REMEDIATION OF THE FAULTLESS UNDERGROUND NUCLEAR TEST: MOVING FORWARD IN THE FACE OF MODEL UNCERTAINTY

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ABSTRACT

The Faultless underground nuclear test, conducted in central Nevada, is the site of an ongoing environmental remediation effort that has successfully progressed through numerous technical challenges due to close cooperation between the U.S. Department of Energy, (DOE) National Nuclear Security Administration and the State of Nevada Division of Environmental Protection (NDEP). The challenges faced at this site are similar to those of many other sites of groundwater contamination: substantial uncertainties due to the relative lack of data from a highly heterogeneous subsurface environment. Knowing when, where, and how to devote the often enormous resources needed to collect new data is a common problem, and one that can cause remediators and regulators to disagree and stall progress toward closing sites. For Faultless, a variety of numerical modeling techniques and statistical tools are used to provide the information needed for DOE and NDEP to confidently move forward along the remediation path to site closure. A general framework for remediation was established in an agreement and consent order between DOE and the State of Nevada that recognized that no cost-effective technology currently exists to remove the source of contaminants in nuclear cavities. Rather, the emphasis of the corrective action is on identifying the impacted groundwater resource and ensuring protection of human health and the environment from the contamination through monitoring. As a result, groundwater flow and transport modeling is the linchpin in the remediation effort. An early issue was whether or not new site data should be collected via drilling and testing prior to modeling. After several iterations of the Corrective Action Investigation Plan, all parties agreed that sufficient data existed to support a flow and transport model for the site. Though several aspects of uncertainty were included in the subsequent modeling work, concerns remained regarding uncertainty in individual parameter values and the additive effects of multiple sources of uncertainty. Ultimately, the question was whether new data collection would substantially reduce uncertainty in the model. A Data Decision Analysis (DDA) was performed to quantify uncertainty in the existing model and determine the most cost-beneficial activities for reducing uncertainty, if reduction was needed. The DDA indicated that though there is large uncertainty present in some model parameters, the overall uncertainty in the calculated contaminant boundary during the 1,000-year regulatory timeframe is relatively small. As a result, limited uncertainty reduction can be expected from expensive characterization activities. With these results, DOE and NDEP have determined that the site model is suitable for moving forward in the corrective action process. Key to this acceptance is acknowledgment that the model requires independent validation data and the site requires long-term monitoring. Developing the validation and monitoring plans, and calculating contaminant boundaries are the tasks now being pursued for the site. The significant progress made for the site is due to the close cooperation and communication of the parties involved and an acceptance and understanding of the role of uncertainty.

INTRODUCTION

The hundreds of locations where nuclear tests were conducted underground are dramatic legacies of the Cold War. Though presenting unique challenges in terms of many groundwater transport issues, underground nuclear tests share much in common with other sources of groundwater contamination; in particular, the problem of uncertainty. Uncertainty is introduced to the analysis of groundwater transport through lack of data for the values, and spatial distribution of values, for flow and transport parameters. Though site characterization presents the opportunity to reduce uncertainty, uncertainty cannot be eliminated because our knowledge of the subsurface is limited to samples of a very small portion of the whole. The magnitude of the difficulty presented to scientists, managers, and regulators dealing with sites of subsurface contamination is easier to grasp by comparing to weather or stream forecasting. Both of those systems can be directly observed, yet their prediction accuracy is still significantly limited by data collection and computational constraints. We face not only those problems, but the additional hurdle that the vast majority of the subsurface system will always be hidden from us.

Though not immediately obvious, there is an advantage presented by the great depth of underground nuclear tests, as compared to more common groundwater pollution problems. The practical limitations of trying to reduce uncertainty through installing and testing characterization wells are more readily accepted when the source of contamination is located 1,000 m below ground surface. This is in contrast to some shallow groundwater contamination sites where the acceptance of uncertainty may be inhibited by the ability to install dozens of wells. Yet even at such shallow sites, it is impossible to eliminate the uncertainty inherent in subsurface transport calculations and the increase in the number of wells may threaten the site’s integrity.

A deep underground nuclear test in a remote portion of Nevada provides an opportunity for the U.S. Department of Energy, National Nuclear Security Administration, the State of Nevada Division of Environmental Protection (NDEP) and supporting scientists from the Desert Research Institute (DRI) to address uncertainty in subsurface flow and transport directly and identify credible ways of moving forward to site closure despite knowing uncertainty will remain. The site and its particular characteristics will be presented first. The approach to the corrective action work at the site will then be described. Next, the scientific and technical implementation of the corrective action approach through numerical modeling is presented. The role of uncertainty in regulator oversight is then described, as well as approaches used to integrate uncertainty in decision-making. Finally, continuing work on the site is described and conclusions presented.

