DEPARTMENT OF THE ARMY
ASSISTANT SECRETARY OF THE ARMY
(RESEARCH, DEVELOPMENT AND ACQUISITION),
WASHINGTON, D.C. 20310-0103

ARMY SCIENCE BOARD

INFRASTRUCTURE AND ENVIRONMENTAL ISSUE GROUP PANEL FINAL REPORT

on

"GROUND WATER MODELING IN THE ARMY ENVIRONMENTAL RESTORATION PROGRAMS"

May 1994

DISCLAIMER

This report is the product of the Army Science Board (ASB). The ASB is an independent, objective advisory group to the Secretary of the Army (SA) and the Chief of Staff, Army (CSA). Statements, opinions, recommendations and/or conclusions contained in this report are those of the Infrastructure and Environmental Issue Group Study on "Ground Water Modeling in The Army Environmental Restoration Programs," and do not necessarily reflect the official position of the United States Army or the Department of Defense (DoD).

CONFLICT OF INTEREST STATEMENT

Conflicts of interest did not become apparent as a result of the Panel's recommendations.

REPORT DOCUMENTATION PAGE	Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY (Leave Blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	May 1994	Army Science Board Issue Group Study

4. TITLE AND SUBTITLE

Ground Water Modeling In The Army Environmental Restoration Programs

5. FUNDING NUMBERS

N/A

6. AUTHOR(S)

Chair: Dr. Gail Charnley
Dr. Crystal C. Campbell
Ms. Kim Green
Dr. Jay Sculley
Dr. George Piegari
Dr. Alan Karr
Dr. Martin Alexander

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Army Science Board
Office of the Assistant Secretary of the Army (Research, Development and Acquisition),
ATTN: SARD-ASB
Washington, DC 20310-0103

8. PERFORMING ORGANIZATION REPORT NUMBER

N/A

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Assistant Secretary of the Army
Research, Development and Acquisition ASA(RDA)
ATTN: SARD-ZA
Washington, DC 20310-0103

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

N/A

11. SUPPLEMENTARY NOTES

N/A

12a. DISTRIBUTION/AVAILABILITY STATEMENT

APPROVED FOR PUBLIC RELEASE;
DISTRIBUTION IS UNLIMITED

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words) This is the report of the findings and recommendations of a ground water study panel convened by the Army Science Board's Infrastructure & Environment (I&E) Issue Group to evaluate the role and practice of ground water modeling (GWM) in the Army's environmental restoration programs and to assess future research program needs.

Cleaning up contaminated ground water and soils is an exceptionally difficult problem. Contaminants often exist in complex hydrogeologic conditions in which a variety of different physical, chemical, and biological processes are occurring. Complexities in subsurface characteristics make characterizing contaminant transport challenging. Ground water models mathematically approximate contaminant fate and transport processes in certain subsurface water conditions, providing a tool for site characterization that can help clarify the trade-offs associated with alternative clean-up remedies..

A number of different elements within the Army (or its contractors) use a variety of ground water models to carry out site restoration projects. The Army's ground water modeling activities have met with various degrees of success. To alleviate identified usage problems, the Army plans to initiate a more aggressive and comprehensive research, education and out-reach program -- the Ground Water Modeling/Simulation Program -- to support better use of ground water models. The program focuses on the development of an integrated Ground Water Modeling Systsm and includes activities such as: evaluation of existing modeling technologies; provision for an integrated user environment (including education, training and technical support); integration of multiple data base management systems; and, undertaking basic research on transport and flow of Army-specific contaminants in varied hydrogeologic conditions.

The findings of the ASB panel fall into three broad categories: examination of the role of GWM in Army activities; review of training and other technical support needed for more effective ground water modeling efforts; and, evaluation of the GWM/Simulation Research Program.

14. SUBJECT TERMS

Ground water modeling, site restoration, environmental restoration ground water contamination

15. NUMBER OF PAGES

25

16. PRICE CODE

N/A

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	None

GROUND WATER MODELING IN THE ARMY ENVIRONMENTAL RESTORATION PROGRAMS

Prepared for

U.S. Army Corps of Engineers

Prepared by

The Army Science Board
Infrastructure and Environmental Issue Group
Panel on Ground Water Modeling

October 1, 1993

TABLE OF CONTENTS

GROUND WATER MODELING IN THE
ARMY ENVIRONMENTAL RESTORATION PROGRAMS

EXECUTIVE SUMMARY

The Army's Environmental Strategy for the 21st Century directs the Army to give immediate priority to sustained compliance with all environmental laws and to continue to restore previously contaminated sites. The Army currently has over 5,500 known contaminated sites — located on 1,300 Army installations — that require further study and possible remedial action. By law the Army is required to restore them to an environmentally safe condition. The Army spends more funds on ground water-related problems at Army installations than on any other environmental remediation activity. Thus, there is a critical need to develop innovative technologies and processes that can help the Army clean up polluted ground water resources more effectively. Ground water modeling (GWM) is one such technology.

This is the report of the findings and recommendations of a ground water study panel convened by the Army Science Board's (ASB) Infrastructure and Environmental (I&E) Issue Group to evaluate the role and practice of (GWM) in the Army's environmental restoration programs and to assess future research program needs.

Cleaning up contaminated ground water and soils is an exceptionally difficult problem. Contaminants often exist in complex hydrogeologic conditions in which a variety of different physical, chemical, and biological processes are occurring. Complexities in subsurface characteristics make characterizing contaminant transport challenging. Ground water models mathematically approximate contaminant fate and transport processes in certain subsurface water conditions, providing a tool for site characterization that can help clarify the trade-offs associated with alternative clean-up remedies. Models alone cannot determine particular outcomes with certainty; they help determine the range of outcome probabilities.

A number of different elements within the Army (or its contractors) use a variety of ground water models to carry out site restoration projects. Because the utility of models is highly dependent on the validity of the model assumptions and the quality of the data, modeling requires a sophisticated, knowledgeable user with the capability to know not only *how* to use the model, but more importantly, *when* and *where* to use *which* model.

The Army's GWM activities have met with various degrees of success. To alleviate identified usage problems, the Army plans to initiate a more aggressive and comprehensive research, education and out-reach program — the Ground Water Modeling/Simulation Program — to support better use of ground water models. The program focuses on the development of an integrated Ground Water Modeling System (GMS) and includes activities such as: evaluation of existing modeling technologies; provision for an integrated user environment (including education, training and technical support); integration of multiple database management systems; and, undertaking basic research on transport and flow of Army-specific contaminants in varied hydrogeologic conditions.

The findings of the ASB panel fall into three broad categories: examination of the role of GWM in Army activities: review of training and other technical support needed for more effective GWM efforts; and, evaluation of the proposed Ground Water Modeling/Simulation Research Program.

1. Role of GWM in Site Restoration

1.1 Finding: The Army has not provided guidelines for the conduct of site restoration activities that include use of GWM as an integral part of site restoration, especially at the beginning of a project.

1.2 Finding: Regulators and managers often have unreasonable expectations with regard to what models can be used to accomplish, and are seemingly unaware of their limitations.

Recommendation: The Army should establish policies articulating the role of ground water models in environmental protection and site restoration projects and develop guidelines that will include GWM as an integral part of planning and conducting these activities.

2. Training and Technical Support Requirements

2.1 Finding: Many Army personnel responsible for site restoration do not have adequate expertise to apply, review, and understand ground water models. Army personnel need and desire additional education, training, technical support and assistance to use ground water models appropriately and to manage projects involving GWM effectively.

2.2 Finding: The ground water model user community within the Army is spread among diverse organizations and has widely varying skills, with no process for mutual support.

Recommendation: The Army should establish a Technical Support Center to provide: training to increase the number of qualified personnel; technical assistance to respond to issues relating to appropriate use and interpretation of GWM results; and, technology transfer — spreading technical and user information involving the use and limitations of GWM — to Army personnel involved with site restoration activities.

3. Ground Water Modeling/Simulation Research Program

3.1 Finding: The proposed program for Ground Water Modeling/Simulation Research, especially the GMS, is an ambitious one. It appears to be sound scientifically, and if implemented will help to meet the requirements of the Army's Environmental Restoration program. It is not apparent, however, that the quality and level of resources — funds or personnel — are sufficient to meet the goals of the program.

Recommendation: The proposed research program should be implemented and a process established to ensure close interaction with the user community to guide program priorities. The program should be a dynamic one and be modified as requirements and resources change. Most importantly, project resources — time, budget, and talent — must reflect the true needs and scope of project goals.

An independent advisory group should be established to monitor and review the adequacy of planning and programming, as well as to assure technical credibility.

3.2 Finding: Components of the proposed GMS will be completed after many Army site restoration efforts are underway. Incremental development of the GMS with clear user-defined intermediate products is therefore critical to address immediate needs. Ground water models are currently available that can be used by the Army in its site characterization and remediation efforts, although field-scale verification of many models is incomplete.

Recommendation: Technology transfer must be a continual part of the GMS development process, with intermediate GMS products transferred to the user community (including contractors) as developed. Initial GMS research program efforts should be devoted to: improving user capability for extant models; field-scale research and improving the predictive capability of existing models; and, improving the scientific understanding of flow, transport, and fate processes.

3.3 Finding: There are Army-specific contaminants, such as explosives, on which little research is likely to be performed outside the Army. There is a need for additional basic research to characterize the behavior of these contaminants and to provide accurate input to ground water models used in Army site restoration activities.

Recommendation: The research program should give priority to investigating and characterizing physical, chemical, and biologic processes that affect Army-specific contaminants.

GROUND WATER MODELING IN THE ARMY ENVIRONMENTAL RESTORATION PROGRAMS

Part I
Ground Water Models: Background Facts

The U.S. Army Corps of Engineers'(COE) Directorate of Research and Development asked the I&E Issue Group of the ASB to convene a panel to evaluate the current state- of-the-art in GWM in the Army's environmental restoration programs and to help them assess and shape the future direction of research programs in this area. This report describes the findings and recommendations of the ASB ground water study panel.[1]

1. <u>Army Environmental Responsibility</u>

The Army and the Department of Defense (DoD), as owners and occupiers of millions of square miles of land, harbors, wetlands and natural resources, are aware of the growing importance of their role as stewards of the environment. The Army's Environmental Strategy for the 21st Century recognizes this role explicitly and pledges them to providing environmental leadership: "The Army will be a national leader in environmental and natural resource stewardship for present and future generations as an integral part of our mission."[2] To fulfill this mission and respond to a broad array of legislation protecting the environment, surface, and underground water resources, the Army has developed an environmental strategy. Among other goals, it directs the Army to give immediate priority to sustained compliance with all environmental laws and to continue to restore previously contaminated sites. To achieve these goals, the Army will need to develop and use its environmental resources — both technological and human — more efficiently and effectively.

As this nation's environmental consciousness increases, the need to protect clean water and restore contaminated water resources becomes more critical. Local and regional surface water has become a significant component of the nation's and the Army's environmental agenda. And although unseen — much of our water resources lies below ground in subsurface aquifers — the condition of our nation's ground water resources is a growing concern. Pollution of subsurface water supplies has a more injurious impact on the environment and ecology than surface water contamination. These injuries are more difficult to remedy; the impacts, more lasting. The Environmental Protection Agency (EPA) recently noted that, "[g]round-water contamination is one of the most prevalent and challenging problems at hazardous waste sites in both the Superfund and RCRA (Resource Conservation and Recovery Act) Corrective Action Programs. Ground-water contamination is present at more than 70% of the sites on the National Priorities List [Superfund] and almost 50% of the permitted RCRA land disposal facilities."[3] Activities on military installations have a significant impact on the environment and ecology of

---

[1] The term "ground water" is variously written as one or two words. Reflecting usage of both the Water Science and Technology Board and the dictionary, this report uses the two word variant except where quoting or citing another usage.

[2] <u>U.S. Army Environmental Strategy into the 21st Century</u>, Department of the Army, Washington, DC 1992, p 1.

[3] U.S. Environmental Protection Agency, "Considerations in Ground-water Remediation at Superfund Sites and RCRA Facilities — Update," Memorandum, Directive No 9283.1-06, Washington D.C., May 27, 1992.

lands and wetlands on and adjacent to military installations, and these activities can detrimentally affect both surface and ground water supplies. Thus, there is an emerging critical need to develop innovative technologies and processes that can help the Army and the nation more effectively address the clean-up of our nation's ground water resources.

Ground water contamination constitutes a risk to human and environmental health on Army installations in addition to threatening the surrounding communities. The Army currently has over 5,500 known contaminated sites — located on 1,300 Army installations — that require further study and possible remedial action.[4] The Army is required by law to remediate these damaged sites, i.e., to restore them to environmentally safe condition. Currently thirty-four of these contaminated sites are on the National Priority List, marked for highest clean-up priority under the Superfund Program mandated by the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA) legislation.

Ninety percent of all Army contaminated sites face problems of polluted ground water and 60 percent of the Army's current clean-up efforts are focused on remediation efforts relating to contaminated ground water.[5] The costs — in terms of resources, time and funds — associated with these environmental clean-up efforts are, and will continue to be, significant. The Army spends more funds on ground water-related problems at Army installations than on any other environmental remediation activity. It is estimated, for example, that the potential costs to address soil- and ground water-related problems at the Rocky Mountain Arsenal outside of Denver, Colorado and at the Aberdeen Proving Ground in Aberdeen, MD may top $1.7 billion over the next few years.[6] While few sites will necessitate the level of effort required in the latter two installations, cost estimates for the Army to clean up its ground water generally range from $3 to $6 billion.[7]

The Army environmental restoration program does not operate in a vacuum. Many Army clean-up activities, including ground water, are affected by the regulatory activities of the EPA as well as those of regional, state, and local jurisdictions. This overlay may control the time allowed for evaluation of a particular contaminated site and strongly influence the Army's choice of assessment and remedial tools and techniques. Another important factor affecting the Army's current site restoration effort is the fact that the Army must rely heavily on the expertise of private contractors — who have varying degrees of capability and familiarity with assessment technologies -- to implement and accomplish environmental restoration projects. All of these factors underscore the importance of building a greater capability in order to properly manage and monitor these Army environmental projects in an efficient and cost-effective manner.

---

[4] A Review of Ground Water Modeling Needs for the U.S. Army, National Research Council, September 1992, p. 3.

[5] "DOD Groundwater Modeling/Simulation Research Plan", Presentation, USAE Waterways Experiment Station (WES), Vicksburg, MS, n.d. (as to ratio of ground water problems).

[6] op cit., p. 4.

[7] U.S. Army Corps of Engineers, Plan for Development of a Comprehensive, Integrated System of Groundwater Models and Analysis Tools for Use in DOD Installation Cleanup, USAE Waterways Experiment Station, Vicksburg, MS, 5 Nov. 1992, p. 3, citing the Annual Report to Congress for Fiscal Year 1991, Defense Environmental Restoration Program, Department of Defense, Feb. 1992.

2. Environmental Restoration and the Role of Ground Water Models

Cleaning up contaminated ground water and soils is an exceptionally difficult problem. Contaminants often exist in complex hydrogeologic conditions in which a variety of different physical, chemical, and biological processes are occurring. Complexities in subsurface characteristics can affect ground water conditions and make characterizing contaminant transport challenging. Notwithstanding these difficulties, the CERCLA remediation process requires the Army (and other organizations responsible for environmental damage) to make a determination of the nature and extent of existing contamination and predict further contaminant migration in order to conduct risk assessments, to evaluate, design, and implement remedial alternatives, and to monitor the progress of a clean-up. The cost to alleviate polluted ground water conditions and potential risk to health precludes undertaking remedial actions based on a trial and error process. To address these issues in the most cost-effective manner, the Army must improve its technical capability to evaluate and predict the effectiveness of a variety of remedial alternatives as part of the initial remedial decision process — long before clean-up work is actually begun.

The use of technological tools as an aid to understanding the complex interactions among surface water and engineering projects is not new. For instance, for many years the Army COE has used realistic models of waterways to help inform engineering decisions that have a potential effect on surface water flow. Today, use of these physical models is supplemented by computer simulations, mathematical models that approximate physical reality and guide engineering decisions before actual construction is under way.

Computer-aided systems are also used to gain greater understanding of subsurface water conditions. GWM is one such tool. These models attempt to represent the physical realities of the underground water environment with mathematical equations.[8] Mathematical ground water flow and solute transport models are now widely used in engineering, geology, hydrogeology, environmental sciences, and hazardous waste remediation studies.[9] In the context of contaminated ground water, models can mathematically approximate contaminant fate and transport processes under certain subsurface water conditions. These models are used as tools to evaluate simple or complex hydrogeologic environments, estimate current levels of contamination at particular locations, estimate the direction and rate of migration of contaminant plumes in ground water, estimate potential human exposure to contaminants, and help design and evaluate remediation strategies for contaminated ground water.

Models alone cannot determine particular outcomes with certainty; they help determine the range of outcome probabilities. When there is a good theoretical understanding of the unseen hydrogeologic conditions and the physical, biological, and chemical interactions that have an impact on contaminant behavior, ground water models can help make subsurface conditions more transparent. Model results can clarify the trade-offs associated with alternative clean-up remedies and improve environmental decision-making. In the context of developing alternative remedial strategies, models can help define and characterize the degree of uncertainty. Thus, in determining the best approach to an environmental

---

[8] Ground Water Models, Scientific and Regulatory Applications, Water Science and Technology Board, Committee on Ground Water Modeling Assessment, Commission on Physical Sciences, Mathematics and Resources, National Research Council, National Academy Press, Washington, D.C. 1990.

[9] op cit.

clean-up project, models play a facilitative role; they support sounder decision-making but they do not mandate particular outcomes. In the course of the ASB ground water panel's investigations, this critical understanding concerning the proper role of GWM was often unclear, a problem which the panel addresses later in this report.

While models might be immediately useful in many instances, there are limits to modeling capabilities that must be understood by users and decision-makers. In many ways the application of models is still more of an art than a science. GWM software is not "user friendly." Ground water models require a fairly sophisticated user with the capability to know not only *how* to use the model, but more importantly, *when* and *where* to use *which* model. Ground water models can be relatively simple or highly complex; unidimensional or multidimensional. The utility of models is highly dependent on the validity of the model assumptions and the quality of the data. Appropriate site sampling is of prime importance for the application of models. Thus, GWM ultimately can help managers make more cost-effective decisions, the use of the modeling process itself is expensive and labor-intensive.

In some instances — perhaps many — models inadequately replicate complex physical phenomena because of the limits of theory and the fact that the underlying hydrogeologic and chemical interactions are not well understood. As researchers acknowledge: "Many of the processes affecting ground water flow and contaminant transport are largely unknown."[10] In addition, predictions from ground water models generally lack field verification. Given these circumstances, GWM is most useful for replicating flow processes in porous media. Some transport and chemical mass transfer processes are also well understood and modeled. Models are less likely to be useful under more complex hydrogeologic conditions, or in simulating chemical/mass transfer processes under complex conditions.[11]

Despite these difficulties, a number of different elements within the Army, including the Army Environmental Center (AEC), individual installations, and COE districts, use a variety of ground water models to carry out environmental clean-up projects. Because Army resources are limited and overworked, personnel responsible for site characterization and remediation often must rely on contractor support for these activities, including GWM components. The Army bears the ultimate responsibility for site restoration projects, however, and must be able to evaluate and assess the effectiveness of contractor efforts.

The Army's GWM efforts have met with various degrees of success. The study panel finds that, generally speaking, problems encountered by the Army in using such models are:

- Regulators and managers often have unreasonable expectations with regard to what models can be used to accomplish, and are seemingly unaware of their limitations.

- The most appropriate modeling tools are not always used; models may be applied inappropriately, or unsuitable assumptions may be made by the user. For example, a three-dimensional flow model may be attempted when a simpler model, or no model at all, may better

---

[10] Plan for Development of a Comprehensive, Integrated System of Ground Water Models and Analysis Tools for Use in DOD Installation Cleanup, op cit., p 3.

[11] A Review of Ground Water Modeling Needs for the U.S. Army, op cit., Table 1, Progress in Modeling, p. 8.

address a particular question. At a particular site, no model may accurately represent the spatial and temporal distribution of ground water flow and, thus, be unable to predict contaminant, water, and porous media interactions in a multidimensional, dynamic biochemical environment.

- Using the most appropriate model may be costly and time-consuming, while — given the framework of mandated regulatory process — time and resources available to comply with the regulatory process may be severely limited.

- Model software may be poorly documented and their applications at particular sites inadequately reported, making it difficult for users to interpret and defend modeling results.

- Lastly, and perhaps most importantly, the results of GWM activities may be disappointing because Army personnel with sufficient modeling experience or expertise to use models effectively and appropriately are in short supply. Appropriate use or application of ground water models is not simple. It takes experience and in-depth knowledge to know *when* and *where* to use *which* type of model to address *what* questions.

Too often, the cumulative impact of these problems is ineffective use of ground water models in the Army's site remediation activities. In turn, the problems associated with model usage and understanding can negatively affect the selection of remedial strategies which, however well-intended, may prove to be ineffective. The importance of the consequences and costs (especially those associated with remediating polluted ground water), and the potential benefits of improved analysis and understanding *prior to* implementing a site clean-up project, present a strong argument for encouraging more effective use of ground water models by the Army.

In addition, both to protect clean water resources as well as to restore polluted systems, the Army's drive for environmental leadership must improve the installation commander's ability to understand and forecast the interrelation of military activities and environmental consequences before they occur. New and emerging technologies, among them the use of ground water models, can facilitate the process of understanding the impact of military activities on the unseen water below.

3. The ASB I&E Issue Group Study

Recognizing that GWM plays a critical role in environmental activities, the Army plans to initiate a more aggressive and comprehensive research, education, and outreach program to support their use of ground water models. In connection with this new initiative, in August 1991, Dr. Robert Oswald, Director, Research and Development, U.S. Army Corps of Engineers[12] requested that Mr. James Jacobs, Chair, ASB, convene a committee to undertake an assessment of "Ground Water Modeling in the Army's Restoration Programs" (Appendix A). A ground water modeling study panel was established, composed of several members of the ASB I&E Issue Group (Appendix B).

