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Implications of uncertainty in exposure assessment for groundwater contamination

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Abstract Decision-making on regulation, mitigation, and treatment of drinking water contamination depends, in part, on estimates of human exposure. Assessment of past, present and potential future exposure levels requires quantitative characterization of the contaminant sources, the transport of contaminants and the level of actual human exposure to the contaminated water. Failure to consider the uncertainties in these three components of exposure assessment can lead to poor decisions such as implementing an inappropriate mitigation strategy or failing to regulate an important contaminant. Three examples from US Geological Survey hydrogeologic studies in southern California are presented to illustrate some of the unique uncertainties associated with exposure assessment for groundwater contamination.

INTRODUCTION

Exposure assessment for groundwater contamination requires quantitative characterization of the contaminant sources, of the transport of contaminants in groundwater and of the level of human exposure to contaminated groundwater. Characterization of these factors in complex groundwater systems is often difficult and imprecise. In this paper, three examples from hydrogeologic studies in southern California are presented to illustrate the potential uncertainties and resulting difficulties in exposure assessment for groundwater contamination. Consideration of these uncertainties can prevent resources from being devoted to remedial strategies that do not reduce health risks.

IDENTIFYING AND CHARACTERIZING SOURCES OF GROUNDWATER CONTAMINATION

Source characterization for groundwater contamination has several unique characteristics. First, groundwater contaminant sources are not visible and are, therefore, difficult to locate and quantify. Second, many sources are long lived; activities carried out many years ago may still contribute to groundwater contamination today and current activities may create sources that will remain a threat for many years into the future. Third, changing hydrogeologic conditions – rising or falling water levels or changing amounts of recharge resulting from climatic variability – can greatly change the character of a contamination source. Because of uncertainties in identifying and locating potential sources and in determining which sources are actively releasing contaminants into the groundwater system, it is difficult to assess the long-term health risks posed by groundwater contamination. When contamination is discovered in the groundwater system, there may be difficulties in determining the source. Attributing contamination to the wrong source might lead to improperly designed remediation strategies.

The difficulties involved in identifying and characterizing sources of groundwater contamination are shown in a study of sea water intrusion in the coastal plain of the Santa Clara-Calleguas basin in Ventura County, California, This coastal plain area is commonly referred to as the Oxnard Plain. An extensive monitoring network has been in place to monitor sea water intrusion in the aquifer system beneath the Oxnard Plain since the 1960s. On the basis of data from this network, the area of sea water intrusion in the Oxnard aquifer, which is the main upper-system aquifer, was estimated to be approximately 60 km^2 (County of Ventura Public Works Agency, 1990). The two sea water plumes, whose chloride concentrations are greater than 500 mg l^{-1}, are shown in Fig. 1. The existing monitoring network consists of former production wells, generally screened over wide intervals. Although the goal of monitoring is to reduce uncertainty, even an extensive monitoring network such as exists in the Oxnard Plain can yield misleading results if the three-dimensional characteristics of the groundwater contamination are not considered.

In order to investigate the three-dimensional nature of contamination in the Oxnard Plain, the US Geological Survey completed 20 multiple well monitoring sites. Each site consists of three to five 5 cm (2 in.) polyvinyl chloride (PVC) wells installed in a single drill hole and isolated by low-permeability bentonite grout. One of these multiple well sites was installed approximately 50 m from an existing monitoring well within the northern high chloride plume in Fig. 1. Measured chloride concentration in the existing well, presumed to be representative of conditions in Oxnard aquifer, was 1900 mg l^{-1} (see Fig. 2), nearly 40 times the background concentration of 50 mg l^{-1}. Measured chloride concentration in the Oxnard aquifer in the new well was only 180 mg l^{-1}. However, the chloride concentration measured in the shallow perched aquifer, which overlies the Oxnard aquifer, was 23 000 mg l^{-1}. As described by Izbicki (1991) and Stamos *et al.* (1992), the casing of the original monitoring well failed, allowing the extremely saline water from the overlying perched aquifer to enter the Oxnard aquifer. The source of high chlorides in the perched aquifer is sea water that was trapped in the deposits during deposition or that resulted from coastal flooding and evaporative concentration of salts.

The results of this three-dimensional characterization of sea water intrusion indicate that chloride concentrations in the Oxnard aquifer are much lower in this area than was previously assumed and that the areal extent of sea water intrusion in the Oxnard aquifer is considerably less than the previous estimate of 60 km^2. The results also indicate that contamination of individual wells from a different source, downward leakage from the perched aquifer, may be more of a concern than previously realized (see Predmore, 1993). Therefore, remediation of this problem will require different solutions than those developed prior to this study when sea water intrusion was thought to be the only source of contamination.