DESCRIPTION OF THE SITE AND THE PROBLEMS IT PRESENTS

Though the vast majority of nuclear tests were conducted within the borders of the Nevada Test Site (NTS), 11 underground tests were conducted elsewhere and are known as the “Offsite” tests. The Central Nevada Test Area (CNTA) was designated as a supplemental testing area for higher-yield nuclear tests that needed to be farther from Las Vegas than the NTS due to ground motion. CNTA is located approximately midway between Tonopah and Ely. The Faultless test was the only test performed at CNTA, though others were originally planned. The Faultless test was detonated on January 19, 1968, with an announced yield range of 200 to 1,000 kt (1). At a depth of 975 m, the working point is in the saturated zone. As a result, the major concern at the site is transport of radioactive contaminants through the groundwater system.

CNTA is located within Hot Creek Valley, which extends approximately 110 km between north-south-oriented mountain ranges of the Basin and Range physiographic province. The valley is a long graben containing a thick sequence of Quaternary- and Tertiary-age fill (up to 1,200 m) underlain and bounded on either side by Tertiary-age volcanic rocks (principally tuffs and rhyolite lavas) (Figure 1). Annual precipitation averages 19.4 cm/yr and the nearly mile-high valley floor supports a sagebrush environment.

The water table in the vicinity of Faultless occurs almost 200 m below land surface (bls). The groundwater system has two components: a shallow section (defined using data from less than 300 m bls) where flow is directed southward down Hot Creek Valley, and a deeper section (defined using data from 1,500-2,100 m bls) of regional flow northeastward to Railroad Valley. In the northern part of the valley, hydraulic head decreases with increasing depth indicating a recharging environment. In the southern part of the valley, head increases with increasing depth and artesian conditions are encountered, characteristic of a discharge area.

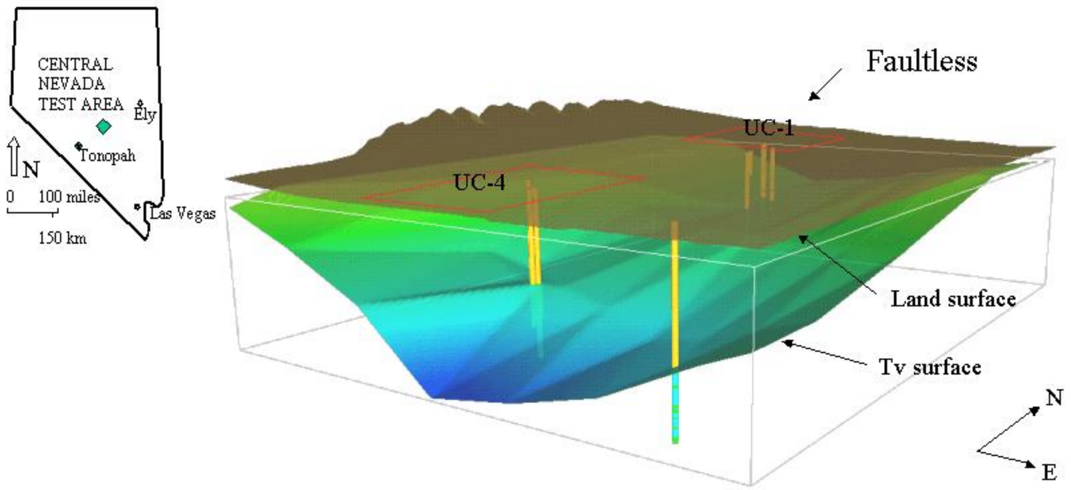

Fig. 1. Three-dimensional cross-section view looking northward up Hot Creek Valley, revealing the alluvium-filled basin underlying the ground surface. Below the block of blue-green alluvium are Tertiary volcanics.

The Faultless nuclear test was located midway down the valley in a region without strong vertical gradients. At the emplacement hole, UC-1, 732 m of alluvium were encountered, underlain by tuffaceous sediments and zeolitized tuffs to the 998 m total depth of the hole. The detonation occurred at a depth of 975 m, in the tuffaceous sediment section. Using rough, generic relationships between yield, cavity size, and depth of burial, the cavity radius is grossly estimated to be about 100 m. Within this cavity, the radionuclides from the test are distributed in surface deposits (assumed to be immediately available for groundwater transport) and in nuclear melt glass (released to groundwater as the glass slowly dissolves). Processes of sorption and matrix diffusion occur during transport through the aquifer.