The Terms Of Reference (TOR) indicate that the ground water study objectives are twofold: (a) evaluate the current use of ground water models in the Army's Restoration Programs and to assess the degree to which the Army is using the existing modeling capability to meet current and projected requirements; and, (b) review the Army's Ground Water Modeling Research Program [as proposed] to

[12] Under the Department of Defense "Project Reliance", the Corps of Engineers has lead responsibility for ground water protection and restoration.

ascertain if it is directed towards meeting the Army's Restoration Program requirements.[13] In their evaluation, the ASB panel was asked to also "identify gaps between the state of Army practice (including that of its contractors) and the state of the art...and recommend remedial actions ...[for] effective use of ground water models."

The ASB study panel first met on March 31, 1992 in conjunction with an Army-sponsored GWM use and needs workshop in Denver, Colorado. The ASB study panel met three more times in Washington, D.C., and one meeting was held at the Army COE WES, Vicksburg, Mississippi, where the proposed Ground Water Modeling Research Program is to be located. Presentations were made to the study panel by individuals from various components of the Army and the COE, private industry, academia, and the EPA.

Concurrent with this ASB study, the U.S. Army COE WES contracted with the National Research Council's (NRC) Water Science and Technology Board (WSTB) to evaluate the current state-of-the-art in ground water flow and contaminant transport modeling. In 1990, some members of this NRC panel had participated in a major study of the scientific use and application of ground water models. The purpose of the 1992 study was to review and update modeling developments since that time. The WSTB study provided technical support for this ASB study. Results of the WSTB study are kept on file at the ASB office.

The findings and recommendations contained in this report represent the consensus of the ASB study panel after its deliberate review and evaluation of oral presentations and written reports or other material provided at panel meetings or in response to panel questions. In addition to these technical studies and information briefings, the ASB panel obtained user-based perspectives from participants attending the March 1992 workshop. Additional user-based insights were obtained from an extensive user survey that was administered by the WES. The survey questionnaire was distributed to Army personnel in COE field offices, certain Army installations, and major elements of the U.S. Army Toxic and Hazardous Material Agency (USATHAMA), all of whom have participated in or have responsibility for site restoration efforts that involve GWM. Responses to the questionnaire were received from 77 individuals representing installations, USATHAMA, and 17 different COE districts and divisions. WES later processed, analyzed, and reported the survey results (Appendix B). Additionally, a major component of the background materials and presentations reviewed by the study panel relate to the proposed DOD Groundwater/Modeling Simulation Research Plan. These materials, prepared by WES, are noted in the bibliography.

---

[13] Terms of Reference, Groundwater Modeling in the Army's Environmental Restoration Programs, 1991.

Part II
Findings and Recommendations

The findings of the ASB panel fall into three broad categories, the first two of which — examination of the role of GWM in Army activities and review of training and other technical support needed for more effective GWM efforts — address the issues in part (a) of the TOR. Evaluation of the proposed Ground Water Modeling/Simulation Research Program, addresses part (b) of the TOR.

1. Role of Ground Water Modeling in Site Restoration

1.1 Finding: The Army has not provided guidelines for the conduct of site restoration activities that include use of GWM as an integral part of site restoration, especially at the beginning of a project.

The EPA's Office of Solid Waste and Emergency Response, which has primary responsibility for establishing site restoration requirements, has noted that there are no existing policies on the use of models in the CERCLA hazardous waste/superfund programs. In practice, data requirements and guidelines for model selection and acceptability are inconsistent and, within EPA, region-specific. The Agency is still striving to develop an integrated approach for the use of ground water models in site restoration activities. In this regulatory vacuum, the Army must develop its own clear policy concerning the roles and purposes of GWM.

Guidelines do not, and should not, prescribe or standardize assessment techniques or models. Because appropriate use of ground water models reflects the unique characteristics of each site, the requirements for their use must be site-specific. Under these conditions, providing specific, detailed and prescriptive guidance for model use would not be productive.

Guidelines developed by the Army should address the conduct of studies from conceptualization and planning through post-implementation review and foster careful, thoughtful analysis of each specific problem. Most importantly, guidelines should highlight the need for initiating any modeling effort at the beginning of a project as an integral part of the site characterization and remediation planning process. Modeling objectives should be stated clearly at the outset because they serve as the basis for decisions that are made throughout site restoration. In particular, *model requirements should guide data collection* during the initial site characterization process, when the site conceptual model is being developed based on a preliminary understanding of the physical, chemical, and biological processes that characterize the affected area. This conceptualization is very important. It is used to guide data collection, and provides the foundation for critical assumptions leading to the selection of appropriate ground water models. The initial conceptualization is then modified iteratively as knowledge and data permit. Collecting data in the absence of a modeling objective and consideration of model requirements is likely to be neither cost- nor time-effective.

1.2 Finding: Regulators and managers often have unreasonable expectations with regard to what models can be used to accomplish, and are seemingly unaware of their limitations.

The application of ground water models is a scientific practice that can play many roles in the design and implementation of site restoration activities. As such, they are subject to the common wisdom regarding mathematical models representing complex physical and biological processes, i.e., all models are wrong, but some are useful. Every contaminated site is unique and although it is commonly used as such, GWM is not intended to be a deterministic procedure that provides reliable predictions of future contamination scenarios. Rather, *GWM is a tool that can be used in a probabilistic sense to provide bounds on predicted scenarios and to help guide decision-making.*

Many within the Army appear to be unaware that GWM is not an end in itself. Even if everyone currently expected to perform or evaluate GWM for the Army had the expertise to do so reliably (and we find they do not), policy-makers must understand that the only thing reliable about the modeling predictions themselves is that they will differ. *GWM is a tool that can reduce the uncertainty related to decision-making when designing a sampling strategy, estimating the likelihood of human exposure and consequent health risks, and selecting remedial alternatives.* Models can be used to estimate the probabilities of outcomes. They should not be used to give deterministic answers; they do not of themselves determine the "right" remedy for a given situation. As a consequence, it is very important that the role of ground water models in the site restoration process be clearly established and modeling objectives be stated explicitly so that later disillusionment and misunderstanding can be avoided.

Reducing the flow and transport characteristics of multiple dissolved contaminants and nonaqueous phase liquids to a mathematical equation that accounts for the myriad chemical, physical, and biological processes that alter those 'characteristics in an ill-defined underground environment is destined to be a very uncertain procedure. The utility of predictions will differ depending on the underlying assumptions made, the natural heterogeneity of natural systems, and the structural differences between models and the real world. Thus it is *unrealistic* to rely on GWM to define site characteristics, while it is *realistic* to rely on ground water models to characterize the uncertainty associated with predicting the location and concentration of contaminants at a site.

Recommendation: **The Army should establish policies articulating the role of ground water models in environmental protection and site restoration projects and develop guidelines that will include GWM as an integral part of planning and conducting these activities.**

2. Training and Technical Support Requirements

2.1 Finding: Many Army personnel responsible for site restoration do not have adequate expertise to apply, review, and understand ground water models. Army personnel need and desire additional education, training, and technical support and assistance to use ground water models appropriately and to manage projects involving effectively.

Discussion at the March 1992 workshop on GWM use and needs and the results from the user's questionnaire clearly indicate that many Army personnel responsible for the use of modeling in site restorations do not have the education or training to properly use or review such models. The results of the questionnaire reveal critical dichotomies: the majority of the respondents identified themselves as having *little or no expertise* in GWM while simultaneously identifying themselves as *users of modeling results* in site restoration decision-making.

Army users lack in-house experience with modeling. A very small number of the questionnaire respondents or workshop participants involved with on-going or completed modeling studies considered themselves to be "adept" in the understanding and use of ground water models. Another 25% classified themselves as "experienced" users, and approximately 25% of the questionnaire respondents reported they had no experience with ground water models, but nonetheless had responsibility for restoration of

Army sites where GWM was being conducted or was going to be conducted. Participants in the Denver workshop felt they lacked adequate understanding of the conceptual limitations of particular models and model assumptions, and were unable to translate particular site situations into terms they could use in ground water models. Assuming these responses accurately reflect the state of modeling expertise in the Army, this bleak situation is likely to become worse: the number of modeling studies that the respondents expect to undertake for their organizations in the next five years is more than twice the number undertaken in the last ten years.

To supplement the limited number of qualified Army personnel, the Army places heavy reliance on the expertise of contractors; approximately 80% of ground water model applications in the Army programs are accomplished through contracts with private consultants. Often the contractor will recommend the selection of a model, perform the actual modeling application, and finally, interpret the results. Although the contractual partnership does not relieve Army project managers and Army technical support elements of their duty to oversee and monitor performance of site restoration activities, including the contractor's use of ground water models, these managers come from a wide variety of disciplines. They often do not have hydrogeologic or modeling experience. This diversity leads to managers relying on contractors' abilities to differing degrees, abilities that are also quite variable in quality.

Army users are not unaware of these limitations and problems. But despite the users' own recognition of their lack of modeling expertise, they judged the outcome of modeling efforts harshly; only one-half of the 61 GWM studies identified as on-going or complete were considered successful. Reasons cited for this record included lack of contractor expertise with respect to ground water models and/or a lack of in-house ground water analytic expertise sufficient to properly oversee and evaluate contractor efforts. Users felt (and the panelists concur) there is an insufficient level of technical support for GWM activities within the Army and no cadre of experts or center of expertise with the ability, time, and mission to provide needed assistance to the user community. All of these deficiencies contribute to inconsistent, sometimes inappropriate, or even disuse of GWM techniques within the Army's environmental restoration programs.

These problems underscore the fact that among some Army users there is a serious need for knowledge of basic modeling concepts and recognition of appropriate uses of models in support of decision-making. Within the broad user community there is a desire and growing need for better education, training and guidance in the use, applicability, and limitations of various ground water models, to better address current needs and to prepare for the increase in the number of site clean-ups for which the Army will have management responsibility in coming years.

Even the "experienced" model users expressed a desire for more information and technical support. Their questionnaire responses reflected a desire for better in-house technical assistance to accomplish many tasks including: protocols for the use of ground water models; improved contractor selection; in-house review of contractor products; quality control and quality assurance; and, improved access to or knowledge of reliable evaluations of particular ground water models.

2.2 Finding: The ground water model user community within the Army is spread among diverse organizations and has widely varying skills, with no process for mutual support.

The Army suffers from a lack of centralized scientific leadership, which is critical for gaining better understanding of the complex scientific problems associated with the use of ground water models. Ground water clean-up and related modeling efforts are being conducted within many organizational components of the U.S. Army but existing technical support, which is often provided through informal networks of personal contacts, does not uniformly meet the needs of the Army. Institutional support, such as the Army's COE research laboratories, WES and CRREL, currently can provide only limited assistance.

The absence of centralized scientific and expert leadership and responsibility within the highly complex and technically sophisticated arena of GWM accounts for much of the lack of coordination and diversity in the use of such models. Lack of centralized oversight and inadequate provision for technical assistance and support contributes to the frustration and disappointment voiced by many Army ground water model users. Given the number of challenging ground water evaluation and remediation problems across a multitude of Army sites and the uneven and unequal level of expert resources available to address these problems, disappointment with modeling outcomes is not surprising.

There are several Army or DoD programs with some linkage to or responsibility for environmental restoration, with the major clean-up and restoration programs being the Defense Installation Restoration Program (DIRP), for site restoration on existing, in-use bases and the Formerly Used Defense Sites (FUDS), Program, for clean-up of abandoned and unused military sites. It should be noted, however, that many different organizations and entities are nominally responsible for program execution, and thus for ground water assessment and clean-up.[14] Despite the plethora of environmental restoration responsibility, none of these entities has the responsibility or resources for coordinating or assuring that GWM efforts are conducted effectively and efficiently within the Army as a whole.

For example, the U.S. Army COE Military Programs Directorate (USACE-CEMP) is responsible for execution of clean-ups at FUDS. This work is executed through the COE districts and, in some cases, division offices, which are responsible for conducting site restoration projects that involve ground water contamination, and thus potentially involve the use of ground water models. Although most of the COE district offices have responsibility for remediating similar types of sites with similar types of contamination and varying levels of site complexity, there is a wide variation in the level of effort, resources, and expertise available to conduct GWM. For instance, the COE Tulsa District has a relatively high level of resources (both personnel and equipment) and ground water expertise. Designated a "model district" with more flexible on-site authority than other districts, Tulsa is one of the most progressive Corps districts in the conduct of ground water restoration projects. In contrast, other USACE district offices that have few personnel with appropriate educational background or ground water expertise and limited computational equipment are also responsible for performing similar site restoration efforts. And despite its ground water leadership and expertise, the Tulsa District Office does not have the mission nor the resources to provide GWM assistance to other Army or even Corps organizations.

---

[14] Other programs with some programmatic responsibility for installation clean-up or science and engineering research and technology development to facilitate such ends are: the Base Review and Closure (BRAC), Program addressing clean-up activities on bases identified for closure and turned over to other authorities in the near future Project Reliance, a DoD interagency program in which certain organizations have lead responsibility for research and development (R&D) addressing particular environment restoration needs (i.e., the USACE has responsibility for GWM and providing technical support to other DoD organizations, integrating modeling components, and process R&D on explosives, metals, flow, and cold region concerns); the Army Hazardous Toxic and Radioactive Waste Program; and, some individual, site-specific programs such as the Rocky Mountain Arsenal restoration project.

Another COE organization, the Missouri River Division (MRD), has been designated the Mandatory Center of Expertise for Hazardous Toxic and Radioactive Waste (HTRW) for all of USACE. This responsibility includes providing review and assistance to USACE Districts executing HTRW projects at FUDS sites, including those with GWM aspects. MRD has approximately 2.5 full-time personnel committed to such review and, according to presentations to this panel, is currently able to review only 15% of the documents generated on site restoration projects. Although a large amount of GWM expertise resides at MRD, the technical assistance provided by MRD tends to be very limited and focused on special projects. They cannot provide routine support.

The USATHAMA, now part of the newly-created AEC, is responsible for the Installation Restoration Program (IRP), which is an element of the Defense Environmental Restoration Program (DERP). USATHAMA's mission is to work on active DERP projects, i.e., to work on properties now owned or operated by the active Army. Within USATHAMA there is a small (5 person) group that conducts most of the modeling-related activities at the agency. Given the limited resources of this group and its large field work mission, USATHAMA currently cannot provide assistance to other Army entities, nor is such assistance within its mission.

In addition to these organizations, some of the U.S. Army's installations with particularly difficult site problems, such as the Rocky Mountain Arsenal, have also developed some degree of understanding and experience in the use of GWM. But like the COE districts, the expertise and resources in the area of GWM vary greatly and none of it is available to address Army-wide needs.

Recommendation: **The Army should establish a Technical Support Center to provide: training to increase the number of qualified personnel; technical assistance to respond to issues relating to appropriate use and interpretation of GWM results; and, technology transfer — spreading technical and user information involving the use and limitations of GWM — to Army personnel involved with site restoration activities.**

The Technical Support Center should have the capacity to provide:

- Training programs at a variety of skill and understanding levels for Army personnel involved in ground water restoration including basic modeling concepts, state-of-the-practice and state-of-the-art ground water models, and the use of models in decision-making.

- Expert personnel *dedicated* to provide technical assistance at a variety of levels to enhance the Army's endeavors in site restoration, especially with regard to GWM efforts.

- Technical assistance available to Army personnel on all aspects of ground water management such as site characterization methods, characterizing uncertainty, model selection and use, and especially the limitations of ground water models.

- Guidance to Army decision makers on the implications of the results of ground water studies.

- Mechanisms such as workshops, user groups, short courses, newsletters, electronic bulletin boards, etc. to facilitate: technology transfer of information on new developments, new techniques, and new applications of ground water models *to* users of ground water models at Army sites; and, communication *among* users of ground water models at Army sites to accommodate information exchange and collaboration on similar problems related to GWM and management of ground water problems.

3. The Ground Water Modeling/Simulation Research Program

Before discussing the findings and recommendations of the study panel on the proposed Ground Water Modeling/Simulation Research program, some further detail about the research proposal is needed. Under Project Reliance, the USACE has the lead responsibility for research on cleaning up water pollution caused by military contaminants common to all DOD organizations (e.g., explosives, metals) as well as Army-specific hazardous wastes. In connection with this responsibility, the COE WES — long-associated with surface water studies and research — has developed an R&D plan for improved use and further development of ground water models and simulations. A key focus of this initiative is the development of a comprehensive, integrated, state-of-the-art GMS to facilitate Army and DoD activities such as risk assessment, site characterization, and clean-up of contaminated ground water.

As part of this GMS, WES proposes to undertake activities in five technical areas: (1) evaluate existing technology; (2) develop an integrated user environment; (3) conceptualize subsurface processes; (4) develop flow, transport, and remedial simulations; and, (5) provide technical assistance. Researchers will assess and evaluate existing modeling software programs with the goal of developing a comprehensive expert system for modeling suitable for use in differing hydrogeologic environments. Plans for this database management software system have the goal of rationalizing and integrating a variety of existing ground water modeling programs with differing capabilities and operative modalities. GMS is designed to be "user-friendly," i.e., possess point and click operation, interactive ability, and be capable of providing graphical visualization of results. Additionally, it will have a standardized data format and be capable of translating, integrating, and manipulating dissimilar data types from differing software/hardware platforms into a single database management system.

The GMS includes elements other than integration of existing software, which is a very large job in itself. Another critical research goal is to gain better understanding of ground water flow and transport processes relating to Army-specific compounds in differing hydrogeologic environments: a key component of the proposed R&D effort "will be the improvement and, where needed, creation of process formulations for military-unique compounds in highly heterogeneous environments."[15] Through field trials and demonstration programs, the research program will also provide an opportunity to verify both existing and new conceptual theories, which provide the foundation for development of effective systems. Furthermore, the plans call for technology transfer (a key mission for federal laboratories) with research and model development combined with demonstrations, feedback, and other extensive outreach activities providing information and training on ground water models and modeling to users throughout the Army.

[15] Plan for Development of a Comprehensive, Integrated System of Ground Water Models, op cit. With the exception of fuels and solvents (where the Air Force has the research lead) this research will address chemical compounds of interest to the Army and the Air Force.

3.1 Finding: The proposed program for Ground Water Modeling/Simulation Research, especially the GMS, is an ambitious one. It appears to be sound scientifically, and if implemented will help to meet the requirements of the Army's Environmental Restoration program. It is not apparent, however, that the quality and level of resources — funds or personnel — are sufficient to meet the goals of the program.

Based on the ASB panel's evaluation of the issues and the expert opinion of members of the NRC Water Science and Technology Board panel as well as potential users, we believe that the proposed GMS program is sound scientifically and that on the whole, WES personnel appear qualified to undertake it. There are many ground water models now in existence: none are perfect but perhaps they go as far as the state of theory and knowledge permit. It is clear there is an immediate need to provide technical assistance and advice concerning these programs to the many users throughout the Corps. The GMS has the potential to help users in the field and facilitate self-education through embedded training and self-help tools, especially if it is made user-friendly, is easy to update, and has easy data convertibility and integration across differing models. The WES GMS proposes to address these issues and more.

An ambitious program with challenging goals has been outlined. The ambition and challenge embedded in this research should be applauded. But the WES team and those in upper management who have the responsibility for monitoring the performance of this team will have to work to assure that real priorities get the proper attention. The Ground Water Modeling/Simulation research program is a large, complex, lengthy project, and requires program management that is continually attentive to a variety of issues including cost, schedule, research objectives, external research progress, model computational capabilities, and regulatory contexts.

That the GMS research program is ambitious is evident not only from the scope of the proposed research, but also in its scale in terms of funding, personnel, and projected time to accomplish its goals. The demonstration and implementation of the first version of this system is late 1995, with the second (state-of-the-art) version available by the year 2000. At this time the proposed budget for this effort is $28.4 million, allocated among the five task areas over a seven-year period. It should be noted that almost half of the proposed budget ($13.4M) is unfunded; the rest of the funds come from a variety of DoD programmatic funding, and $1.3M is coming from reimbursable studies for site-specific investigations.[16]

This effort will involve partnering with the Air Force and other non-DoD agencies, in particular EPA and the Department of Energy (DoE), which WES and others view positively. WES will have the lead role for development of this GWM effort, which is a new research direction for WES researchers (although some in the WES group have some academic or operational experience with ground water models). However, the WES team does have experience in mathematical modeling of surface water flow and WES has been involved in site characterization and remediation activities for many years. The plans call for a multidisciplinary research team of 16 members, including 13 Ph.D.s with backgrounds in

[16] DOD Groundwater Modeling/Simulation Research Plan, op cit., p. 21.

hydrogeology, engineering, geochemistry, biology, mechanics, visualization, and computational methods.[17] In discussion with WES personnel, however, the study panel could not determine how many of these personnel will be able to dedicate their full time work effort to this project or whether the budget included personnel costs.

Given the scope and complexity of the project, the study panel stresses the importance of instituting a continual process of user assessment, feedback, and evaluation of user problems to ensure that the research goals stay focused on user requirements. A peer review system should also be instituted to keep the GMS development technically on track. Two meetings in 1992 (the one in Denver in March and another in Omaha in November) provided user feedback that has already had a positive impact. At this time, an on-going mechanism for productive exchange of ideas appears to be in place and current project managers are committed to continued interaction with the user community. The ASB panel is concerned, however, that once the GMS project is under way, imaginative personnel may be tempted to follow "interesting" but tangential issues.

The central focus of the WES proposal must always be the support of model users and site clean-up activities. The user community, out in the field, is the real world where products are measured by their overall effectiveness for the purposes for which they are intended. The focus on facilitating site clean-up activities implies that the GMS researchers must pay constant attention to technology transfer, technical support, and training. For researchers these are neither easy nor familiar concepts. Thus, the system must embed a process of continual interaction with the user community, reinforced and monitored by institutional commitment (e.g., by WES and Corps managers).

---

[17] DOD Groundwater Modeling/Simulation Research Plan, op cit., p. 11.

Other concerns regarding the general approach and requirements for GMS research which were often voiced by users or by the ASB panelists in their discussion are:

- It is currently more important that existing ground water models be used fully and effectively than that new models be developed; i.e., training, technical support and expertise should have priority at this point.

- The GMS must be compatible with readily available hardware being used by client groups at the time it is released.