CONTAMINANT TRANSPORT

Once contaminants are released into the groundwater system, they may be physically

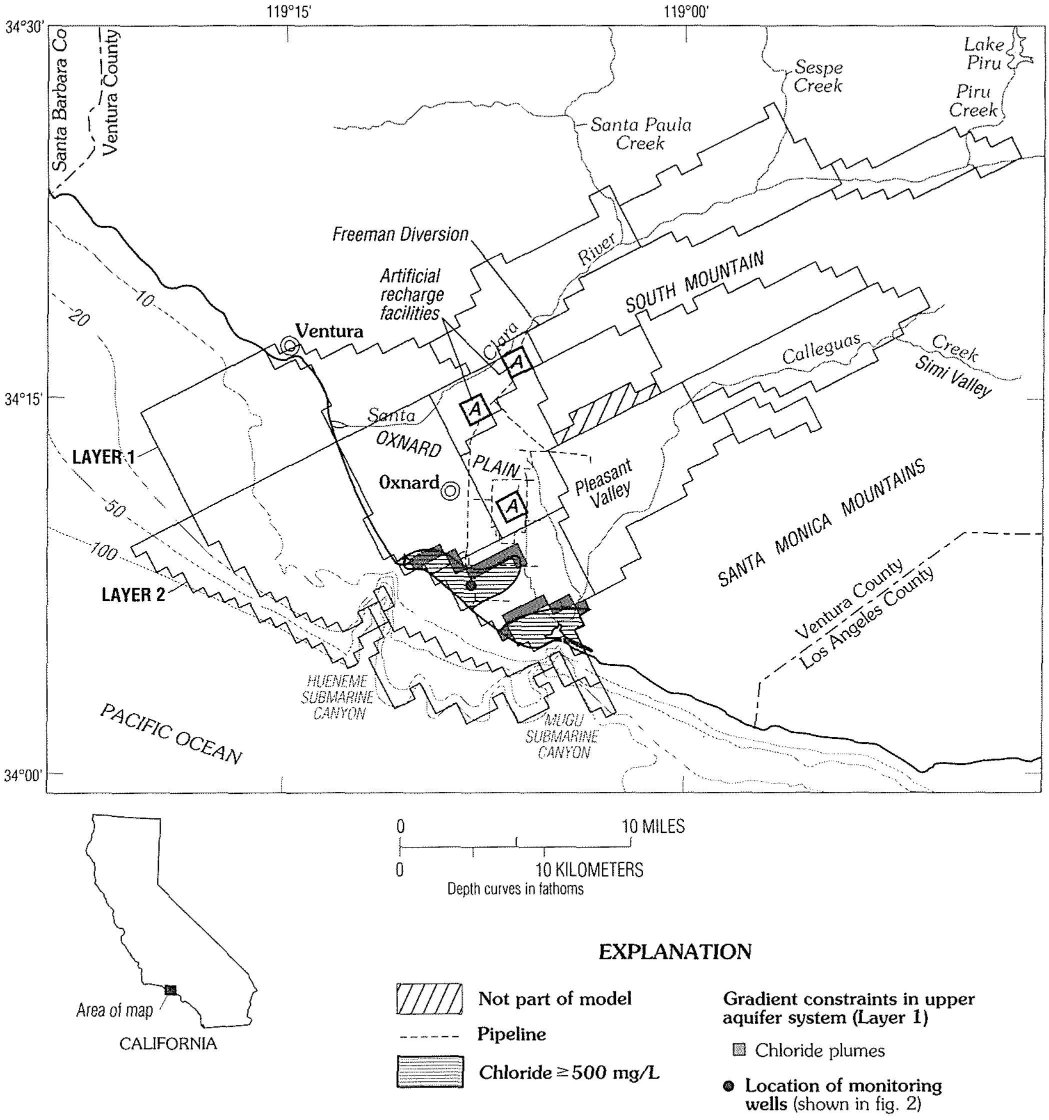


Fig. 1 Santa Clara-Calleguas basin.

transported and may be transformed by chemical and biological processes. Much current hydrogeologic research is devoted to increasing our understanding of these processes and to developing methods for modeling them in real systems. From a risk assessment/risk management perspective, the highest priority research tasks are those that result in better estimates of contaminant concentrations at locations of potential human exposure.

