SAND2008-3069C

SENSITIVITY ANALYSES OF RADIONUCLIDE TRANSPORT IN THE SATURATED ZONE AT YUCCA MOUNTAIN, NEVADA

Bill W. Arnold, Teklu Hadgu, and Cedric J. M. Sallaberry

Sandia National Laboratories, P.O. Box 5800, Albuquerque, NM 87185-0735, bwarnol@sandia.gov

Simulation of potential radionuclide transport in the saturated zone from beneath the proposed repository at Yucca Mountain to the accessible environment is an important aspect of the total system performance assessment (TSPA) for disposal of high-level radioactive waste at the site. Analyses of uncertainty and sensitivity are integral components of the TSPA and have been conducted at both the sub-system and system levels to identify parameters and processes that contribute to the overall uncertainty in predictions of repository performance. Results of the sensitivity analyses indicate that uncertainty in groundwater specific discharge along the flow path in the saturated zone from beneath the repository is an important contributor to uncertainty in TSPA results and is the dominant source of uncertainty in transport times in the saturated zone for most radionuclides. Uncertainties in parameters related to matrix diffusion in the volcanic units, colloid-facilitated transport, and sorption are also important contributors to uncertainty in transport times to differing degrees for various radionuclides.

I. INTRODUCTION

The saturated zone is an important pathway for the potential release of radionuclides to the accessible environment from the proposed high-level radioactive waste repository at Yucca Mountain. Groundwater moving downward in the unsaturated zone below the repository would transport radionuclides to the water table, where predominantly lateral migration would carry them to locations of potential future pumping and release to the biosphere. Consequently, analysis of radionuclide transport in the saturated zone is a component of the Total System Performance Assessment (TSPA) model for assessing the potential impacts of the repository and associated risks to human health.

Previous radionuclide transport simulation methods in the saturated zone and the results of sensitivity analyses have been reported in Arnold et al.[1] Although the basic modeling structure remains the same in current simulations, the underlying saturated zone site-scale flow model has been recalibrated and uncertainties in some parameters have been reevaluated with the acquisition of additional data.

The purpose of this study is to update the uncertainty and sensitivity analyses of potential radionuclide transport in the saturated zone using current models and parameter uncertainty distributions. Sensitivity analyses are conducted at both the sub-system and total system levels, using metrics such as simulated radionuclide transport times and cumulative radionuclide release.

II. UNCERTAINTY AND SENSITIVITY ANALYES

II.A. Saturated Zone Flow and Transport Simulations

The site-scale saturated zone flow model forms the basis for the simulation of groundwater flow and radionuclide transport in performance assessment calculations for Yucca Mountain.[2] The three-dimensional site-scale saturated zone flow model consists of a 30 km by 45 km model domain and represents a synthesis of geological and hydrological information about the site. The model is calibrated to observations of water levels in wells and estimated groundwater flow rates at the lateral boundaries taken from the Death Valley regional groundwater flow model.[3] Additional confidence in the site-scale saturated zone flow model is obtained by comparisons between simulated flow paths and hydrochemistry data, calibrated values of permeability and measured values, simulated specific discharge and independently estimated values of groundwater flux, and simulated heads and water-level measurements not used in the calibration process.

Physical processes relevant to radionuclide transport , including advection, dispersion, matrix diffusion in fractured units, sorption, and colloid-facilitated transport, are added to the site-scale saturated zone flow model in the site-scale saturated zone transport model.[4] A particle-tracking method is used to simulate the movement of radionuclide mass from beneath the repository to the boundary of the accessible environment. The model domain, numerical grid, and hydrogeologic framework are the same in the site-scale saturated zone flow model and the site-scale saturated zone transport model and both models are implemented with the FEHM software code.[5]

The site-scale saturated zone transport model is coupled to the TSPA simulations using an abstraction in which a Monte Carlo suite of saturated zone transport simulation results are obtained.[6] Each simulated radionuclide breakthrough curve assumes a continuous unit source rate at the water table beneath the repository and corresponds to a vector of sampled uncertain saturated zone parameters. The computationally efficient convolution integral method is used to couple the radionuclide breakthrough curves with the transient radionuclide source from the unsaturated zone within the TSPA model. In addition to the three-dimensional saturated zone flow and transport abstraction model described above, a one-dimensional radionuclide transport model is implemented directly within the TSPA model to simulate decay chains.

