Subtitle C), municipal waste (RCRA subtitle D), and underground storage tanks (RCRA Subtitle I) regulatory programs.

Subtitle C of RCRA established a program to manage hazardous wastes from "cradle to grave," including the generation, transportation, treatment, storage, and disposal of hazardous wastes. Facilities regulated by OSW under RCRA include containers, tanks, surface impoundments, waste piles, land treatment units, landfills, incinerators, underground injection wells, and chemical, physical, and biological treatment processes. RCRA also authorizes corrective action cleanups at facilities from which hazardous wastes have been released into the subsurface. Regional and state permitters and enforcement personnel need methods to establish ground-water monitoring programs to detect pollutants migrating from facilities and to monitor compliance with permit conditions. Information on the transport and transformation of contaminants in ground water is needed to assess potential health and environmental impacts of various regulatory options and to clean up ground water contaminated by improper hazardous waste disposal.

Subtitle D of RCRA established a program to assist states who voluntarily develop and implement municipal waste management plans. It also required OSW to issue minimum technical standards to which all municipal waste disposal facilities must comply before accepting solid wastes. These minimum standards are outside the voluntary state program and cover ground-water monitoring, siting of facilities, and corrective actions. EPA municipal waste activities declined in the early 1980s, but now are on the increase because of many reported instances of ground-water contamination from municipal waste dumps. The 1984 amendments to RCRA required EPA to revise, if necessary, the criteria for municipal waste facilities, incinerator ash monofills, and land application units. To support environmentally safe municipal waste management, the states need information on suitable monitoring strategies, methods to predict the transport and transformation of contaminants in ground water, and remediation methods for cleaning up contaminated soils and ground water. The revised Subtitle D Solid Waste Disposal Facility Criteria were published in the Federal Register in October, 1991, and will become effective in October, 1993.

Subtitle I of RCRA established a program to regulate over 1.5 million underground storage tanks (USTs), hundreds of thousands of which are suspected to be leaking petroleum products. OUST has developed performance standards for new tanks and regulations for leak detection, prevention, and corrective action at all underground tank sites. Because of the number of tanks, OUST has designed a program in which the states have responsibility, after approval of their programs by EPA, for controlling leakage from underground tanks. The 1986 amendments to CERCLA provided for a Leaking Underground Storage Tank Trust Fund to finance corrective actions necessitated by leaking underground tanks. OUST and the states need information on methods to monitor the subsurface around USTs and clean up contaminated aquifers and soils.

Superfund

OERR is responsible for mitigating threats from abandoned, high-priority, hazardous waste sites under CERCLA and its amendments. The Hazardous Substance Response Trust Fund (Superfund) was established to finance EPA-lead remedial actions at CERCLA sites, short-term removal actions to lessen imminent threats, emergency responses to accidental spills, and research. EPA policies and procedures for implementing Superfund responses are contained in the National Contingency Plan (NCP), which delineates criteria for when—and to what extent—a removal or remedial response should be undertaken.

Preliminary assessments must be conducted at sites reported as possible sources of contamination or illegal dumping (now over 31,000 sites). If the preliminary assessment shows that there is an immediate need for action, a removal action may be initiated to stabilize or eliminate the release. EPA on-scene coordinators (OSCs) in the Regions direct Superfund-financed removal activities. When a preliminary assessment shows that the site may threaten human health or the environment, the site is inspected to collect sufficient information to rank its hazard potential, including risks to ground water. If a long-term remedial response is required, a lead organization is determined, which may be OERR, the state, or the responsible party; the latter under supervision of OWPE. The site remedial response is managed by a Regional remedial project manager (RPM) when OERR has the lead.

Sites are subjected to a remedial investigation to gather data necessary to determine the type and extent of soil, ground water, and other contamination at each site and a feasibility study to analyze cleanup needs and alternative approaches. After completing these studies, a remedial design is developed, including detailed engineering plans, drawings, and specifications.

OSCs, RPMs, and their state counterparts need monitoring procedures and analytical protocols to quickly and effectively assess the degree of hazard posed at waste sites. They need methods to determine the transport and transformation of contaminants in the subsurface and innovative remedial technologies to clean up contaminated sites. Although microbial degradation of contaminants in the subsurface has great potential to cost-effectively clean up some Superfund sites, a great deal of research is required to determine which contaminants are amenable to *in situ* microbial remediation and how to evaluate controlling processes, design criteria, costs, byproducts, and site-specific effects.

Enforcement powers have been granted to EPA to gain the compliance of recalcitrant RCRA facility and underground storage tank owners, oversee Superfund site cleanups, and recover the costs of site cleanups financed by Superfund. These enforcement powers are employed by OWPE and its counterparts in the Regions and states. Enforcement personnel need ground-water information similar to that needed by RCRA, Superfund, and UST regulatory, permitting, and response personnel in order to defend the scientific and technical merit underlying decisions in these programs.

Drinking Water

Under the authority of SDWA, OGWDW publishes maximum contaminant level goals and promulgates national primary drinking water regulations for all contaminants that may have an adverse effect on human health and are known or anticipated to occur in public water systems. The list of potential contaminants must be updated every three years. OGWDW will propose regulations in 1993 requiring the disinfection of ground water not under the influence of surface water, which is used as source water for public supply systems. These regulations are planned to be promulgated in 1995. Variances may be granted if it can be shown that the source water is likely to be free from pathogen contamination and other distribution system requirements. The Clean Water Act also contains provisions affecting ground-water quality, including provisions for area-wide waste treatment management plans and protection of ground water quality from nonpoint sources of pollution.

Approximately 40% of the chemical waste generated in the United States is disposed by injection into the subsurface. Both SDWA and HSWA contain provisions to protect ground water quality from the injection of waste into the subsurface by means of deep wells. Regulations for underground injection control have been based on ensuring that the use of injection wells for the disposal of waste will not endanger human health or the environment.

OGWDW is also responsible for the wellhead protection program mandated by SDWA. SDWA requires each state to develop an EPA-approved wellhead protection program to protect public water wells from contaminants. Most states already have an EPA-approved program in place or are actively developing such a program. EPA-approval requires consideration of a number of technical elements, which include: the hydrogeologic setting, delineation of protection areas, and assessment of potential contaminant sources.

To carry out their ground-water protection responsibilities, OGWDW and the States must develop methods to assess the risk to human health from various categories of potential contamination sources, determine the likelihood that a chemical will persist in the subsurface, and develop wellhead protection strategies. To support these activities, research is needed to improve methods for detecting and monitoring ground water contamination, predict the transport and transformation of pollutants in ground water, and use *in situ* technologies to remediate ground-water contamination.

Pesticides

FIFRA established a program that bans all pesticides unless they are registered with OPP. OPP has set forth guidelines specifying the kinds of information required to support the registration of a pesticide, including data on the anticipated extent of use, pattern of use, and level and degree of potential exposure to humans and the environment. When used in accordance with commonly recognized practice, pesticides must not cause unreasonable adverse effects to the environment. Although the extent of exposure to human populations through drinking water is not certain, EPA recently completed a National Pesticide Survey (NPS) to help evaluate the degree of nitrate and pesticide contamination in drinking water wells. The focus of the survey was on drinking water quality in wells and results showed an abundance of nitrate contamination in many community water system wells and rural drinking water wells. Results also showed that many community water system wells and rural drinking water wells contain at least one pesticide or pesticide degradate that exceed national Health Advisory Levels and Maximum Contaminant Levels. The Agency's *Pesticides and Ground-Water Strategy* stresses a localized approach for protecting ground water from pesticide contamination by building Regional and state capabilities and encouraging the states to develop pesticide management plans.

Techniques are needed to predict the fate of pesticides in the subsurface on a site-specific basis and measure environmental exposures of pesticides that threaten human health, impair important environmental functions, and endanger untargeted biota.

RESEARCH PROGRAM OVERVIEW

Three laboratories have lead responsibilities for ground-water research: the Robert S. Kerr Environmental Research Laboratory in Ada, Oklahoma (RSKERL-Ada), Environmental Research Laboratory in Athens, Georgia (ERL-Athens), and Environmental Monitoring Systems Laboratory in Las Vegas, Nevada (EMSL-LV). The Risk Reduction Engineering Laboratory in Cincinnati, Ohio (RREL-Cin), also conducts ground-water research, but concentrates primarily on water and soil treatment technologies.

ORD's ground-water research program can be organized into five areas: site characterization and monitoring; transport and transformation; *in situ* aquifer remediation; underground source control; and technology transfer and technical assistance.

Ground-Water Research Areas

Site Characterization and Monitoring

The placement and spacing of monitoring wells, procedures for sample collection and preservation, and quality assurance and quality control (QA/QC) are fundamental requirements for the collection of credible data to support ground-water protection decisions. ORD's monitoring research program is developing, evaluating, and adapting geochemical and geophysical monitoring techniques to meet the needs of EPA and the regulated community, evaluating site characterization methods to improve monitoring well network design, and refining procedures for data reduction and interpretation. The lead laboratory for monitoring research is EMSL-LV.

Transport and Transformation

Predicting contaminant behavior in the subsurface is one of the most difficult tasks for ground-water protection programs. Transport research considers the physical movement of water and contaminants in the subsurface. Transformation research considers biotic and abiotic processes in the saturated and unsaturated zones that change the form, species (for example, of metals and ionizable organics), or composition of ground water contaminants. The knowledge gained about transport, transformation, and speciation phenomena is incorporated into predictive models to enable the prediction estimation of contaminant behavior in the subsurface and potential exposures to humans and the environment. The lead laboratories involved in fate and transport research are RSKERL-Ada and ERL-Athens.

In Situ Aquifer Remediation

Cleaning up a polluted aquifer is a technically difficult process, if it can be done at all. Effective cleanup methods are needed to remove contaminants from many different hydrogeologic settings. ORD's aquifer remediation research is developing methods to recover contaminants from aquifers for on-site treatment, making *in situ* remediation techniques more effective and less expensive, and identifying factors that contribute to the success or failure of existing cleanup techniques. Advances in aquifer remediation methods are highly dependent on advances in the understanding of subsurface processes affecting the behavior of contaminants in the subsurface. Aquifer remediation research projects are often conducted in conjunction with transport and transformation research. RSKERL-Ada is the lead laboratory in subsurface remedial processes. RREL-Cin operates a remedial technology program which concentrates on above-ground and *in situ* soil clean-up technologies

Underground Source Control

A major source of ground-water contamination is the improper injection of hazardous wastes into the subsurface. Leaking well casings, abandoned and improperly sealed wells, injection of agricultural, industrial, and urban drainage waste waters into shallow aquifers, and upward migration of hazardous wastes from deep injection into drinking water supplies all need to be evaluated to determine safe underground injection practices. ORD maintains a small research program in underground source control which develops protocols for injection well practices, evaluates well casing test methods, and studies the interaction of injected material with subsurface materials. The lead laboratory for underground source control research is RSKERL-Ada.

Technology Transfer and Technical Assistance

Field personnel in EPA Regions, states, and local governments must deal with an extremely broad and complex range of technical information. They benefit from close support from scientists and engineers in ORD laboratories. Ground-water issues are a major category of technical requests from client offices. To be effective, research results must be disseminated to targeted operational personnel, program managers, and decision makers in a timely manner and effective format. ORD's lead in technology transfer is the Center for Environmental Research Information (CERI). In addition, all laboratories routinely conduct technology transfer and offer technical assistance.

Related Research Areas

ORD also conducts research in the areas of health effects, above-ground treatment technologies, and surface source control. Although closely related to ground-water research, they are not considered components of the ground-water research program in this research description.

Health Effects

The major route of human exposure to ground-water contaminants is through drinking water. Illnesses attributed to ground-water contamination account for a significant amount of all reported waterborne diseases. Research on the health effects of particular pollutants is used to establish credible safe drinking water standards, demonstrate to the public that the standards are based on sound data, and design health-based cleanups of hazardous substances in the environment. ORD's Office of Health and Environmental Assessment (OHEA) conducts a research program to develop methods for predicting human exposure risks from hazardous materials, including the estimation of exposure to contaminants found in drinking-water supplies. Since adverse health effects are the same regardless of whether exposure is through ground water or surface water, research on health effects is not considered part of the ground-water research program.

On-Site Treatment Technology

EPA has a major research, development, and demonstration program investigating technologies for treating hazardous substances on site (above ground) to reduce or eliminate their volume, toxicity, or mobility. This program provides performance and cost data on available technologies for treating volatile and non-volatile organics, inorganics, metals, and microbes. Information on treatment technologies is being developed for the drinking water, Superfund, hazardous waste, and pesticides programs. On-site treatment technologies are often used for treating ground-water contaminants after they are pumped to the surface. However, on-site treatment technologies are not included in this description because they are not specific to ground water. Technologies for bringing contaminants to the surface for on-site treatment are being developed for corrective action/remediation of contaminated soil. These technologies are discussed under the section on *in situ* aquifer remediation because they may also be used for that purpose. RREL-Cin has expertise in this area for research on *in situ* on-site treatment of contaminated soils.

Surface Source Control

The surface source control research program develops technologies to prevent soil and ground-water contamination in and around Superfund sites, RCRA facilities, and underground storage tanks. Engineering research activities include: 1) improving land-disposal containment systems, such as slurry cut-off walls, landfill covers; and 2) developing methods for treating hazardous wastes and soils by leachate recirculation, soil washing, *in situ* flushing, and chemical stabilization/ solidification. ORD also develops guidance and procedures for siting, designing, maintaining, and closing hazardous and municipal facilities, underground storage tanks, and other waste management facilities. The objective of this research is to reduce the health risks from soil contamination or contaminant migration to ground water. RREL-Cin is active in this research.

CURRENT RESEARCH PROGRAM

The FY91 ground-water research program had a budget of approximately $25 million and 105 FTEs. The FY92 ground-water research budget is proposed to be increased to approximately $30 million and 106 FTEs (see Appendix A). ORD deliverables, outputs, and other accomplishments expected to be completed in FY91, FY92, and beyond are listed in Appendix B.

Site Characterization and Monitoring Research

The goal of ground-water monitoring research is to develop techniques for detecting and quantifying changes in hydrogeology and subsurface water quality. Techniques that are being developed to monitor the subsurface more effectively include well and sampling methods, geophysical methods, wellhead protection methods, underground storage tank methods, and advanced field technologies. Demonstrations of these methods are being conducted to test their effectiveness, and modeling techniques are being developed to optimize use of monitoring data.

Well and Sampling Methods

Conventional monitoring of ground water involves drilling monitoring wells, using various devices for collecting samples (bailing, pumping, *in situ* samplers), and sending the samples to a laboratory for analysis. A great deal of research in the past few years has provided monitoring well construction methods and sampling techniques that produce samples more representative of the source. EMSL-LV is continuing its effort to improve ground-water monitoring methods through the development of guidance on sampling frequency, well casing materials, and monitoring well network design. Investigations are being conducted to provide an understanding of the temporal variability of ground-water quality in an arid environment and validate elements of ground-water sampling protocols.