THE CORRECTIVE ACTION APPROACH AT THE FAULTLESS SITE

In 1996, DOE and NDEP entered into a Federal Facility Agreement and Consent Order (FFACO) to address the environmental restoration activities for DOE sites in Nevada. The main focus of the agreement was to address restoration activities on the NTS but it also included work to be performed at the CNTA (inclusive of the Faultless task location), and several other locations. As part of the FFACO, a Corrective Action Strategy was developed on how environmental restoration work would be carried out, identifying four major steps and associated documentation to complete the corrective action process. The four main documents each represent critical decision points, agreed upon by the DOE and NDEP. These documents include 1) the Corrective Action Investigation Plan, identifying the process for characterizing and investigating the site in question; 2) the Corrective Action Decision Document, which analyzes the remediation alternatives and recommends the best remediation alternative; 3) the Corrective Action Plan, which describes how the selected remediation alternative will be implemented; and 4) the Closure Report, which documents the completed corrective action and identifies long-term monitoring and stewardship requirements. A key aspect of the process is that at each critical decision point, opportunities exist for the DOE and NDEP to make a determination on whether results are acceptable or if there is a need to return to an earlier step in the process to collect more data to eliminate unacceptable uncertainty.

It was recognized that each Offsite location could be separated into remediation efforts addressing the characterization and cleanup of areas impacted by activities on the ground surface, and efforts addressing deep subsurface contamination of groundwater associated with the test itself. This allows surface cleanup to proceed separate from the subsurface investigations. The Corrective Action Strategy described a detailed approach for addressing groundwater contamination for the NTS and indicates that the general approach could be applied to the Nevada Offsites subsurface investigations as well. However, it was also recognized by the NDEP and DOE that the Nevada Offsite locations were different enough from the NTS that changes could be incorporated into this strategy that could streamline the approach taken for these single event locations in comparison to the multiple event locations of the NTS.

The corrective action strategy used for the Faultless study involves predicting a contaminant boundary using computer modeling, a proof-of-concept period to ensure the groundwater model accurately depicts the groundwater system, followed by the establishment of a long-term monitoring program. First, a Corrective Action Investigation Plan was developed. The Plan described a conceptual model for the site, discussed model selection and approaches, and described a process to determine acceptability of the results. Once the work identified in the plan was completed, a decision could be made by DOE and NDEP to either collect more data or move forward with the prediction of a contaminant boundary, representing the area of potential contamination. The contaminant boundary is a risk-based boundary using the Safe Drinking Water Act regulatory level standards to define a boundary over a 1,000-year time frame. A major assumption of the strategy is that the only possible alternatives for remediation include long-term monitoring coupled with institutional controls or contaminant control, such as pumping and re-injection of groundwater to restrict contaminant flow.

THE SCIENCE BEHIND THE APPROACH

Tasked with ultimately generating contaminant boundaries at prescribed confidence levels, the methodology employed needed to be three-dimensional in nature and capable of quantifying uncertainty. A variety of stochastic models have been developed over the past two decades (2,3,4) that treat an aquifer as a single realization of a stochastic process of the physical and chemical parameters of concern. Using these stochastic approaches, groundwater velocities and contaminant concentrations can be described in a statistical sense. To avoid some limiting assumptions associated with analytical solutions, a numerical model was chosen and employed in a stochastic framework via the Monte Carlo approach (*e.g.,* 5,6,7).

The region around Faultless was intensively characterized in the 1960s for selection as a supplemental underground testing area. As a result, data from 58 straddle packer tests were available to support the model. Unfortunately, these data are spread through a sizable area and data specific to the immediate vicinity of Faultless are limited. Recognizing and working with this limitation led to the uncertainty in the flow and transport models. The conceptual model for flow uses three principal hydrogeologic units: 1), alluvium 2) tuffaceous sediments, bedded tuffs, and partially welded tuffs, and 3) rhyolites and densely welded tuffs. The rhyolites and densely welded tuffs are assumed to be highly fractured and faulted and, where present, are considered to be the primary pathways for groundwater flow and transport. Porous medium flow is assumed in the alluvium and tuffaceous sediments. The precise locations of the various units and their values of hydraulic conductivity (K) are only known at the few borehole locations. The natural hydrogeologic heterogeneity is described in two aspects. The occurrence of the hydrogeologic units throughout the bulk of the model is allowed to be uncertain, and the assignment of K to a unit is also uncertain.

The geometry of the hydrogeologic units is simulated using the Sequential Indicator Simulation (SIS) algorithm (8). Surface and subsurface geophysical data are used to divide the saturated hydrogeologic section into the three units described above (alluvium, volcanic rocks with low K, and volcanic rocks with high K). The alluvium is only found above the volcanic rocks and this boundary is constructed from estimates of alluvium thickness by Healey (9), made using drilling, aeromagnetic, and seismic data. Uncertainty in the alluvium/volcanic boundary at locations distant from the wells is allowed through a 150-m-thick zone centered on the estimated boundary location. The distinction between the two volcanic categories, and their relative geometry, is determined using borehole lithologic, electrical resistivity, and hydraulic conductivity data. The more limited "hard" data of K measurements are supplemented by a relationship identified between the K data and more abundant resistivity logs. The use of "soft" resistivity data to infer K maximizes the information used from available data. A spatial correlation structure is identified for the volcanic units and used for the SIS runs. Hundreds of individual representations of the spatial distribution of the three hydrogeologic categories are generated, each adhering to the spatial statistics and each equally likely to represent the true distribution. The simulations are conditioned at known data locations. For each SIS realization, the Sequential Gaussian Simulation (SGS) algorithm is implemented (10) to produce maps of *K*. Variogram models of the spatial structure of *K* for each hydrogeologic category are developed from the field data. One *K* field is produced using SGS for each category of every SIS realization. The final *K* map for each SIS realization is generated by assigning the *K* value appropriate for each cell, based on the cell's category (Figure 2).