- Enhanced compatibility of data bases among ground water programs and other data management tools are crucial to the early success of the program. Because timeliness is a critical factor in site characterization and assessment, redundant data entry should be eliminated through development of software translator programs.

- Simplified user interfaces will meet identified user needs, but simplification must not obscure the particular ground water model assumptions and limitations (theoretical concepts) embedded in each model -- assumptions which, if hidden, increase the potential for uninformed and erroneous use of models. Any new ground water model must be well-documented and supported with training.

Finally, the ASB panelists would like to voice two major concerns regarding the professional and financial resources for this project. First, professional: because WES' previous modeling activities focused on surface water phenomena, particular care must be taken to assure that this new program has the active involvement of persons with expertise in ground water phenomena. The GMS development team should represent a critical mass of knowledge-based scientific personnel, both to generate truly innovative approaches and to have the time and ability to implement innovations in a successful project. The project requires a dedicated team, not a part-time team. Selecting team personnel from among WES personnel now available, rather than recruiting on the basis of appropriate knowledge and specialized expertise, should be avoided.

The absence of a statistician/stochastic modeler in the composition of the research project team is particularly troubling. Modeling is a mathematical concept based on probability theory. A qualified person with statistics background is needed to achieve a credible product. GWM deals with probabilistic concepts in a very complex arena; statistical methods must be considered for evaluating and determining risk, and approaches for site and ground water cleanup; and evaluating remedial effects. The notion that these complex statistical issues can be addressed by those with limited training or training in different analytical methods (as was implied by at least one project manager) is unjustified. The proposal appears to underestimate the difficulty of software development (e.g., the very difficult design and implementation problems that can arise when modules/models are to have a common interface and yet satisfy differing software and hardware platform requirements; the complexity of the requirements for these models; and, the realities of incorporating graphics capability). Furthermore, there appears to be limited awareness concerning recent research advances in the software development field external to WES and the Army, advances that should be exploited in construction of the GMS (e.g., use of project management software to estimate cost and time). The WES team would be well-advised to establish an on-going external peer review group to ensure that their researchers bring the best technical insight to this project.

To spark innovation within the WES team, WES should bring in additional talent well-grounded in statistical and ground water theory. We recognize that the ability to bring in additional talent dedicated to this project depends on adequate project financing, however, which is the second of our resourcing concerns. Although much thought and planning have been devoted to the proposal, it is simply not clear that a program of such size, complexity, and duration can be accomplished within the proposed budget and time schedule. This opinion is based more on the personal experience of some of the ASB panelists with large modeling projects, rather than on a detailed review of the GMS proposal's schedules, personnel resources, equipment, and budget. Such details go beyond the TOR of this panel.

Initiating a project of this scope and complexity requires people dedicated to achieving the team goals and funding resources that support a focused effort. The WES staff working on the proposed program is very enthusiastic. While enthusiasm is a necessary component of a successful project, management review must guard against underestimating the effort needed for this project, which might increase the likelihood of getting the proposal approved and funded, albeit under-resourced (lacking a critical mass of experienced personnel) and/or under-funded. Such underestimation may not be intentional, but conceptual difficulties may be overlooked and task estimates under-programmed in a desire to ensure the acceptance of the basic proposal.

The funding process is intricate, but the project funding must be appropriate to its scope and goals. If funding turns out to be insufficient to perform all components, it is essential that priorities be established at an early stage (with user involvement) so that the scope of the project can be reduced and refocused in a rational manner. Additionally, creative ways to leverage Army resources, for example, through partnerships with other government agencies, industries, and universities, should be explored. Such a "partnering" effort already appears to be underway.

Recommendation:

- **The proposed research program should be implemented and a process established to ensure close interaction with the user community to guide program priorities. The program should be a dynamic one and be modified as requirements and resources change.**

- **Project resources — time, budget, and talent — should be reassessed to reflect the true needs and scope of project goals.**

- **An independent advisory group should be established to monitor and review the adequacy of planning and programming, as well as to assure technical credibility.**

3.2 Finding: Components of the proposed GMS will be completed after many Army site restoration efforts are underway. Incremental development of the GMS system with clear user-defined intermediate products is therefore critical to address immediate needs. Ground water models are currently available that can be used by the Army in its site characterization and remediation efforts, although field-scale verification of many models is incomplete.

The Army is under the environmental restoration gun: the urgency of Army clean-up problems as well as periodic review of the efficacy of remedial measures required by EPA, dictate immediate action, even if improved modeling tools for remediation analysis and decision-making are not available until some future time. It is especially important that the GMS research team be prepared and willing to provide intermediate products (e.g., a common data format and translator programs) that meet immediate needs. The GMS project may be unique: there are many intermediate by-products — necessary steps to the GMS goal — that can be of use to the user community as they develop. These intermediate outcomes will thus leverage modeling effectiveness as products are developed as well as provide a constituency and support for further research efforts.

The NRC WSTB panel, and modeling practitioners (COE and external consultants), repeatedly noted that there are models currently available for use by the Army in its immediate site characterization and remediation efforts. Existing models (if used effectively) were considered by the user community and the WSTB panel to be generally adequate to represent current data, science, questions, and computers. These models are not perfect; better ones can and will be developed. Users are less concerned with the need for new models and more concerned with the need to cope with the complexity and specialization of existing models. Some ground water models are better for some situations than others but lack of time for training and incompatible data bases (thus necessitating re-keying data) finds users relying on the models they know rather than on a model that is right for a given situation. Overwhelmingly, the need for more effective, informed use of existing models was deemed more important by users than the development of new models.

There is another important by-product provided by this project: an opportunity for field-scale verification studies of existing models. Verification (testing conceptual theory and mathematical characterization in actual field practice environments) is necessary for credible use of models, and in particular for understanding the predictive capabilities of models. Ten percent of those who responded to the users' questionnaire stated "poor model credibility" as their reason for not using ground water models. The WSTB report also had as one of its key findings the need to "undertake field-scale research and testing of model applications."[18] In addition, a recent EPA Science Advisory Board report noted that "[t]here should be better confirmation of models with laboratory and field data."[19]

The Army is in a unique position to undertake field-level verification studies because it possesses the requisite data and knowledge of various models and has the complex field sites on which to test theory in practice. The ASB panel was pleased that a key component of the program proposed by WES is the verification of ground water models. It is also significant that the proposed program plans to enhance the probabilistic (versus deterministic) nature of modeling by incorporating statistical criteria in the verification process.

Recommendation: **Technology transfer must be a continual part of the GMS development process, with intermediate GMS products transferred to the user community (including contractors) as developed. Initial GMS research program efforts should be devoted to: improving user capability for extant models; field-scale research and improving the predictive capability of existing models; and, improving the scientific understanding of flow, transport, and fate processes.**

---

[18] National Research Council, A Review of Ground Water Modeling Needs for the U.S. Army, Water Science and Technology Board, September 1992, p. 2.

[19] Environmental Engineering Committee, Resolution on Use of Mathematical Models by EPA for Regulatory Assessment and Decision-Making, EPA Science Advisory Board, Environmental Protection Agency, Washington D.C. 1989.

3.3 Finding: There are Army-specific contaminants, such as explosives, on which little research is likely to be performed outside the Army. There is a need for additional basic research to characterize the behavior of these contaminants, to provide accurate input to ground water models used in Army site restoration activities.

While obvious, this finding is very important. *Given its limited resources, the Army should focus on its unique problems.* This issue was clearly identified both in the COE user workshops as well as in the external community of experts. The WSTB concluded that the Army should: "[i]nvestigate the physical, chemical, and biological processes occurring in subsurface contamination with explosives, since these contaminants are less likely to be studied by other agencies and may have unique problems."[20] We concur. In general, new ground water models are needed to address new data, new science, new questions, or new computational capabilities. Basic research on contaminant flow and transport processes in subsurface geologic conditions undertaken by the Army and WES should focus on Army problems. Minimally, it must be determined to what extent Army problems are truly unique, for there is always the possibility that progress on Army-specific problems will have broader impact on the modeling of contaminants. However, Army-specific compounds are likely to be addressed by no one but the Army, while more general issues are being addressed elsewhere, such as by universities or government contractors.

Recommendation: **The research program should give priority to investigating and characterizing physical, chemical, and biological processes that affect Army-specific contaminants.**

---

[20] A Review of Ground Water Modeling Needs for the U.S. Army, op cit.

BIBLIOGRAPHY

Butler, D.K, M.J. Cullinane, P.F., Hadala, J.P. Holland, I. May and T. McDaniel, Army Groundwater Modeling Use and Needs Workshop, US Army Corps of Engineers, Waterways Experiment Station, Vicksburg, MS, September 1992.

Heijde, Paul, K.M. van der, Aly I. El-Kadi, and Stan A. Williams, Groundwater Modeling: An Overview and Status Report, U.S. Environmental Protection Agency, R.S. Kerr Environmental Research and Development, Ada, OK, December 1988.

National Pesearch Council, Ground Water Models: Scientific and Regulatory Applications, Water Science and Technology Board, Comm. on Ground Water Modeling Assessment, Comm'n on Physical Sciences, Mathematics, and Resources, National Academy Press, Washington, D.C 1990.

National Research Council, A Review of Ground Water Modeling Needs for the U.S. Army, Water Science and Technology Board, Commission on Geosciences, Environment, and Resources, National Research Council, Washington, D.C. September 1992.

U.S. Army Corps of Engineers, Army Groundwater Modeling Use and Needs Workshop, Available Abstracts, USAE Waterways Experiment Station, Vicksburg, MS, n.d.

U.S. Army Corps of Engineers, "Groundwater Modeling/Simulation Research Plan", "Task Area 1: Evaluation of Existing Technology" , "Army Groundwater Modeling/Simulation Research", "Integrated User Environment", "Implementation and Demonstration", Major R&D Initiatives Completed", "Improved Site Characterization", Presentations, USAE Waterways Experiment Station, Vicksburg, MS, n.d.

U.S. Army Corps of Engineers, Plan for Development of a Comprehensive, Integrated System of Groundwater Models and Analysis Tools for Use in DOD Installation Cleanup, USAE Water ays Experiment Station, Vicksburg, MS, 5 November 1992

U.S. Army Corps of Engineers, "Questionnaire on Army Use of Groundwater Flow and Contaminant Transport Models", USAE Waterways Experiment Station, Vicksburg, MS, n.d.

U.S. Army Corps of Engineers, "Groundwater Modeling in the Corps of Engineers", Presentation, Missouri River Division, USACE, n.d.

U.S. Army Corps of Engineers, "Review of Questionnaire on Army Use of Groundwater Models", "Army Groundwater Modeling Users Workshop", Presentations, USAE, Waterways Experiment Station, Vicksburg, MS, n.d.

U.S. Army Corps of Engineers, "Tulsa District Groundwater Modeling Expertise, Presentation, G. Hall, Tulsa, OK, n.d.

U.S. Environmental Protection Agency, "Consideration in Ground-Water Remediation at Superfund Sites and RCRA Facilities — Update", Memorandum, Directive No. 9283.1-06, D.R. Clay, Office of Solid Waste and Emergency Response, Washington, D.C. May 27, 1992.

U.S. Environmental Protection Agency, "Five Year Strategy to Address Groundwater Contamination under CERCLA", Office of Emergency and Remedial Response, Washington, D.C., July 31, 1992.

U.S. Environmental Protection Agency, "Report of EPA Models Management Initiative", Presentation, n.d.

U.S. Environmental Protection Agency, Report on the Usage of Computer Models in Hazardous Waste/Superfund Programs, Phase II, Final Report, Office of Solid Waste and Emergency Response, Washington, D.C. December 1990.

U.S. Nuclear Regulatory Commission, "NRC Capabilities in Performance Assessment and Computer Modeling of High-Level Waste Disposal Facilities", Advisory Committee on Nuclear Waste, Letter to Commissioner Rogers, Washington, D.C. December 2, 1991.

GLOSSARY

AEC	Army Environmental Center
ASB	Army Science Board
BRAC	Base Review & Closure
CERCLA	Comprehensive Environmental Response, Compensation & Liability Act
COE	Corps of Engineers
CRREL	Cold Regions Research & Engineering Lab
DERP	Defense Environmental Restoration Program
DIRP	Defense Installation Restoration Program
DOD	Department of Defense
DOE	Department of Energy
EPA	Environmental Protection Agency
FUDS	Formerly Used Defense Sites
GWM	Ground Water Modeling
GMS	Ground Water Modeling System
HTRW	Hazardous Toxic & Radioactive Waste
I&E	Infrastructure & Environment
IRP	Installation Restoration Program
MRD	Missouri River Division
NRC	National Research Council
RCRA	Resource Conservation & Recovery Act
R&D	Research & Development
TOR	Terms of Reference
USACE	US Army Corps of Engineers
USACE-CEMP	US Army Corps of Engineers - Corps of Engineers Military Programs
USATHAMA	USA Toxic & Hazardous Material Agency
WSTB	Water Science & Technology Board
WES	Waterways Experiment Station

APPENDIX A

ISSUE GROUP STUDY REQUEST
BACKGROUND
TERMS OF REFERENCE
PROPOSED ISSUE GROUP MEMBERS

DEPARTMENT OF THE ARMY
U.S. Army Corps of Engineers
WASHINGTON, D.C. 20314-1000

February 27, 1992

REPLY TO
ATTENTION OF:

Mr. James Jacobs
Chair
Army Science Board
The Pentagon, Room 3E359
Washington, DC 20310-0103

Dear Mr. Jacobs:

I am requesting the Army Science Board to initiate a Issue Group Study titled: "Groundwater Modeling in the Army's Environmental Restoration Programs." Enclosure 1 is a background paper that describes the problem while Enclosure 2 is a proposed Terms of Reference (TOR). I have discussed the proposed study with Dr. Crystal Campbell, Chairperson, Infrastructure and Environment Panel, and she has concurred with the proposed TOR. Enclosure 3 is a list of the Senior Staff Assistants, Technical Staff Assistants, and suggested members of the Issue Group.

During the 31 March - 1 April 1992 period, the Army is conducting a groundwater modeling use and needs workshop in Denver, Colorado. I would like to initiate the proposed study in conjunction with the workshop. The workshop will provide the Issue Group members an opportunity to become familiar with the current situation regarding groundwater modeling in the Army's restoration programs. Enclosure 4 is a draft meeting notice for the 31 March - 1 April 1992 for the Federal Register.

Sincerely,

ROBERT B. OSWALD
Director, Research
and Development

Enclosures

CF:
CETHA-CO
CEMP-ZB/CEMP-RT(T. McDaniel)
CEWES-ZA (Wahlin)/CEWES-HV-C (J. Holland)
OASA(IL&E) (R. Newsome)
ENVR-EH (B. Pringle)
CETHA-IR (I. May)
CERD-M (T. Hart)
SGRD-UGB-E (M. Small)

GROUNDWATER MODELING
IN THE
ARMY'S ENVIRONMENTAL RESTORATION PROGRAMS

BACKGROUND

Activities at numerous military installations have produced groundwater contamination which pose human health problems and threaten wildlife habitat and wetlands on and adjacent to these facilities. The Army is legally required to cleanup these sites, and the overall cost will be significant. The Army is spending more funds on groundwater-related problems than any other cleanup activity at Army installations.

Remediation of contaminated groundwater and soils is an exceptionally difficult problem because contaminants often exist in complex hydrogeologic conditions where a variety of physical, chemical, and biological processes are occurring. The ability to determine the nature and extent of existing contamination and to predict further contamination migration is required to conduct risk assessment, evaluate, design and operate remedial alternatives, and monitor the progress of cleanup. Trial and error remedial actions are unacceptable when human health and cost are considered. Therefore, the Army must improve its capability to evaluate and predict the effectiveness of potential remedial technologies to develop viable and cost effective solutions.

Groundwater modeling is one of the tools being used to aid in solving remediation problems. A number of different elements within the Army, e.g, CETHA, individual installations, Corps district offices, etc. are using a variety of groundwater models throughout the remediation process. These modeling efforts have met with varying degrees of "success." The problems encountered appear to be related to the following factors:

- unreasonable expectations - sometimes managers and regulators do not understand model limitations or adequately define their needs (models are no substitute for experience and judgement)

- level of effort is not correctly geared to the actual problem (a 3-D flow model is attempted when an analytical or no model may better address a particular question)

- modeling experience or expertise may not be available

- there may be a lack of data to adequately select, develop, calibrate, and verify a model

ENCLOSURE 1

- misapplication of model type to problem (misunderstanding the hydrogeology and/or the model assumptions)

- it may be costly and time consuming to develop a model adequately (schedule driven projects, poor estimating)

- poor documentation of models and of modeling efforts (difficult to interpret and defend results)

- lack of appropriate models to accurately represent the spatial and temporal distribution of groundwater flow and predict contaminant, water, and porous media interactions in a multidimensional, biochemodynamic environment

These and other problem areas related to groundwater modeling need to be address to more effectively use groundwater modeling as a tool to aid in the remediation process.

GROUNDWATER MODELING
IN THE
ARMY'S ENVIRONMENTAL RESTORATION PROGRAMS

TERMS OF REFERENCE

a. Evaluate the current use of groundwater models in the Army's Installation Restoration Program and assess the degree to which the Army is using the existing modeling capability to meet current and projected requirements. Items to consider in this evaluation include:

(i) Identify gaps between the state of Army practice (including its contractors) and the state of the art that are or may be critical to or impede the effective use of modeling for site characterization, remedial alternatives evaluation, and monitoring (e.g., risk assessment, remedial alternatives evaluation, design and operations.)

(ii) If gaps discussed in (i) are identified, recommend remedial actions, including institutional or administrative changes, to remove the impedance(s) to effective use of groundwater models.

b. Review the Army's Groundwater Modeling Research Program to ascertain if it is directed towards meeting the Army's Restoration Program requirements. As part of this review identify the role of the research community in increasing the effectiveness of the Army's use of current groundwater models.

ENCLOSURE 2

PARTICIPANTS LIST

ARMY SCIENCE BOARD
INFRASTRUCTURE AND ENVIRONMENTAL ISSUE GROUP STUDY
ON
"GROUNDWATER MODELING IN THE ARMY ENVIRONMENTAL RESTORATION PROGRAM"

STUDY CHAIR
Dr. Gail Charnley
Consultant in Toxicology

STUDY PARTICIPANTS

Dr. Martin Alexander
Cornell University

Dr. Crystal Campbell
Padanaram Associates

Ms. Kim Green
Branch Manager
Environmental Services
Ogden Environmental & Energy Services

Dr. Alan Karr
Professor of Mathematical Sciences and Associated Dean for Special Projects

Dr. George Piegari
Head of the Department of Mathematics and Computer Science

Dr. Jay Sculley
Grumman Corporation

SPONSOR
Dr. Robert B. Oswald (CERD)
Department of the Army
HQ, US Army Corps of Engineers

SENIOR STAFF ASSISTANTS
Dr. Thomas L. Hart (CERD-M)
Department of the Army

TECHNICAL STAFF ASSISTANTS
Ms. Tomiann McDaniel (CEMP-RT)
Department of the Army
HQ, US Army Corps of Engineers

Mr. Ira May (Cetha-IR)
US Army Toxic and Hazardous Materials Agency

APPENDIX B

SUMMARY OF RESPONSES TO USER QUESTIONNAIRE

PART III: SUMMARY OF RESPONSES TO QUESTIONNAIRE ON ARMY USE OF GROUNDWATER MODELS

14. Introduction. In early February 1992 a questionnaire (provided in total in Appendix D) was developed at the Waterways Experiment Station (WES) that solicited information on Army use of and experience with groundwater flow and contaminant transport modeling tools in support of contaminated site characterization and remediation. The questionnaire also sought user input on the research and development (R&D) requirements for future model development. The questionnaire was mailed to 22 Corps of Engineers (CE) district and/or division offices, generally to specific individuals designated by Military Programs Directorate, Headquarters, Corps of Engineers (CEMP) personnel. Forty-seven (47) responses from 17 CE offices were received. Responses were obtained from 28 users at the US Army Toxic and Hazardous Materials Agency (USATHAMA), representing seven USATHAMA elements, and from two Army installations (Aberdeen Proving Grounds, MD, and Fort Richardson, AK). While only two installations were polled directly, USATHAMA representatives provided input for all other known uses of groundwater models at Army installations. Thus, it is believed that the vast majority of potential Army groundwater model users doing modeling in support of contaminated site cleanups received questionnaires.

15. An analysis of the questionnaire responses is presented in the following paragraphs. The results of this analysis are presented in the forms of graphs, tables, and simple statistics (such as percentages) for each question posed. This document seeks to present a snapshot of where the Army finds itself relative to groundwater modeling at this time.

16. This part of the report is arranged by section for each survey question. Following these sections, additional analysis of the global survey is provided, along with a summary.

17. Question 1. What percentage of the hazardous and toxic wastes (HTW) problems you are encountering at military or Superfund sites is associated with

____ Petroleum Hydrocarbons

____ Organic Solvent Liquids

____ Explosives

____ Metals

____ Other (please specify) ____________________

The responses to this question are given in Figure 2, with an overall response (2a), and a breakdown for the CE and USATHAMA/Installation responses (2b and 2c, respectively). The designation o. "high, medium, or low" was developed based on these criteria:

<u>high</u> - response percentage greater than 33 percent

<u>medium</u> - percentage between 10 percent and 33 percent

<u>low</u> - percentage less than 10 percent

18. As shown, the Army is most strongly concerned about hydrocarbons, organic solvents, and explosives cleanup. A growing concern with metals appears looming as we..., given the elevated medium vote casted for this class of containment. The "other" category contained several things including pesticides, PCB's, radionuclides, and herbicides. Note also that, other than a slight change of order of priority, very little difference was found between the CE responses (Figure 2b) and the THAMA/Installation responses (Figure 2c).

19. <u>Question 2</u>. For the sites referred to above, how many of them are, or are projected to be, involved with the cleanup of contaminated groundwater resources for both saturated and unsaturated conditions? ____(military) ____ (Superfund) What percentage of the total number of your HTW sites is this number? ____(military) ____(Superfund) The responses to this question were very difficult to analyze due to relative incompleteness of the responses. Of the information that could be analyzed, over 60 percent of the respondents said their HTW (hazardous and toxic wastes) sites had contaminated groundwater as a principal concern, with military and Superfund sites both receiving significant representation. <u>This number, however, is probably low.</u> Communication with multiple USATHAMA personnel, and several CE offices, indicated that over 85 percent of all Army RI sites investigated to date have groundwater contamination as a point of prime concern (given that a concern is registered at all).