Groundwater contaminant transport is a three-dimensional process occurring in a spatially heterogeneous medium. There are important data limitations that preclude characterization of the governing parameters and important computational limitations that can make simulation of field problems difficult. Many researchers have addressed the issue of uncertainty in simulating groundwater contaminant transport and in designing remedial actions for mitigating the contamination. Most work thus far has focused on the spatial variability in hydraulic conductivity. Another factor that may lead to important transport uncertainties is climatic variability. The following example illustrates how climatic variability, and the resulting variability in surface water supplies, can affect the transport of contaminants and reliability of remediation strategies.

A simulation-optimization model was developed to evaluate alternative regional strategies for controlling sea water intrusion in the Santa Clara-Calleguas basin (see Reichard, 1995). A two-layer simulation model using the US Geological Survey Modular Model (McDonald & Harbaugh, 1988) was combined with the nonlinear optimization package, MINOS (Murtagh & Saunders, 1987), through the modeling language GAMS (Brooke *et al.*, 1988). The simulation-optimization model determined values for pumping rates, artificial recharge rates and pipeline deliveries that would most efficiently meet water demand and control sea water intrusion. Constraints on hydraulic gradients near the sea water plumes were employed as surrogates for controlling intrusion (see Fig. 1).

In the study area, the water that is used for artificial recharge and is delivered through the pipelines is surface water diverted from the main river in the basin, the Santa Clara River. The optimization model yields a water management strategy that will control hydraulic gradients near the sea water plumes, given all the assumptions in the model, including average flow conditions in the river. The reliability of this control strategy will depend on the uncertainty and variability in all components of the hydrologic system. A Monte Carlo analysis was done to test the sensitivity to one component, the natural variability in streamflow available to divert to artificial recharge facilities and pipelines.

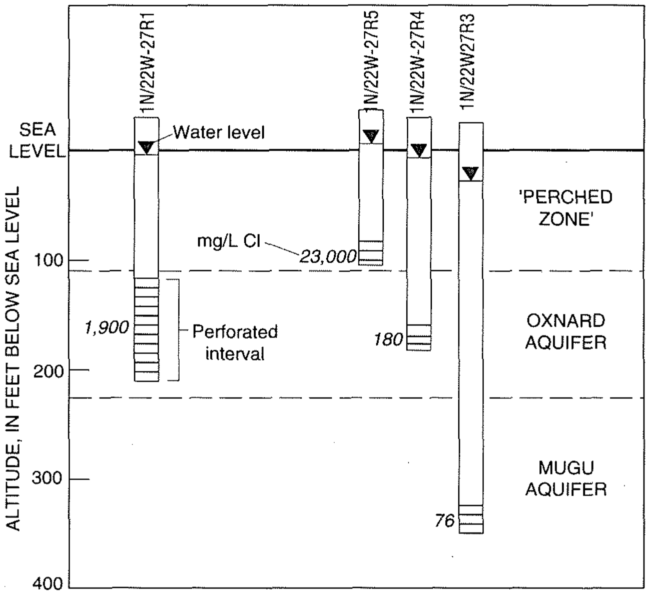


Fig. 2 Comparison of chloride concentrations in existing monitoring well and in multi-monitoring site (see Fig. 1 for location).