Among the sources of ground-water contamination are the leachates from Superfund and RCRA sites. In recognizing that the target analytes identified by EPA monitoring methods account for a small percentage of the potentially hazardous organic contaminants present in these leachates, EPA instructs its contract laboratories to identify other chemicals that are present at high concentrations. Similar identifications are needed in characterizing ground water. EMSL-LV is coordinating research at Las Vegas and ERL-Athens to expand the number of compounds that can be identified reliably and cost effectively in hazardous waste disposal site leachates and ground water. Knowledge of chemicals present in these ground-water sources will provide a basis for significantly improved assessments.

Geophysical Methods

Advanced geophysical methods for the detection, mapping, and monitoring of contaminants in ground water and the vadose (unsaturated) zone of show great promise in saving the Regions and states time and expense in characterizing the subsurface. EMSL-LV is developing a number of new geophysical (remote sensing) methods to delineate subsurface characteristics and contaminant locations.

Geophysical research for RCRA hazardous waste sites concentrates on adapting borehole technologies to lower the cost of hazardous waste facility monitoring. A number of new instruments and techniques have recently been developed and are being evaluated for hazardous waste site investigations. These new technologies include the development of radar tomography techniques and a new transient electromagnetic sounding (TEM) instrument. Field evaluations of these new technologies will be conducted and results compared to standard surface, borehole, and surface-to-borehole geophysical techniques along with coring of the wells.

To support the implementation of SDWA provisions concerning underground injection control (UIC) and wellhead protection, EMSL-LV is testing cost effective monitoring technologies for protecting ground-water sources of drinking water. EMSL-LV is examining the resolution and detection limits of surface-to-borehole electrical resistivity methods for mapping and monitoring of fluid movement from underground injection wells. If successful, this geophysical method would provide the only method for monitoring the deep injected contaminants. Other geophysical methods are also being investigated for detecting near-surface contamination caused by upward movement of contaminants through abandoned wells and fracture zones.

Seismic techniques have proven effective for characterizing the subsurface at many locations. In particular, seismic shear-wave methods in combination with compression-wave (p) surveys have been very successful. An improved shear-wave source for shallow seismic studies has been developed by EMSL-LV for characterizing the subsurface in urban areas. EMSL-LV is also examining the effects of the interaction between organic chemicals and clay minerals on the response of resistivity surveys. In addition, new electromagnetic systems are being developed for hazardous waste site investigations.

New modifications in ground penetrating radar (GPR) equipment, field procedures, and field investigations are being evaluated by EMSL-LV. This technology makes use of the fact that radar pulses directed into the ground are reflected back toward the surface at points where a contrast exists in the electrical properties of subsurface materials. GPR surveys can provide high-resolution data for delineating subsurface properties at hazardous waste sites.

Wellhead Protection

In contrast to RCRA and Superfund monitoring needs, where contaminants are monitored to detect migration from a site, wellhead protection monitoring designs must provide warning of contaminants migrating toward a water supply well or well field. In addition, wellhead protection areas can be very large, requiring many wells or monitoring points. EMSL-LV is developing guidance on cost-effective monitoring strategies for wellhead protection areas to warn of contaminants nearing drinking water wells.

Underground Storage Tank Methods

To support the implementation of underground storage tank regulations, EMSL-LV is emphasizing the development of protocols for installing external leak detection systems, site characterization procedures for determining the boundaries of active leaks, and methods to monitor cleanups and remediation as well as technology transfer.

Installers of underground storage tank monitoring systems need guidance on the design and performance characteristics of external monitoring systems. To provide this guidance, EMSL-LV is evaluating external vapor monitoring methods for petroleum hydrocarbons. Standard operating procedures for external vapor monitoring devices are being developed to help installers select and install effective systems. EMSL-LV is also conducting a study to monitor a permeable peat barrier designed to remove petroleum contaminants from the ground water. This study will include the monitoring of dissolved hydrocarbons in the ground-water up-gradient, on the sides, and the down-gradient of permeable barriers that contain peat, carbon, and time-released fertilizer. Methods are also being developed to monitor benzene, toluene, ethylbenzene, and xylene (BTEX), major carcinogenic components in petroleum, by analyzing soil, soil gas, and ground water. BTEX is the most water-soluble fraction of petroleum, and is therefore the most threatening to ground-water supplies.

Natural biodegradation processes can be expected to reduce contaminant migration and eventually result in complete contaminant degradation after removal of the contamination source. Field methods are being developed to monitor vapor and ground-water movement around USTs and devise practical biodegradation solutions for state regulators and consultants. Passing this valuable information to consumers through publishing UST issue papers.

Advanced Field Technologies

New technologies capable of rapid data generation in the field are greatly reducing the amount of time required to assess contaminants at Superfund sites. EMSL-LV has established an advanced field monitoring methods research program to identify, evaluate, and accelerate the development of promising on-site monitoring technologies. These technologies enable rapid screening for contaminants at a site but are not intended to be substitutes for traditional sampling and analysis. Technologies currently being emphasized in the program are fiber optic-based sensing, immunoassay detection methods, and portable X-ray fluorescence (XRF) systems.

X-ray fluorescence spectrometry methods are being developed for detecting metal contaminants and fiber optic technologies for *in situ* monitoring of organic contaminants in ground water. The application of these technologies will provide site investigators and operators of hazardous waste facilities with a field technology to rapidly screen for hazardous constituents migrating from a site. EMSL-LV has developed a portable, ultraviolet field spectrofluorometer (Luminoscope) for detecting aromatic hydrocarbons in ground water, soil, and waste material.

The temporal and spatial behavior of volatile organic compounds (VOCs) and characterization of VOC-contaminated sites are important considerations when designing a monitoring system as well as evaluating and interpreting data. EMSL-LV is conducting studies to improve site characterizations and contamination assessments at Superfund sites. These studies will provide practical, field tested methods for site characterization that will allow consistent collection, analysis, and interpretation of site data.

Demonstrations

Establishment of the Superfund Innovative Technology Evaluation (SITE) program was required by the Superfund amendments of 1986 to speed up commercialization and application of promising new technologies. Under the SITE program, the performance of monitoring technologies are demonstrated at Superfund sites by their developers, while EPA provides quality assurance oversight and analysis of the demonstration results. The SITE program currently consists of ten demonstration projects for soils and ground-water research.

SITE demonstrations emphasize simple, rapid, and inexpensive field-deployable monitoring instruments that utilize fiber-optic, immunoassay, XRF and other innovative technologies. Procedures for proper operation of these technologies are being developed as systems are demonstrated. Field demonstrations concentrate on carefully selected technologies because the expense of field work limits the number of technology demonstrations. EMSL-LV is currently adapting a prototype of the Ultrasonic Ranging and Data System (USRADS) to the XRF. This adaptation will greatly enhance field screening methods and further optimize data presentation during the initial Superfund site investigation and throughout the remediation process. This will save time and expense and enable Superfund site managers to make better and more timely decisions in the field.

Legislation is pending in Congress that would exempt municipal waste combustion (MWC) ash from RCRA and require EPA to develop special regulations for MWC ash disposal under Subtitle D. To support development of these regulations, EMSL-LV is conducting monitoring studies for MWC ash. The objectives of the research are to characterize the behavior of MWC ash in standardized laboratory test procedures and evaluate the sensitivity of leaching results to controllable testing factors. The results will provide the technical basis for guidance on cost-effective ground-water monitoring strategies appropriate for RCRA Subtitle D MWC ash monofills.

Models

In support of EPA's monitoring research, models are being developed to optimize prediction of the migration of contaminants, characterize subsurface heterogeneities, and optimize ground-water monitoring network design. EMSL-LV is developing new geostatistical methods to improve monitoring network designs for contaminated hazardous waste sites. In addition, mathematical models for evaluating data requirements are being developed. The main focus of this research is on development of models to guide the practitioner in analyzing and testing data, developing reasonable models to describe spatial variability, testing various modeling assumptions, and statistically testing boundary value solutions.

Transport and Transformation Research

Lack of understanding the movement of contaminants in the subsurface and their transformation by natural environmental processes severely restricts the Agency's ability to protect ground-water quality and to design effective systems for cleaning up contaminated ground water. The impacts of regulatory options can be evaluated based on predictions of contaminated concentrations at some point of exposure. Such predictions are dependent on a qualitative and quantitative understanding of subsurface processes. Research into the transport and transformation of contaminants in the subsurface is fundamental to advances in monitoring, aquifer remediation, and underground source control research.

Research to gain a better understanding of contaminant transport and transformation involves hydraulic processes, abiotic processes, biotic processes, hazardous waste exposure assessment methods, wellhead protection methods, and pesticides exposure assessment methods. EPA established the National Center for Ground-Water Research (NCGWR) in September, 1979, as a consortium of Rice University, the University of Oklahoma, and Oklahoma State University, for developing and conducting a long-range exploratory research program to help anticipate and solve emerging ground-water problems. The Hazardous Substance Research Center (HSRC) program was also established to support research for hazardous substance management.

Hydrologic Transport Processes

RSKERL-Ada's highest priority research is the investigation of complex subsurface properties and processes that enhance or retard the transport of organic contaminants. Although the flow of water through uncontaminated, homogeneous aquifers is reasonably well understood, the processes affecting the transport of contaminants by ground water, particularly in heterogeneous aquifers, is poorly understood. This RSKERL-Ada research concentrates on developing an understanding of processes that either retard or facilitate the movement of contaminants in the subsurface and using this information to improve the capability of predicting contaminant concentrations.

"Facilitated transport" encompasses processes that increase contaminant mobility, which can result in ground-water contaminants moving faster than expected. Because contaminants leaking from hazardous waste facilities are commonly complex mixtures of organic compounds, RSKERL-Ada is investigating the effects of solvents within these mixtures on the mobilization of other contaminants. Data from experiments are used to develop and evaluate mathematical descriptions of the phenomenon.

Laboratory tests have shown that significant amounts of immiscible contaminants, such as gasoline, can be trapped in soil pore spaces, making them difficult to remove from the subsurface. RSKERL-Ada is studying how these contaminant residuals are released from pore spaces, the effect of trapped contaminants on transport of dissolved contaminants, and the use of solvents to enhance contaminant release from pore spaces.

The movement of contaminants through soil macropores and fractured bedrock is one of the most difficult conditions to predict. The predominant flow, which can be very rapid, is through macropore cracks and fracture zones in the bedrock. Movement also can occur through the rock matrix, depending on its porosity. Laboratory and field studies are providing data on the processes of porosity, diffusion, sorption, and ion-exchange that control transport in fractured systems. These data are being used to develop and test models that predict the transport of contaminants in fractured bedrock.

Estimation of Transformation and Transport Constants

To apply the results of mechanistic process studies to the prediction of transport and transformation, it is necessary to know appropriate physical properties and equilibrium and rate constants for the many potentially hazardous organic chemicals that are found in ground water. Measurement of such properties and constants is prohibitively expensive for large numbers of chemicals and the accuracy of measurements is usually poor, for hydrophobic chemicals in particular. ERL-Athens is developing computational methods that will permit the rapid, accurate, and inexpensive estimation of such constants. "Sparc Performs Automated Reasoning in Chemistry" (SPARC) has the capability of crossing chemical boundaries to cover all organic chemicals and uses algorithms based on fundamental chemical structure theory. The system quantifies reactivity by combining principles of quantitative structure-activity relationships, linear free energy theory, and perturbed molecular orbital theory. CRAMS (Correlations of Reactivity and Molecular Spectra) correlates the vast amount of information contained in molecular spectroscopic properties with chemical reactivity and applies the correlations to the estimation of properties of chemicals found in ground water. The two systems are complementary.

Abiotic Processes

RSKERL-Ada transport and transformation research emphasizes investigations of organic contaminant transport. RSKERL-Ada's research into transport phenomena for the drinking water program concentrates on sorption processes affecting organic contaminants. Past research with organic contaminants has indicated a number of important sorption processes that need study. While sorption can retard the spread of contaminants in ground water, it can also make contaminant removal very difficult and time consuming. RSKERL-Ada also conducts research on the spatial variability of subsurface properties, transport of metals attached to colloids, viability of hazardous waste land treatment and fate of residual hazardous wastes after closure of RCRA facilities.

A series of RSKERL-Ada research projects are investigating the processes that control the sorption of miscible and immiscible organic contaminants to subsurface materials. The comparative sorption of organic cations to clay minerals, soils containing low levels of organic material, and soils containing high levels of organic material is being studied. In addition, the effects of dissolved natural organic carbons on the partitioning of immiscible organic contaminants between water, dissolved organic carbons, and soils is being investigated. Algorithms that can describe these subsurface processes quantitatively are being developed, validated through laboratory and field experiments, and included in predictive models.

Vapor-phase transport in the unsaturated zone is an important transport route for organic contaminants, such as gasoline and many solvents. This transport is influenced by soil moisture content, distribution of organic vapors between the condensed and vapor phases, and amount of organic vapor present in soil pore spaces. RSKERL-Ada is conducting laboratory research to quantify the influence of soil moisture content on the sorption and transport of a number of selected organic vapors. The collected data will be used to test existing models for soil vapor transport.

RSKERL-Ada is studying whether the sorption of pollutants to organic materials in soils and aquifers is influenced not only by the equilibrium capacity of sorption but also the strength, or energy, of sorption. The strength of the sorption process is one factor potentially influencing bioavailability and degradation of pollutants in the subsurface. Methods for defining this factor are being studied.

RSKERL-Ada is also investigating an abiotic process that can significantly affect organic contaminants in certain subsurface environments. The role of subsurface soils containing iron and sulfur minerals in the transformation of halogenated organic compounds is being studied. The surface area, elemental composition, sorption, and other parameters expected to affect reactivity are being studied to determine the properties that control these reactions. Reaction rates are being measured to enable the development of a mathematical model describing this process.

ERL-Athens conducts research on sorption processes to complement that of RSKERL-Ada. Investigations of the sorption of ionizable organic pollutants, particularly carboxylic acids, have led to the development of process models that accurately predict the partitioning of such compounds between water and solids in sediments and aquifer materials. Studies are now underway on the partitioning of organic cations, particularly aromatic amines at low *p*Hs, which bind to solids by mechanisms different from those for organic anions. Research indicates that these compounds bind to humic materials by strong covalent binding that is irreversible.

ERL-Athens also conducts research on abiotic fate of metals in aquatic systems, including aquifers. For example, partition coefficients were measured for 13 metals and metalloids of particular interest to the Office of Solid Waste because of potential leaching and transport into ground water. Profiles of *p*H versus concentration in the aqueous phase were generated that showed a strong tendency for metal cations to be solubilized as the *p*H decreases, and gave credibility to the use of the model MINTEQ to predict speciation (and transport) of metals at various *p*Hs.