20. <u>Question 3</u>. How many of your groundwater-related cleanup studies (over the last ten years) contained, or are projected (over the next five years) to contain, a groundwater modeling effort? ____ If this number is zero, skip to Question 10. Respondents listed 127 groundwater model ng studies that had been conducted in the last ten years, or were projected over the next five years. Additio..l analysis of the information provided .n Table 2 (see Appendix D for Table . details) of the questionnaire revealed that 61 of

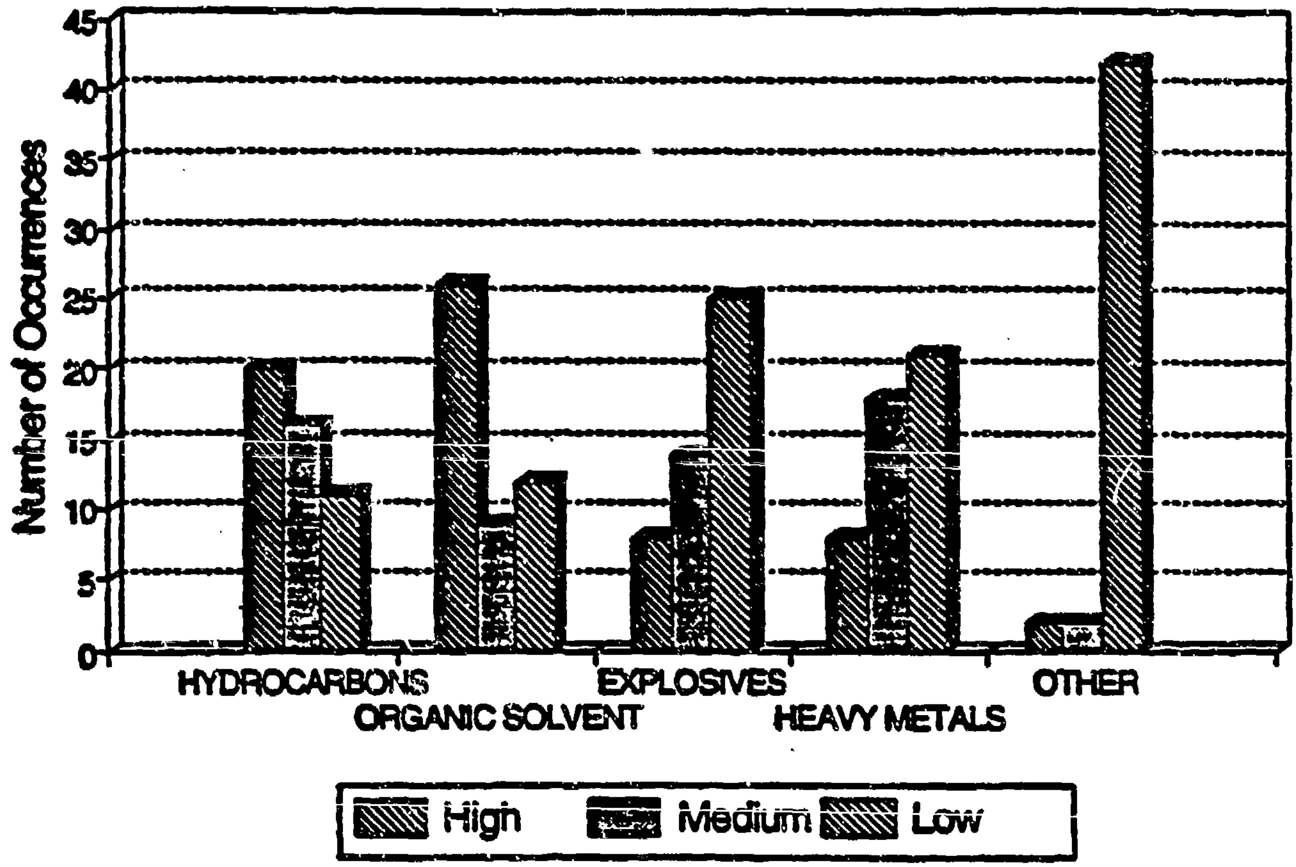


Figure 2a. Army contaminants all respondees

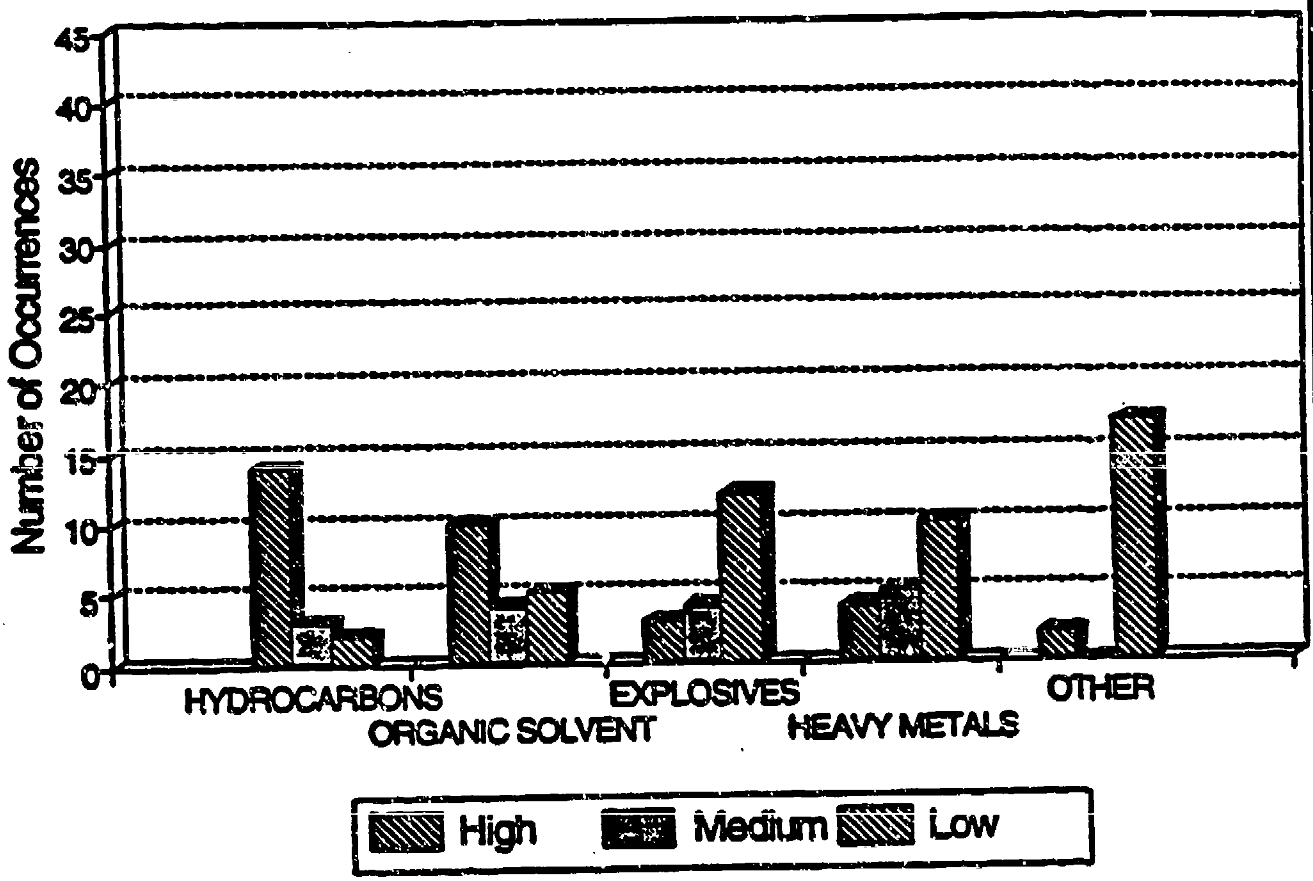


Figure 2b. Army contaminants CE districts/divisions

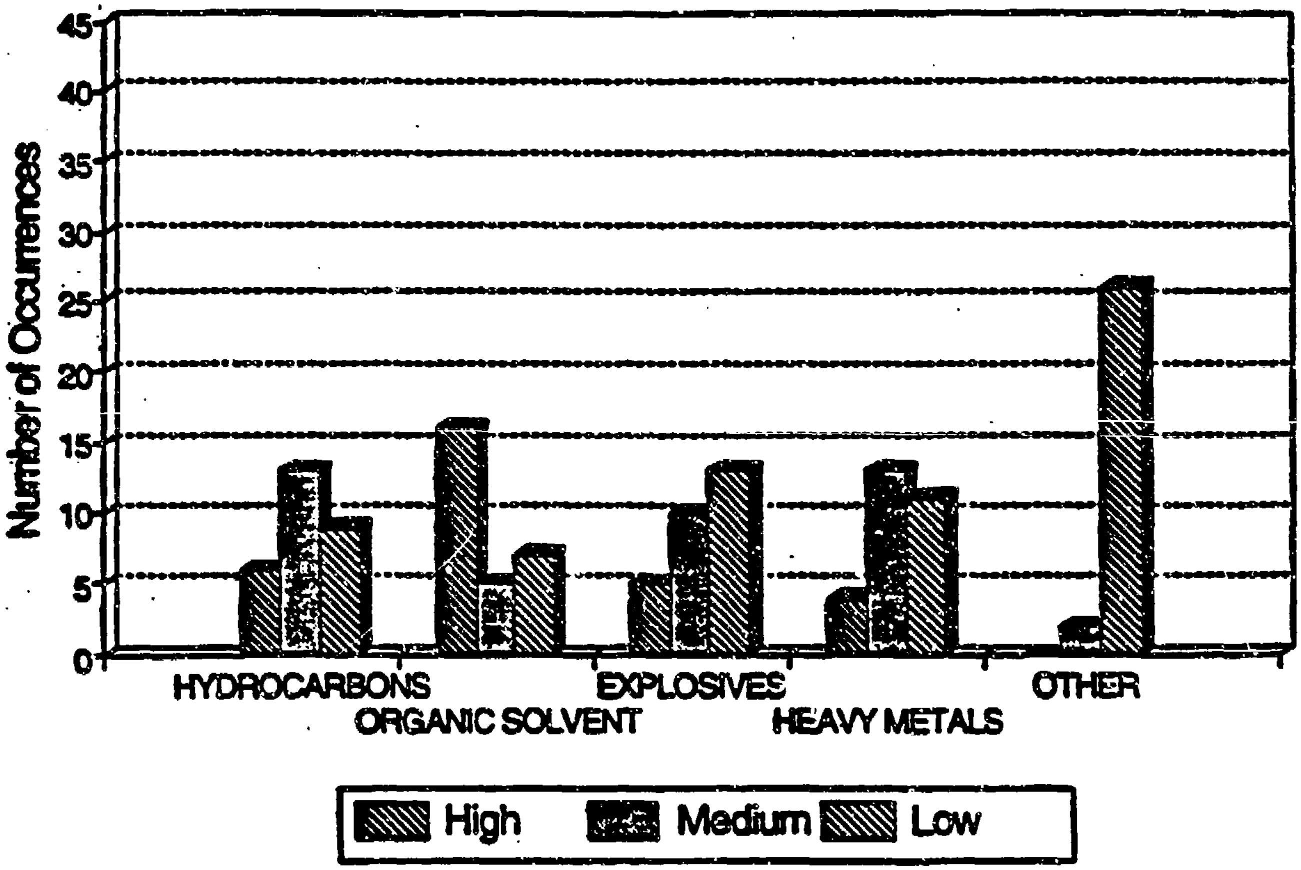


Figure 2c. Army contaminants
CETHAMA and installations

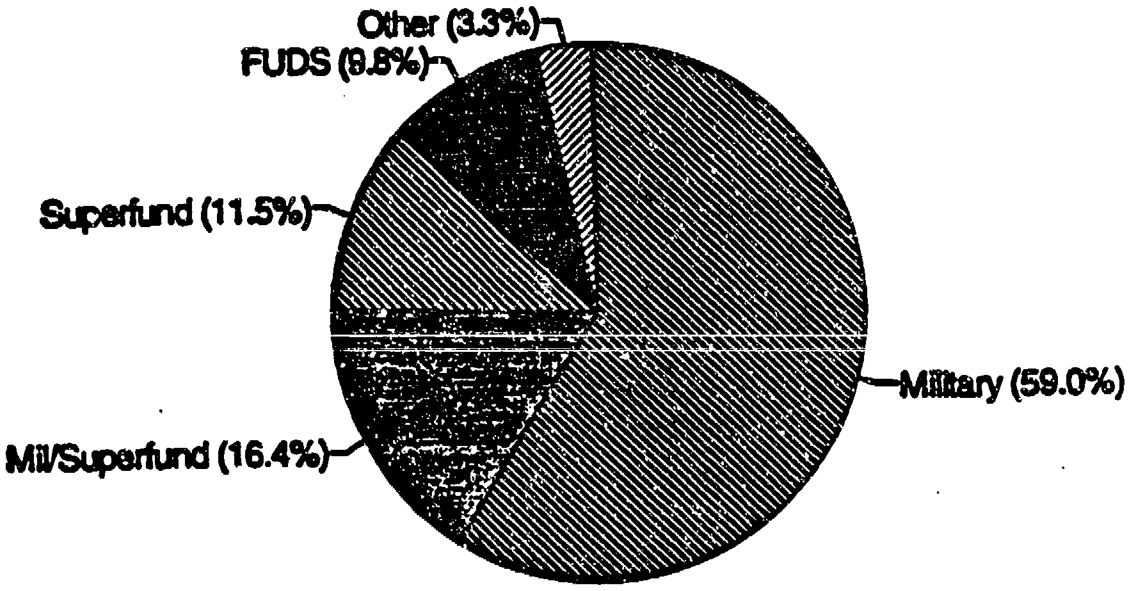
these studies were ongoing or completed, with the remainder planned. Note also that eleven of the respondents to the questionnaire had no ongoing, completed, or planned groundwater modeling studies at this time. Six of these respondents were from USATHAMA, with five being from the CE.

21. Question 4. For each groundwater modeling study planned or executed, please provide the information requested in the attached Table 1. Please reproduce additional sheets as needed (see Appendix B for additional details of Table 1). An enormous amount of information was derived from Table 1. The analysis of this information was constrained to those responses for which the model studies were either ongoing or completed (based on information provided in Table 2). This was deemed most appropriate given the types of information requested in Tables 1 and 2. As stated previously, this amounted to analysis of 61 ongoing/completed studies.

22. As shown in Figure 3, 36 of these studies (59.0 percent) were for military installations; 10 (16.4 percent) were for combined military/Superfund sites; 7 (11.5 percent) were for Superfund sites; 6 (9.8 percent) were Formerly Used Defense Sites (FUDS); and 2 (3.3 percent) were of the "other" category (1 civil works project and 1 "no response").

23. Figure 4 provides the models employed for the ongoing/completed model studies. The model cited with the greatest number of applications is the MODFLOW model, with 24 of 61 total responses. This is of little surprise, given that the model is currently among the best models available that is executable on multiple (personal computer to supercomputer) computing platforms.

24. As shown in Figure 5, most of the Army's model studies to date have been two-dimensional (2D) or three-dimensional (3D). These studies have been for both steady-state and transient conditions (Figure 6) in generally saturated environments (Figure 7). This latter point is of importance because it reflects the fact that, to date, most of the cleanup concerns requiring modeling have been related to questions of whether or how fast a contaminant will travel through the saturated zone to a domestic water supply (given present or possible future hydrologic conditions) as part of a risk assessment. This also explains the multi-dimensionality of the vast majority of studies, given the basic heterogeneous nature of the soil matrix and the potential for movement along multiple axes.



51 Completed Studies
10 Ongoing Studies

Figure 3. Distribution of sites with completed/ongoing modeling studies

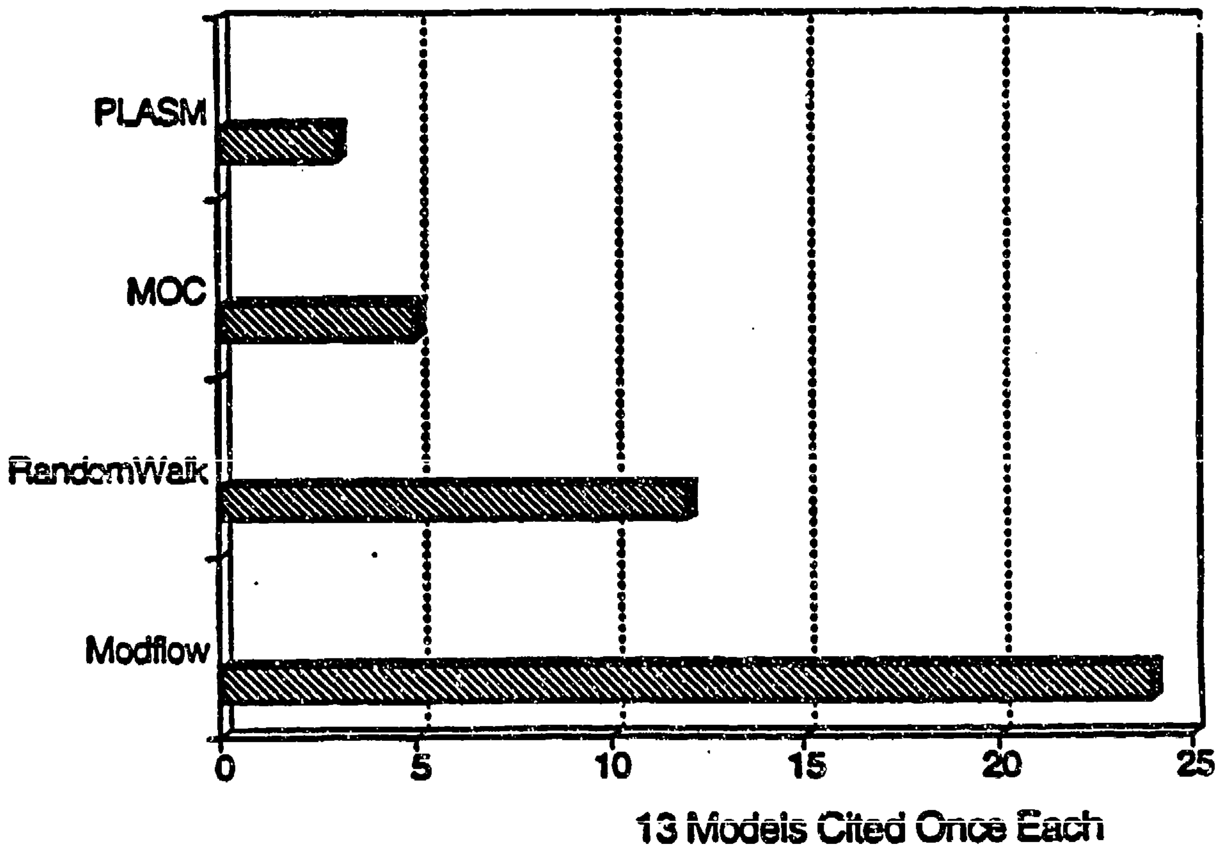


Figure 4. Number of uses of cited models in Army groundwater cleanups

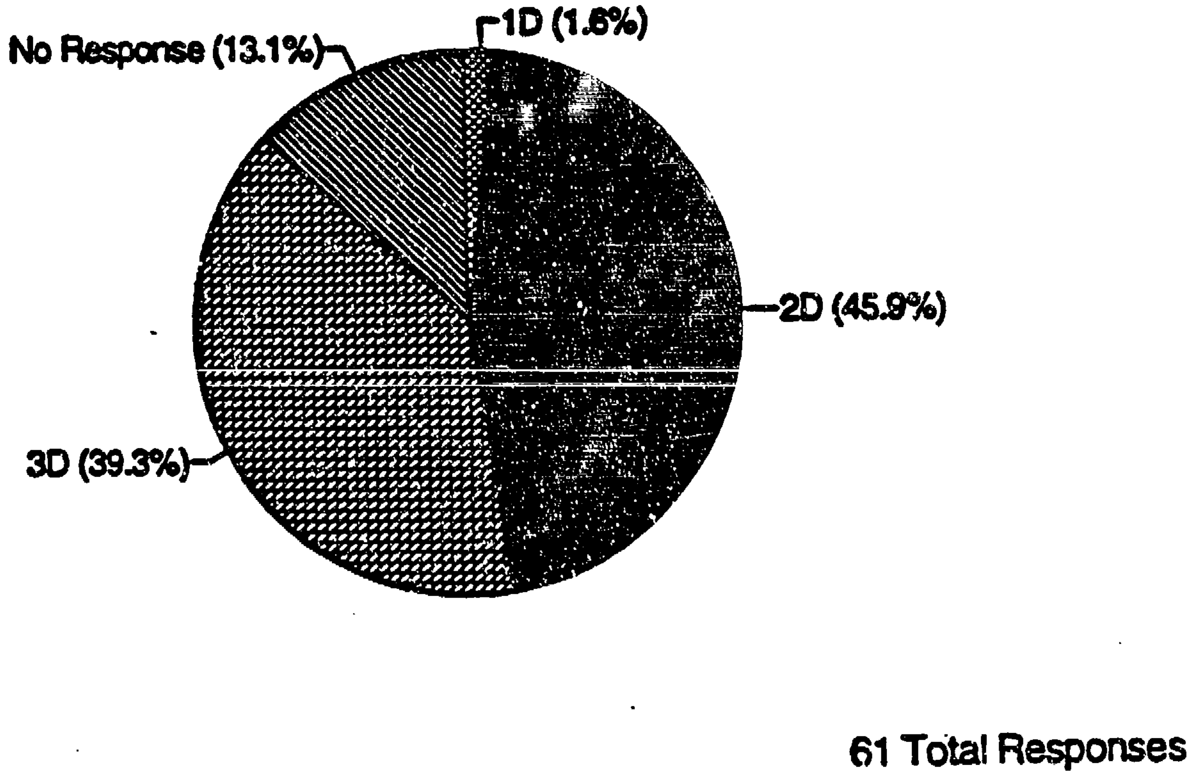


Figure 5. Cited dimensionality of model applications

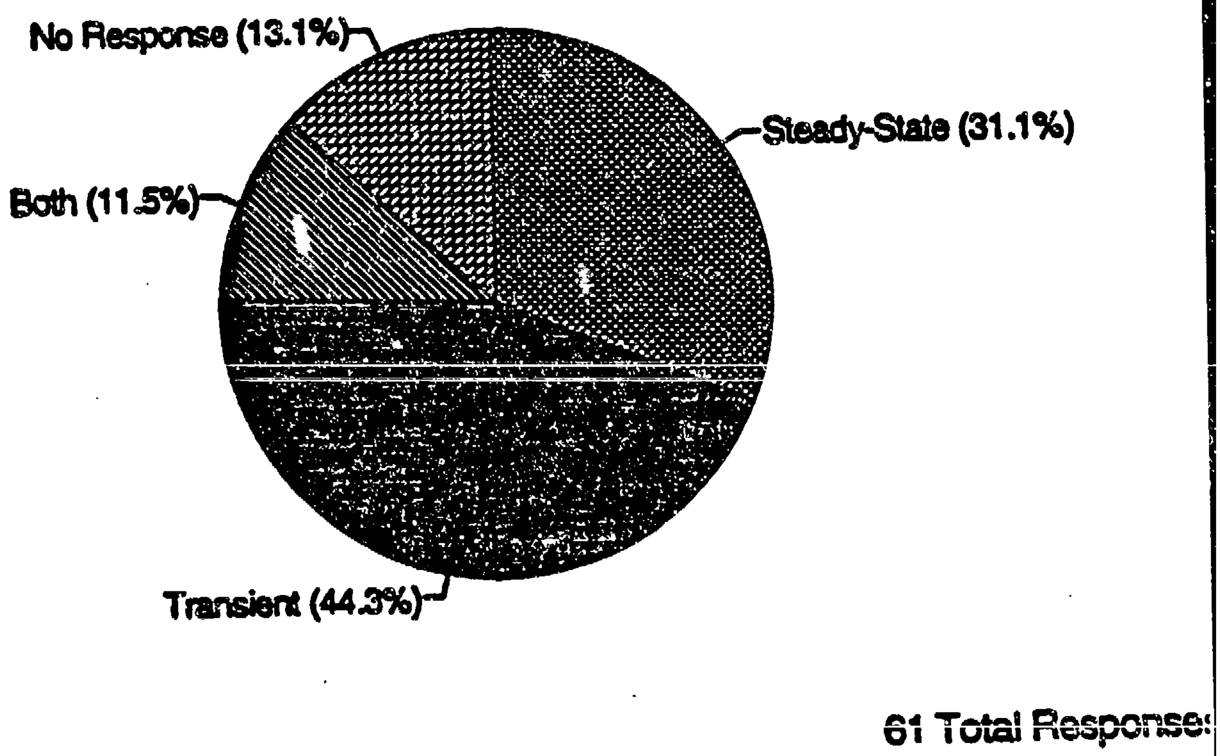


Figure 6. Steady-state or transient applications?