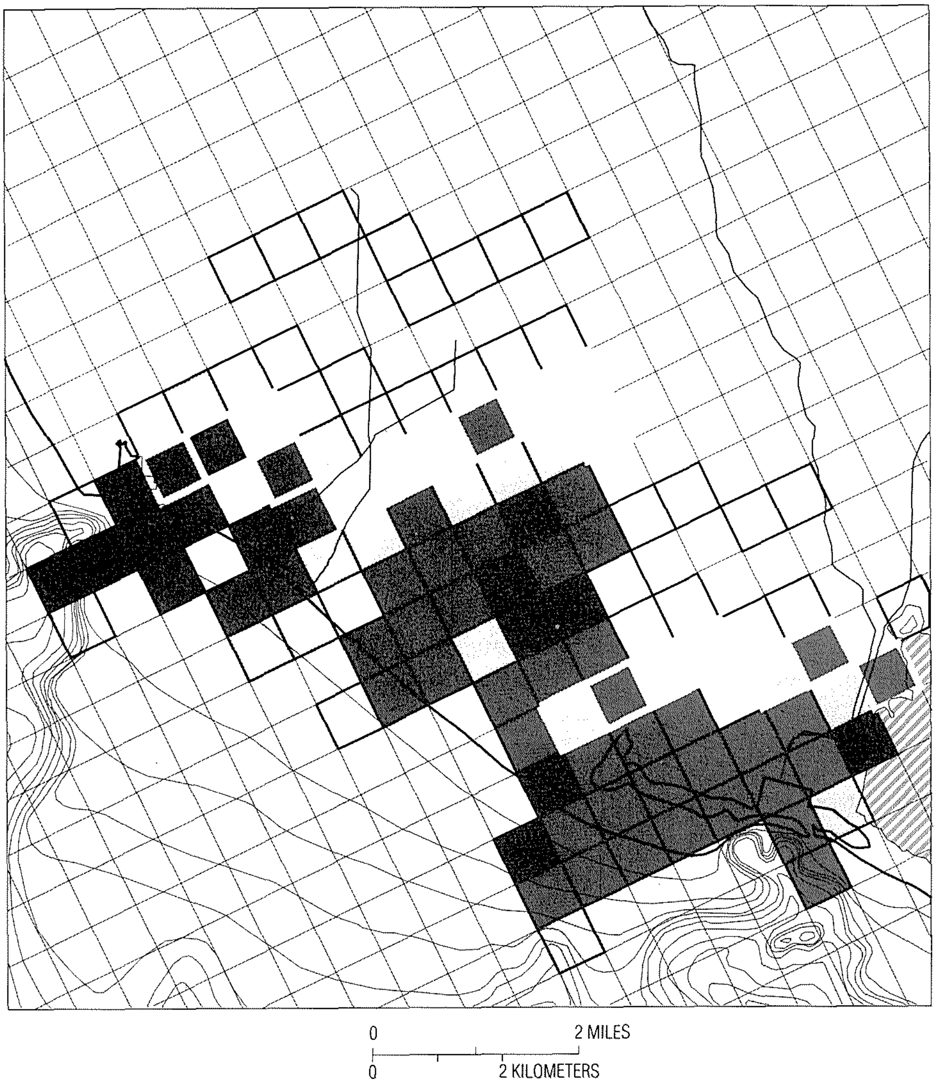
The results from the simulation-optimization model imply a set of decision rules for pipeline deliveries, artificial recharge rates and pumping rates as a function of river diversions in a given year. This set of decision rules was applied to fifty 15-year sequences of Santa Clara River diversions, randomly sampled from the cumulative distribution function of water available for diversion, using the Latin Hypercube method (Palisade Corporation, 1991). The cumulative distribution function was based on historical daily streamflow data for the period 1955-1991. These randomly sampled 15-year sequences are referred to as realizations. The transient groundwater levels resulting from applying the decision rules to each 15-year realization were simulated using the groundwater flow model. A transient particle tracking algorithm (Zheng, 1991) was then applied to the simulated water levels for each realization in order to estimate the advective movement of the chloride plumes in the upper aquifer system. All other transport processes, including dispersion, chemical reactions and density effects, are not considered. For the particle tracking simulations, particles were initially placed at the landward edge of the plumes (see Fig. 1). For each realization, the final locations of the particles were recorded. The results from all 50 realizations for each model cell block are summarized in Fig. 3, which shows the initial particle location and the total number of particles that ended up in each model cell. As can be seen, most particles move seaward, indicating effective hydraulic control of the sea water plume. However, there are some realizations in which particles move landward, indicating that the advective component of sea water intrusion has not been controlled. This tends to occur in the driest 15-year realizations – those with the least surface water availability. In these realizations, less recharge and more pumpage results in landward movement of sea water.

This Monte Carlo analysis, which is based on 50 realizations, cannot provide an accurate, quantitative estimate of the reliability of the model-computed remediation strategy. However, it can qualitatively characterize the likelihood that the remedial strategy will succeed, given what we know about the variability of surface water supplies. The analysis indicates that climatic variability may be an important source of uncertainty in contaminant transport and remediation. Risk management strategies should take this variability into consideration, particularly for regional water quality issues.

QUANTIFYING HUMAN EXPOSURE TO CONTAMINATED GROUNDWATER

Humans will be exposed to contaminated groundwater only if the water is pumped from a well and is delivered – either directly or through a distribution system – to locations where humans come in contact with it. Several steps must occur before such contact takes place, during which contaminant concentrations may change and additional toxic chemicals or microbes may be introduced (see Fig. 4).