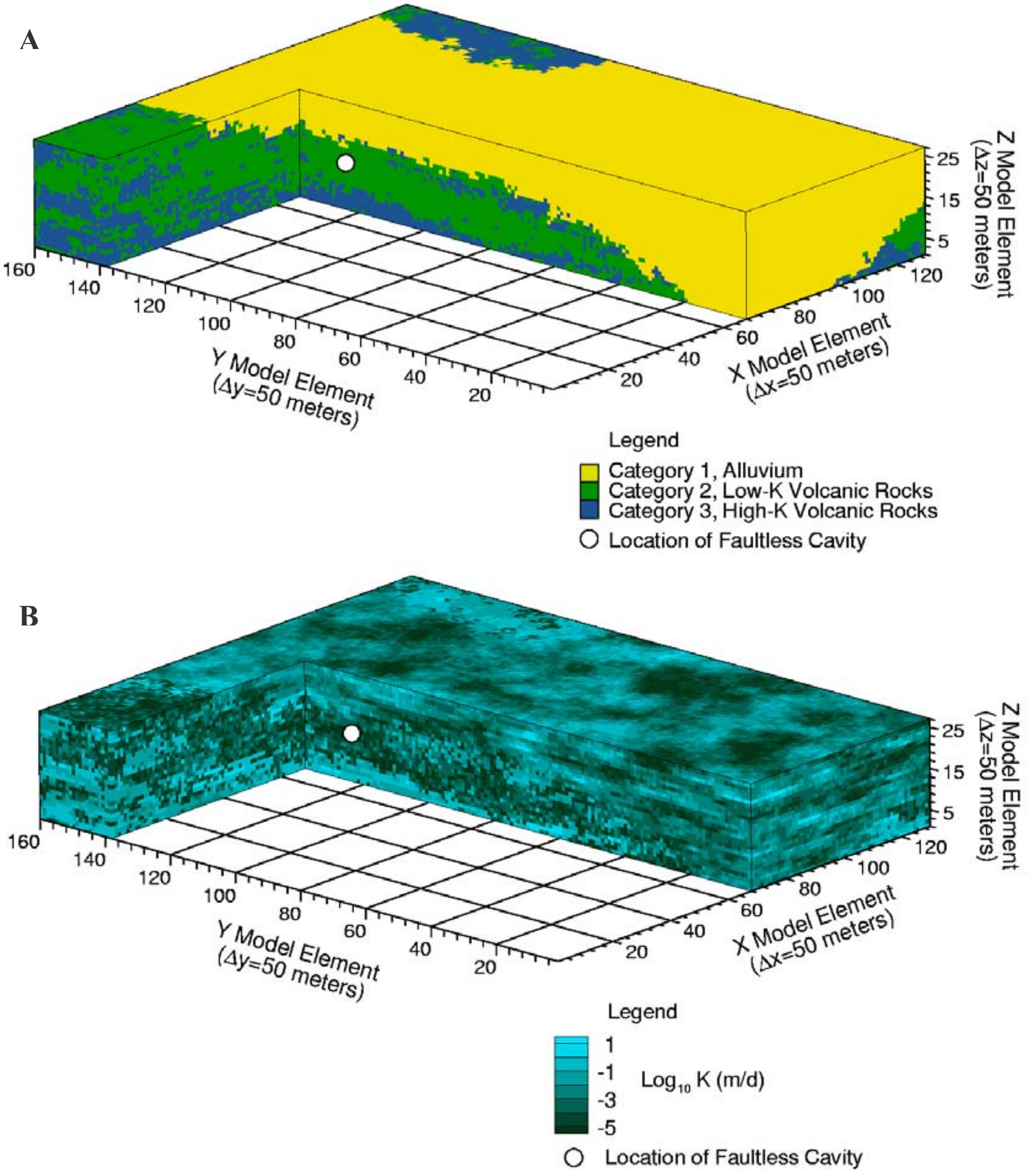

Fig. 2. (A) The model domain showing a single realization of the three hydrogeologic categories. A section of the volume closest to the viewer is removed to show the distribution of categories simulated near the Faultless cavity. (B) The corresponding distribution of simulated hydraulic conductivity.