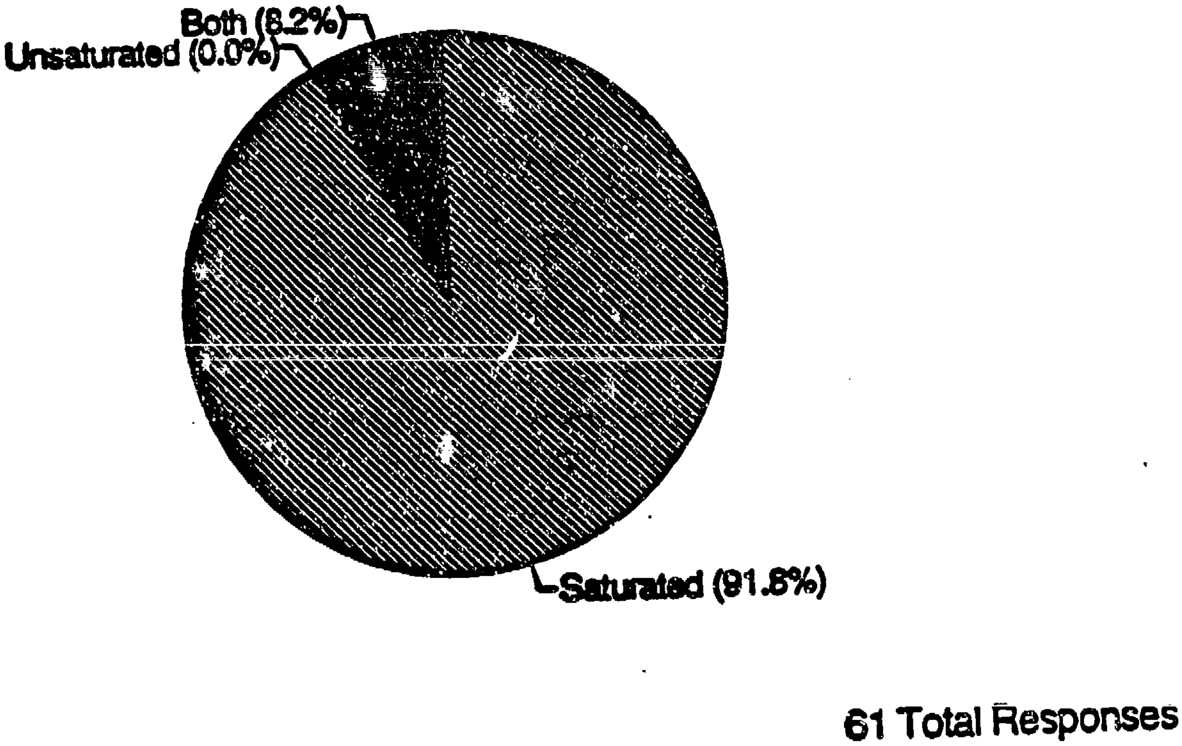


Figure 7. Type of application cited: saturated or unsaturated conditions

25. Figure 8 provides responses for the phases of study the Army has conducted the ongoing/completed groundwater modeling within. Note that the majority of these modeling efforts has been conducted in association with remedial investigation (RI), followed by remedial treatment, design/operation (RE) and feasibility study (FS).

26. As illustrated in Figure 9, the majority of ongoing/completed groundwater model studies have entailed the execution of both flow and transport models (in either a coupled or uncoupled mode). Forty-two of the 61 respondents gave this response, followed by 18 "flow-only" responses. These results point toward the often non-conservative* nature of the contaminants simulated numerically in Army-sponsored studies that require the more rigorous modeling associated with transport simulation. However, most of the 18 studies citing "flow-only" responses listed a variety of non-conservative contaminants as those of concern in connection with the modeling. This is, hopefully, an artifact of the requirement often expressed by regulatory agencies that the Army simulate "worst case" conditions. These conditions usually entail simulation of flow only as an expression of conservative* contaminants that neither lag behind the flow of water, become attached to nor are trapped by soil particles or biodegrade. This achieves, in theory, the strongest contaminant concentration that reaches a location of concern the fastest. If this result is not an artifact of regulatory conservatism it represents a misunderstanding of the kinetics of the contaminants being modeled. Note, also, that this result again points toward the idea that the majority of Army modeling has probably been in support of a risk analysis, with the use of modeling as part of a remedial design being a secondary factor (as shown in Figure 8).

27. Figure 10 provides one last snapshot of the modeling the Army is doing. As shown, the Army has been simulating a number of contaminant classes, most notably solvents. The lack of modeling emphasis on explosives and hydrocarbons is in contrast with the prevalence of these materials in groundwater at Army installations shown in Figure 2. Alternatively, the result most likely represents a lack of experience or confidence with the modeling of explosives and hydrocarbon transport by either the Army, its contractors, the regulatory agencies or all three.

---

* Conservative contaminants are biochemically non-reactive. Non-conservative contaminants are chemically and/or biologically reactive.

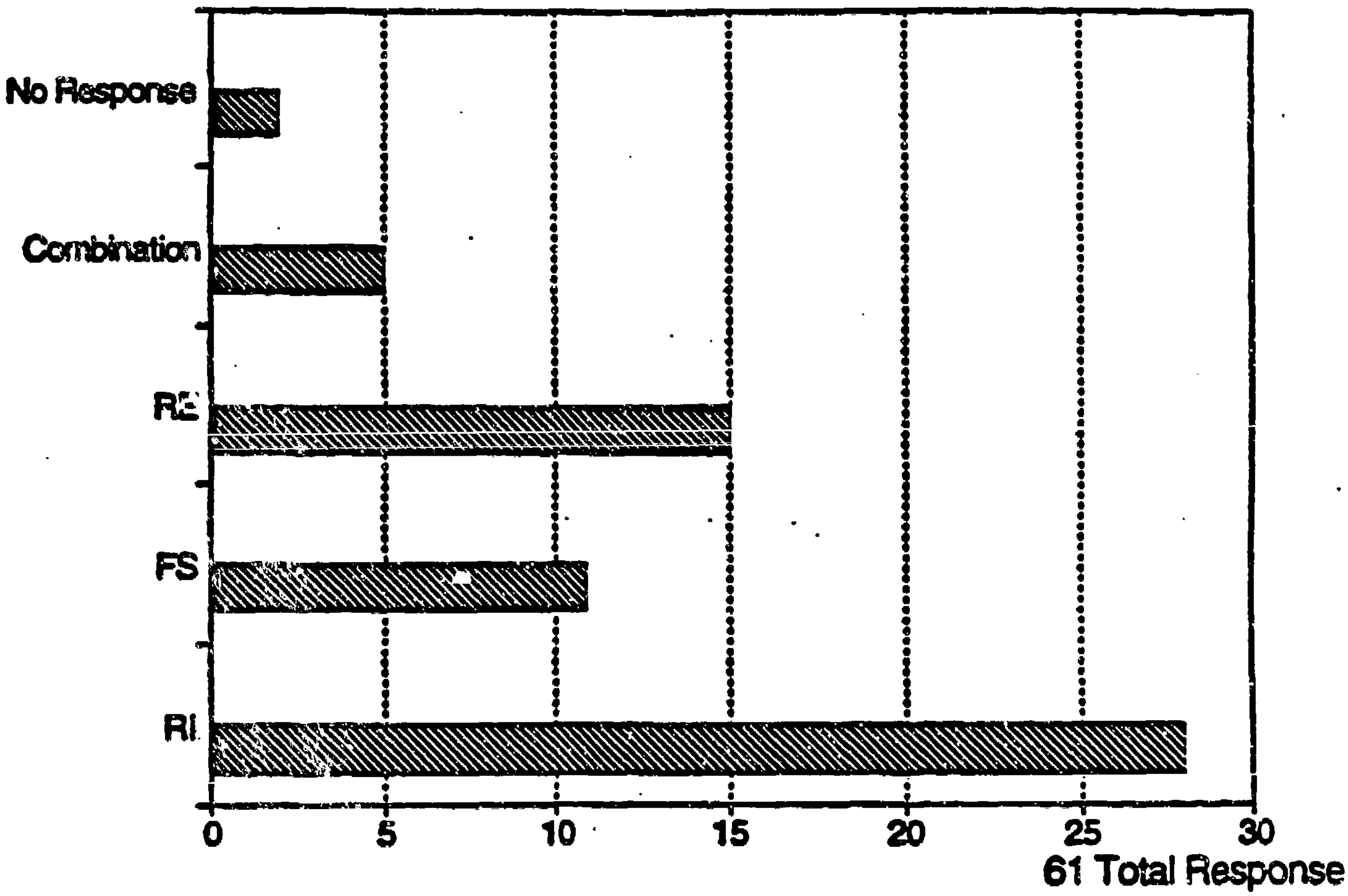


Figure 8. Phase of study employing groundwater models

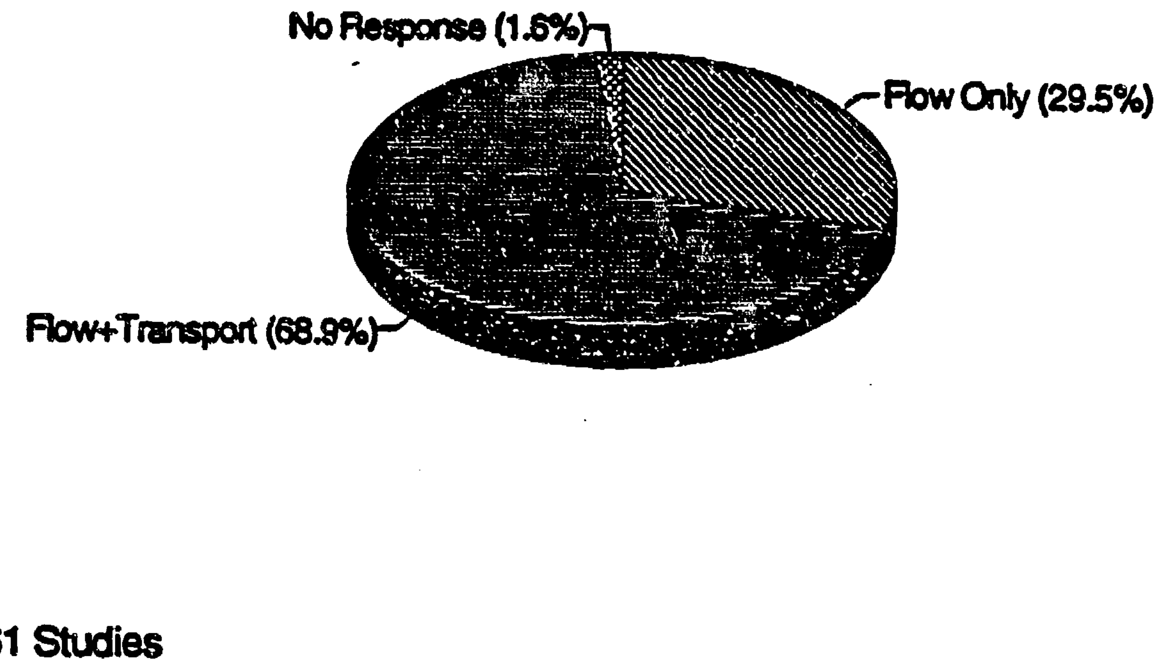


Figure 9. Flow or flow and transport modeled for ongoing/completed studies

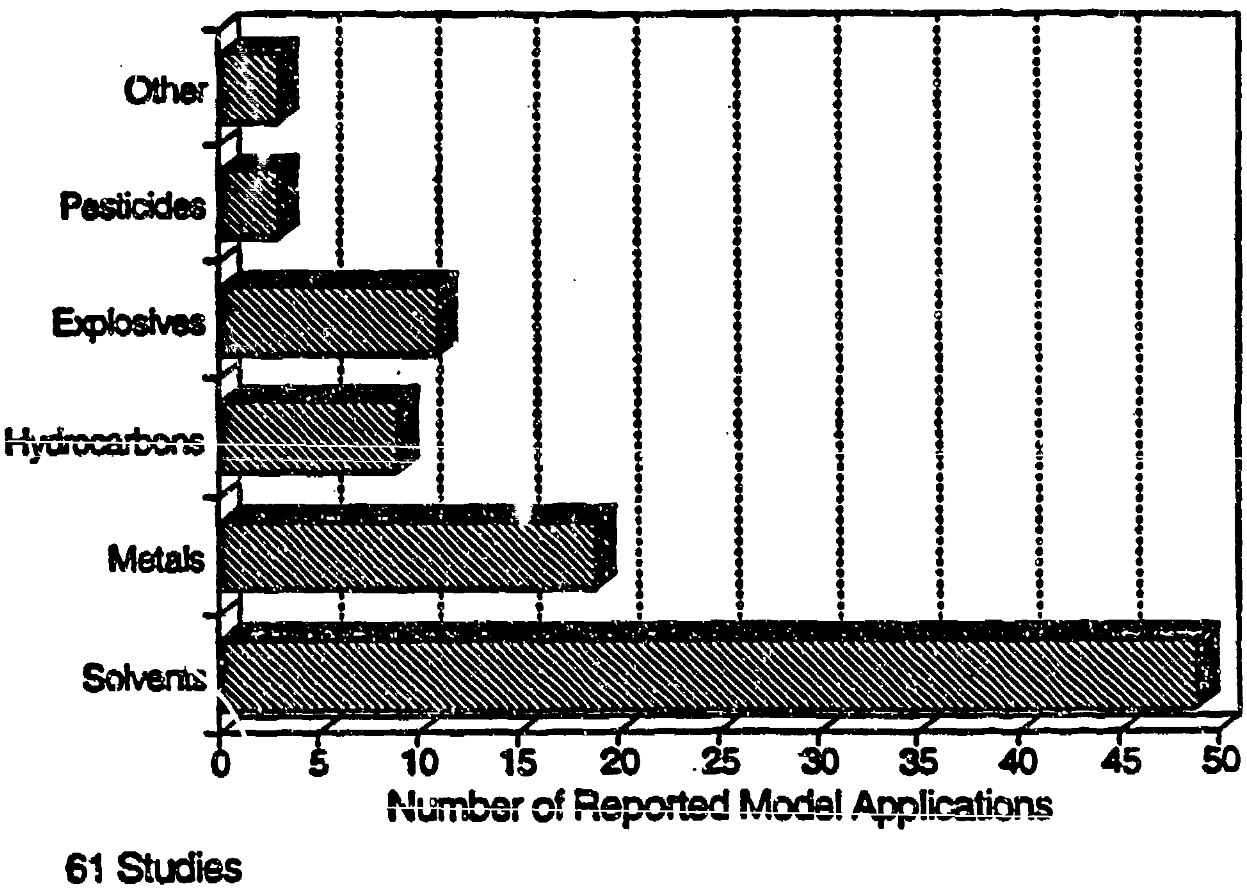


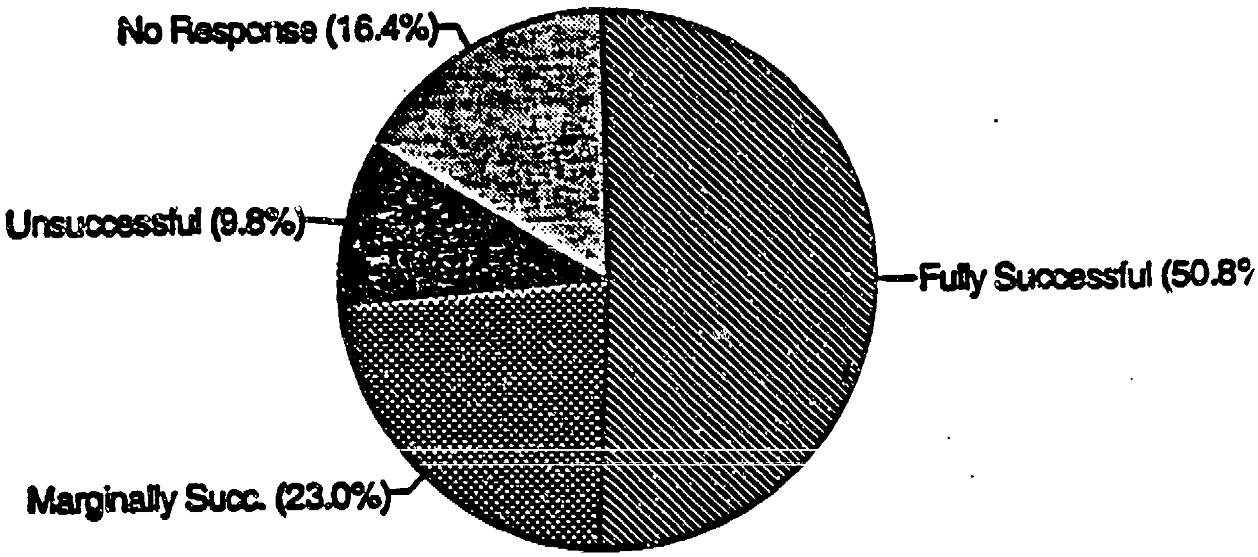
Figure 10. Contaminant types being evaluated with groundwater models

28. A final piece of information requested in Table 1 had to do with the types of computing hardware on which groundwater models were being run. The vast majority of those who did respond to this question listed the personal computer environment as the one they were currently operating within.

29. Question 5. For each groundwater modeling study listed in Table 1, please provide the information requested in the attached Table 2 on a sheet per study basis. Please reproduce additional sheets as needed (see Appendix D for additional detail). Figure 11 shows that, of the 61 studies listed as ongoing or completed, only about one-half of them were felt to be successful. The remaining studies were listed as a combination of marginal, unsuccessful, and no-response. Approximately 80 percent of these 61 studies were contracted. Figure 12 shows the relationship among successful, unsuccessful, and marginal studies and whether said studies were contracted, done in-house, or done as a combination of the two. As shown in the figure, there is no bias associated with who does the studies; all study agents succeed or fail with equal ease.

30. Figure 13 provides some insight into why respondents thought their modeling studies were marginal or unsuccessful. Eleven of 39 respondents (28.2 percent) listed poor or incomplete site characterization as the prime reason for less-than-successful modeling applications. The additional answers are noteworthy as well. Seven respondents said that technical gaps in the state-of-modeling precluded their successful use in their applications. Five responses listed poor study documentation as proof of a marginal or unsuccessful study. Coupled with four responses each that listed a lack of contractor expertise and a lack of in-house analysis expertise as prime contributors to lessened study success, this strongly suggests the need for increased in-house expertise (through training, technical assistance and hiring). Such expertise should greatly reduce the likelihood of poor contractor selection, and would improve study monitorship through heightened technical interaction, statement of in-house expectation of contractor products, and in-house review of contractor results.