First, the contaminated groundwater is intercepted by a supply well. The pumped groundwater may come from different vertical zones with different water quality and the water produced by the well will be a mixture of these waters. Second, the water is transported from the well to points of potential human contact. Municipal wells generally feed into a distribution system, which commonly contains a mixture of water from several wells and from surface supplies. It is also possible for additional chemical and



EXPLANATION

Cumulative number of particles in cell:

☐ 1-3 Particles ☐ 4-8 Particles ▨ 9-16 Particles ■ 17-24 Particles

Fig. 3 Results of Monte Carlo evaluation of reliability of remediation strategy in the upper aquifer system, showing initial particle locations (white outlined cells) and total number of particles in each cell after 15 years, summed over 50 particle tracking simulations.

microbial contamination to occur during this step. Third, the water may be treated – at the supply well, within the distribution system, or at the point of use – before exposure occurs. Finally humans are exposed to contaminants through ingestion, inhalation and dermal absorption. Although concern in the past has focused primarily on ingestion exposure, there is increasing recognition that inhalation and dermal absorption may be equally important for some chemicals (McKone, 1989).

The problem of translating identified groundwater contamination into human exposure is illustrated by data collected from a pump-and-treat operation at a US Marine Corps base near Barstow, California. On the basis of water samples from several water table monitoring wells, a plume of tetrachloroethylene (PCE), in which concentrations were as high as 70 ppb, was delineated (Southwest Division Naval Facilities, 1992). An extraction well was constructed in the middle of the plume in order to pump and treat the contaminated water. The extraction well was continuously perforated from the water table to a depth of 20 m below the water table. Although the extraction well was drilled in the middle of the plume, the PCE concentration of water samples from the well was about 2 ppb, less than the US Environmental Protection Agency drinking water standard of 5 ppb. A velocity log of the perforated interval of the well made during pumping indicated that little if any water was entering the well from the contaminated deposits near the water table, whereas almost all of the water was being produced from an uncontaminated coarse grained zone near the bottom of the well. In this case, a well constructed in the middle of the contamination plume yields water that appears to be of minimal threat to human health. Thus, plume concentrations can provide misleading estimates of drinking water concentrations.

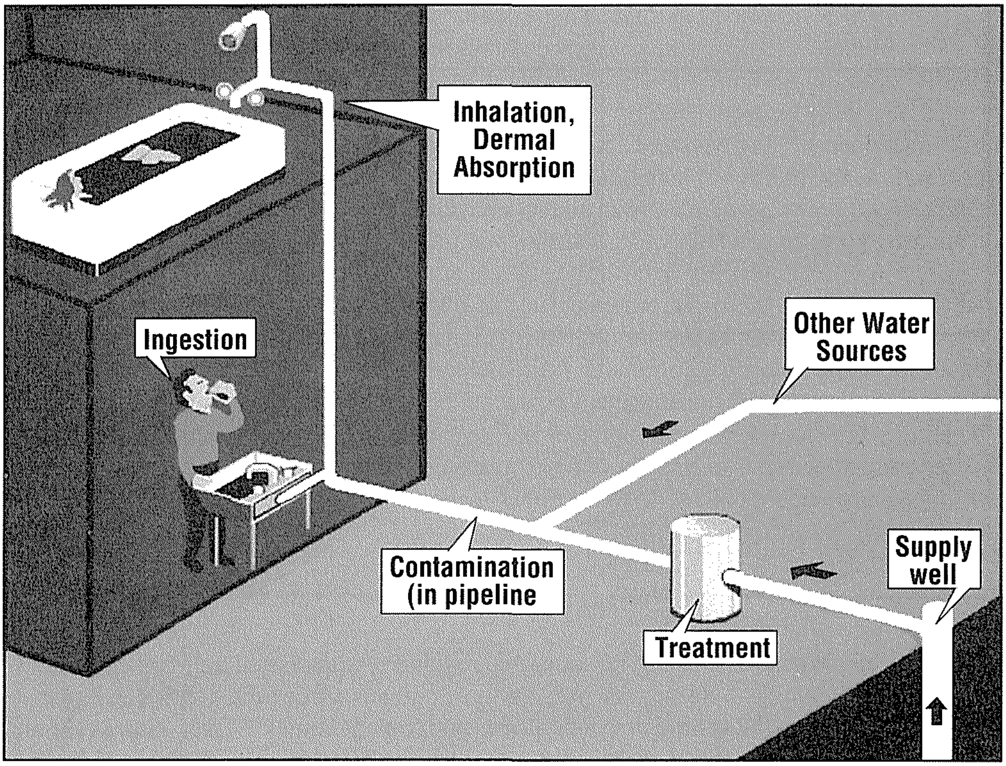


Fig. 4 Processes and pathways in human exposure to contaminated groundwater.