An understanding of the transformation process is essential to predicting the fate of organics in aquifer systems. ERL-Athens research has focused on two important processes—hydrolysis and redox reactions. Hydrolysis is a commonly occurring process that may completely transform a pollutant to an innocuous product in a few minutes. However, recent studies have shown that even relatively stable halogenated hydrocarbons, such as TCE and other commonly used solvents, can react with water with half-lives of a few years, a timeframe of a concern to ground water.

Redox reactions are interesting processes in ground water because of the facility with which reduction or oxidation occurs in anaerobic or aerobic systems, respectively, and because the products are harder to predict and may be toxic. Halogenated aromatic and aliphatic hydrocarbons have also been shown at ERL-Athens to reduce to lower order halogenated species with half-lives of minutes to years. A knowledge of the mechanisms of these processes may lead to technology for chemical remediation of contaminated ground water. The chemical reduction process, for example, is being adapted to treatment of nitroaromatics in wastes from munitions manufacturers.

Biotic Processes

Other high-priority transport and transformation research includes the transformation of organic compounds by indigenous microorganisms. RSKERL-Ada conducts smaller research projects to study the transport of viruses and bacteria through the subsurface.

Subsurface biological processes have a significant impact on transformations of ground-water contaminants. RSKERL-Ada is conducting laboratory microcosm experiments to develop an information base on the aerobic degradation of classes of organic contaminants and pesticides by microorganisms native to different subsurface environments. The research is evaluating important physical and chemical subsurface soil characteristics, microbial activity in different soils, enzymes involved in the degradation processes, and predominant chemical reactions. Correlations between microbial type, sediment type, and biodegradation potential are being sought to determine processes that limit or stimulate biodegradation.

Since the discovery of abundant microbial activity in anaerobic subsurface environments, studies of anaerobic biodegradation of organic contaminants are being emphasized to find ways to improve biodegradation potential in anaerobic environments. Models for predicting the anaerobic biodegradation of contaminants in the subsurface are being developed and their performance evaluated using field and laboratory data.

Although the natural microbial degradation of organic contaminants in the subsurface is being used to clean up contaminated sites, the movement of microorganisms in the subsurface and their colonization in areas of contamination are not well understood. Remediation techniques presume that contaminated aquifers already harbor organisms that are capable of degrading the contaminant. Site-specific information is needed that can be used to evaluate the prospects for colonization of a contaminated aquifer or the unsaturated zone by microorganisms. RSKERL-Ada is developing an understanding of the properties of microorganisms and subsurface materials that determine the transportability of bacterial strains through geologic material and whether a particular site will be colonized by microorganisms capable of degrading wastes.

In addition to protecting drinking water from organic, pesticide, metal, and other hazardous contaminants, public water supplies need to be protected from disease-causing viral contaminants. Improved models are needed to refine the transport of viruses through both saturated and unsaturated zones and to examine the influence of pumping wells on their movement. An improved model will have more accurate capability of delineating zones around drinking water wells, within which potential sources of viral contamination should not be placed if contamination by viruses is to be avoided. A model has been developed by RSKERL-Ada for personal computers.

ERL-Athens conducts research on the biotic processes to complement that of RSKERL-Ada. Fundamental research focuses primarily on investigations of the microbial physiology of anaerobic microorganisms, microbial ecology of reductive dehalogenation processes, identification of specific electron donors and key environmental factors that influence the rate and extent of dehalogenation under anaerobic conditions, and development of model(s) describing the anaerobic degradation process. Applied research is aimed at developing, testing, and evaluating anaerobic assays, and determining key pathways for the degradation of single and mixtures of organic chemicals often observed in ground-water environments and hazardous waste sites. This work leads directly to the development of tested protocols, which will be used in the development of appropriate remediation and migration strategies to ensure effective and consistent decisions-making that will affect the Nation's ground water.

Hazardous Waste Exposure Assessment Methods

The data and mathematical descriptions developed through research for the RCRA program are being used by RSKERL-Ada and ERL-Athens to develop and test models for predicting the concentrations of hazardous wastes released from RCRA facilities. A goal of RSKERL-Ada's ground-water modeling research is to provide field-evaluated models to predict the concentrations of contaminants in the subsurface at some point of discharge or use. RSKERL-Ada is also developing and testing in the laboratory a numerical model to predict two-dimensional, multi-phase, multi-component flow. RSKERL-Ada develops and applies model testing and evaluation methodologies to improve access to quality assured models.

Two large physical models that simulate ground-water flow and subsurface conditions have been constructed at RSKERL-Ada. The model aquifers are instrumented to track the transport and fate of introduced contaminants. The aquifers are artificially contaminated and then monitored to assess contaminant movement and the results of *in situ* cleanup methods. Although these physical model tests are conducted under simplified conditions, they provide a cost-effective transition from bench-scale verification of model predictions to expensive, full-scale field testing.

Most subsurface formations are heterogeneous, but the impact of variability in subsurface properties that control pollutant transport and fate is not well understood. RSKERL-Ada is developing methods for characterizing the variability of subsurface properties on a site-specific basis and evaluating the impact of spatial variability on transport processes and chemical and biological reactions at selected sites. Statistically valid and field-tested methods are being developed for use by field personnel for cost-effectively characterizing the spatial variability of subsurface properties at waste sites.

ERL-Athens' transport and transformation research objective is to develop and refine exposure assessment models for use by OSW in evaluating land disposal and facility closure options. The development of data on metal and organic contaminant reaction rates for use in these models is an important aspect of ERL-Athens research.

ERL-Athens is refining "MINTEQA2", a metals fate model being used by OSW to determine the potential human health and environmental impacts of RCRA regulatory options. The current research supporting MINTEQA2 includes incorporating non-linear sorption algorithms and a built-in thermodynamic database for metals sorption into the model, evaluating lead pathways, and testing MINTEQA2 at sites in Globe, Arizona and Leadville, Colorado. A new interactive preprocessor has been developed to facilitate automatic assembly of MINTEQA2 input files, and a new convergence algorithm has been developed for the model.

A lanthanide ion probe spectroscopic method for efficiently measuring metal complexation constants with complex natural humic materials was developed and applied. The new method has thus far been used to generate new thermodynamic data for use in the MINTEQA2 code and has enabled the evaluation of metal/humic interactions in a number of soil and sediment systems. Results were specifically applied in evaluating leachate transport from waste disposal sites.

ERL-Athens conducts research to estimate reaction rates that control the transport and transformation of organics in the unsaturated zone and ground water. This data is needed to improve input data for the EPA Composite Model for Landfills (EPACML), a ground-water model for estimating organic contaminant attenuation and transport through the unsaturated zone and ground water. ERL-Athens has developed an approach for estimating microbial and abiotic rate-constants based on mathematical modeling of molecular structure. Detailed laboratory studies are being conducted to describe hydrolysis and redox transformation reactions as a function of key environmental parameters (*p*H and redox potential) and molecular structure. Molecular structure is determined by spectroscopic analysis (which is much less expensive than laboratory rate constant measurements) and correlated to the transformation rates of similarly structured compounds determined in the laboratory.

A range of organic contaminants has been subjected to laboratory assays to examine how their chemical structure and key environmental parameters influence microbial degradation. Models that describe the rate and extent of microbial degradation of benchmark chemicals are being refined. Degradation rates for additional organic contaminants are then estimated in a model by relating their structure to the benchmark chemical degradation rates. Laboratory experiments are conducted to determine the effects of important environmental variables and to verify selected estimated biodegradation rate constants.

Wellhead Protection Methods

ORD and OGWDW have prepared a five-year research plan and established a State and Local Review Group (SLRG) to help ensure that wellhead protection research meets the needs of anticipated users. RSKERL-Ada is conducting research on wellhead protection area (WHPA) delineation methods, point-source assimilative capacity, multiple source assessment, and technology transfer and technical assistance.

Wellhead Protection Area delineation research includes: joint work with the state of Utah, U.S. Geological Survey (USGS), and Region VII to develop a method for protecting springs; evaluation of a WHPA delineation model developed by OGWDW; and evaluation of regional ground-water flow models. In addition, projects to evaluate WHPA delineation uncertainty, delineate WHPAs in fractured rock systems, consider viruses in WHPA delineation methods, and improve simple delineation methods are being completed. In the longer-term, a draft research plan has been prepared for developing methods to account for the capacity of the subsurface to assimilate point sources of contaminants and existing information on assimilative capacity is being compiled.

Existing ground-water quality data is being collected to create a database for the development of models relating multiple sources of contaminants within WHPAs to shallow ground-water quality. The study includes statistical evaluations to determine the significance of hydrogeologic factors, such as depth to ground water, surface geology, ground-water flow direction, and recharge. Statistical relationships between human activities and ground-water quality and subsurface characteristics will be used to determine areas where there is high potential for ground-water contamination. A geographical information system will be developed to allow easy management and interpretation of Regional information.

A risk-management strategy for wellhead protection is being developed for formulating land-use controls within a protection area. The project will be conducted in three phases: development and verification of the theoretical framework for determining risk distribution within a wellfield; development and verification of particle tracking algorithm to calculate the risk distribution; and application of the proposed strategy within an existing WHPA to demonstrate its usefulness.

ERL-Athens is developing a model for the drinking water program, called Computer Assisted Simulations for Chemical and Demographic Evaluations (CASCADE) to estimate subsurface assimilative capacity in agricultural areas. Climate and soils databases that have been developed specifically to support model application and parameter estimation will be fully integrated into CASCADE, complete with graphical display features and ease of manipulation. A ground water database is necessary to support CASCADE and will be developed during the course of this research project. A site will be chosen where data availability is consistent with the model application and typical of the situation faced by expected users to field demonstrate CASCADE for typical users.

Pesticides Exposure Assessment Methods

ERL-Athens transport and transformation research for the pesticides program has two major components—the development of modeling packages to predict the fate and transport of pesticides in the subsurface, and major field projects to test the models and collect data on subsurface processes that control pesticide fate. Limited laboratory research is also conducted to fill gaps in parameters necessary for pesticide exposure modeling.

A final report on the results of the Dougherty Plains project, which evaluated ERL-Athens Pesticide Root Zone Model (PRZM) and provided information on pesticide leaching potential, has been released. ERL-Athens has also completed the third growing season's data collection effort at a cooperative field site near Plains, Georgia and developed an interim report on the performance of the PRZM and RUSTIC Pesticide transport models. This research effort is being conducted in cooperation with the U.S. Department of Agriculture (USDA), USGS, and the University of Georgia. Data produced have also been used to test and refine a new transport code called the Aggregate model that accounts for intra-particle diffusion processes. ERL-Athens is also working to improve the soils and meteorological databases in a Database and Parameter Estimator (DBAPE) modeling support package.

A new input data collector called PIC (PRZM Input Collator) has been developed for use with PRZM. The PIC system draws on databases from DBAPE and greatly facilitates user application of PRZM. Mapping capabilities are included.

ERL-Athens is developing a multimedia model for determining pesticide exposures to birds, animals, soil insects, and terrestrial ecosystems. The Terrestrial Ecosystem Exposure Assessment Model (TEEAM) includes PRZM and components for spray application, runoff, plant transport, and wildlife. Other components to be added include surface ponding and volatilization. A test version has been developed. The model is not inherently limited to pesticide exposure and may be adapted for use in estimating exposures from hazardous wastes.

Laboratory studies are also being conducted to relate pesticide molecular structure to the sorption of pesticides to solids in anaerobic aquifers and to determine the key parameters that influence sorption processes. This information is being used to estimate pesticide reaction rates and equilibrium constants to improve pesticide exposure models.

RSKERL-Ada conducts research of a more applied nature under the RCRA program. By statute, the land treatment of hazardous wastes (including residual wastes at closed RCRA facilities) must be limited to those wastes that either can be treated to performance standards or that have been demonstrated to show no migration from the soil treatment zone for as long as the waste remains hazardous. RSKERL-Ada is conducting land treatability studies at wood preserving, food processing, paint stripping, and oil refinery industry sites. This involves collecting waste and soil samples from specific sites and conducting laboratory evaluations of the movement and natural degradation of the wastes.

EPA's Pollution Prevention Initiative, a plan to provide scientific tools to states for implementing EPA's *Pesticides and Ground Water Strategy*, will provide guidance, software, and field tests to assist States in delineating and monitoring areas vulnerable to ground-water contamination from pesticides. Under this initiative, ERL-Athens is currently conducting work on a pesticide vulnerability assessment method called Pesticide Assessment Tool for Rating Investigations of Transport (PATRIOT). This system will utilize DBAPE for analyzing soils databases and providing State and local agencies a useful screening mechanism for identifying areas of potential pesticides to ground water. The product will be a simplified screening procedure that makes use of ORD's most current data sources and software capabilities. It will consist of a combined flow and transport model, pesticide chemodynamic and use databases, soils databases management, soil water retention parameter generator, and ranking procedures. PATRIOT will be applicable at county and subcounty if digitized surveys are available.

ERL-Athens will coordinate with EMSL-LV on integration of PATRIOT with Geographic Information Systems (GIS) and application of the integrated system at the Yuma, AZ and DelMarVa field sites. Data on pesticide occurrence is currently being collected on the DelMarVa. This information will be used to determine patterns of land use and will be related back to monitoring strategies. PATRIOT will lead to the creation of a document describing GIS database design for pesticides management that addresses the acquisition, processing, use, and maintenance of data in GIS format. Region III is coordinating with the United

States Geological Survey (USGS) National Water Quality Assessment (NAWQA) program and utilizing National Pesticide Survey data on the DelMarVa peninsula. This plan involves leveraging and building upon USGS' field work in progress on the DelMarVa.

OPP plans an expansion of the existing Pesticide Information Network (PIN), which currently is a collection of three OPP-generated databases on a computer bulletin board system accessible and free to the public. These three databases include: the pesticide monitoring inventory; the restricted use products field; and the chemical index. As of FY93, the following databases will be added: the pesticides in ground water database; environmental fate one-liner database; canceled and suspended use products; and certification and training bibliography. This expansion of the system and revisions of some of the software will make more information accessible to State users. A final summary report will be completed in FY93.

Midwest Agrichemical Surface/Subsurface Transport and Effects Research

The USGS and the USDA are implementing a joint research program to determine the effects of agricultural practices on ground-water and surface water quality as part of the President's Initiative on Enhancing Water Quality. A significant component of this initiative, the Management Systems Evaluation Areas (MSEA) project, is evaluating the effects of alternative farming practices on surface and subsurface water quality at five primary research, and a number of satellite sites in the midwest. EPA will be joining this inter-agency research program in FY92 through implementation of its Midwest Agrichemical Surface/Subsurface Transport and Effects Research (MASTER) program. Five ORD laboratories are involved in research for the MASTER program: ERL-Athens, ERL-Corvallis, EMSL-LV, RSKERL-Ada, and ERL-Duluth.