TABLE I. Uncertain Parameters in Saturated Zone Flow and Transport Simulations

Parameter	Description	Uncertainty 5%tile, 50%tile, 95%tile (unit)
GWSPD	Groundwater specific discharge multiplier	0.312, 1.00, 3.21 (-)
FISVO	Flowing interval spacing in volcanic units	4.84, 25.8, 50.4 (m)
DCVO	Effective diffusion coefficient in volcanic units	1.19×10^{-11}, 5.01×10^{-11}, 3.62×10^{-10} (m^2/s)
FPVO	Fracture porosity in volcanic units	1.0×10^{-4}, 1.0×10^{-3}, 3.16×10^{-2} (-)
HAVO	Ratio of horizontal anisotropy in permeability	0.203, 4.33, 14.9 (-)
LDISP	Longitudinal dispersivity	5.84, 100., 1710 (m)
NVF26	Effective porosity in alluvial unit 26	0.0961, 0.180, 0.264 (-)
NVF11	Effective porosity in alluvial unit 11	0.0961, 0.180, 0.264 (-)
FPLANW	Northwestern boundary of the alluvial uncertainty zone	0.050, 0.500, 0.950 (-)
SRC1X	Source location 1 relative easting	0.050, 0.500, 0.950 (-)
SRC1Y	Source location 1 relative northing	0.050, 0.500, 0.950 (-)
KDNPVO	Neptunium sorption coefficient in volcanic units	0.990, 1.30, 3.92 (mL/g)
KDNPAL	Neptunium sorption coefficient in alluvium	4.00, 6.35, 8.70 (mL/g)
BULKDENS	Bulk density of alluvium	1780, 1910, 2040 (kg/m^3)
KDUVO	Uranium sorption coefficient in volcanic units	5.39, 6.78, 8.16 (mL/g)
KDUAL	Uranium sorption coefficient in alluvium	2.90, 4.60, 6.30 (mL/g)
KDRAVO	Radium sorption coefficient in volcanic units	145., 550., 955. (mL/g)
KDRAAL	Radium sorption coefficient in alluvium	145., 550., 955. (mL/g)
KDSRVO	Strontium sorption coefficient in volcanic units	39.0, 210., 381. (mL/g)
KDSRAL	Strontium sorption coefficient in alluvium	39.0, 210., 381. (mL/g)
KDSEVO	Selenium sorption coefficient in volcanic units	3.37, 10.5, 32.0 (mL/g)
KDSEAL	Selenium sorption coefficient in alluvium	3.37, 10.5, 32.0 (mL/g)
CONCCOL	Concentration of colloids in groundwater	1.58×10^{-9}, 1.00×10^{-7}, 2.74×10^{-5} (g/mL)
KDAMCOL	Americium sorption coefficient onto colloids	3.86×10^{5}, 7.50×10^{5}, 6.88×10^{6} (mL/g)
KDAMVO	Americium sorption coefficient in volcanic units	3030, 5500, 7970 (mL/g)
KDAMAL	Americium sorption coefficient in alluvium	3030, 5500, 7970 (mL/g)
KDCSCOL	Cesium sorption coefficient onto colloids	100., 667., 3330 (mL/g)
KDCSVO	Cesium sorption coefficient in volcanic units	3000, 4790, 6580 (mL/g)
KDCSAL	Cesium sorption coefficient in alluvium	185., 610., 958. (mL/g)
KDPUCOL	Plutonium sorption coefficient onto colloids	1440, 5710, 50000 (mL/g)
KDPUVO	Plutonium sorption coefficient in volcanic units	26.0,104., 130. (mL/g)
KDPUAL	Plutonium sorption coefficient in alluvium	76.0, 99.5, 123. (mL/g)
KDSNCOL	Tin sorption coefficient onto colloids	112000, 316000, 891000 (mL/g)
KDSNVO	Tin sorption coefficient in volcanic units	141., 3160, 70800 (mL/g)
KDSNAL	Tin sorption coefficient in alluvium	141., 3160, 70800 (mL/g)
CORVO	Colloid retardation factor in volcanics	6.00, 26.0, 419. (-)
CORAL	Colloid retardation factor in alluvium	8.00, 34.0, 3140 (-)

II.B. Parameter Uncertainty

Uncertainty in saturated zone flow and radionuclide transport arises from a number of sources and is evaluated by defining uncertainty distributions for key model parameters. The uncertain parameters in the saturated zone and their descriptions are listed in Table I. Parameter values at the 5^{th}, 50^{th}, and 95^{th} percentiles for each uncertain parameter are listed in the last column of Table I to give an indication of range and central tendency for parameter values. See Ref. 6 for a complete description of each uncertain parameter and the justification for the uncertainty distributions used in the uncertainty analyses.