31. Question 6. Are groundwater models overly expensive or difficult to use for your applications? ____ If the answer is no, please continue to Question 7. If the answer is yes, please check the following that supports your answer:



61 Studies

Figure 11. Evaluation of relative success of ongoing or completed studies

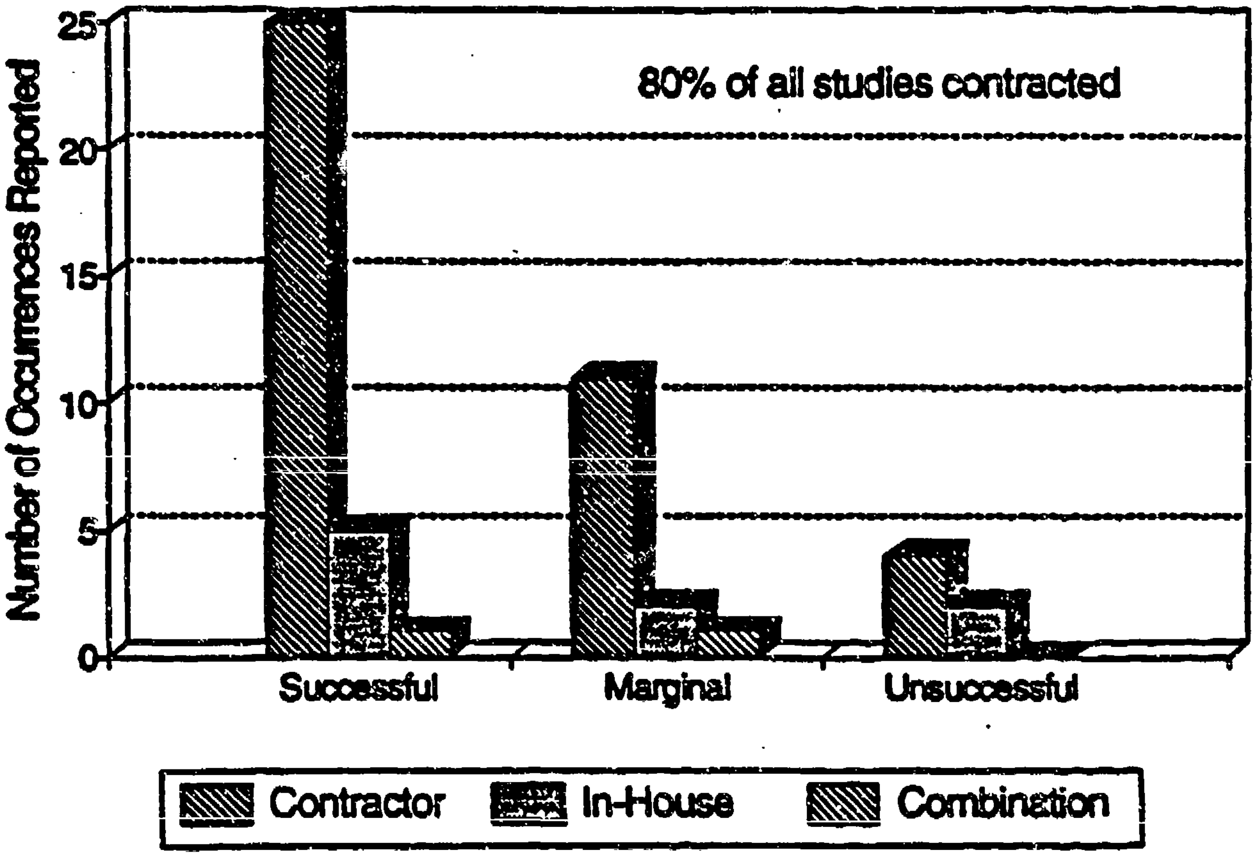


Figure 12. Relative success of modeling as a function of who models

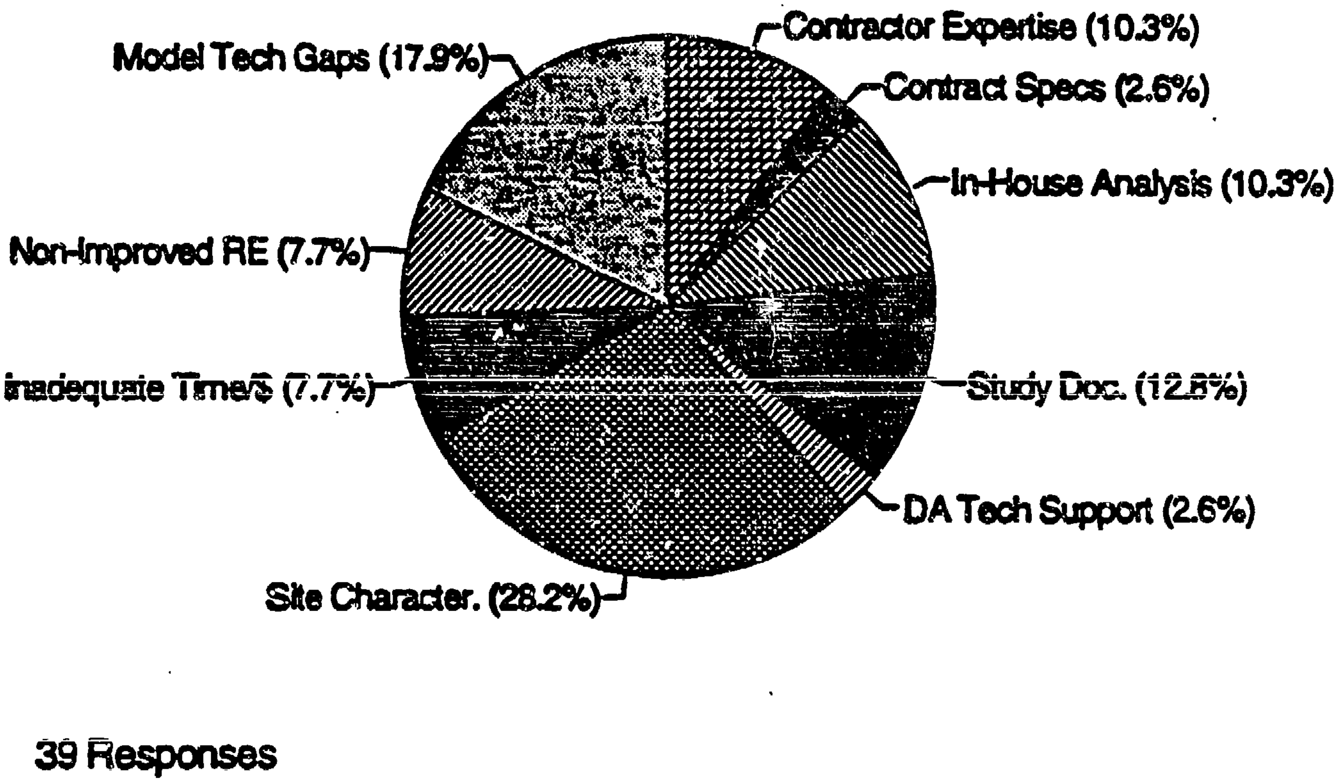


Figure 13. Reasons for marginal or unsuccessful studies

____ Models typically require more cost or effort than the information gained from them is worth.

____ User manuals or other instructions for using the individual models are inaccurate, incomplete, and/or out of date.

____ Too much labor and/or time is required to compile the field data needed to define the problem to be modeled.

____ Too much labor and time is required to put results of model analyses in a form that is useful for making engineering decisions.

____ Other; please explain. ______________________________

There were 47 total responses to this question; their distribution is given in Figure 14. Respondents were split on this question.

32. As shown in Figure 15, those responding "yes" to Question 6 above felt that the costs of getting the data required to effectively execute a groundwater model were excessive. This is of some concern because the same data required to execute a model are, in general, those required to conduct a thorough site characterization. Additional respondents cited the effort to conduct the modeling effort as a contributing reason for their answer. Presumably, the intensity of this effort, including data collection, parameter estimation, model calibration, and analysis was deemed too high by the respondents. When coupled with concerns about analysis costs, be they associated with time or labor usage, or concerns about poor model documentation, the reasons respondents thought groundwater models were too difficult or too expensive to operate suggest a few ideas: (a) the time model users have in the RI/FS process to conduct any model studies, whether elaborate or simple, is short; (b) the groups presently doing site characterization consider data collection to support numerical models to be outside the scope of data they normally collect for adequate site conceptualization; and, (c) the difficulties present users have in implementing models, as exemplified by model documentation concerns, when coupled with the two above concerns, may be great enough to discourage more extensive use of groundwater models in the Army.

33. It is interesting that nearly one-third of the respondents to Question 6 above gave no response to the question. An analysis to the overall questionnaire responses from this group is shown in Figure 16. All of the respondents in this group cited, in one way or another (i.e., the group had only five ongoing or completed studies, and these were all contracted), a lack

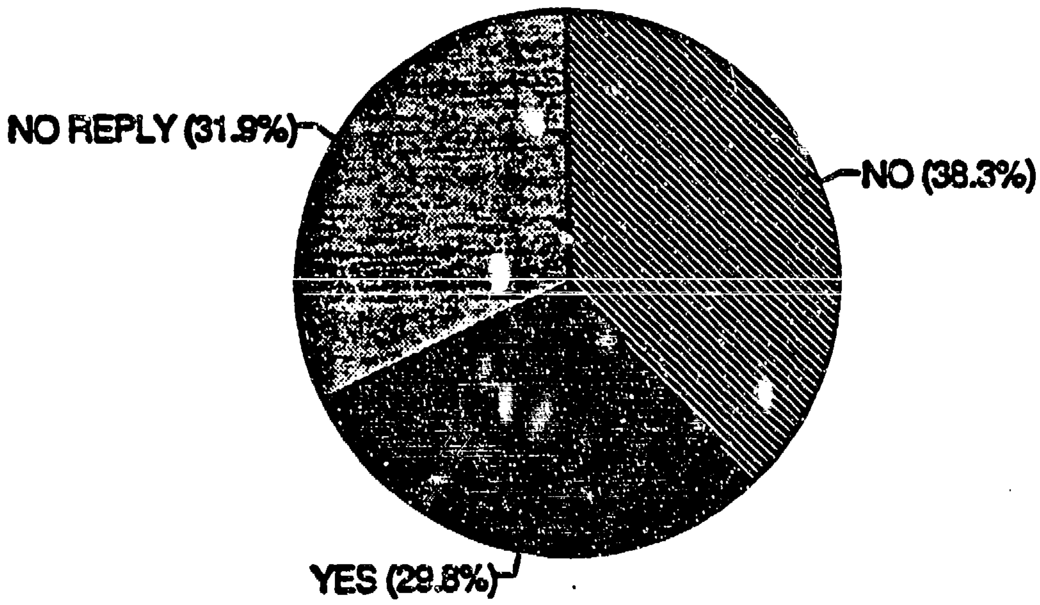


Figure 14. Are groundwater models too difficult or expensive to use?

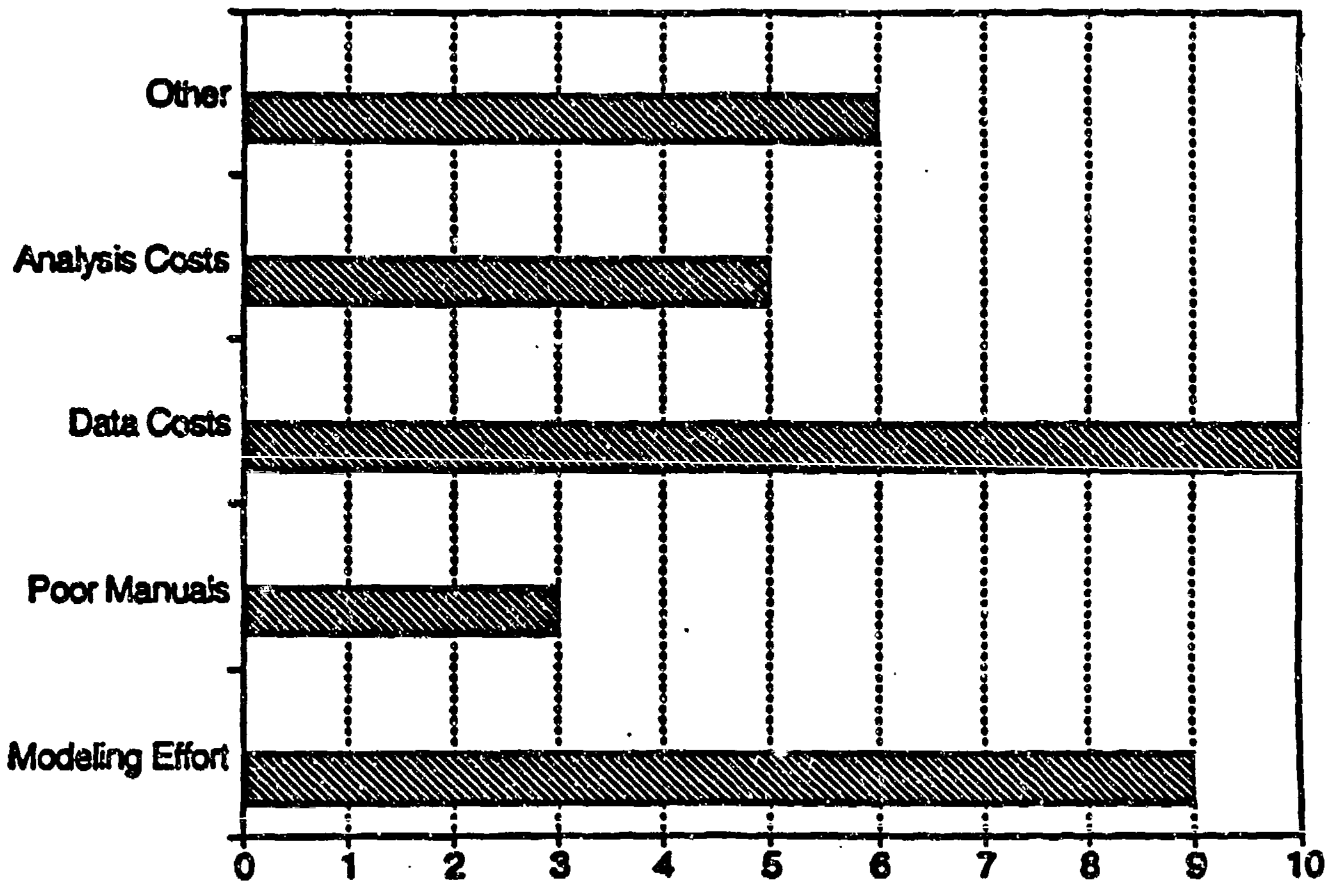


Figure 15. Reasons why groundwater models are felt too difficult/expensive

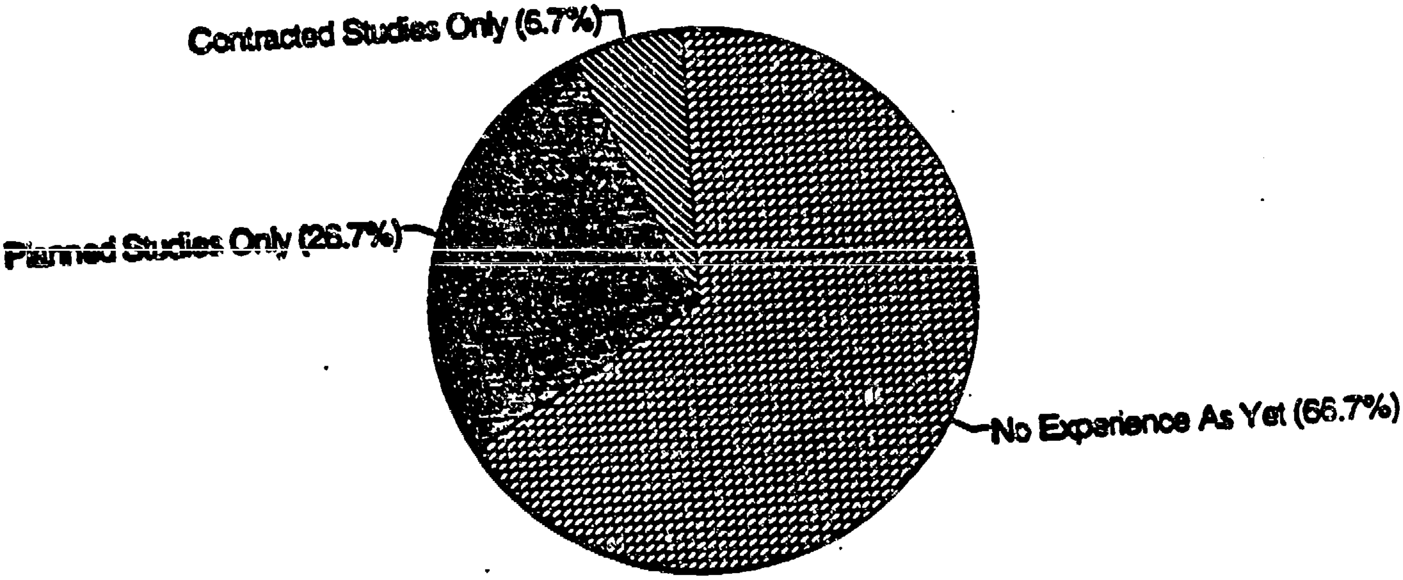


Figure 16. Reasons for non-response to question on model difficulty/expense

of in-house groundwater modeling experience as the primary reason for their lack of response to Question 6. As we will discuss in a later section, this finding is extremely important because of its potential impact on future studies, and on the quality of in-house review of future contractor studies.

34. Question 7. Was your answer to Question 6 based on your own experience, discussions with contractors, or both? ______________ Continuing with examination of the experience base of the Army modeling community, the results to Question 7 are provided in Figure 17. We have discussed above the "minimal experience" group (that is, the group that gave no response to Question 6). Let us now examine the three other groups listed in Figure 17.

35. In an effort to analyze the Figure 17 responses, a set of criteria were established relative to the overall experience base of Army model users. Required in this analysis was that the respondent have ongoing or completed modeling studies rather than just planned studies alone. This resulted in the size of the "experienced" group being reduced from 32 (those answering yes or no to Question 6) to twenty-one. We then investigated any trends in responses based on the respondent's answer to Question 7. Analysis of an additional variable, whether the model studies to date have been done in-house, by contract, or as a combination of both, failed to produce any obvious trends.

36. Nine "experienced" Army modelers said that groundwater models were overly difficult or overly expensive to use (Question 6). Twelve said no. Of the "yes" group, all cited their own experience, or a combination of their own and contractors', as the basis for their response to Question 6. One of the "no's" cited their "own" experience; the remaining 11 cited a combination of their own and contractors', or just contractors', as their experience basis.

37. Let us now return to the group of 32 original respondents to Question 7, removing for a moment the experience criterion used above. Analyzing these data further, of the nine respondents who listed the basis for their answer to Question 6 as their own experience, seven said that models were overly difficult or overly expensive to use. One said no, and one had no response to Question 6. Eight of the nine in this group were listed among the "experienced" modelers as discussed in Paragraph 23. Conversely, of the six modelers who listed contractor experience as their basis for answering Question 6, all six responded that models were not overly difficult or expensive to use. This group had only seven studies planned or executed between the six of them, and four of the six were listed among the "experienced" group.

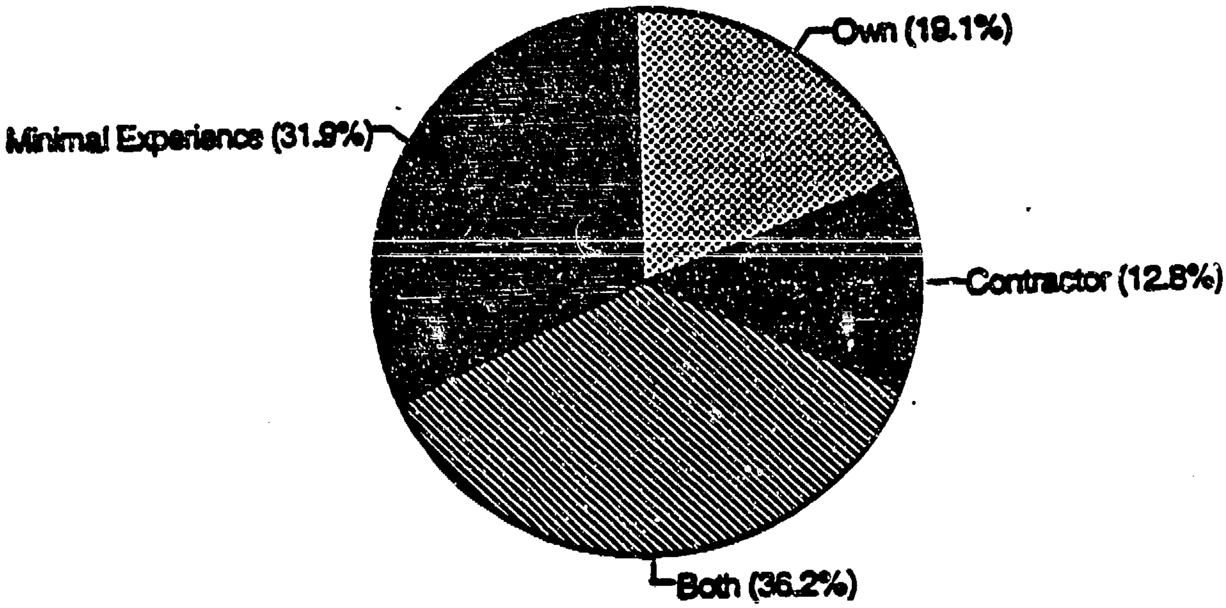


Figure 17. Experience basis for answer to question on model expense/difficulty

38. Finally, 17 respondents to Question 7 listed "both" contractor and in-house experience as the basis for their answer to Question 6. Ten of the 17 said that models were not overly difficult or expensive to use.

39. From this analysis, it would appear that those modelers having in-house experiance in modeling generally thought that groundwater models were overly difficult or expensive to use. Further, those thinking the converse were generally using solely contractor, or a combination of their own and contractor, experience to justify their answer. While this is a bit of a mixed bag, the result does again support the need for additional in-house training and expertise in groundwater modeling tools. It is obvious that the level of Army in-house experience is greatly impacting the answers given to Question 6.