Goals for MASTER include: determining the environmental benefits (ground water, surface water, and related ecosystems) of midwestern agricultural management systems proposed for best management practices; identifying measures for preventing ecological and hydrologic degradation and restoring ecosystem functions at the watershed level; and providing diagnostic and predictive tools to the states for implementing cross-media water-quality management programs based on sound ecological and hydrological practices. This will be done at site-specific, watershed, and regional scales. Developing guidelines for minimizing hydrologic and ecological impacts of agrichemicals requires an understanding of the rate and pathways of chemical movement through the landscape, the degree of agrichemical exposures to biological components, and the effects of this exposure.

One of the primary research efforts under MASTER will be the development and testing of watershed and regional scale methodologies for assessing the ecological impacts of various agricultural production practices. A cooperative research/modeling effort is being implemented in FY92 at the Walnut Creek Site, near Ames, Iowa, to develop the necessary processes data, geographic information systems, and modeling tools for addressing the watershed and regional scale-up questions. Results from this first year pilot assessment will be used as a platform for building assessment methodologies applicable to the 12 state midwestern corn belt area in future years. The ultimate products will be aimed at the development of modeling tools and databases for evaluating the effectiveness of various agricultural production scenarios in sustaining/improving the quality of the agroecosystem.

National Center for Ground-Water Research

OER provides base funding for the National Center for Ground-Water Research (NCGWR), which is supplemented through agreements with RSKERL-Ada, universities, the private sector, and other governmental units. The Center works with RSKERL-Ada and other EPA laboratories to ensure that the exploratory research program is cooperatively planned and linked to the Agency's mission. In the last five years, the Center has developed the quantitative data needed for designing *in situ* biorestoration processes. Coordination of laboratory studies has helped basic science for ground-water problems.

The objective of the NCGWR is to improve understanding of the subsurface environment and its interaction with synthetic organic compounds in the subsurface, especially in ground water associated with hazardous waste sites. The four major areas of responsibility for the Center's research are methods for ground-water quality investigations; transport and fate of pollutants in the subsurface; characterization of the subsurface environment; and information transfer. The NCGWR conducts five research projects under cooperative agreements with RSKERL-Ada, including research into land treatment, anaerobic microbial degradation, unsaturated zone transport modeling, isolation of a bacteria for degrading trichloroethylene (TCE), and case studies of Superfund site remedial activities. OER is supporting projects to study transport and transformation processes and to apply new information to *in situ* aquifer remediation methods.

Studies at Rice University have shown that exposure to contaminants results in the preferential growth of microbes that produce agents that may enhance the bioavailability (and degradation) of contaminants in aquifers. Other research at Rice University has included the development of a conceptual understanding of source effects from residual oil residing above the water table as well as experimentation in the laboratory and field to investigate this release mechanism. A multi-phase unsaturated zone contaminant transport (MUCT) model was developed to describe the fate of an oily waste and the simultaneous vertical flow of water and a second immiscible phase fluid through porous media.

A study at the University of Oklahoma used microcosms to probe the anaerobic biodegradation of several aromatic compounds and pesticides known to contaminate aquifers. An automated data-acquisition device has been invented and is now in practical use to measure the production or consumption of gaseous end-products of anaerobic metabolism. Research at Oklahoma State University has explored the co-metabolism of the ground-water pollutant TCE. To understand the process involved in this research, Oklahoma State University is attempting to engineer, through recombinant DNA techniques, organisms capable of aerobic TCE degradation in the absence of inducing substrates. The bacteria *Alcaligenes eutrophes JMP134* has been identified to remove TCE from growth media when aromatic catabolic pathways are activated by the presence of 2,4-D or phenol.

The Center's experimental and modeling studies are being integrated into a conceptual framework of the bioremediation process. If this effort is successful, it will result in an engineering process design manual for microbially enhanced restoration of contaminated ground water.

The Center's information transfer activities include numerous presentations on subsurface chemical transport and aquifer remediation research results at local, national, and international meetings. Another highlight of the Center's technology transfer program was the start of training activities for the Superfund University Training Institute (SUTI) in cooperation with RSKERL-Ada.

Hazardous Substance Research Center Program

The EPA established the Hazardous Substance Research Center (HSRC) program in response to provisions in the 1986 amendments to CERCLA and the Agency's 1988 Appropriation Act. The fundamental mission of all centers is to provide the philosophical framework, organizational structure, and resources required to foster and support integrated, multidisciplinary, and collaborative research that advanced the science and technology of hazardous substance management. The HSRCs form an integrated national program of basic and applied research, technology transfer, and training. The attention of the five cooperative multidisciplinary and multi-university centers is on the problems of managing hazardous substances. Drawing financial support from academia, industry, state and federal government, the centers are able to leverage the research resources provided by EPA. The centers also bring together a critical mass of researchers to conduct complementary and integrated research projects. Industry, regulatory, academic, and other representatives come together, through the advisory committee process, to help shape the center's research agenda.

Office of Exploratory Research Grants Program

OER established and manages a program that awards grants to qualified investigators who will conduct research in environmental chemistry, physics, engineering, biology, and health science. Topics supported include the identification and characterization of hazardous substances, intermedia transport, and fate of pollutants, human and ecological risk assessment, incineration, emission reduction, and wastewater treatment. Projects are currently being conducted in response to a request for applications on innovative restoration technologies for treatment of heavy metals at Superfund sites. This research is an effort to further extend the application of existing technologies to other types of soil or mixtures of heavy metals where a technology has previously been successfully demonstrated with single contaminants in sandy soils. Applications are being accepted in FY92 for research on pump-and-treat technologies.

In Situ Aquifer Remediation Research

In situ aquifer remediation methods show great potential as an alternative remedial action when a site has large volumes of soils with low levels of contamination or when contaminants are too deep or inaccessible for surface removal. In this case, the cost of excavation for off-site disposal or on-site (above ground) treatment are high in relation to the risk. *In situ* aquifer remediation research is often conducted in coordinated projects with fate and transport research because of the necessity for determining the location and movement of contaminants prior to remediation. The goal is to evaluate and develop cost-effective methods for *in situ* aquifer cleanup. Aquifer remediation research is conducted for the RCRA hazardous waste, Superfund, and drinking water programs.

In situ aquifer remediation research emphasizes the development of *in situ* microbial degradation technologies, field demonstrations of these technologies, and modeling to help analyze remedial options. Another research area is the development of contaminant recovery techniques to more efficiently extract contaminants from the subsurface so that on-site treatment technologies can be applied.

Delivery and Recovery Techniques

Efficient recovery of contaminants without excavation of soils is essential to on-site treatment processes and remedial actions. Processes for delivering and mixing materials in subsurface soils are also essential for effective chemical and biological treatment of contaminated soils. RREL-Cin develops delivery and recovery technologies and evaluates their effectiveness, cost, and cross-media impacts. Technologies showing potential for commercial success are tested through the ORD SITE program conducted by RREL-Cin. Hydrofracturing and shallow directional drilling are two promising delivery/recovery techniques.

Since 1987, EPA has funded a coordinated program at RREL-Cin's Hill Facility on theoretical, laboratory, and field investigations of hydraulic fracturing and directional drilling for improving remediation. The combination of directional drilling and hydraulic fracturing uses water pressure to create precisely located horizontal cracks in soils; these cracks are held open by injecting a mixture of sand and an organic binder, These long, sand filled lenses can then be used to enhance vapor phase recovery of organic contaminants, extraction of ground water, or injection of steam and hot air for *in situ* heating. The process is also being adapted for delivery of materials (nutrients, organisms, solid oxygen sources) to enhance bioremediation and to control movement of liquids during leachate recirculation treatment of MSW landfills on EPA's National Priorities List. The cost and performance of this technology is being evaluated by RREL-Cin at a soil vapor extraction (SVE) site and a bioremediation site to provide guidance on its effective use and bring it to commercial technology stage in FY92-93.

RREL-Cin is also conducting laboratory and pilot-scale research on optimizing the design of trenches for recovering leachates and ground water. This design effort includes the development of an interactive computer program that will simultaneously optimize cost and performance for combinations of recovery trenches and vertical wells.

Optimizing Pump-and-Treat Technologies

A common means to recover contaminants from ground water is pumping the water to the surface where a variety of treatment technologies can be applied. A problem commonly encountered with this pump-and-treat technique is that, after an initial rapid decrease in the concentration of extracted contaminants, the last fraction of the contaminants takes a very long time to extract. Pulsed pumping—the intermittent operation of a pump-and-treat system—is a technique that can lower the expense of pumping and treating large volumes of water to remove low concentrations of contaminants. During periods when pumps are shut off, contaminants trapped in pore spaces or sorbed to subsurface materials can diffuse into more mobile ground-water zones. When the pumps are turned back on, contaminated ground water can be removed at the maximum concentration. RSKERL-Ada initially conducted research in this area, and RREL-Cin is now continuing research to improve understanding of the site-specific conditions that affect the performance of this extraction process. This information will be used to optimize pulsed-pumping systems and ensure uniform recovery.

Pump-and-treat systems in operation at Superfund sites have been failing to reach clean-up level goals in projected timeframes for several reasons that include inadequate knowledge of site characteristics, the presence of non-aqueous phase liquids (NAPLs), and incomplete understanding of contaminant related processes. RSKERL-Ada's Subsurface Cleanup and Mobilization Processes (SCAMP) was initiated to address these knowledge gaps for optimizing pump-and-treat technologies. SCAMP research is designed to enhance the effectiveness of pump-and-treat remediation. It is a five-year effort with funding at one million per year beginning in 1991. The major long-range output from this initiative will be a guidance document for planning and implementing pump-and-treat remediation at contaminated sites.

The overall objective of the research is to acquire process and characterization information that will allow development of a decision-making framework for predicting the appropriateness and potential efficacy of pump-and-treat for site remediation. SCAMP research will initially concentrate on dense non-aqueous phase liquids (DNAPLs), which have created major policy and technical implications to OSW and Superfund. DNAPLS move slowly in the subsurface but can move through fractures into lower aquifers and diffuse into the matrix of rocks. They can travel in the opposite direction of the ground-water flow, and are difficult to detect in the subsurface. Research projects will include improving methods for characterizing complex sites and using surfactants and solvents to accelerate the removal of DNAPLs. In the longer term, RSKERL-Ada plans to conduct field tests of site characterization methods and accelerated pump-and-treat technologies and evaluate other removal technologies, such as horizontal wells.

The effort will consist of: a guidance document for characterizing a DNAPL site; site characterization of ground-water flow and transport in fractured rock systems; supercomputer simulation of pump-and-treat remediation; evaluation of technologies for cleanup of contaminated sites; investigation of surfactant enhanced remediation; surfactant-enhanced remediation of subsurface DNAPL contamination; surfactant solubilization of non-aqueous phase chemicals; evaluation of an enhanced pump-and-treat system using RSKERL's large physical models; and analytical chemistry support for in-house pump-and-treat research.

Vapor Phase Extraction Techniques

Most contaminant recovery processes involve removal of contaminants through the water phase. However, particular classes of contaminants may be extracted more effectively through their vapor phase. RREL-Cin is examining data generated on major contaminant groupings to determine which contaminants can be recovered effectively from unsaturated zones in the vapor phase. Promising vapor-phase recovery technologies being evaluated include soil vacuum extraction for recovering VOCs and techniques that can be combined with vacuum extraction to increase recovery of VOCs, such as radio frequency heating and steam injection.

RSKERL-Ada is investigating the movement of VOCs during forced-air ventilation of the unsaturated zone. Physical properties of the soil, such as porosity, pore size distribution, and water content, are the primary limits to the transport of vapor-phase VOCs in the unsaturated zone. The impacts of these properties on vapor-phase movement of contaminants will be determined in laboratory studies and the results will be used in models for designing remediation systems.

SVE is in wide use for removing VOCs from soil. RREL-Cin has developed a new procedure to determine the extent of hydrocarbon removal from soil by SVE and the reduction of aqueous solute leachability of residual hydrocarbons following SVE. This procedure uses aqueous leaching and toxicity characteristic leaching procedure (TCLP) methods to determine the concentration and composition of solutes. Remediation experiments are being conducted in two large experimental aquifers at the Oregon Graduate Institute to examine an integrated SVE system for removing VOCs from sand and gravel media. SVE has also received attention at RSKERL-Ada, particularly with respect to geochemical controls on SVE processes and to the combination of the technology with subsurface biodegradation.

Bioremediation

Microbial degradation treatment systems (biosystems) use microorganisms to break down hazardous wastes to non-hazardous compounds. Biosystems offer the capability of using the broad versatility of microorganisms for degrading mixed wastes; the ability to tailor treatment processes toward specific compounds or groups of compounds at specific sites; the potential to eliminate soil excavation and transportation costs; and the minimization of air emissions caused by the movement of contaminants.

ORD's biosystems research program for Superfund includes the development of systems for *in situ* aquifer remediation and on-site treatment applications. Only *in situ* biosystem applications are included in this ground-water research description. Biosystems research is a centrally coordinated, multi-laboratory program combining the capabilities of RREL-Cin, RSKERL-Ada, and ERL-Athens.

RREL-Cin conducts two projects to develop innovative *in situ* biosystem applications. In the first, laboratory and field testing is being conducted to determine the potential for the bacteria FM4100, genetically engineered by General Electric, to degrade polychlorinated biphenyls (PCBs) in Superfund soils. The comparison of this organism to the performance of *Pseudomonas putida* will enable the first analysis of a native- versus a recombinant-DNA organism for degrading PCBs on soils. RREL-Cin's other project involves the design of an *in situ* soil contamination treatment technology using the white rot fungus, *Phanerochaeta chrysosporium*. Bench-scale studies will be designed to determine its ability to degrade pentachlorophenol (PCP) and selected major constituents of creosote through the use of carbon-labeled substrates and measurements of resulting carbon dioxide concentrations.

RSKERL-Ada, in cooperation with the U.S. Coast Guard at the Traverse City, Michigan, Coast Guard Station, is completing combined laboratory, field, and modeling studies on the effect of enhancing natural microbial aerobic degradation processes to remediate fuel spills. Research on enhanced natural microbial degradation of a gasoline spill by the addition of hydrogen peroxide and a jet fuel spill by addition of nitrate to the ground water is being studied. Recovery wells have demonstrated reclamation of any existing nitrate not consumed by subsurface bacteria. Laboratory test results and data from characterization of the site were used to identify and evaluate the hydrological, chemical, and biological parameters that control *in situ* microbial remediation. The field studies were used to evaluate BIOPLUME II, a mathematical model of *in situ* microbial remediation used to estimate the time and cost of returning a site to a specific level of restoration. A final report on *in situ* remediation of the gasoline spill has been completed and a final report is being prepared on results of the jet fuel spill cleanup. The progress of the field demonstrations were followed and the results compared with model projections. The model can be used to design biorestoration projects at other sites. RSKERL-Ada has begun additional bioremediation field demonstrations at the Park City, Kansas site to evaluate denitrification techniques for bioremediation of a refinery spill. The site has been cored to estimate the quantity of hydrocarbon to be remediated, and twelve monitoring wells have been installed.