CONCLUSIONS

This paper has summarized three components of groundwater contamination exposure assessment – characterization of sources, environmental transport and actual human exposure – and illustrated some of the relevant uncertainties. Although the discussion focused on groundwater contamination, exposure assessment for surface water contamination can also be divided into the same three components. There are, however, some unique uncertainties associated with groundwater contamination. An example was presented to illustrate uncertainties in each of the three exposure assessment components. Note that there are aspects of each example that pertain to all three components.

In the first example, the extent of sea water intrusion in an aquifer was overestimated because the source of the high chloride water was incorrectly identified. Even though an extensive monitoring program was in place, characterization of the contamination was difficult because the groundwater contaminant sources were not visible and because there was a lack of three-dimensional data to accurately characterize the contamination.

In the second example, the uncertainty in the reliability of a potential remediation strategy was evaluated. Climatic variability affects the availability of surface water and, hence, the amount of recharge and pumpage in the system. A combination of particle tracking and Monte Carlo analysis allowed the quantification of the likelihood that the potential remediation strategy would be effective over the range of possible surface water conditions. Much research has addressed uncertainties associated with the spatial variability of hydraulic properties. This example illustrates an additional consideration: the importance of recharge/discharge uncertainties in evaluating groundwater transport problems and in designing remediation plans for risk management.

In the third example, the problem of translating groundwater contamination into human exposure was illustrated. In this example, groundwater pumped from an extraction well in the middle of a contaminant plume does not result in significant exposure levels. Well design, well operation and local hydraulic conditions can act to increase or decrease exposure levels in ways that may not be immediately obvious.

The three examples illustrate the benefits of establishing an extensive monitoring network for collecting three-dimensional data and of quantitatively evaluating the reliability of remediation strategies before implementation. A final point to consider is that both extensive monitoring networks and "reliable" remediation strategies are likely to be expensive. From a risk management perspective, this implies that priority setting will be required for groundwater monitoring and remediation and that prevention of groundwater contamination is extremely important. Large portions of the world's groundwater resources are uncontaminated. With proper management, they can remain so.

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REFERENCES

Brooke, A., Kendrick, D. & Meeraus, A. (1988) *GAMS, A User's Guide*. The Scientific Press, Redwood City, California, USA.

County of Ventura Public Works Agency (1990) *Oxnard Plain of Ventura County 1989 seawater intrusion study.*

Izbicki, J. A. (1991) Chloride sources in a California coastal aquifer. In: *Proc. Ground Water in the Pacific Rim Countries*, 71-77. Irrigation Div., American Society of Civil Engineers, USA.

McDonald, M. G. & Harbaugh, A. W. (1988) A modular three-dimensional finite-difference ground-water flow model. *Techniques of Water Resources Investigations of the US Geological Survey*, Book 6, Chapter A1.

McKone, T. E. (1989) Household exposure models. *Toxicol. Lett.* **49**, 321-339.

Murtagh, B. A. & Saunders, M. A. (1987) *MINOS 5.1 User's Guide.* SOL Report 83-20R, revised 1987, Stanford University, Stanford, California, USA.

Palisade Corporation (1992) *@Risk, Version 2.01 Users Guide*, Newfield, New York.

Predmore, S. K. (1993) Use of a geographical information system to identify abandoned wells. *USGS Open File Report 93-147.*

Reichard, E. G. (1995) Ground-water/surface water management with stochastic surface water supplies: A simulation-optimization approach. *Wat. Resour. Res.* (in press).

Southwest Division Naval Facilities Engineering Command (1992) Marine Corps Logisitics Base, Barstow, California, Groundwater investigationplan. Preliminary draft, Stage G. *Technical Memorandum TM-0006, San Diego, California.*

Stamos, C. L., Predmore, S. K. & Zohdy, A. A. R. (1992) Use of D-C resistivity to map saline ground water. In *Proc., Water Forum, '92*, 80-85. Irrigation and Drainage Div., American Society of Civil Engineers, USA.

Zheng, C. (1991) Path3d 3.0, a ground-water path and travel time simulator. S. S. Papadopulos and Associates, Inc., Bethesda, Maryland, USA.