40. Question 8. In your experience, are groundwater models comprehensive enough to account fo. the major details of real field problems? ____ Alternatively, do you believe your organization generally collects data sets comprehensive enough for groundwater model use? ____ Figure 18 illustrates the responses to this question. Again, there is no clear trend in these answers. It is interesting that eight of ten CE district/division respondents to this question said models were comprehensive enough; two-thirds of USATHAMA respondents said no. The responses to the data set question were mixed. Additionally, 12 "experienced" modelers said models were comprehensive enough; eight said no (one did not respond). It is not clear what this trend suggests. It is entirely possible that many of the questions the Army is currently facing, especially in CE district/division offices, can be answered with better packaging of existing technology. However, the results also suggest that the need is recognized by a sizeable portion of the user community for improvements to both models and data gathering techniques.

41. Question 9. Rank the following items by assigning them a High (H), Medium (M), or Low (L) importance in making groundwater models more useful tools for your site applications. Note that the abbreviation for each item appears at the end of said item.

____ software for personal computers (PCs) or work stations with a graphical user interface that enables easier input of data to groundwater models (PCGUI)

____ software for PCs or work stations with a graphical user interface to aid in visualizing groundwater model results (PC Visuals)

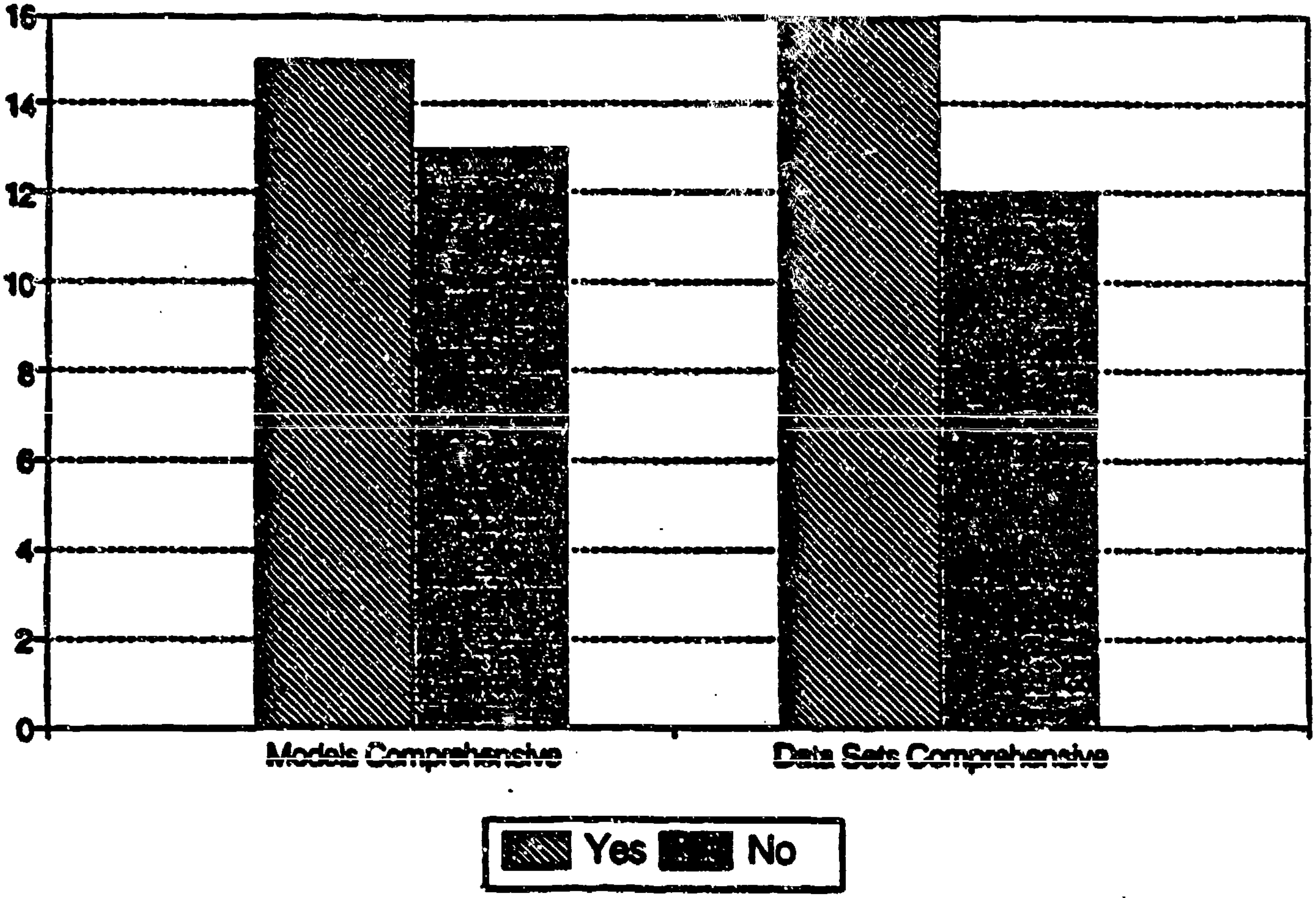


Figure 18. Are groundwater models and data sets comprehensive enough

____ software that would aid in extracting information from model results in the form of tables and plots similar to those now used to evaluate field data (Extraction)

____ interfaces that would couple groundwater models to CADD and GIS software (Interfaces)

____ a data base of typical geophysical and biochemical parameter values for specific soil types and contaminants (Par. Dbase)

____ a data base that would provide citations to pertinent published information on groundwater models (Cit. Dbase)

____ a probabilistic modeling capability that includes measures of uncertainty in geologic conditions, aid in parameter estimation, and theoretical limits of modeling reliability (Prob. Model)

____ guidance on the use and limitations of existing groundwater models for site characterization, feasibility studies, and remediation operation (Guidance)

____ an expert system to aid users in the selection of appropriate groundwater models. The system would also provide users with recommendations for model parameter selection (Expert Sys.)

____ groundwater modeling systems that have remedial alternatives integrated fully within their flow and transport models (Rem. Sim.)

____ Army-wide standardized groundwater modeling tools that have obtained EPA approval for use (Std. Mod.)

____ Army technical support personnel to assist in model choice and application (Tech Supp.)

The results of this question are given in Figures 19a and b. The trends in these results again illustrate the users' desires for improved methods for the use of existing models, as illustrated by (1) the high marks for personal computer-based graphical user interfaces for existing models, and by the call for (2) visualization and (3) guidance on model use. From these three items, a second group, made up of extraction methods, expert systems, probabilistic models, general interfaces to GIS, and standardized modeling tools, was bunched together in importance. These items point toward a combination of development for existing tools and the creation of new research products. Army technical support, integrated remediation simulation tools, parametric databases, and a citation database were the lesser desired products of those mentioned in the survey, respectively. It is interesting that the Army technical support item scored below the median line for all items in contrast to the general tone of responses to questions elsewhere in the questionnaire

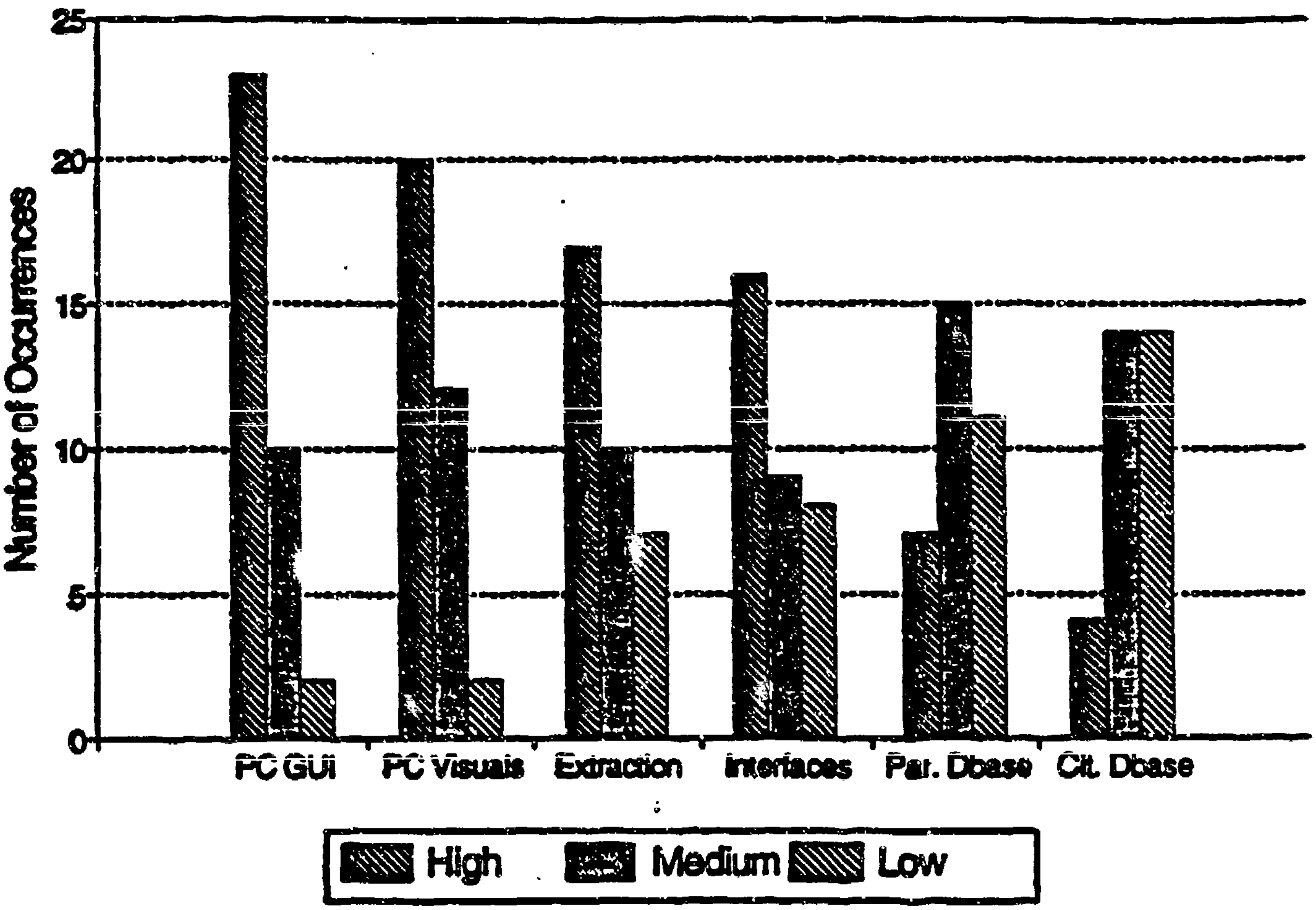


Figure 19a. User ranking of p[illegible]al modeling R&D activities

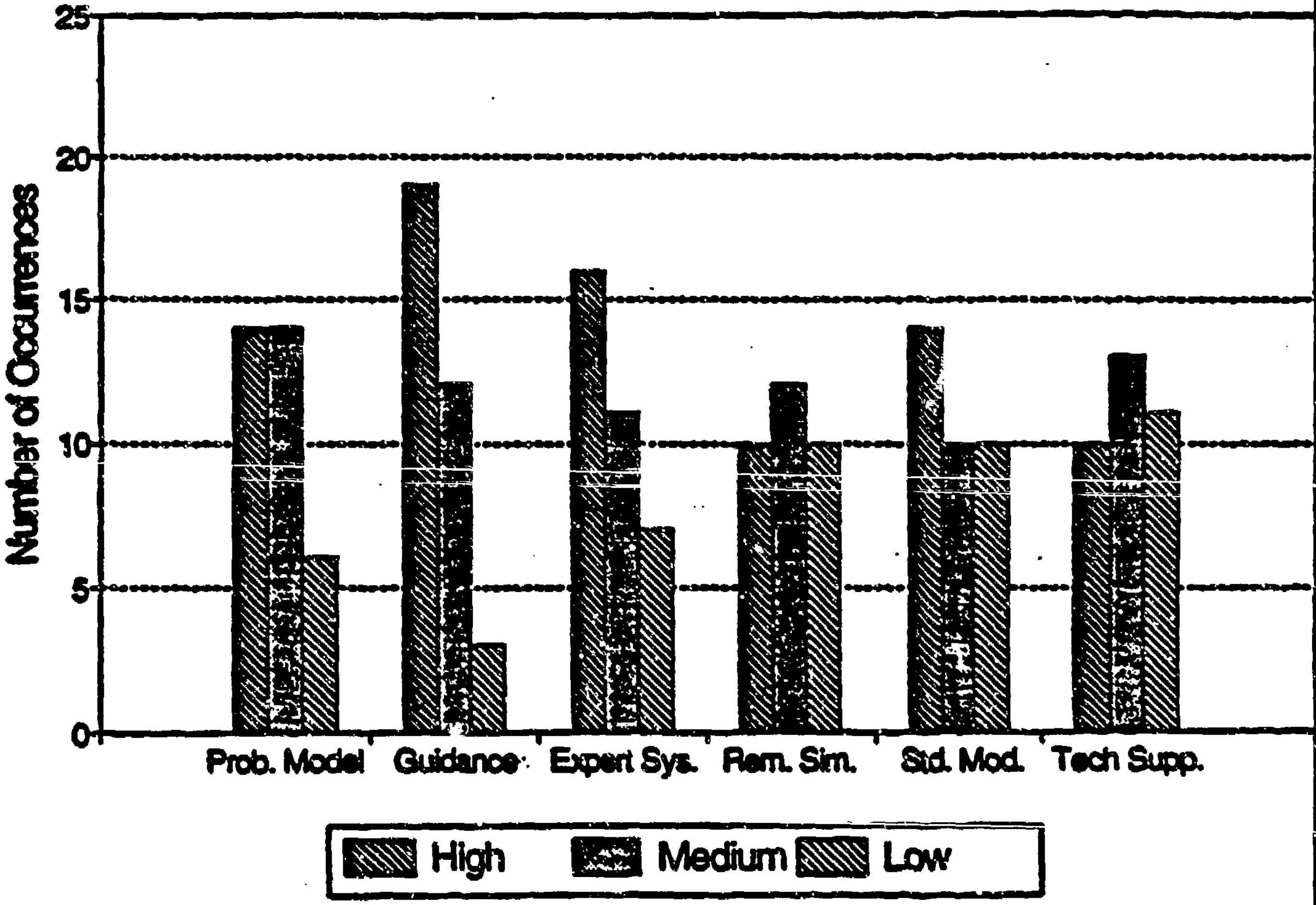


Figure 19b. User ranking of potential modeling R&D activities

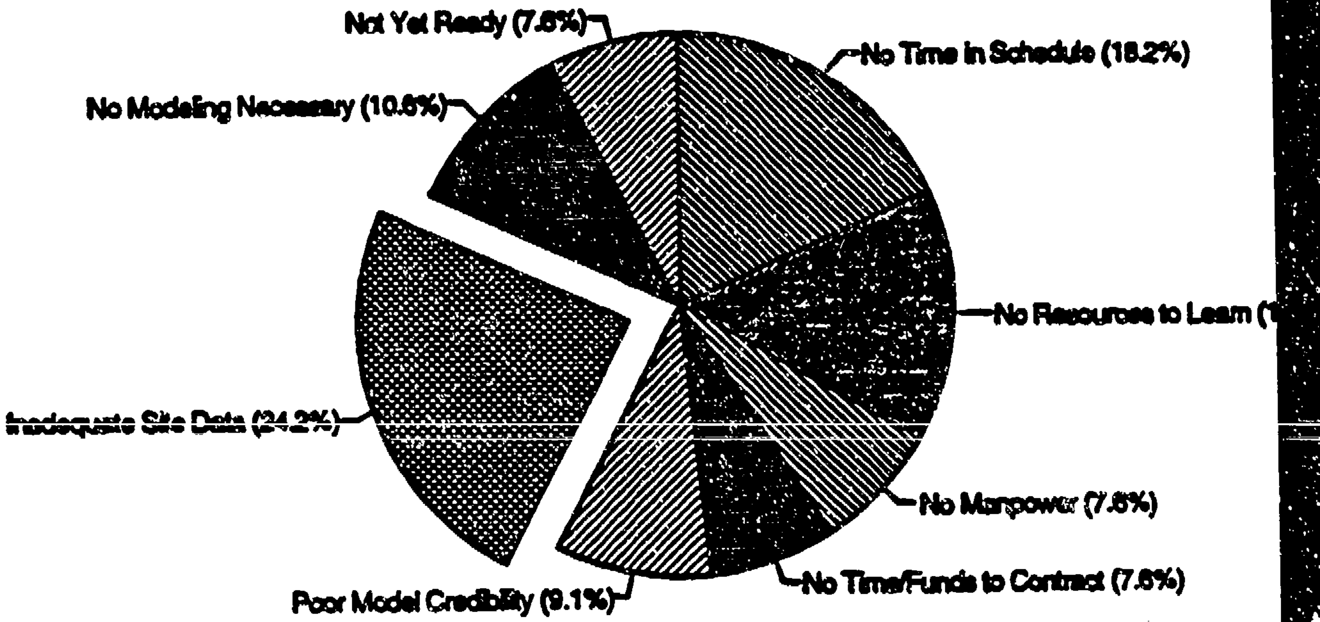
which were quite positive on this point. Additionally, it may be possible that the ordering of all but the three items in the highest grouping reflects, again, the level of experience of the users at this time. The responses may more accurately reflect the field's overriding desires to do better with existing tools than any focused priority for the development of improved tools.

42. Question 10. If you are not using groundwater models for your groundwater cleanup studies, please indicate why (check each that is appropriate):

- ____ Generally insufficient time for model usage within normal project schedules
- ____ Insufficient funding or time to learn the use in-house of most groundwater models
- ____ Insufficient in-house manpower to apply groundwater models
- ____ Insufficient time to contract groundwater modeling efforts
- ____ Insufficient funds to pay for contracted modeling efforts
- ____ Current groundwater models have insufficient levels of credibility for decision making
- ____ Typically an insufficient amount of site data exists to warrant groundwater model use
- ____ No groundwater modeling was deemed necessary. Please explain the rationale for this decision ________________
- ____ Other; please explain. ________________________

The most often given responses for this question are given in Figure 20. Inadequate site data was the reason for not using modeling in remediation and site characterization studies. This is quite disconcerting, for it seems a complete site characterization or remediation scheme design would, in general, require the same data, or nearly so, as a modeling investigation.

43. The remaining responses illustrated in Figure 20 can be divided into two basic groups: (a) "Our schedules are so tight that we do not have the time, manpower, or funds to do an adequate job of modeling"; and (b) "We are not ready for modeling yet, or modeling is not ready for us." The lack of in-house experience discussed in multiple sections above again comes into play in these answers. However, a second concern appears. Several respondents seem to be saying that the site characterization/remediation process itself, either through regulatory or Army rigidity, does not provide for ample time to



66 Total Responses

Figure 20. Reasons for groundwater model non-use

do a concerted, complete modeling study. One must wonder, if this is indeed the case, how a concerted, complete site characterization or remediation design is effected.

44. Question 11. Would you employ models more often if the items above in Question 9 were available? ____ If the answer is yes, please be sure you ranked the items in Question 9. Of the 47 responses to this question, 19 said yes; 15 gave no response; and, 13 said no. This leads one to ask what these results really suggest, given the distribution of the responses. The intent of the question was to ascertain if the conduct of the research and development discussed in Question 9 would induce more effective use of groundwater modeling tools. Taken at face value, it appears that some of the respondents to Question 11 would not make more effective use of groundwater models regardless of the development proposed. However, it may be that the question was framed too ambiguously to really provide usable results. For example, some of those answering no to Question 11 might believe that they were then using, or had already planned to use, groundwater models effectively prior to any proposed R&D. On the other hand, those answering no could be averse to groundwater models under any circumstances. Given the plausibility of each of these postulates, it may be advisable to discount the overall worth of the responses to Question 11.

45. Question 12. Do you have any access in-house to additional groundwater models that are not listed in Table 1?* If so, please provide the names of those models below and whether they are run on personal computers (designate PC and class of PC; i.e., 286, 386, etc.), workstations (designate WS with workstation name) or mainframes (M with machine name):

MODEL NAME	COMPUTER
________	________
________	________
________	________

Ten models, or direct variations thereof (usually associated with graphical interface extensions to the original model), were listed. The MODFLOW** model

---

* See Appendix D.

** McDonald, M. G., and A. W. Harbaugh. 1984. A Modular Three-Dimensional Finite-Difference Ground-Water Flow Model, Open-File Report 83-875, US Geological Survey, Reston, Virginia.

led the way by far, followed by PLASM*, RANDOMWALK**, and SUTRA†. Several additional models were mentioned in individual responses. None of the in-house models were being housed on a supercomputer by the Army user community. In fact, all of the respondents stated that their models were operating on personal computers or workstations except two, who listed VAX hardware as their computing platform. The models listed, and the computing platforms mentioned, are very important in that they indicate a general requirement for personal computer modeling tools in the near future. The question of what level of PC on which to conduct development (i.e., 286, 386, 486), and what level of development is appropriate given the changing hardware world, is one that will require additional review and discussion between Army model users and developers. However, there can be no question that the current computing platform of choice of the Army user community is the personal computer.

46. Question 13. When evaluating groundwater modeling proposals presented by contractors, which of the following is generally the deciding factor in contractor selection? (Check one please)

____ Quality of proposal based on in-house technical review

____ Quality of proposal based on external technical review. Who generally conducts this review? ____________

____ Known reputation of contractor

____ Other; please explain ____________

Thirty-six responses were provided to this question as shown in Figure 21. The importance of this question, and the next one, is tied directly to the level of in-house experience the Army has in groundwater modeling. Recall that 80 percent of all ongoing or completed Army groundwater model studies have been contracted. Further, recall that one-third of respondents to this

---

* Prickett, T. A., and C. G. Lonnquist. 1971. Selected Digital Computer Techniques for Groundwater Resource Evaluation, Illinois State Water Survey, BULLETIN 55, Urbana.

** Prickett, Thomas A., Thomas G. Naymik, and Carl G. Lonnquist. 1981. A "Random-Walk" Solute Transport Model for Selected Groundwater Quality Evaluations, Illinois State Water Survey, BULLETIN 65, Champaign.

† Voss, C. I. 1984. SUTRA - Saturated-Unsaturated TRAnsport - A Finite-Element Simulation Model for Saturated-Unsaturated, Fluid Density-Dependent Ground-Water Flow with Energy Transport or Chemically-Reactive Single Species Solute Transport, Water Resources Investigations Report 84-4369, US Geological Survey, Reston, Virginia.