Research is being conducted to develop an understanding of the properties of microorganisms and subsurface materials that determine whether a particular site will be colonized by contaminant degrading microorganisms. Related research is defining the environmental factors affecting the survival and transfer of the genetic elements from genetically engineered microorganisms in the subsurface environment. This information is used to develop methods for predicting the transport of microorganisms and their genetic elements for use with bioremediation techniques.

The discovery of extensive anaerobic bacteria in the subsurface has led to increased interest into their use in remediation of contaminated sites. RSKERL-Ada recently completed a project to determine the capacity of microorganisms in aquifers to transform monoaromatic (single benzene ring) hydrocarbons in the absence of oxygen. This information will be used to predict the influence of the geochemical environment, particularly the presence of iron phases, on biotransformations of hazardous organic compounds in subsurface materials.

ERL-Athens is conducting experiments to determine the extent to which sorption processes affect the degradation of specific classes of hazardous organic chemicals and to determine if the addition of emulsifying agents can enhance bioremediation. The degradation rate of sorbed or highly insoluble substrates can be increased by making the substrates more available to the microorganisms. ERL-Athens is examining the effects of emulsifiers on the degradation of insoluble compounds, including 4-chlorophenol, chlorobenzenes, and polyaromatic hydrocarbons (PAHs) and enhancing the degradation of PCB mixtures. The results of these experiments will be used to develop mathematical models to predict the effects of emulsifying agents.

The Office of Solid Waste and Emergency Response (OSWER) and ORD have jointly instituted a Bioremediation Field Initiative to provide assistance to the Regions in conducting field tests and evaluating bioremediation site cleanups in Superfund, RCRA, Underground Storage Tank (UST), and state non-NPL sites. The initiative is designed to fully document performance of full-scale field applications of bioremediation, provide technical assistance to sites in a feasibility or design stage, and regularly provide the Regions with information on treatability studies, design, and full-scale operations of bioremediation projects in the Regions. Over 140 sites have been identified nationally where bioremediation is being planned or where full-scale systems have been put in place. Presently, eight sites are undergoing performance evaluations under the initiative, providing an in-depth analysis of process efficiency. The waste types include petroleum products, creosote, solvents, and PAHs.

One of the most difficult ground-water remediation problems is contamination by DNAPLs. Common DNAPLs that are hazardous constituents include solvents, wood preservatives, coal tars, and certain pesticides. RSKERL-Ada is currently studying the feasibility of DNAPL removal by air-sparging from the bottom of the water table. Once experimental data have been collected, the data will be integrated into conceptual models for larger scale studies.

Underground Storage Tank Remediation Research

Several hundred thousands of USTs containing petroleum products and hazardous materials are leaking, posing a serious threat to the nation's ground-water supplies, and to public health and welfare. The 1984 Hazardous & Solid Waste Amendments to RCRA mandated that EPA regulate these UST systems, and develop guidelines to administer the Leaking Underground Storage Tank (LUST) Trust Fund established under CERCLA to finance corrective actions at LUST sites. EPA's Office of Underground Storage Tanks (OUST) was established to develop regulations and implement a national program to prevent and clean up contamination from leaking USTs. RREL's UST program, which is located at the Edison Laboratory in New Jersey, was established to provide technical support to OUST, specifically in rulemaking under RCRA Subtitle I and in implementing the provisions of the LUST Trust Fund under CERCLA. The overall approach has been to evaluate prevention, detection, and corrective action technologies to identify cost-effective and reliable techniques and equipment for LUSTs and to provide technical assistance on site assessment decision tools and cleanup technologies for LUST Trust Fund program guidance and implementation.

Research and demonstration activities will be conducted at the Edison Laboratory on techniques and equipment to: improve determination of site conditions in preparation for site remediation; more quickly design and install UST remediation hardware; achieve complete site remediation more quickly by improving contaminant removal both *in situ* and above ground; provide cheaper treatment alternatives for UST remediation side-waste streams; and confirm the progress and completion of UST remediations. Cleanup technologies developed for petroleum and hazardous chemical releases under RCRA and CERCLA will be evaluated and optimized. Outputs will provide information and assistance to EPA, state, and local agencies, and practicing professionals concerning cost-effective, site-specific decisions about the need, degree and type of cleanup required, and will transfer corrective action technologies to the user communities.

Pilot scale experiments are being conducted for optimizing and enhancing soil vapor extraction system design and operation, including air sparging and aquifer heating techniques. Other pilot scale research includes *in situ* bio-venting and *ex situ* bio-oxidation processes for treating petroleum contaminated soil. The Edison Laboratory is also conducting research on pulsed pumping techniques, water table manipulation, and thermal desorption to treat petroleum contaminated soils at LUST sites and initiate assessment for chemicals found at LUST sites.

Underground Injection Control Research

In addition to the geophysical research work conducted at EMSL-LV for the UIC program, additional underground injection control research focuses on the evaluation of methods to prevent toxic substances from entering aquifers that supply drinking water. This research is conducted by RSKERL-Ada and emphasizes techniques to protect ground water from underground injection of wastes through Class I and Class V injection wells. Class I injection wells are those where municipal and industrial wastes, including hazardous wastes, are injected deeply into the subsurface below aquifers that can potentially be used to supply drinking water. Class V wells include a wide variety of injection wells where waste waters are often injected into ground-water containing aquifers. Class V wells include agricultural, storm-water, and industrial drainage wells; septic systems; wastewater treatment plant effluent disposal wells; industrial process water wells; automobile service station disposal wells; aquifer recharge wells; and abandoned drinking water wells.

Hazardous Waste Injection Methods for Class I Wells

There are a number of unresolved scientific questions regarding the risks involved with disposal of wastes through Class I underground injection wells. RSKERL-Ada has completed a research project to determine the movement of injected fluids and the integrity of confining layers of subsurface rocks. Research is being conducted on methods for determining the mechanical integrity of injection wells and the effectiveness of methods for plugging abandoned wells.

The mechanical integrity of injection wells constructed of various materials are being tested to develop methods for determining if wells are leaking into underground sources of drinking water. Two research wells have been constructed to provide a means for conducting field tests of specific mechanical integrity equipment. Tests are being conducted on each well to evaluate the ability of various down-hole tools to determine the quality of the cement bond between the cement and the casing, detect the movement of fluid behind the casing, and test the integrity of the tubing, casing, and packers. A third well, installed using fiber glass casing and intentional imperfections, will be used to determine the sensitivity of logging tools to detect these imperfections.

RSKERL-Ada is studying the effectiveness of plugging abandoned wells with drilling mud to prevent the migration of injected hazardous wastes upward through the wells to potable ground-water supplies. An instrumented test well is being used to determine the effect of temperature, time, pressure, and composition on the strength of mud plugs and to evaluate techniques to enter previously plugged abandoned wells to determine the effectiveness of plugging materials used.

Class V Well Injection Methods

There are an estimated 170,000 Class V wells in the United States. Many of these are unregulated. RSKERL-Ada is conducting research to determine the impact of Class V wells on the environment and methods for improving Class V injection well practices. Background information on the impact of current Class V well design, use, and effects on ground-water quality is being compiled.

Information is also being developed on the transport and fate of contaminants introduced into the subsurface via Class V injection wells, focusing on those well classes presenting high potential for ground-water contamination. Methods and criteria for regulating Class V wells will be developed from this information.

Technology Transfer and Technical Assistance

Technology transfer and technical assistance are key elements of ORD's research program and are integral parts of all laboratory activities.

Technology transfer is a cyclical process that incorporates the assessment of specific user needs, development of research results in a format targeted to specific audience needs, timely dissemination of the technical information, and evaluations of whether or not the technical information satisfied user needs. ORD ground-water technology transfer audiences include EPA headquarters; EPA Regional, state, and local regulatory, enforcement, and permitting staff; academia; independent consultants; regulated industries; trade associations; and the general public. Technology transfer mechanisms include manuals, research symposia, conferences, and handbooks on the use of state-of-the-art technologies, journal articles, fact sheets on topics of special interest, modeling packages with manuals for their proper use, training courses, seminars, video tapes, electronic bulletin boards, and technical information clearinghouses. The transfer of research results is considered an integral part of each ORD research project. Technology transfer is coordinated through CERI in Cincinnati, Ohio.

Technical assistance is the direct, person-to person transmission of scientific and engineering information to help specific users apply state-of-the-art technologies and procedures to specific problems in the field. Technical assistance is provided upon request to EPA headquarters and Regional staff. Each of the four ORD laboratories involved in ground-water research have staff dedicated to providing technical assistance or directing requests to appropriate experts. Many researchers are contacted directly based on their publications and through the ORD *Ground-Water Research Technical Assistance Directory* (see appendix B).

Technology transfer and technical assistance ensure that RCRA, Superfund, drinking water, and pesticide regulatory approaches to protecting ground-water quality incorporate the latest scientific information on subsurface processes, remediation monitoring methods and equipment. It also ensures that permitting, remedial, and enforcement actions are scientifically credible and defensible. Technology transfer and technical assistance projects are conducted under the Superfund and drinking water programs. Technical assistance is also provided for the RCRA and pesticides programs as integral parts of research projects.

ORD and OSWER have jointly established Technical Support Centers (TSCs) at the four ORD laboratories involved in ground-water research: the Ground Water Fate and Transport TSC at RSKERL-Ada; Monitoring and Site Characterization TSC at EMSL-LV; Exposure Monitoring and Ecological Risk Assessment TSC at ERL-Athens; and Engineering and Treatment TSC at RREL-Cin. The TSCs, in response to Regional Superfund staff requests for assistance, provide direct technical expertise in the field, review site technical reports, conduct workshops on emerging issues, and maintain technical information clearinghouses. A parallel program for RCRA corrective action staff began in FY91.

Geophysical Technical Support

EMSL-LV provides technical assistance and training on the use of geophysical techniques to characterize Superfund sites, conduct field investigations, and review reports and workplans. Geophysical support encompasses the use of seismic, electromagnetic induction, resistivity, magnetometers, groundpenetrating radar, and borehole electromagnetic induction techniques. Technical support on the use of additional methods can also be provided through cooperative agreements with the USGS and the U.S. Army Corps of Engineers.

Transport and Transformation Technical Support

RSKERL-Ada has developed an interdisciplinary team of ground-water contamination experts who provide site- and case-specific technical assistance to Superfund Regional staff on a when-and-where-requested basis. Through the Ground-Water Fate and Transport TSC, RSKERL-Ada helps field staff assess the extent of ground-water contamination, predict the transformations and movements of contaminants in the subsurface, and evaluate *in situ* aquifer remediation options. The team also develops training and seminar material in cooperation with CERI and serves as an interface between the ground-water research community and EPA, state, and local staff actively involved in dealing with contaminated sites.

In addition to direct technical support, RSKERL-Ada's technical assistance team participates in relevant research projects in order to present existing state-of-the-art technical information in a user-friendly format. RSKERL-Ada has completed consolidation of materials on the use of a USGS solute transport model (MOC) and is working on the development of a user-friendly software package to allow easy use and interpretation of an unsaturated zone organic phase contaminant transport model (ContPro). A report intended to provide new Superfund field staff with introductory information on ground-water modeling needs, responsibilities, and guidance has been completed. Another manual is under development to provide guidance to field staff on site-specific field techniques for quantifying the physical and chemical properties of contaminated heterogeneous aquifers, including data needed for modeling contaminant behavior. The RSKERL-Ada team is also modifying existing geostatistical computer programs now being used by researchers so that they are useful to field staff who do not have extensive training in geostatistical methods. Finally, a manual that consolidates existing information on the use of pump-and-treat methods is under development, with particular emphasis on estimating the length of time required for a pump-and-treat system to remediate a contaminated site.

ERL-Athens established the Center for Exposure Assessment Modeling (CEAM) in 1987 to facilitate the use of models that can estimate contaminant exposure through ground water and other sources. The Exposure Modeling and Ecological Risk Assessment is a part of CEAM and provides exposure assessment assistance to Superfund and RCRA staff. CEAM also provides technical assistance to all EPA programs and will perform about 40 assessment projects during FY92.

Direct technical support is provided by ERL-Athens at specific sites, with emphasis on multi media assessments and the uncertainties associated with model estimations. The results of the more intensive site support projects are developed into case studies for use as training aids and as technology transfer documents.

ERL-Athens also provides rate and equilibrium constants necessary for predicting the fate and transport of organic chemicals in ground water. Values judged to be the best are available for parameters such as hydrolysis rate, octanol/water partition coefficient, and solubility are provided upon request. Data are extracted from the literature and carefully screened for validity, computed by ERL-Athens, or measured in the Athens Laboratory. Data considered to be of adequate reliability are entered into the FATE database, which is being developed by the Laboratory.

RSKERL and ERL-Athens are also working directly with OSWER on two projects involving the application of subsurface fate and transport models. In one, ORD has been asked to advise the Superfund program on the use of unsaturated zone models for setting soil clean-up levels at Superfund sites based on potential leaching of soil contaminants to ground water. In a second project, ORD has been asked by OSW to assist in the Regulatory Impact Analysis for new corrective action rules for solid waste management units. This involves selecting and applying a multi-media model, which includes the ground-water transport pathway, to estimate the human health and environmental impact of corrective action regulatory alternatives.

Aquifer Remediation Technical Support

RSKERL-Ada has established the Subsurface Remediation Information Clearinghouse (SRIC) to help transfer information on technologies for cleaning up contaminated ground water and soils to Superfund remediation field staff. The emphasis of the clearinghouse is on *in situ* technologies such as microbial remediation and specialized pumping techniques. The clearinghouse includes information on transport and transformation processes, remedial technology evaluations, guidance on the use of remedial technologies, case histories, and related research publications. Information to be included in the clearinghouse is evaluated by RSKERL-Ada staff and experts in other agencies and universities for its benefit to users. A protocol for evaluating the performance of ground-water remediation activities at Superfund sites is being developed for inclusion in the SRIC. Case studies of selected Superfund sites are being conducted to investigate the effectiveness of modeling and monitoring approaches. SRIC staff disseminates information in the clearinghouse, conducts literature reviews, and provides information services to EPA, other federal and state agencies, and researchers. OHEA provides technical support at Superfund sites through site assessments and remedial investigations.

OHEA also sponsors remedial work related to karst aquifers, which are aquifers where flow is appreciable through fractures, other joints, and bedrock—any or all of which have been enlarged by solution of bedrock. One of the biggest challenges faced in karst aquifer remediation is finding ways to cleanup contaminated karsts, and there is a need for the development of karst aquifer protection methods, and ground-water monitoring within karst aquifers.

Training and Model Evaluation

RSKERL-Ada provides technical support and evaluations of models for the investigation, management, and protection of ground-water sources of drinking water. A series of narrated slide presentations have been developed for use as self-training aids to help field staff keep abreast with new research findings and technologies. Modules that have been completed include basic geology, fundamental hydrogeology, monitoring well installation, ground-water models, ground-water contamination, and ground-water sampling. Training courses are also provided periodically upon request.