Uncertainty in groundwater flow is evaluated with regard to the groundwater specific discharge along the flow path from beneath the repository and the horizontal anisotropy in permeability. Geological uncertainty is incorporated with regard to the contact between the volcanic units and the alluvium along the flow path. The release of radionuclides from four regions beneath the repository is varied among the saturated zone transport simulations to account for uncertainty in the radionuclide source location. Uncertainty in transport parameters is evaluated for sorption coefficients, effective porosity, dispersivity, flowing interval spacing, matrix diffusion coefficient, and colloid retardation factors and concentration.

Monte Carlo simulations of groundwater flow and radionuclide transport are performed by sampling the parameter uncertainty distributions to create 200 realizations of the saturated zone system. Radionuclides to be included in the TSPA model are divided into 12 groups based on modes of transport and transport properties and 200 realizations of each group are simulated. A steady-state groundwater flow solution is first obtained for each realization, using an estimated multiplier to flow rate for future glacial-transition climatic conditions. Glacial-transition climatic conditions are representative of average conditions at the site over the majority of the next 10,000 years and for time periods of up to 1,000,000 years.

Figure 1 shows the results of the saturated zone transport simulations for the non-sorbing species of carbon, technetium, and iodine. The upper plot shows the 200 breakthrough curves simulated in the Monte Carlo analysis. Many of the simulated breakthrough curves have long "tails" characteristic of transport in a fractured medium in which some fraction of the contaminant mass is delayed by diffusion into the rock matrix. The abrupt increase in mass release at 10 years for a few of the faster realizations is a result of the 10-year time step used in the model. The lower plot in Figure 1 shows the histogram of median transport times (mid-point of the breakthrough curve) for all 200 realizations. The differences in the breakthrough curves and the range of values of median transport time are indicative of the aggregate uncertainty in the underlying input parameters to the model. As, described earlier, these uncertainties in simulated radionuclide transport are propagated to the TSPA model for regulatory analyses. Figure 1 is illustrative of the simulated saturated zone breakthrough curves. Breakthrough curves were also obtained for the other radionuclide groups, with longer transport times resulting for sorbing species.

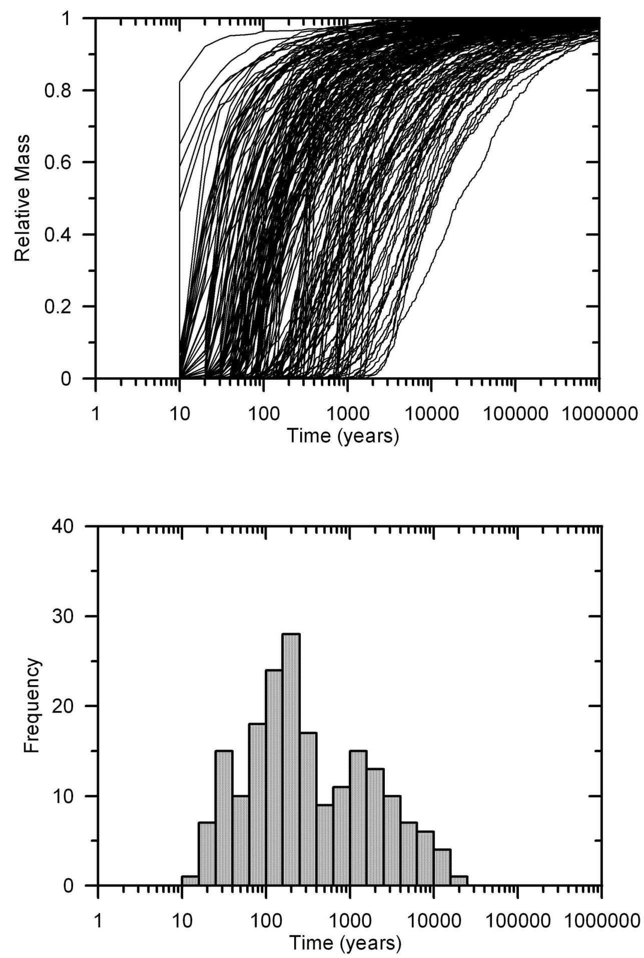

Figure 1. Saturated zone mass breakthrough curves (upper) and median transport times (lower) for carbon, technetium, and iodine at 18-km distance. Breakthrough curves are for future glacial-transition climate, do not include radionuclide decay, and are from source region 1. (Ref. 6, Fig. 6-6[a])

II.C. Stepwise Regression

Sensitivity analyses have been performed to evaluate the relative importance of the uncertain parameters with regard to simulated transport times in the saturated zone and with regard to simulated dose in the TSPA model. In both cases the relative importance of a particular input parameter to the uncertainty in the predicted variable is a function of the inherent sensitivity of the model to that input parameter and of the amount of uncertainty in that parameter.