Using the *K* maps as the foundation for groundwater flow calculations, hundreds of equiprobable flow fields are created for the site. These in turn are the basis for transport calculations, performed using a random-walk particle tracking method. Two conceptual models of transport were evaluated: a porous medium conceptualization, and a conceptualization of fracture flow in the welded tuff unit. Transport processes include nuclear melt glass dissolution, retardation, matrix diffusion (for fracture flow conceptualizations), and radioactive decay. Details of the treatment of hydrogeologic heterogeneity, the flow modeling, and transport modeling can be found in Pohlmann et al. (11).

The resulting model of contaminant transport for the Faultless site found very limited transport through the 1,000-year timeframe prescribed by the FFACO. Movement was generally downward and to the north of the nuclear test (Figure 3). Radionuclides with shorter half lives did not “survive” to the breakthrough plane at the site boundary. For longer lived radionuclides, peak mean breakthrough at the boundary occurred between 2,000 years (for species with no retardation behavior) and millions of years (for retarded species). The characteristics of very low hydraulic conductivity and downward directed gradients at the cavity control the transport behavior of radionuclides from the Faultless test.

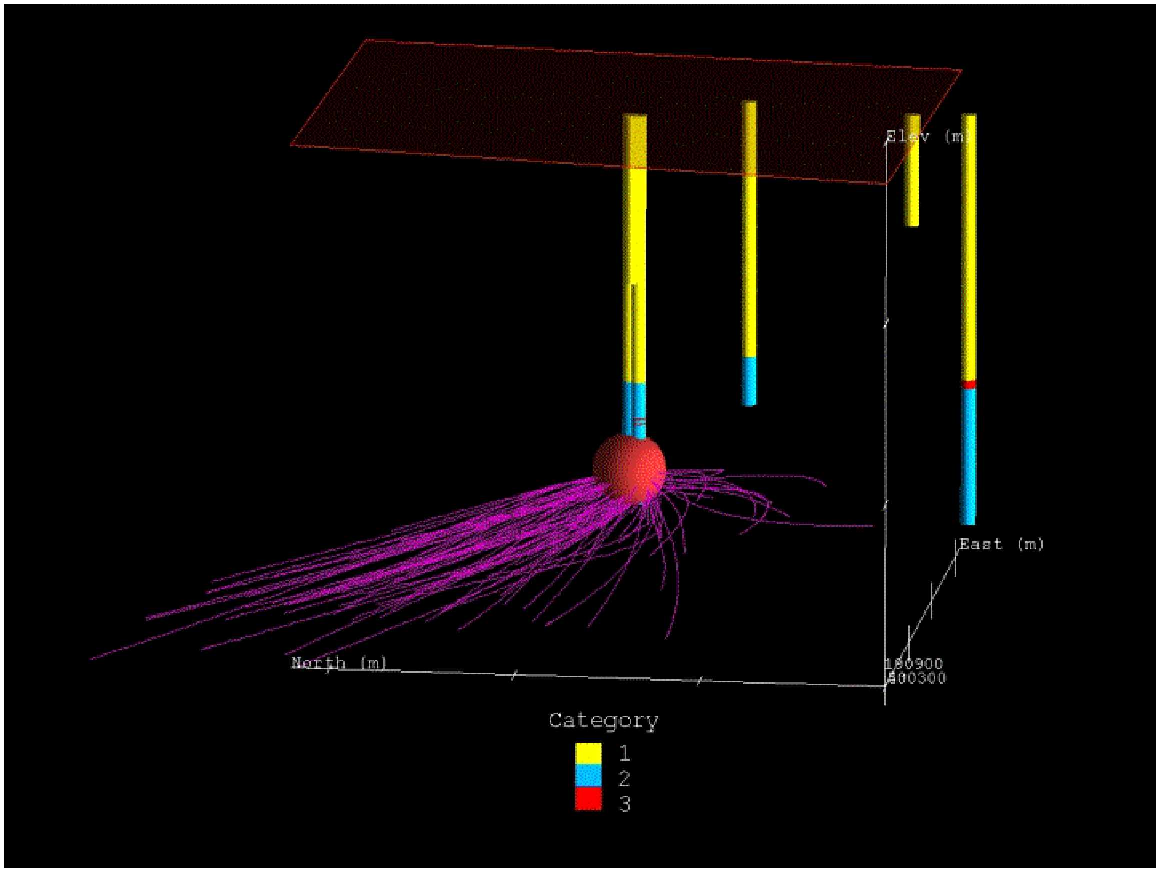

Fig. 3. Particle pathlines showing the direction of transport for hundreds of transport realizations. Radionculides move generally downward and to the north. Yellow = alluvium; blue = tuffaceous sediments; red = welded tuff. The red outline on the top is of the UC-1 withdrawal area (1 sq. mi.).