RSKERL-Ada has developed a close relationship with the International Ground-Water Modeling Center (IGWMC) at the Colorado School of Mines. The school operates a clearinghouse for technical information on the use of mathematical transport and transformation models and software. The two major tasks of the clearinghouse are the dissemination of ground-water models and information on their application and the distribution and support of modeling software. The Center regularly offers short courses and seminars on the use of models and carries out a research program to evaluate the quality of the confusing array of existing ground-water transport and transformation models.

Superfund Technical Assistance Response Team

The Technical Support Branch in RREL-Cin provides the Regional Superfund Offices with engineering technical assistance to Remedial Project Managers on problems arising during the remediation of individual sites. In terms of site specific assistance, RREL-Cin organized the Superfund Technical Assistance Response team (START). The START program provides site specific, long-term technical assistance to a limited number of Superfund sites that have been selected by the Regional Offices in conjunction with ORD. Sites selected for the START program receive comprehensive engineering assistance on multiple phases of the remedial investigation and feasibility (RI/FS) process. The Engineering Technical Support Center (ETSC) also provides similar site-specific assistance, but the focus of this center is on quick response and short term assistance.

The START program deals primarily with complex sites that have high regional priority relative to the selection of technologies available to the program, but in FY91, the program will be limited to handling 45 sites per year. START has first priority on available technical support capacity.

The START program has been using the Computer Assisted Site Evaluation (CASE) system, developed by RREL-Cin, to provide technical support to Regional Projects Managers in the assessment and remediation of contaminated sites. CASE is a computer system that has been developed to improve and expedite the process of hazardous waste site assessment. The system, based at EPA's Center Hill Facility, is available as a service to the Regions. Capabilities of the system include; 3-D spatial modeling of the site geology, hydrogeologic cross-sectioning, contaminant concentration mapping, contaminant volume calculation, ground-water modeling, and modeling of various remedial actions. The system has been applied to four Superfund sites in Pennsylvania, Florida, Washington, and Ohio, and is ready to be applied in the Regions.

RSKERL-Ada provides technical assistance through their Center for Subsurface Modeling Support (CSMoS). This Center is for model technical assistance. They distribute and service all models and databases developed by RSKERL-Ada and also provide general support on model application to vadose zone and ground-water contaminant transport problems.

Forum Issue Papers

OSWER and ORD established the Superfund Technical Support Project (TSP) in 1987 to provide technical assistance to RPMs and OSCs. The Forums, TSCs, and OSWER's Technology Innovation Office frequently discuss Superfund site problems and successes, useful technologies and procedures, technical needs, and current ORD research, development, and demonstration projects. TSP efforts are communicated to the Regions through the Ground water and Engineering Forums, which are comprised of one or more professionals from the Superfund and RCRA Corrective Action programs in each of EPA's ten Regions. These Forums exchange up-to-date information related to remedial activities at hazardous waste sites and are committed to the identification and resolution of engineering and ground-water issues impacting remediation. The Forums propose topics and set priorities for potential issue papers and work with the Centers in developing issue papers and conducting workshops on emerging technical topics. The TSP improves communication of technical information and the consistency of Superfund site remedial actions.

Forum Issue Papers were initiated as a means of addressing a number of technical issues identified by the Forums as critical to remediation decisions. These documents are intended to be brief, readable summaries of the current state-of-the-science of particular technical issues. For a listing of current ground water related issue papers, see Appendix C.

Relationship of ORD Research to Other Ground-Water Research in EPA

In addition to ground-water research conducted by ORD and coordinated by EPA's research committees, EPA program offices sponsor a significant amount of research at ORD's laboratories, conduct research through program office contractors for short-term data needs, and synthesize current knowledge into technical guidance documents. A major example of program offices co-sponsoring ORD research is the support of OSW and OPP for exposure assessment modeling at ERL-Athens. In addition, ORD laboratory directors and staff frequently contact program office clients to better understand program and research needs. The program offices, particularly OGWDW and OSWER, also have increased activities to provide direct technical assistance to Regional and state staff.

OGWDW develops and transfers existing knowledge and methods to state and local agencies for protecting ground-water sources of drinking water. Because the states develop and implement their own ground-water protection programs under EPA leadership, OGWDW has concentrated on providing policy, program management, and technical guidance to the states. Much of this work involves the collection of existing technical information on hydrogeologic assessment and pollutant source management tools that have already proven effective in other roles and putting this information into a format appropriate for various state and local audiences. In addition, OGWDW conducts pilot studies, workshops, and training programs with states and local governments.

The Office of Policy, Planning, and Evaluation (OPPE) has been involved with ERL-Athens in the development of a linked economic and ground, surface, and air modeling system called the Comprehensive Economic Environmental Policy Evaluation System (CEEPES). CEEPES is being developed under a cooperative agreement with the Center for Agricultural Research Development at Iowa State University. USDA is contributing staff resources to the effort and USGS is conducting monitoring to help verify the system. The system will be used to evaluate alternative agricultural policy and management systems.

OHEA has designed the Integrated Monitoring

Evaluation System (IMES) for assisting users in choosing appropriate ground-water models. Each user defines his criteria and the system will search for models that fit user-defined needs. Version one of IMES was developed in FY91 and is currently being reviewed. The system includes models for four media: ground water, surface water, non point source, and air, and all models included in the system have been used by EPA.

Coordination Among Federal Agencies

The Federal Coordinating Committee for Science, Engineering, and Technology (FCCSET) of the Office of Science and Technology Policy in the Executive Office of the President has drafted its final report on federal ground-water research—*Federal Ground-Water Science and Technology Programs: The Role of Science and Technology in Addressing Four Key National Ground-Water Issues* (May, 1991). The report is intended to help government officials understand federal research efforts that address Congressionally mandated programs involving ground-water assessment, management, and protection.

This report relates the ground-water research and engineering described in the earlier Subcommittee report, *Federal Ground-Water Science and Technology Programs: The Role of Science and Technology in the Management of the Nation's Ground-Water Resources*, to four ground-water issues thought by the Subcommittee to be most critical to the Nation: ensuring long-term ground-water supplies; remediating contaminated ground water; minimizing agricultural contamination of ground water; and disposing of nuclear waste.

Recent ground-water development trends suggest the critical need to manage existing ground-water supplies and to protect ground-water quality. Ensuring that ample ground water is available for use where it is needed both now and in the future, and taking into account the physical limitations of the natural system is an important policy objective of the FCCSET report. Other objectives include ensuring that ground water is of suitable quality for current and future uses, and developing a better scientific base for the management of water quality and quantity. Priority research goals in support of these policy objectives include improved: management strategies to control the sources of contamination; understanding of the impacts of various land uses on ground-water quality; models to predict the transport and fate of various pollutants, coupled reaction-flows, and the flow of water through fractured rock and karst terranes; data on the kinetics of mineral-water reactions; data on the kinetics of the interactions of toxic substances with geologic materials; inductive methods to eliminate or reduce the need for expensive observation wells; and sampling and data analysis techniques.

EPA and other federal agencies involved in ground-water research employ a number of mechanisms to coordinate their research and technology transfer programs, including:

- Specific interagency delegations of authority to provide lead agency coordination;
- Memoranda of Understanding (MOUs) that set forth specific responsibilities and areas of cooperation;
- Standing and *ad hoc* committees and technical workshops to monitor agreements and share information;
- Jointly conducted projects or programs that employ the combined expertise of several agencies;
- Cooperative research that is jointly funded by federal and state governments;
- Interagency coordination that occurs at the scientific planning level; and
- Interagency cooperation to validate models.

EPA and USGS signed a MOU in August, 1981, providing an umbrella under which each agency's programs are coordinated. A second MOU was signed in June, 1985, to coordinate ground-water data collection and technical assistance. EPA and USGS regularly exchange visiting scientists and participate in each other's technical meetings on ground water. In addition, the two agencies have established a bilateral committee to coordinate their respective research programs and prevent duplication of effort.

EPA and USDA signed an interim MOU in

October, 1988, providing an umbrella agreement for coordination in surface and ground-water quality improvement and maintenance. Through the MOU, the Office of Water (OW) uses the expertise of USDA's Soil Conservation Service to increase technical assistance to states in the development and implementation of state-wide water quality programs and projects. EPA also participates on an interagency committee to guide the water quality research of USDA's Cooperative State Research Service.

During FY90, USDA disseminated Requests for Proposals that were prepared by Project Investigators to identify areas for experimentations and monitoring. The first full year of project operation was devoted to preparing project sites and characterizing area conditions. The committee, coordinating mechanisms, and management systems will implemented. The Water Quality Working Group, which is chaired by the USDA, is responsible for the monitoring and directing of the President's Water Quality Initiative in its entirety. The MSEA project is under the purview of this working group's research Task Group. The responsibilities of this task group include interpreting goals and objectives and ensuring continued cooperation of participating agencies; supporting the MSEA project in achieving its objectives; ensuring coordination of MSEA project participants, and developing recommendations and modifications to the MSEA workplan as needed to achieve the broad goals of the MSEA program.

USDA and EPA are also working together on an FY93 initiative, Environmental Quality in Agroecosystems, for reducing ecological impacts of agricultural practices and making food consumption safer. USDA is increasing its efforts on reducing the environmental impacts from agricultural production, and EPA needs to play an active role in incorporating environmental quality objectives into agricultural production practices. This agroecosystem initiative builds on the MASTER program, and expands joint work between EPA and USDA to ensure that changes to agricultural production practices over the next decade result in meaningful, cost-effective improvements in environmental quality. USDA expertise on agricultural production and EPA expertise on environmental protection need to be blended toward this common goal.

Interagency coordination between the Department of Energy's (DOE's) Office of Energy Research, USGS, EPA, and other agencies is predominantly at the scientific planning level. Since 1983, DOE has sponsored over 20 meetings to assist in setting scientific direction for its fundamental research programs. All federal agencies have participated in Office of Energy Research reviews, providing program coordination and information exchange. Also, EPA and DOE signed an MOU in January 1990 for joint research on radioactive or mixed-waste sites. This MOU provides new opportunities for cooperative research on contaminant treatment systems as well as subsurface research projects.

In addition to coordinating research with other federal agencies through interagency agreements and coordinating committees, EPA conducts joint ground-water research projects with the USDA, USGS, U.S. Air Force, U.S. Army, U.S. Coast Guard, U.S. Navy, DOE, National Research Council, and the Tennessee Valley Authority.

External Research Reviews

Several major documents have been written with recommendations for research needed to implement the Agency's multiple mandates for protecting ground-water resources. The Science Advisory Board distributed its *Review of the EPA Ground-Water Research Program* in July, 1985. The Hazardous Waste Ground-Water Task Force distributed an *Evaluation of the RCRA Subpart F Ground-Water Monitoring Program* in February, 1986, and its final report *Hazardous Waste Ground-Water Task Force: 1987 Status Report* in October, 1988. Two other reports contained recommendations on the development and use of ground-water models: the Science Advisory Board's *Resolution on Use of Mathematical Models by EPA for Regulatory Assessment and Decision Making* (January, 1989) and the National Research Council's *Ground-Water Models: Scientific and Regulatory Applications* (November, 1989).

The Science Advisory Board's 1985 review of EPA's ground-water research program recommended the creation of a strong central direction for the research program, increased resources for training and technology transfer, proactive research on ground water contamination sources not addressed by specific mandates, and development of faster methods for ground-water sampling and analysis that maintain data quality. Funding increases were also recommended in specific ground-water research areas: monitoring; basic transport and fate; remedial methods for fractured geologic formations; and identification of suitable geologic environments for isolating hazardous wastes by means of deep injection wells.

The Hazardous Waste Ground-Water Task Force of 1986 considered technical problems in ground-water monitoring technology as a component of their overall evaluation of the RCRA Ground-Water Monitoring Program. Six technological needs were identified: (1) improved understanding of the behavior of individual contaminants and contaminant classes and sampling strategies for each class; (2) investigation of the use of plume dispersion as a basis for monitoring well horizontal spacing, screen depth, and length; (3) identification of sampling equipment and techniques best suited for specific hydrologic settings or monitoring needs; (4) estimation of the effect of sampling equipment on monitoring data; (5) selection of key indicators for contaminant classes according to geological setting; and (6) establishment of analytic methods for certain hazardous constituents.

The Science Advisory Board's review of the use of mathematical models in EPA regulatory decision-making contained recommendations relevant to ORD development and testing of ground-water transport, transformation, and exposure assessment models. The report recommends an increase in validation of models by laboratory and field studies, increased communication of the sensitivity and uncertainty of environmental model predictions, and more stringent peer review of models and expert systems. The National Research Council's report discussed the scientific bases on which existing models are founded, approaches and philosophies routinely used in the application of models to regulatory decision making, and guidelines on the development and use of models intended for application to the regulatory process. In addition to these broad ground-water research program reviews, EPA laboratories frequently conduct peer reviews of specific elements of the research program to ensure the scientific credibility of research directions and projects.

ORD is addressing these recommendations to the extent practicable within its available funding. Internal EPA reviews by the research committee are conducted to determine which of the competing research needs should be addressed.

Internal Research Reviews

In addition to external reviews of the ground-water research program, ORD's ground water matrix manager conducts research program reviews each year in concert with the budget development cycle. The objectives of the reviews are to evaluate research progress and results, determine whether planned research projects and their resources are sufficient to meet the needs of Program and Regional Offices, decide whether additional projects are necessary, and determine whether the timing and substance of planned deliverables are suitable.

The FY91 ground-water research program review was attended by representatives from the Office of Technology Transfer and Regulatory Support (OTTRS), OEPER, OEETD, OMMSQA, NCGWR, program offices, and the Regions. Research needs identified at the review included work on expert systems for site characterization, application of GIS to siting decisions, and the combining of ground-water databases with statistical expert systems for better management of ground-water monitoring data. A number of other research needs were raised in the areas of nitrates, RCRA corrective action, statistical applications for underground injection control, and demonstrations of subsurface treatment trains in the field.

Many of the research needs expressed in these ground-water research program reviews are being addressed by established research programs. Other needs have not yet been fully addressed due to funding constraints and competing priorities.

Research Results

ORD has developed many innovative procedures, methods, and equipment for advancing research capabilities and the scientific basis of Program and Regional office regulatory, permitting, and enforcement programs. Numerous technical articles, handbooks, and technical resource documents have been published describing these accomplishments. Appendix C lists major reports recently produced by ORD's ground-water research program.

EPA uses information systems to disseminate information to the Regions and States. EPA's Cleanup Information Bulletin Board system (CLU-IN), formally named the OSWER Bulletin Board, is designed for use by hazardous waste cleanup professionals to find current events information regarding innovative technologies, to consult with others who are on-line, and to access hazardous waste databases. The Alternative Treatment Technology Information Center (ATTIC) system is designed to provide technical information on alternative methods of hazardous waste treatment. ATTIC is designed for use by site remediation managers in the federal, state, and private sectors to obtain technical information in the form of abstracts or report summaries. The ORD bulletin board is operated by CERI, and contains a database of over 17,000 searchable abstracts of all ORD publications, including publications on ground-water research.