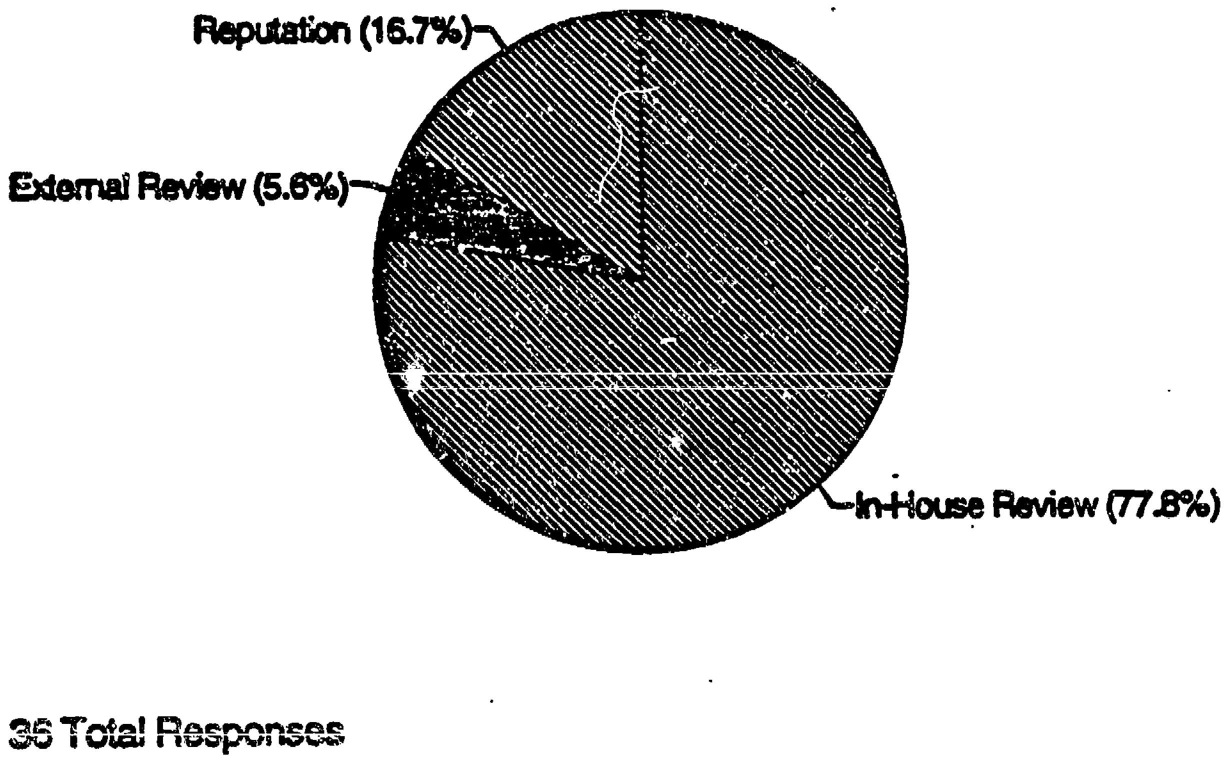


Figure 21. Methods used in evaluation of contractors' proposals for modeling

questionnaire have said that they feel they lack the experience to comment on whether groundwater models are overly expensive or difficult to use. With that, note that of the people who responded to Question 13, over three-fourths said they conduct in-house review only in the assessment of contractors' proposals. Note also that six of 36 respondents said they go primarily on contractors' reputations when assessing the worth of contractors' proposals.

47. Question 14. When groundwater modeling results are presented, which of the following is generally the primary means of assessing the reliability of those results? (Check one please)

___ In-house technical review

___ External technical review. Who generally conducts this review? ______________________________

___ Other; please explain ______________________________

____

____

The results of responses to Question 14 are shown in Figure 22. Note that in-house review is used almost exclusively to review groundwater modeling results. Coupled with the results from Question 13, and recalling the overall experience level of Army modelers, it is imperative that steps be taken quickly to improve in-house groundwater modeling expertise. The ramifications of these results relative to the quality control of contractors' studies are unquantifiable from the results of this questionnaire.

48. Question 15. Please provide any additional comments you have including your projected future needs for groundwater models.

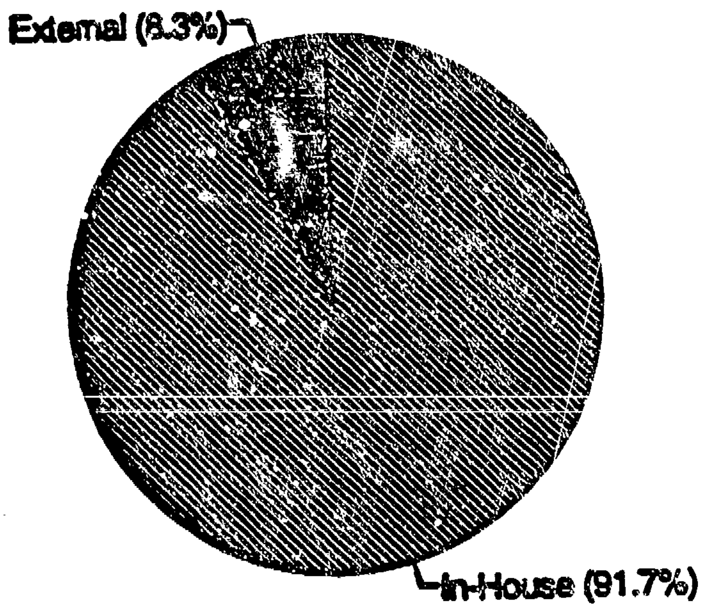
____

____

____

There was a variety of comments provided in this section. The most common response was an explanation for the respondents' failure to complete the questionnaire. The usual reason for this failure, or reticence, was a cited lack of modeling expertise required to complete the text.

49. Question 16. Please provide (reproductions or originals) or either cover pages or references to any contractor and in-house reports dealing with the modeling of groundwater flow and/or transport at Army sites. Reference materials were provided by several respondents. These materials are being used in-house.



36 Total Responses

Figure 22. Methods used in review of groundwater modeling results

50. Summary. In early February 1992 WES developed a questionnaire that solicited Army use of and experience with groundwater flow and contaminant transport modeling tools in support of contaminated site characterization and remediation. The questionnaire also sought user input on the research and development (R&D) requirements for future model development. The questionnaire was mailed to 22 Corps of Engineers (CE) district and/or division offices. Forty-seven (47) responses from 17 CE offices were received. Additionally, questionnaire responses were obtained from 28 users at the US Army Toxic and Hazardous Materials Agency (USATHAMA), representing seven USATHAMA elements, and from two Army installations (Aberdeen Proving Grounds, Maryland, and Fort Richardson, Alaska). While only two installations were polled directly, THAMA representatives provided input for all other known uses of groundwater models at Army installations.

51. These responses were analyzed for trends and content as presented above. From these analyses, certain points have appeared:

a. The Army is presently investigating organic solvents, hydrocarbons, and explosives as their primary contaminants of concern. Heavy metals were listed as of medium concern.

b. The Army is performing modeling primarily for military installation restoration, followed by Superfund activities.

c. Army groundwater model users have limited in-house experience in modeling. To date, approximately 80 percent of all ongoing or completed modeling efforts have been contracted. Several questionnaire respondents expressed a lack of sufficient modeling experience to complete the questionnaire. There are organizations within the Army, however, that have acquired significant levels of modeling experience.

d. A sizeable portion of the experience base Army model users employ for decision making regarding modeling results is derived directly from contractors' experiences and comments.

e. Users expect an increase in requirements for groundwater modeling over the next five years. Questionnaire respondents cited 67 expected modeling studies in the next five years, in contrast to the 61 ongoing or completed studies (over the last 10 years) reported.

f. The needs for all levels of training and guidance on the use, applicability, and limitations of groundwa er modeling tools were stressed in users' responses.

g. The need to make much improved use of existing modeling tools through interface and visualization extensions to current models, modification of existing technology, etc., was stressed in users' responses.

h. Additional R&D needs, ranging from probabilistic model development to parameter database creation, were ranked by questionnaire respondents.

i. The need for Army in-house technical assistance was suggested by the overall tenor of users' responses. The form for this assistance was not recommended by users.

j. Most experienced Army groundwater model users felt existing models were overly expensive or difficult to use.

k. A variety of reasons for non-use of groundwater models was reported. Chief among them were inadequate site data and resource limitations regarding model training, upkeep, execution, and analysis.

DISTRIBUTION LIST

Addressee	Copies
OSD	
Secretary of Defense, Pentagon, Washington, DC 20301	1
Under Secretary of Defense for Policy, Pentagon, Washington, DC 20301	1
Under Secretary of Defense, Acquisition, Pentagon, Washington, DC 20301	1
Assistant Secretary of Defense (Atomic Energy), Pentagon, Washington, DC 20301	1
Assistant Secretary of Defense (FM&P), Room 3E764, Pentagon, Washington, DC 20301	1
Deputy Under Secretary of Defense for Research and Engineering (R&AT), Pentagon, Washington, DC 20301	1
Chairman, Defense Science Board, Pentagon, Washington, DC 20301	1
Chairman, Joint Chiefs of Staff, Pentagon, Washington, DC 20301	1
Director, DLA, Pentagon, Washington, DC 22310	1
Director, DNA, 6801 Telegraph Road, Alexandria, VA 22310	1
Defense Technical Information Center, Bldg. 5, Cameron Station, Alexandria, VA 22314	12
Assistant to the Secretary of Defense, OSD, Pentagon, 3D-964, Washington, DC 20301	1
NAVY	
Secretary of the Navy, Pentagon, Washington, DC 20350	1
Chief of Naval Operations, Pentagon, Washington, DC 20350	1
Commandant, US Marine Corps, HQ USMC, Code CMC, Washington, DC 20380	1
Under Secretary of the Navy, Pentagon, Washington, DC 20350	1
Assistant Secretary of the Navy (RE&S), Pentagon, Washington, DC 20350	1
Director, Test & Evaluation and Technology Requirements, (N091), Pentagon, Washington, DC 20350	1
Deputy Chief of Naval Operations (Manpower, Personnel & Training), Chief of Naval Personnel, (OP-01), Washington, DC 20350	1
Deputy Chief of Naval Operations (Plans, Policy & Operations), (N3/N5, Pentagon, Washington, DC 20350	1
Commanding Officer, Naval Medical Research and Development Command, Naval Medical Command, NCR, Bethesda, MD 20814	1
Naval Research Advisory Committee, 800 N. Quincy St., Arlington, VA 22217-5000	1
AIR FORCE	
Secretary of the Air Force, Room 4E871, Pentagon, Washington, DC 20330	1
Chief of Staff, Air Force, Pentagon, Washington, DC 20330	1
Assistant Secretary of the Air Force (RD&L), Pentagon, Washington, DC 20330	1
Assistant Secretary of the Air Force (MRAI&E), Pentagon, Washington, DC 20330	1
Deputy Chief of Staff (Acquisition), USAF(AF/AQ), Pentagon, Washington, DC 20330	1
Assistant Chief of Staff, (AF/SA), Room 1E388, USAF, (AF/SA), Pentagon, Washington, DC 20330	1
Air Force Studies and Analyses Agency (AFSAA), 1570 Air Force Pentagon, Washington DC 20330-1570	1
Commander, Air Force Systems Command, Andrews AFB, Washington, DC 20334	1
Air Force Scientific Advisory Board, HQ USAF/SB, 1180 Air Force Pentagon, Washington, DC 20330-1180	1
Chief Scientist of the Air Force, HQ USAF/ST, 1060 AF Pentagon, Washington, DC 20330-5040	1
Air Force Studies Analysis Staff, AFCSA/SAMI, Washington, DC 20330	1
Chief Scientist, ACS Studies and Analyses, USAF/SAN, Pentagon, 1E386, Washington, DC 20330-5420	1

Addressee	Copies
ARMY	
Secretary of the Army, Pentagon, 3E718, Washington, DC 20310	1
Under Secretary of the Army, Pentagon, 3E732, Washington, DC 20310	1
Administrative Assistant, OSA, Pentagon, 3E733, Washington, DC 20310-0105	1
Assistant Secretary of the Army Civil Works, 108 Army Pentagon, Washington, DC 20310-0108	1
General Counsel, OSA, Pentagon, Washington, DC 20310	1
Assistant Secretary of the Army (RDA), Room 2E672, Pentagon, Washington, DC 20310	1
Assistant Secretary of the Army (I,L&E), Pentagon, Washington, DC 20310	1
Deputy Assistant Secretary (Procurement) SARD-ZP, Pentagon, Washington, DC 20310	1
Military Deputy to the Assistant Secretary of Army (RDA), Pentagon, Washington, DC 20310	1
Deputy Under Secretary of the Army (Operations Research), Pentagon, Washington, DC 20310	1
Director, Plans and Projects, OSA, SAAA-PP, Pentagon, 3E741, Washington, DC 20310	1
Assistant Secretary of the Army (Manpower & Reserve Affairs), 111 Army Pentagon, Washington, DC 20310-0111	1
Chief of Staff of the Army, 200 Army Pentagon, Washington, DC 20310-0200	1
Vice Chief of Staff, Army, Pentagon, Washington, DC 20310	1
Director of the Army Staff, Pentagon, Washington, DC 20310	1
Deputy Chief of Staff for Operations and Plans, (DAMO-FDR), 400 Army Pentagon, Washington, DC 20310-0400	1
Assistant Deputy Chief of Staff of the Army for Operations and Plans, Force Development, 400 Army Pentagon, Washington, DC 20310	1
Deputy Assistant Secretary for Research and Technology, SARD-ZT, Pentagon, Washington, DC 20310-0103	1
Deputy Chief of Staff for Logistics, Army HQDA, Room 3E560, Pentagon, Washington, DC 20310-0500	1
Technical Director, HQ TRADOC, ODCSA, ATAN-ZD Fort Monroe, VA 23651-5143	1
Director, Research Institute, US Army Engineer Topographic Labs, Telegraph and Leaf Road, Bldg. 2592, Fort Belvoir, VA 22060-5546	1
Director for Program Evaluation, SARD-DE, Room 2E673, Pentagon, Washington, DC 20310-0103	1
Director, AMC-Field Assistance in Science & Technology Activity, AMC-FAST, Fort Belvoir, VA 22060-5606	1
Department of the Army Office of the Surgeon General, Skyline 6, 5109 Leesburg Pike, Falls Church, VA 22041-3258	1
Deputy Chief of Staff for Personnel (DA DCSPER), HQDA, DAPE-ZXO, Pentagon, Washington, DC 20310	1
Chief, MANPRINT Policy Office, Research & Studies Division, ODCSPER, Pentagon, Washington, DC 20310	1
Director, Civilian Personnel, ODCSPER, Washington, DC 20310	1
Director, Military Personnel, ODCSPER, Washington, DC 20310	1
Comptroller of the Army, Office of the Secretary of the Army, Pentagon, Room 3E588, Washington, DC 20310-0109	1
Deputy Chief of Staff for Intelligence, Pentagon, Washington, DC 20310	1
Department of the Army, Office of the Surgeon General, Liaison, Pentagon, SARD-TM, Room 3E368, Washington, DC 20310	1
Chief, National Guard Bureau, Pentagon, Washington, DC 20310	1

Addressee	Copies
Chief, Military History, Pulaski Building, 20 Massachusetts Ave, NW, Washington, DC 20314	1
Commander, US Army Medical Research & Development Command, SGRD-PR, Fort Detrick, MD 21702-5012	1
Director, US Army TEXCOM Experimentation Center, Fort Ord, CA 93941	1
Director, US Army Space Program Office, DAMO-FDX, 2810 Old Lee Highway, Suite 300, Fairfax, VA 22031-4304	1
Chief of Public Affairs, OSA, Pentagon, 2E636, Washington, DC 20310	1
Chief of Legislation Liaison, OSA, 1600 Army Pentagon, Washington, DC 20310-1600	1
Technical Advisor, US Army, TRADOC, Fort Monroe, VA 23651	1
Commander, US Army Medical Research and Development Command, SGRD-PLR, Fort Detrick, MD 21701	1
Commander, US Army Materiel Command, AMCDCG-T, 5001 Eisenhower Avenue, Alexandria, VA 22333	10
Commander, US Army TRADOC, ATCG-S, (Dr. Berenson), Fort Monroe, VA 23651	5
Deputy Commander, US Army, TRADOC, Fort Leavenworth, KS 66027	5
Office Deputy Chief of Staff for Combat Development, US Army, TRADOC, ATCD-EP, Fort Monroe, VA 23651	1
Deputy Commander, US Army Forces Command, Fort McPherson, GA 30330	2
Director of Force Management, FCJ3-FM, HQ FORSCOM, Fort McPherson, GA 30330	1
Commander, US Army Communications Command, Fort Huachuca, AZ 85613	1
Science Advisor to the Commander, HQ USA FORSCOM, FCSJ-SA (Dr. Suider) Bldg., 200, Fort McPherson, GA 6000	1
Commander, US Army Laboratory Command, AMSLC-CT (Corporate Technology), 2800 Powdermill Road, Adelphi, MD 20783-1145	1
Commander, US Army Tank Automotive Command, AMSTA-CG, Warren, MI 48397-5000	1
Technical Director, US Army Operational Test and Evaluation Command, 4501 Ford Ave., Alexandria, VA 22302-1458	1
Director, US Army Concepts Analysis Agency, 8120 Woodmont Avenue, Bethesda, MD 20814	1
Commander, US Army Nuclear and Chemical Agency, Washington, DC 20310	1
Commander, US Army Foreign Science and Technology Center, 220 7th Street, NE, Charlottesville, VA 22901	1
Commander, US Army Missile and Space Intelligence Center, AIAMS-ZC, Redstone Arsenal, AL 35898-5000	1
Commander, US Army Combined Arms Support Command (CASCOM), Fort Lee, VA 23801-6000	1
Commandant, US Army Logistics Management Center, AMXMC-LS, Fort Lee, VA 23801	1
Director, US Army Research Institute for Behavioral and Social Sciences, 5001 Eisenhower Avenue, Alexandria, VA 22333-5600	5
Director, US Army Research Office, PO Box 12211, Research Triangle Park, NC 27709-2211	1
Program Director, Military Issues and Studies, Center for Social Research and Policy Analysis, P.O. Box 12194, 3040 Cornwallis Road, Research Triangle Park, NC 27709-2194	1
Director, US Army Research Laboratory, ATTN: AMSRL-HR, Aberdeen Proving Ground, MD 21005-5425	3
Director, US Army Materiel Systems Analysis Agency, ATTN: AMXSY-D, Aberdeen Proving Ground, MD 21010-5071	2

Addressee	Copies
Director, (Dr. G. A. Neece), Research & Technology Integration, Army Research Office, PO Box 12211, Research Triangle Park, NC 27709-2211	3
Commander, US Army Info Systems Command, ASCG, Fort Huachuca, AZ 85613-5000	1
Chief, National Science Center for Communications and Electronics, ATZH-STF, Fort Gordon, GA 30905-5689	1
Commandant, US Army War College, Carlisle Barracks, PA 17013	3
Commandant, US Army Command and General Staff College, Fort Leavenworth, KS 66027	3
Commandant, US Army Field Artillery Center and Fort Silll, Fort Sill, OK 73503	1
Commandant, US Army Chemical School, Fort McClellan, AL 36205	10
Commander, US Army Chemical Research, Development and Engineering Center, Aberdeen Proving Ground, MD 21010	1
Commander, Natick, Research and Development Center, STRNC-2, Natick, MA 01760	1
Commander, Combined Arms Center, Fort Leavenworth, KS 66027	5
Commander, Academy of Health Sciences, HSA-CDS, Fort Sam Houston, TX 78234	1
Commander, Eighth US Army, APO San Francisco 96301	5
Commander-in-Chief, US Army Europe & Seventh Army, APO New York 09403	5
Commander-in-Chief, US Army Southern Command, Quarry Heights, Panama, APO Miami 34003	5
Commander, USARJ/IX Corps, AJSA, APO San Francisco 96343	5
Commander, US Army Aviation Systems Command, 4300 Goodfellow Blvd, St. Louis, MO 63120-1798	1
Commander, US Army Security Assistance Command, 5001 Eisenhower Avenue, Alexandria, VA 22333-0001	1
HQDA, DAMO-ZD, Pentagon, 3A538, Washington, DC 20310-0410	1
Commander, US Army T&E Command, Aberdeen Proving Ground, MD 21005-5055	1
Technical Director, US Army Test & Evaluation Command, Aberdeen Proving Ground, MD 21005-5055	1
US Army Communications-Electronics Command, Director RDT&E Center, AMSEL-RD, Fort Monmouth, NJ 07703-5000	1
US Army Communications-Electronics Command, Director RDT&E Center, AMSEL-RD-D, Fort Monmouth, NJ 07703-5201	1
HQ AMC, Physical Science Administrator, AMCAQ-A-ES, 5001 Eisenhower Avenue, Alexandria, VA 22333-0001	1
USASSDC, CSSD-OP, CSSD-DP, PO Box 15280, Arlington, VA 22215-0180	2
Commander, US Army Operational T&E Agency, Park Center IV, 4501 Ford Avenue, Alexandria, VA 22302-1458	1
Commander, Department of the Army, US Army Armament Research, Development & Engineering Center, Picatinny Arsenal, NJ 07806-5000	1
Commander, US Army Depot Systems Command, Chambersburg, PA 17201	1
Commander, West Com, APSA (Science Advisor), Fort Shafter, HI 96858	1
Science Advisor to the CDR, HQ USFK/EUSA-SJS, CS-SO, APO San Francisco 96301	1
Director, R&D Office, CERDZ-A, Office Chief of Engineers, 20 Massachusetts Avenue, NW Washington, DC 20314	1

Addressee	Copies
OTHER	
Director, CIA, Washington, DC 20505	1
Executive Director, Board on Science & Technology (BAST), 2101 Constitution Avenue, HA292B, Washington, DC 20418	1
Chairman, Defense Science Board, Pentagon, 3D865, Washington, DC 20301	1