REGULATOR REVIEW OF THE MODEL AND THE IMPORTANCE OF UNCERTAINTY

The regulatory review process undertaken by the designated regulatory authority, NDEP, is grounded in the consent agreement signed by DOE and NDEP. As stated above, the FFACO specifies the corrective action investigation strategy to be followed and the reports and other deliverable products that NDEP will use to assess progress made in the characterization of the site. These interim deliverable products must form a scientifically credible basis for the final product, a model-predicted boundary of the potential extent of contaminant migration in the next 1,000 years.

Formal regulatory oversight began with NDEP's review and approval of a Corrective Action Investigation Plan in 1999. The Plan detailed each element of the proposed investigation, focused largely on groundwater flow and transport modeling using existing data. As the model was being developed, NDEP was kept informed of progress and significant developments. In September 1999, DOE presented the results of the flow and transport modeling in a report (12) to NDEP for review and comment. The NDEP was troubled that the model relied heavily on stochastic methods to account for the natural heterogeneity and that there was large uncertainty associated with the hydrogeologic input parameters. Regulator comments focused on three areas of concern: 1) the paucity of field data on which the model was based, particularly regarding the location of existing contaminant plumes if present, contaminant transport data, and field verification that a highly transmissive hydrostratigraphic unit identified in the region was not present in the immediate vicinity of the test working point; 2) the nature of the uncertainty ascribed to each input parameter – uncertainty was neither quantified nor adequately qualified; and 3) the lack of an overall assessment of model uncertainty – the concern being that the uncertainty inherent in the data combined with modeling assumptions and statistical constructs of the stochastic methods employed had interacted in a manner that compounded the overall uncertainty and produced a model unsuitable for use in making regulatory decisions.

The regulator, while not rejecting the model outright, asked that the modeling results be used as a tool for additional investigation. NDEP requested that DOE review the available site-specific data. The regulator asked that existing uncertainty be more fully characterized, quantified, and reduced in a revised model. The intent was to focus the evaluation on additional data that could be obtained to improve the model and explore how these data might reduce the overall uncertainty in the model-predicted results.

To address the regulator concerns regarding uncertainty in model parameters, a more rigorous uncertainty analysis was performed. This analysis is termed a Data Decision Analysis (DDA) and built upon an approach developed for another offsite underground test area, the Shoal site (13). The approach for CNTA was designed first to quantify the current model output uncertainty for the flow and transport model. The previous model had quantified the uncertainty in the spatial distribution of hydrogeologic units and the value of K within each unit, but the uncertainty inherent in the other parameters was not included. Depending on the outcome of this first analysis, a secondary objective for the DDA was to determine the most cost-beneficial characterization activities for reducing model uncertainty. The details of the DDA approach used for CNTA are given in (14).

Using a sensitivity analysis performed with the original model, the DDA identified six parameters whose uncertainty is important to the model's ability to predict solute migration. These parameters are: 1) specified head boundary conditions, 2) spatial distribution of the welded tuff, 3) effective porosity, 4) sorption coefficients, 5) matrix diffusion coefficients, and 6) nuclear melt glass dissolution rates. Other parameters are also uncertain, but found to not be as important to predictions of solute migration. In addition, uncertainty in K is included through the stochastic treatment of the spatially heterogeneous K field, as in the original model. The second uncertainty parameter (spatial distribution of the welded tuff), listed above, was also addressed through this process. To accommodate the computational rigors of so many uncertain parameters and the large number of realizations needed for reliable statistics, the original three-dimensional model was converted to a two- dimensional cross section. This process was straightforward due to the boundary conditions in the three- dimensional model being constant along the x-direction.

The first step in the DDA was to determine the prior distributions of the parameters. This is an assessment of the range of potential values and probability associated with each value. Ranges and uncertainty were estimated using site-specific data, augmented by literature values. Two solutes were used for the transport modeling to assess the transport features for a conservative (tritium) and reactive (^{90}Sr) solute. Transport was simulated over the FFACO period of 1,000 years and the contaminant boundary was calculated as the metric of most interest. The maximum radius of the contaminant boundary was used to determine the uncertainty in the predictive capability of the model by comparing the size from one realization to another.

The DDA found that the 90 percent confidence interval for the maximum contaminant boundary ranged from 234 to 308 m for tritium, and from 234 to 302 m for ^{90}Sr. The range between the upper and lower 90 percent confidence intervals (a measure of uncertainty), is 74 m for tritium and 68 m for ^{90}Sr. These results indicate that though there is a large amount of uncertainty in the input parameters, the uncertainty in the prediction of the contaminant boundary within the 1,000-year timeframe is relatively certain, with an error of less than 100 m. This results primarily from the low transport velocities. Uncertainty could potentially be reduced through additional characterization work, to values less than 74 m, but this would provide little value regarding management of the site.