Stepwise regression is used to explore the sensitivity to uncertainty in the saturated zone input parameters in this study. The stepwise process is to construct the linear regression equation one parameter at a time by adding at each step the parameter that explains the largest amount of the remaining unexplained variation. The coefficient of determination, R^2, represents the fraction of the variance that is explained by the linear relationship between the input variables (parameters) and the dependent variable (model prediction). The change in the coefficient of determination (ΔR^2) at each step in which an input variable is added to the regression equation, is a measure of the relative importance of that variable. The input parameters and model predictions are rank transformed in this sensitivity study to extend the method to the monotonic relation between the independent and dependent variables.

The sensitivity analyses using stepwise linear regression at the sub-system level examined simulated saturated zone radionuclide breakthrough curves at the mid-point of the breakthrough curve (median transport time), fast breakthrough (10^{th} percentile transport time), and slow breakthrough (90^{th} percentile transport time). Note that all sensitivity analyses at the sub-system level were performed using simulated breakthrough curves from sources located in source region 1, under the northwestern part of the repository. The TSPA model sensitivity analyses used total simulated dose at particular times in the future as the relevant dependent variable.

III. RESULTS AND DISCUSSION

III.A. Sub-System Modeling Results

The results of the stepwise regression analysis of median transport time for six groups of radionuclides that are transported exclusively as solutes in the saturated zone are shown in Figure 2. Note that the group labeled as Tc (technetium) contains all non-sorbing radionuclides; whereas, the other five species are subject to sorption in the rock matrix of the volcanic units and in the alluvium. Only those parameters that have values of ΔR^2 greater than 0.01 from the stepwise linear regression, for at least one of the radionuclide groups, are included in the plot. For example, the longitudinal dispersivity parameter (LDISP) is an input to all of the saturated zone transport simulations, but uncertainty in this parameter is not a significant contributor to uncertainty in simulated transport time.

The results shown in Figure 2 indicate that the most important parameter with regard to uncertainty in median transport time in the saturated zone for all radionuclide groups is the groundwater specific discharge multiplier (GWSPD). The uncertainty in GWSPD accounts for more than half (ΔR^2 greater than 0.5) of the uncertainty in median transport time for the radionuclides migrating only as soluble species. This result is consistent with sensitivity analyses from previous saturated zone modeling reported in Ref. 1. The importance of this parameter is still dominant, even though the uncertainty distribution for the GWSPD parameter is somewhat narrower, based on new field testing, in the current saturated zone model.[6]

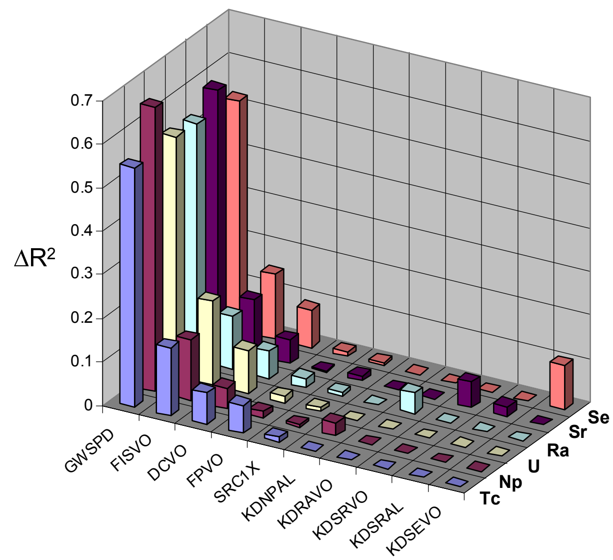

Figure 2. Change in the coefficient of determination from the stepwise linear regression analysis of median transport time for uncertain parameters among six radionuclides transported as solutes.