Within recent years, major research programs have been initiated in the areas of advanced site characterization and contaminant detection equipment, monitoring methods, controlled field studies of microbial degradation techniques, facilitated transport processes that enhance contaminant mobility, methods for incorporating uncertainty analyses within modeling packages, pump-and-treat technologies, and wellhead protection methods. In addition, ORD has significantly expanded its efforts to transfer technical information and provide direct, site-specific, technical assistance to personnel in the field. Reports planned to be completed in FY91 and FY92 under these and other important research programs are listed in Appendix B.

Despite recent advances in understanding of fundamental subsurface processes and ground-water monitoring and remediation technologies, many difficult questions are just beginning to be answered. ORD's future ground-water research program will address the highest priority of these questions.

Future Program

The two themes that ORD's future ground-water research program will emphasize are the prevention and remediation of ground-water contamination.

The prevention research program will encompass identification of threats to ground water from point and nonpoint sources and mitigation of those threats through improved management of the contaminant sources. OW's wellhead protection program offers an opportunity to integrate advances in ground-water research into a comprehensive program to protect drinking water aquifers. Improved site-specific methods will be needed to characterize local point and non-point sources of contamination and define vulnerable ground-water resources in order for state and local governments to develop plans for protecting wellheads. The delineation of wellhead protection areas will require improved predictive models to account for the effects of subsurface biological, chemical, and physical processes on the transport and transformations of contaminants in the subsurface. The correct use of these models will depend, in part, on the quality of input data that is used. ORD's research into rate constants and physical properties such as dispersivity, hydraulic conductivity, and effective porosity can therefore be expected to continue. Cost-effective monitoring methods will also be needed for early detection of contamination from a multitude of possible sources before they can percolate into ground-water resources.

The success of ground-water remediation depends largely upon understanding subsurface processes. Some of the more important processes for which research is needed include contaminant multiphase behavior partitioning among solid and liquid media, biotic and abiotic transformations, and transport in fractured media. Predictive tools, such as models, will be needed to better account for these processes. Cost-effective monitoring methods are also needed for detecting contaminants, characterizing site-specific subsurface conditions, and tracking changes in ground-water quality during remediation of contaminated ground water. Improved knowledge of subsurface conditions will also lead the way for improvements in the design of technologies for remediation, such as innovative ground-water pumping systems. ORD efforts to meet these prevention and remediation objectives in the future will continue to be approached through focused research projects in support of EPA's programs, with attention to coordination, technology transfer, and technical assistance.

APPENDIX A. ORD GROUND-WATER RESEARCH BUDGET

The following is a generalized table showing the distribution of ORD resources into major categories of subsurface research.

ORD Ground-Water Budget History

	FY 1990			FY 1991			FY 1992 (est.)		
ORD Activity	FTE	S&E	R&D	FTE	S&E	R&D	FTE	S&E	R&D
Subsurface Modeling, Monitoring and Quality Assurance	22	1742	5744	22	1757	4913	22	1667	5302
Subsurface Processes and Effects	79	5789	8033	78	6065	8474	79	6278	12585
Subsurface Engineering and Technology	5	409	2114	5	415	1558	6	545	1831
TOTALS	106	7940	15891	105	8237	14945	107	8490	19718

KEY:
- FTE = "Full-time equivalents" (one person per year)
- S&E = "Salary and Equipment" monies (est. dollars in thousands)
- R&D = "Research and Development" monies for contracts and grants (est. dollars in thousands)

APPENDIX B.
SUMMARY OF OUTPUTS FROM GROUND-WATER RESEARCH PROJECTS

Appendix B presents the outputs of ORD's ground-water research program that are planned to be completed as a result of ground-water research conducted in FY91 and FY92. Some outputs are planned to be completed in FY93 and beyond (outyears) as a result of longer-term research projects.

SITE CHARACTERIZATION AND MONITORING

	FY91	FY92	Outyear
Develop and evaluate ground-water monitoring methods and strategies for RCRA hazardous waste facilities. (PPA I15)			
Ground-Water Monitoring (EMSL-LV)			
Project Report on Field Comparison of Ground-Water Sampling Methods	10/90		
Internal Report on Protocol for Testing Ground-Water Samplers	11/90		
Report on Comparison of Volatile Organic Compound Sampling and Surveillance Methods	4/91		
Guidance Document for Comparing Well Casing Material	8/91		
Complete Guidance Document Summarizing Screening Rules for Monitoring Wells		8/92	
Final Project Report on Quantitative Methods for Monitoring Network Design		8/92	
Project Report on Toolbox for Environmental Monitoring Using Ground-Water Models		9/92	
Final Guidance Document for Site Characterization and Contamination Assessment			4/93
Draft Guidance Document for Site Characterization and Contamination Assessment			10/93
Project Report on Temporal Variability (Arid) and Sampling Procedures for Ground water			12/93
Ground-Water Monitoring (EMSL-LV)			
Final Report on Bioremediation Monitoring of BTEX		5/92	
Journal Article on the Dielectric Tool for Laboratory Porosity Measurements			12/92

Appendix B. Summary of Outputs From Ground-Water Research Projects (Continued)

	FY91	FY92	Outyear
Project Report on Surface/Surface to Borehole Geophysical Methods			6/93
Develop Field Methods for Subsurface Monitoring (EMSL-LV)			
Project Report on Application of Borehole Geophysics to Waste Site Monitoring	10/90		
Molecular Fluorescence and Fiber-Optics Screening Methods (EMSL-LV)			
Development of Synchronous Luminescence Field Methods			10/92
Report on In Situ Fiber-Optic Field Spectrometer (Luminoscope)			10/92
Project Report on Portable Ultraviolet Fiber-Optic Spectrofluorometer for In Situ Screening of Aromatic Compounds in Ground water			12/92
Quality Assurance and Methods Standardization for Ground-Water Monitoring (EMSL-LV)			
Project Report on Technology Transfer and Hands-On Demonstration		6/92	
Develop methods for external leak detection at underground storage tank sites. (PPA R62)			
Characterization and Monitoring of Cleanup Around Storage Tanks (EMSL-LV)			
Report on In Situ Diffusion Coefficient Measurement Barrier Tests	1/91		
Report on Field Test of Peat for Adsorption of Hydrocarbon Contaminants from Underground Storage Tanks	8/91		
Final Report on the BTEX Project for Analyzing Soil, Soil Gas (vapors), and Ground water	9/91		
Assessment Manual for In Situ Biodegradation of Aromatic Hydrocarbons in Soil and Ground water		9/92	
Evaluation of External Vapor Monitoring Sensors		9/92	
Provide monitoring techniques and procedures for Superfund site and situation assessments. (PPA A04)			
Geophysical Methods (EMSL-LV)			
Project Report on the Evaluation of Selected Borehole Geophysical Methods for Hazardous Waste Site Investigations and Monitoring	10/90		
Published Peer Reviewed Paper on Effect of Pipes on Transient Electromagnetic Soundings Used to Map Oil-Field Brine Contamination	10/90		

Appendix B. Summary of Outputs From Ground-Water Research Projects (Continued)

	FY91	FY92	Outyear
Conference Paper on A New Instrument and Inversion Program for Near-Surface Mapping: High Frequency EM Sounding and Profiling ion the Frequency Range 300 KHz to 30 MHz	10/90		
PhD Thesis The Electrical Resistivity Method in Cased Boreholes, The University of California, Berkeley, CA	5/91		
Project Report on a Geophysics Expert System, Version 2.0	6/91		
Conference Paper on Seasonal Variations and Ground Penetrating Radar Repeatability		11/91	
Conference Paper on Novel Antenna Systems for Ground Penetrating Radar		11/91	
Conference Paper on Results of Integrated Surface Geophysical Studies for Shallow Subsurface Fracture Detection at Three New Hampshire Sites		11/91	
Journal Article on Field Survey for Seismic Shear-Wave Source Development		6/92	
Project Report on Field Case Studies of an Improved Ground Penetrating Radar			10/92
Journal Article on Ground Penetrating Radar Detection of Chlorinated Solvents			4/93
Develop and evaluate new field-monitoring techniques and systems that are rapid, inexpensive, and more sensitive. (PPA H03)			
Advanced Field Monitoring Methods (EMSL-LV)			
Internal Report on a Geostatistical Report for Contouring and Spatial Interpolation of Hazardous Waste Data - A Case Study	11/90		
Internal Report on Field-Portable XRF Multi-Analyte Case Study	12/90		
Final Report on the Design of Chemical Coatings for Microsensors in the Detection and Analysis of Hazardous Materials	12/90		
Publication/Presentation of Extraction Disks and Microporous Films for Spectroscopic Field Screening Applications	2/91		
Internal Report on a Comparison in In Situ Analysis Versus Sample Preparation and Homogenization Techniques for Laboratory XRF Analysis	6/91		
Internal Report on a Study of Fundamental Parameters as a Standardless Calibration Technique	9/91		
Adaptation of a Prototype Data Telemetry/Locator System to Portable X-Ray Analyzer		10/91	

Appendix B. Summary of Outputs From Ground-Water Research Projects (Continued)

	FY91	FY92	Outyear
Vadose Zone Methods (EMSL-LV)			
Report on a Comparison of Volatile Organic Compound Sampling and Surveillance Methods			10/92
Draft Guidance Document for Site Characterization and Contamination Assessment			10/93
Develop and evaluate advanced field monitoring methods for Superfund sites. (PPA S01)			
Advanced Field Monitoring Methods (EMSL-LV)			
Presentation on Spectroscopic Field Screening Application	2/91		
Presentation on Extraction Disks and Microporous Films for Spectroscopic Field Screening Methods for Hazardous Wastes and Toxic Chemicals	2/91		
Internal Report on Adaptation of Prototype Data Telemetry/Locator Systems to Portable X-Ray Analyzer		10/91	
Internal Report on Cone Penetrometer Evaluation			10/92
Vadose Zone Field Methods for Site Screening and Assessment (EMSL-LV)			
Report on a Comparison of Volatile Organic Compound Sampling and Surveillance Methods			10/92
Draft Guidance Document for Site Characterization and Contamination Assessment			10/93
Provide the scientific database and methods for the protection of ground-water resources. (PPA F81)			
Ground-Water Monitoring (EMSL-LV)			
Journal Article on Dupont Experiment Conducted to make Surface-to-Borehole Measurements in Test Well Near a Class I Injection Facility in Tennessee	2/91		
Progress Report on Airborne Geophysical Surveys	5/91		
Monitoring Strategies for Wellhead Protection Areas		3/92	
Journal Article: Airborne Electromagnetic Surveys for Underground Injection Control		3/92	
Project Report on Seismic Noise Studies to Detect Contaminant Migration		7/92	
Journal Paper on Seismic Methods for Fracture Delineation			10/92

Appendix B. Summary of Outputs From Ground-Water Research Projects (Continued)

	FY91	FY92	Outyear
TRANSPORT AND TRANSFORMATION			
Provide field-evaluated methods and data to predict the concentrations of wastes released from RCRA hazardous waste facilities. (PPA C25)			
Field Evaluation of Ground-Water Contamination Risks from Hazardous Waste Disposal (Ada)			
Journal Article on an Eulerian-Lagrangian Localized Adjoint Method for the Advection-Diffusion Equation	12/90		
Paper on Hydrocarbon Spill Exposure Assessment Modeling	1/91		
Report on Nitrate Contamination Studies	3/91		
Supply Manual for Multiphase Flow Code		10/91	
Report on Comparing Results of Artificial Aquifer with Model Prediction		11/91	
Report on Multiphase Chemical Transport in Porous Media		11/91	
Journal Article on Transport of Inorganic Solutes in Structured Media		12/91	
Report on QA/QC in Development and Evaluation of Ground-Water Models		1/92	
Research Brief on Numerical Model for Multiphase Chemical Transport Porous Media		2/92	
Journal Article on Transport of Organic Solutes in Structured Media		7/92	
Prediction of Contaminant Behavior in the Subsurface (Ada)			
Journal Article on Cosolvent Effects on Sorption and Mobility of Organic Contaminants in Soils	11/90		
Internal Report on Solute Transport in a Leaky Aquifer by Cubic Spline Collocation	2/91		
Report on Transport of Hydrophobic Organic Chemicals in Multi-Solvent Systems	2/91		
Report on Approximate Multiphase Flow Modeling by Characteristics Methods	3/91		
Course on Use of Multiphase Chemical Transport Model	4/91		
User's Manual-MOFAT: A Two-Dimensional Finite Element Program for Multiphase Flow and Multicomponent Transport	4/91		

Appendix B. Summary of Outputs From Ground-Water Research Projects (Continued)

	FY91	FY92	Outyear
Journal Article on the Influence of Organic Cosolvents on the Sorption Kinetics of Hydrophobic Organic Chemicals	5/91		
Internal Report on the Development of a New Technique for Determining Total Organic Carbon in Contaminated Aquifer Materials	6/91		
Report on Comparisons of Two Dimensional Model Projections and Experimental Measurements of Multiphase Chemical Transport in Porous Media	7/91		
Paper entitled "Toward a Better Understanding of the Complex Geochemical Processes Governing Subsurface Contaminant Transport"	7/91		
Report on Field Evaluation of Treatability Potential of PCP and Creosote Wastes in Soil	8/91		
Journal Article on Comparing Simulated and Experimental Hysteretic Two-Phase Transient Fluid Flow Phenomena	8/91		
Journal Article on Evaluation of Sorption Models in the Simulation of Naphthalene through Saturated Soils	9/91		
Journal Article on Effect of Ionic Strength on the Transport of Bacteria in a Saturated Aquifer Material	9/91		
Internal Data Report on the Prediction of Contaminant Behavior in the Subsurface	9/91		
Journal Article on Transport in Time-Variant Mobile Phases		11/91	
Final Project Report on Laboratory and Modeling Study of Multiphase Flow		5/92	
Computer Code for the Multiphase Flow Model (DNAPL)			12/92
User's Guide for Dual Energy Gamma Ray Adsorption System			1/93
Report on Investigation of Multiphase Wetting Behavior Using Capillary Pressure Data			7/93
Research Brief on Spatial Heterogeneity of Biochemical and Hydrologic Parameters Affecting Metal Transport in Ground water			9/93
Report on Three Dimensional Modeling of Subsurface Flow and Fate and Transport of Microbes and Chemicals			12/94
Spatial Variability of Subsurface Properties and Processes (Ada)			
Research Brief on Methods for Handling Spatial Variability on Subsurface Environments	12/90		
Report on Techniques to Determine Spatial Variations in Hydraulic Conductivity of Sand and Gravel	2/91		

Appendix B. Summary of Outputs From Ground-Water Research Projects (Continued)