Satisfied that uncertainty had been adequately evaluated through the DDA process, NDEP regulators moved forward to a decision that the Faultless flow and transport model was acceptable for the site. This significant ruling was based not only on the results of the model and DDA, but conditioned on NDEP's assessment of future actions at the site, as described below. On its part, based on the modeling, DOE anticipates that contaminant control is not a viable option and that long-term monitoring with institutional controls will be the preferred corrective action alternative. Based on this expectation, the Corrective Action Decision Document and Corrective Action Plan will be combined, allowing for the development of the process to validate the model and develop a long-term monitoring strategy, reducing overall cost and allowing for earlier implementation of long-term monitoring.

PATH FORWARD

While authorizing the corrective action process to move forward, NDEP applied two conditions: that DOE must create a validation plan (in conjunction with a monitoring plan) to address the downgradient region of the model, and that this validation plan must contain clearly defined trigger mechanisms for revisiting the model. The regulator has stressed that a validation plan must verify subsurface conditions downgradient of the test working point. This requirement will serve to further reduce regulator concern over uncertainty in the model. It will also provide the regulator with additional field evidence that may be presented to a skeptical public to help demonstrate that model predictions are reasonable and scientifically valid. All parties acknowledge that engendering public acceptance of a statistically intensive computer representation of contaminant transport may be challenging. Care must be taken to present difficult scientific concepts in an easy to comprehend manner to build public support for regulatory decisions. Public involvement in the corrective action process at the CNTA is facilitated through interaction with the NTS Community Advisory Board (CAB). The CAB is a group of volunteer, independent, and nonpartisan citizens that provides recommendations and advice to DOE on policy, technical issues, and decisions related to cleanup and waste management activities at test facilities in Nevada.

Validation of the model, as defined in the FFACO, is to ensure fidelity of the model to the physical system. A ten-step protocol is described in the agreement, and most of these steps were already performed as part of good scientific process in the original modeling. The protocol defined is: 1) establish model purpose, 2) develop conceptual model, 3) select computer code and verify it, 4) design model, 5) calibrate model, 6) conduct sensitivity and uncertainty analysis, 7) verify model , 8) conduct predictive simulations, 9) present results, and 10) conduct a postaudit. The validation plan requested for Faultless may represent either step 7 or 10, or some combination of both.

"Verification," "validation" and "confirmation" are all concepts in terms of groundwater numerical models that not only do not have established and generally accepted practices, they do not even have widespread agreement on the meaning of the terms as applied to models. Many assert that it is impossible to verify a groundwater numerical model because such a claim would assert a demonstration of truth that can never be attained for our approximate solutions to subsurface problems (15). While all modelers are uncomfortable with the prospect of claiming accuracy for their tools, it is reasonable for the public (principally through their regulator) to expect some assessment that a model is legitimate for the purpose for which it is used. Defining the validation process to attain such legitimacy for the Faultless flow and transport model is now the immediate task ahead. It is also important as this process is created that performance that would invalidate the model is clearly defined. No one wishes to perpetuate endless loops of modeling, checking, then re-modeling, but explicit acknowledgement of the possibility of failure of the model in the validation process is needed for both technical and public acceptance of the process.

Validating the stochastic Faultless model will not eliminate uncertainty from the model calculations. Confidence in the model must be explained to the public and translated into an easy-to-understand statement of acceptable risk, the risk of the incorrect decision. Key to public acceptance is monitoring. Monitoring can be viewed as the final step addressing uncertainty in environmental problems. Groundwater monitoring not only serves to ensure that the system is performing as predicted, it acknowledges the uncertainties inherent in the modeling process and the possibility, however remote, of unexpected outcomes. Designing a technically robust groundwater monitoring network that samples at optimum locations, times, and parameter scales is another non-trivial task ahead for the Faultless site.

CONCLUSIONS

The FFACO provides an important roadmap to corrective action for the Faultless site, which, although not entirely unique, is one of only a few underground nuclear detonation sites in the country outside of the NTS. Intensive environmental characterization of detonation sites has only begun in the last few years. Due to this, Faultless presents an interesting challenge to the regulator as well as the scientist investigating the site. Regulator decisions made at one site may set a precedent for the investigation of additional sites where the corrective action process has yet to be initiated. Yet, a cookie-cutter regulatory approach would be inappropriate given the unique conditions of hydrogeology and test configuration presented by each nuclear test. The regulator is tasked with ensuring that the investigation process followed is both technically sound and scientifically defensible to a skeptical public.

In these uncharted waters, a good working relationship between the regulator (NDEP), the responsible party (DOE), and the technical consultant (DRI) became paramount. A process of cooperative interaction was achieved, somewhat analogous to the Enlibra concept advocated by the Western Governor's Association (WGA). The WGA defines Enlibra as being " based upon principles that have proven effective in resolving environmental and natural resource debates in a more inclusive, faster and less expensive fashion" (16). Enlibra is a term coined by the Western Governors to symbolize balance and stewardship.