It is also evident from Figure 2 that the flowing interval spacing (FISVO) and matrix diffusion coefficient (DCVO) parameters are of significant, but secondary, importance with regard to variations in simulated median transport time in the saturated zone. Uncertainty in the FISVO parameter accounts for about 12% to 19% of the variance in median transport times and the DCVO parameter accounts for about 5% to 10% of the variance in the output. Both of these parameters are related to the process of matrix diffusion by radionuclides in the fractured volcanic units in the saturated zone, with smaller flowing interval spacing and higher diffusion coefficient value resulting in greater matrix diffusion and longer transport times.

The sorption coefficients for neptunium in the alluvium (KDNPAL), radium in the volcanic units (KDRAVO), strontium in the volcanic units and alluvium (KDSRVO and KDSRAL), and selenium in the volcanic units (KDSEVO) are of significant importance, but generally at lower levels than GWSPD, FISVO, and DCVO. The uncertainty in the flowing interval porosity in the volcanics (FPVO) and the easting location of the source (SRC1X) have some impact on the uncertainty in median transport, but at a generally minor level relative to the other parameters.

Similar results from the stepwise regression analysis for radionuclides subject to colloid-facilitated transport are presented in Figure 3. Radionuclides transported by colloids in the site-scale saturated zone transport model fall into two main categories: 1) reversible sorption onto colloids and 2) irreversible attachment to colloids. Radionuclides of plutonium, americium, protactinium, thorium, cesium, and tin are assumed to be in equilibrium among the aqueous phase, sorption onto mobile colloids, and sorption onto the aquifer material in the reversible colloids model (referred to as the K_c model). Radionuclides of plutonium and americium can be irreversibly attached to colloids during release from the waste form and those colloids are subject to retardation during transport in the saturated zone. In addition, some small fraction of the colloids with irreversibly attached colloids can migrate through the saturated zone without retardation.

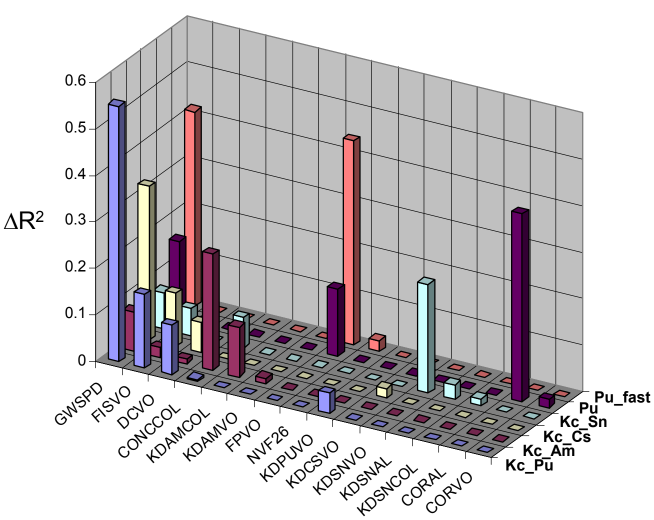

Figure 3. Change in the coefficient of determination from the stepwise linear regression analysis of median transport time for uncertain parameters among radionuclides subject to colloid-facilitated transport.

The stepwise regression results shown in Figure 3 are more complex than those for the radionuclides that transport only as solutes. The GWSPD parameter is the most important uncertain parameter in the cases of reversible sorption of plutonium on colloids (Kc_Pu on the right axis in Figure 3) and reversible sorption of cesium on colloids (Kc_Cs). For americium reversibly sorbed on colloids (Kc_Am), uncertainty in the concentration of colloids in the groundwater (CONCCOL) is the most important parameter, with lesser importance for the sorption coefficient of americium on colloids (KDAMCOL) and GWSPD. For the transport of tin reversibly sorbed on colloids (Kc_Sn), the most important uncertain parameter is the sorption coefficient of tin on the volcanic matrix (KDSNVO), with small, but significant contributions to model uncertainty from GWSPD, CONCCOL, FISVO, sorption coefficient of tin on alluvium (KDSNAL), and sorption coefficient of tin on colloids (KDSNCOL). In the case of plutonium and americium irreversibly attached to colloids (Pu on axis in Figure 3), the most important parameter is the colloid retardation factor in the alluvium (CORAL), with significant contributions to model uncertainty from GWSPD and FPVO). For the fast fraction of plutonium and americium irreversibly attached to colloids (Pu_fast), the dominant input parameters are FPVO and GWSPD, with a small contribution to uncertainty from the effective porosity in the alluvium (NVF26).