	FY91	FY92	Outyear
Journal Article on Large-Scale Natural-Gradient Tracer Test in Sand and Gravel, Cape Cod, Mass: 1. Experimental Design Observed Tracer Movement	5/91		
Book Chapter—Aseptic Sampling of Unconsolidated Heaving Soils in Saturated Zones	7/91		
User Friendly Computer Program for Estimating Hydraulic Properties of Unsaturated Soils for Contaminant Transport Modeling	9/91		
Final Report on Fracture Characterization and Fluid Flow		9/92	
Report on Electromagnetic Properties of Contaminated Soils			12/92
Corrective Action Technologies (Ada)			
Report on Properties Influencing Microbial Colonization of Hazardous Waste Sites	2/91		
Report on Forced Air Ventilation for Remediation of Unsaturated Soils Contaminated by Volatile Organic Contaminants	3/91		
User's Guide for the Mathematical Model LT3VS1 Denitrification on Nonhomogeneous Laboratory Scale Aquifers	3/91		
Internal Report on Full-Scale Treatment for TCE and Ground-Water Design Criteria and Economics	5/91		
Report on the Biotransformation of Monoaromatic Compounds Under Various Anaerobic Conditions	8/91		
Internal Report on Biodegradation of PCBs in Complex Oily Wastes		12/91	
Final Report on a Recombinant Approach to the Isolation and Characterization of a Primary TCE Degrader		1/92	
Internal Report on Chlorobenzene Bioreactor Pilot Study		3/92	
Journal Article on Experimental Procedures and Initial Results of Solvent Enhanced Desorption of PCBs		6/92	
International Conference on SS Remediation		6/92	
Report on Chlorobenzene Bioreactor Pilot Study		7/92	
Report on Feasibility Study for Bioremediation of Trichloroethylene—Contaminant Soil		7/92	
Quantitative Description of TCE in an Aquifer		8/92	
Report on Hot Water Recovery of Light Waste Oils		9/92	
Internal Report on the Role of Protozoa in Aquifer Biorestoration		9/92	

Appendix B. Summary of Outputs From Ground-Water Research Projects (Continued)

	FY91	FY92	Outyear
Summary Report of Data Analysis for RCRA's Regulatory Impact Analysis		9/92	
Journal Article on the Impact of Solvents on the Rate of PCB Desorption			12/92
Provide integrated, multimedia methods and data to estimate potential exposures to hazardous wastes from RCRA facilities. (PPA C28)			
Multimedia Modeling with Uncertainty Analysis (Athens)			
Report on Results of MINTEQA1 Model Performance at Globe, Arizona Site	6/91		
Develop methods to predict subsurface contaminant concentrations to support risk analysis and source control. (PPA F83)			
Subsurface Physical/Chemical Processes Affecting Transport (Ada)			
Report on Sorption Properties of Soil and Aquifer Organic Matter	12/90		
Report on Separation and Identification of Aquifer Organic Matter	12/90		
Journal Article on Transport of Inorganic Colloids in Undisturbed Subsurface Systems	6/91		
Report on Facilitated Transport of Metal Contamination in the Subsurface	6/91		
Article on Transport of Organic Cations and Hydrophobic Organic Compounds in Laboratory Columns		12/91	
Internal Report on FT-IR Studies of the Sorption Properties of Soils and Aquifer Organic Matter		6/92	
Internal Report on Separation and Identification of Aquifer Organic Matter		7/92	
Article on Evaluation of Multi-Site Modeling Approach for Predicting Contaminant Transport in Natural Subsurface Systems		9/92	
Report on Electromagnetic Properties of Contaminated Soils			12/92
Report on Abiotic Reductions Between Haloaliphatic Chemicals and Environmental Reductants at Mineral Surfaces			10/93
Report on Adsorption of Ionic Compounds on Natural Heterogeneous Materials			10/93
Report on Characterization of Organic Matter in Soils and Aquifer Materials			1/95

Appendix B. Summary of Outputs From Ground-Water Research Projects (Continued)

	FY91	FY92	Outyear
Prediction of Microbial Contaminant Concentrations (Ada)			
Report on the Swelling Properties of Soil Organic Matter and their Relation to Sorption of Non-ionic Organic Compounds	6/91		
Screening Model to Predict Virus Transport in Ground water	9/91		
Initiate Transport Modeling for Viruses		1/92	
Journal Article on Facilitated Transport of Metals in the Subsurface		9/92	
Prediction of Biotransformation of Subsurface Contaminants (Ada)			
Report on Anaerobic Biotransformation of Contaminants in the Subsurface	10/90		
Journal Article on Reductive Dechlorination	3/91		
Journal Article on Anaerobic Degradation		12/91	
Research Brief on Biodegradation of Pesticides in Aquifers		1/92	
Evaluate models and management strategies in support of State wellhead protection programs mandated by the Safe Drinking Water Act Amendments of 1986. (PPA F89)			
Develop Methods for Wellhead Protection (Ada)			
Interim Report for the Application of Capacity Criteria to Wellhead Protection	1/91		
Final Report on Evaluation of Wellhead Protection Area Delineation Methods Including Use of the WHPA Codes in Ellis County, Kansas		9/92	
Report on Methods for Delineating Wellhead Protection Zones Around Springs		9/92	
Report on a Survey of Major Contaminant Impacting Public Drinking Water Wells			12/92
Transport Modeling for Delineation of Wellhead Protection Zones: A consideration of Virus and Bacteria Transport			8/93
Development of a Risk-Management Strategy for Wellhead Protection			8/93
Final Report on Demonstration of the Analytic Element Method for Wellhead Protection			10/93
Report on Development of a Risk-Management Strategy for Wellhead Protection			10/93
Report on Delineation of Wellhead Protection Zones: Consideration of Virus Transport			12/93

Appendix B. Summary of Outputs From Ground-Water Research Projects (Continued)

	FY91	FY92	Outyear
Final Report on Validation of Models for Delineating Capture Zones in Wellhead Protection			12/93
Determine how pesticides contaminate ground waters and remedial actions to alleviate the problem. (PPA D07)			
Validation of Predictive Techniques for Environmental Exposure (Athens)			
Report on Results of MINTEQA2 model performance at Globe, Arizona Site		1/92	
Report on Literature-based Testing of MINTEQA2		3/92	

IN SITU AQUIFER REMEDIATION

	FY91	FY92	Outyear
Evaluate Technologies to Manage Uncontrolled Sites. (PPA B01)			
In Situ Control Technologies (RREL)			
Report on Feasibility of Hydraulic Fracturing of Soil to Improve Remedial Actions	8/91		
Paper on Prospects for In Situ Chemical Treatment of Contaminated Soils		12/91	
Pilot Test on Solid Oxygen Source for In Situ Bioremediation		5/92	
Feasibility Study of Leachate Recirculation for In Situ Treatment of MSW Landfills on the NPL		8/92	
Complete Field Tests of Hydrofracturing for Enhancing In Situ Remedial Action			9/93
Evaluate abilities of natural and enhanced microorganisms for biodegradation of hazardous substances in Superfund remedial actions. (PPA B02)			
Enhanced Biorestoration of Contaminated Ground water (Ada)			
Report on Efficacy and Environmental Safety of Using Nitrate to Bioremediate Hazardous Wastes	11/90		
Journal Article on Chemical Relationship Between Soil Gas, Core Material, and Water Quality at an Aviation Gasoline Plume Site	6/91		
Journal Article on Enhanced Biorestoration of Contaminated Ground water	7/91		
Report on Operation of the Pilot Scale Treatment System for TCE Biotreatment		10/91	

Appendix B. Summary of Outputs From Ground-Water Research Projects (Continued)

	FY91	FY92	Outyear
Preliminary Report Listing the Computer Code and Documenting the Results of the Laboratory Studies Used to Calibrate the Model		11/91	
Article Comparing Results of the Batch Microcosm with the Column Study		12/91	
Report on Describing the Performance of Bioventing of Aviation Gasoline In Situ		9/92	
Report on Development and Calibration of a Model Describing In Situ Bioventing of Hydrocarbons from the Subsurface			10/92
Internal Report on Evaluation of Denitrification for Biorestoration of JP-4 Jet Fuel-Contaminated Aquifer			12/92
Final Report on Denitrification for Bioremediation of a Refinery Spill			8/93
Biodegradation Applications to Superfund Site Cleanups (Athens)			
Report on In Situ Biodegradation of Carbon Tetrachloride Under Denitrifying Conditions	11/90		
Report on the Use of Sulfate Reducing Organisms for Bioremediation of Hazardous Waste Components	11/90		
Report on Co-Oxidation of PCBs During Metabolism of Polyaromatic Hydrocarbons			10/92
Internal Report on In Situ Bioremediation of Chlorinated Aliphatic Compounds by Toluene Oxygenase-Containing Bacteria			9/93

UNDERGROUND SOURCE CONTROL

Develop methods to determine the fate of underground injected wastes and develop safer technologies for underground injection control. (PPA F88)

	FY91	FY92	Outyear
Methods of Determining the Mechanical Integrity of Injection Wells (Ada)			
Report on Field Tested Methods for Part 2 of Mechanical Integrity of Injection Wells		2/92	
Report on Test Methods for Flow Behind Pipe from the Injection Well Mechanical Integrity Project			10/92
Report on Potential for Invasion of Underground Sources of Drinking Water Through Mud-Plugged Wells: An Experimental Appraisal			9/94

Appendix B. Summary of Outputs From Ground-Water Research Projects (Continued)

	FY91	FY92	Outyear
Impact of Class I Wells on Subsurface Geological Materials (Ada)			
Report on Methodologies for Identifying Salinity Involved in Ground-Water Contamination	9/91		
Class V Injection Well Practices (Ada)			
Report on Methodology for Prioritizing Aquifer Sensitivity to Class V Wells	9/91		

TECHNOLOGY TRANSFER AND TECHNICAL ASSISTANCE

	FY91	FY92	Outyear
Provide technical support on Superfund settlement agreements, especially to enforcement programs in Regions and states. (PPA F06)			
Geophysical Support (EMSL-LV)			
Funding for Geophysical Technical Support	11/90		
Provide Superfund enforcement and response programs with rapid access to the best available technical information, evidence, and testimony. (PPA F22)			
Clearinghouse for information on Ground-Water Remedial Action Technologies (Ada)			
Workshop on DNAPL Site Characterization and Remediation Options		1/92	
Issue Paper on Remediation of Sites Contaminated with Trichloroethylene		2/92	
Issue Paper on Bioremediation of Contaminated Ground waters		2/92	
Issue Paper on Conducting Field Tests for Evaluation of Soil Vacuum Extraction		4/92	
Internal Report on GIS Application and Geostatistical Analysis of Hardema Co. Landfill		5/92	
Issue Paper on In Situ Bioremediation of Vadose Zone Soils		6/92	
Report on Access to Subsurface Remediation Technology Database (STRD) by On-Line Bulletin Board System		9/92	
Report on Evaluation of Unsaturated/Vadose Zone Models for Superfund Sites			10/92
Report on Identification and Compilation of Unsaturated/Vadose Zone Models Possibly Applicable to Setting Soil Remediation Levels at Superfund Sites			11/92

Appendix B. Summary of Outputs From Ground-Water Research Projects (Continued)

	FY91	FY92	Outyear
Summary Paper on In Situ Bioremediation of Chlorinated Solvents in Contaminated Aquifers			11/92
Ground-Water Technical Support (Ada)			
Protocol for Evaluating Effectiveness of Ground-Water Remediation Activities at Superfund Sites	1/91		
Final Report on Determining Partition Coefficients for TCE on Aquifer Material from the Main Street Superfund Site		12/91	
Report on Status of Available Ground-Water Models		1/92	
Issue Paper on Basics of Ground-Water Modeling		4/92	
Internal Report on the Characterization of Subsurface Contamination and Transport Potential to Ground water and at Chrome Plating Sites		6/92	
Report on Demonstration of Electromagnetic Borehole Flowmeter at three Superfund Sites		7/92	
Report on the Superfund Vadose Modeling Evaluation		9/92	
Journal Article on Demonstrating Methods for Generating Input Data for Modeling Pump-and-Treat Remedial Action			10/92
User's Manual for the Application of the Electromagnetic Borehole Flowmeter Techniques			10/92
Ground-Water Methods, Information Transfer & Applications			
Journal Article on Transport of Inorganic Colloids in Undisturbed Subsurface Systems	6/91		
Report on Facilitated Transport of Metal Contaminated in the Subsurface: Part II - Colloidal Transport	6/91		
Issue Paper on Chemical Enhancements to Pump-and-Treat		1/92	
Issue Paper on Behavior of Metals in the Soil Environment		6/92	
Issue Paper on Fundamental and Principles of Soil Science as Related to Contaminant Mobility in Soils		6/92	
State of the Art Document on Soil Venting		8/92	

APPENDIX C. RECENT ORD GROUND-WATER PUBLICATIONS

EPA publications in the 600 and 625 series (ORD) may be obtained by calling EPA's Center for Environmental Research Information at FTS 684-7562 (513-569-7562). Publications referenced by a PB number are also available from NTIS. This list encompasses both publications and journal articles.

General

ORD Ground-Water Research Plan: Strategy for 1991 and Beyond. EPA 600/9-90/042, September, 1990.

Ground-Water Research Technical Assistance Directory. EPA-600/9-91/006, March 1991.

Protecting the Nation's Ground Water: EPA's Strategy for the 1990s-The Final Report of the EPA Ground-Water Task Force. EPA 21Z-1020, July, 1991.

Forum Issue Papers

Ground-Water Sampling for Metals Analyses. EPA 540/4-89/001, March, 1989

Accuracy of Depth to Water Measurements. EPA 540/4-89/002, August, 1989

Soil Sampling and Analysis for Volatile Organic Compounds. EPA 540/4-91/001, February, 1991

Characterizing Soils for Hazardous Waste Site Assessments. EPA 540/4-91/003, March, 1991

Contaminant Transport in Fractured Media: Models for Decisions Makers. EPA/540/4-89/004, August, 1989

Facilitated Transport. EPA 540/4-89/003, August, 1989

Basic Concepts of Contaminant Sorption at Hazardous Waste Sites. EPA 540/4-90/053, October, 1990

Dense Nonaqueous Phase Liquids. EPA/540/4-91/002, March, 1991

Performance Evaluations of Pump-and-Treat Remediations. EPA 540/4-89/005, October, 1989

Reductive Dehalogenation of Organic Contaminants in Soil and Ground Water. EPA 540/4-90/054, January, 1991

Site Characterization and Monitoring

Sampling Frequency for Ground-Water Quality Monitoring. V.W. Lambou, EPA-600/X-86-081, 1986.

Underground Storage Tank Monitoring: Observation Well Based Systems. R.A. Scheinfeld, J.B. Robertson, and T.G. Schwendeman, Ground Water Monitoring Review, 6(4):49-55, Fall 1986.

The Effect of Sampling Frequency on Ground-Water Quality Characterization. R. Rajagopal, Ground Water Monitoring Review, 6(4):65-73, Fall 1986.

Appendix C. Recent ORD Ground-Water Publications (Continued)

Handbook: Ground Water. EPA-625/6-87-016, March 1987.

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Appendix C. Recent ORD Ground-Water Publications (Continued)

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