In any agency directed environmental investigation, the regulator endeavors to form an understanding of the technical aspects of a project that is independent of that held by the responsible party and its technical consultant. The regulator is keenly aware that the consultant is beholden to its client. Yet it is often the consultant, not the client or regulator, that has garnered the most intimate understanding of the data and technical issues at a site. The consultant's long-term credibility is based on a prove track record of scientifically credible work. To help NDEP and DOE with the complexities of the site, the Faultless investigation required an involved, technically qualified, and scientifically unbiased consultant. When coupled with a responsible party willing to allow the consultant to propose an innovative method and a regulator that recognized that site conditions required a unique approach, what resulted was a cooperative and productive work environment. Through the careful evaluation of existing data and value of data collection, it is now possible to maximize the return of a field effort, and rather than sit wells simply for characterization data, locate wells that will both validate the model and serve a future monitoring need. While planning begins for the validation and monitoring effort, the flow and transport model will be used to calculate a contaminant boundary for the site so that DOE and NDEP have a basis whichto begin their negotiations on site closure.

The progress made toward closure of the Faultless underground test site was gained through cooperative relationships and through the acknowledgment and understanding by all parties of the role of uncertainty in the process. Accepting that uncertainty is inherent and cannot be eliminated, quantifying the impact of uncertainty, and using a wider vision of the future management of the site allowed movement forward in the environmental restoration process.

REFERENCES

1. U.S. Department of Energy, 2000. United States Nuclear Tests July 1945 through September 1992. U.S. DOE Nevada Operations Office report DOE/NV/209-Rev15, 162p.
2. Delhomme, J.P., 1979. Spatial variability and uncertainty in groundwater flow parameters: A geostatistical approach. *Water Resour. Res*. 15 (2), 269-280.
3. Dagan, G., 1986. Statistical theory of groundwater flow and transport pore to laboratory, laboratory to formation, and formation to regional scale. *Water Resour. Res*. 22(9), 120S-135S.
4. Gelhar, L.W., 1986. Stochastic subsurface hydrology from theory to applications. *Water Resour. Res*. 22 (9), 1355-1455.
5. Tompson, A.F.B. and Gelhar, L.W., 1990. Numerical simulation of solute transport in three-dimensional, randomly heterogeneous porous media. *Water Resour. Res*. 26 (10), 2541-2562.
6. Hassan, A.E., Cushman, J.H., and Delleur, J.W., 1997. Monte Carlo studies of flow and transport in fractal conductivity fields: Comparison with stochastic perturbation theory. *Water Resour. Res*. 33 (11), 2519-2534.
7. Hassan, A.E., Cushman, J.H., and Delleur, J.W., 1998. A Monte Carlo assessment of Eulerian flow and transport perturbation models. *Water Resour. Res*. 35 (5), 1143-1163.
8. Alabert, A., 1987. Stochastic imaging of spatial distributions using hard and soft information. M.S. Thesis, Appl. Earth Sci. Dept., Stanford Univ.
9. Healey, D.L., 1968. Gravity survey of northern Hot Creek Valley, Nye County, Nevada. U.S. Geological Survey Technical Letter: Central Nevada-18.
10. Deutsch, C.V., and Journel, A.G., 1998. GSLIB Geostatistical Software Library and User's Guide. 2nd Oxford University Press.
11. Pohlmann, K., Hassan, A., and Chapman, J., 2000. Description of hydrogeologic heterogeneity and evaluation of radionuclide transport at an underground nuclear test. *J. Contam. Hydrology* 44, 353-386.
12. Pohlmann, K., Chapman, J., Hassan, A., and Papelis, C., 1999. Evaluation of groundwater flow and transport at the Faultless underground nuclear test, Central Nevada Test Area. U.S. Department of Energy, Nevada Operations Office report DOE/NV/11508-41, 129p.
13. Pohll, G., Tracy, J., and Forsgren, F., 1999. Data Decision Analysis: Project Shoal. U.S. Department of Energy, Nevada Operations Office report DOE/NV/11508-42, 27p.
14. Pohll, G., and Mihevc, T., 2000. Data Decision Analysis: Central Nevada Test Area. U.S. Department of Energy, Nevada Operations Office report DOE/NV/13609—07, 25p.
15. Oreskes, N., Shrader-Frechette, K., and Belitz, K., 1994. Verification, validation, and confirmation of numerical models in the earth sciences. *Science* 263, 641-646.
16. Western Governors' Association, 1999. WGA Annual Meeting in Jackson Hole, Wyoming as Policy Resolution 99 - 013, "Principles for Environmental Management in the West," June 15, 1999, http://www.westgov.org/wga/initiatives/enlibra/default.htm (December 2001). SPONSORS: Governors Kitzhaber and Leavitt.