Stepwise regression analyses were performed for three metrics of radionuclide transport time corresponding to early arrival (fast), mid-point arrival (median), and late arrival (slow), as described earlier. The median transport time for the breakthrough curves is representative of the migration of the bulk of the radionuclide mass. The fast breakthrough time is representative of early arrival, which may be significant for cases in which radioactive decay would eliminate the late-arriving radionuclide mass.

The results of the stepwise regression analysis for neptunium transport times in the saturated zone for the three alternative metrics of transport time are shown in Figure 4. The results for the median transport time are the same as those shown in Figure 2 for neptunium, in which the GWSPD parameter is the most important, the FISVO and DCVO parameters related to the process of matrix diffusion are of secondary importance, and the KDNPAL and FPVO parameters are of small, but significant, importance. For the fast transport time (early arrival on the breakthrough curve), the uncertainties in the FISVO and DCVO parameters are less important to uncertainty in the fast transport time prediction. In addition, the importance of the KDNPAL, FPVO, and NVF26 parameters is greater for the fast transport time, relative to the median transport time. For the slow transport time (tail of the breakthrough curve), the importance of the GWSPD parameter is somewhat diminished and the importance of the FISVO and DCVO parameters is enhanced. The SRC1X and KDNPVO parameters show a small increase in importance relative to the median and fast transport times.

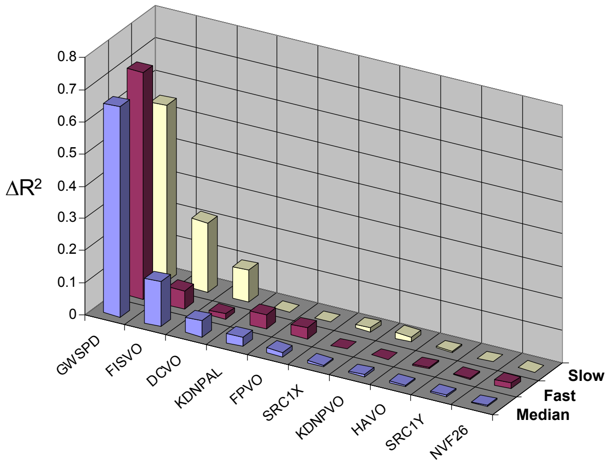

Figure 4. Change in the coefficient of determination from the stepwise linear regression analysis of uncertain parameters for the 50th percentile (median), 10th percentile (fast), and 90th percentile (slow) of the breakthrough curves for neptunium.

These results are consistent with differences in the impact of the matrix diffusion process on different parts of the breakthrough curve. Matrix diffusion is of relatively less importance to the radionuclide mass that arrives early (fast transport time) because this is the fraction of the mass that has been transported through the saturated zone with little retardation via diffusive interaction with the matrix. Consequently, those parameters related to matrix diffusion (FISVO and DCVO) have lower importance with regard to uncertainty in the fast transport time, relative to their ΔR^2 values for the median transport time. Similarly, the matrix diffusion process and sorption in the volcanic matrix are of relatively greater importance in determining the mass that arrives in the tail of the breakthrough curve and the parameters associated with these processes (FISVO, DCVO, and KDNPVO) are of greater importance in the uncertainty in the slow transport time. Overall, the regression analysis results for the three alternative metrics are generally consistent, suggesting that the median transport time is representative of radionuclide transport.

III.B. System-Level Modeling Results

The saturated zone flow and transport abstraction model results are used in the TSPA model to simulate the transport of radionuclides through the saturated zone. There is direct simple relationship between sensitivity analysis results at the sub-system level and results at the system level. First, the results analyzed in TSPA are influenced by the uncertainty upstream of the saturated zone (waste package, engineered barrier system, and unsaturated zone). Moreover the considered outputs are not the same and may have non-linear relationship amongst them. However, one should expect that an important parameter in the sub-system should also appear as important in the system level, as long as the saturated zone model plays an important role in the uncertainty of the entire system.

In order to evaluate this theory and confirm that the saturated zone model performs as expected in the system, the influence of the uncertain input parameters has been compared in the system and the sub-system level for three radionuclides considered in the analysis: neptunium (^{237}Np), dissolved plutonium (^{239}Pu) and technetium (^{99}Tc). For the system level sensitivity analysis, the igneous intrusive scenario has been selected. Because the packages are considered as entirely destroyed, the uncertain parameters related to waste package properties and behavior won't have any effect, and a better comparison between the sub-system results and the TSPA results can be made. The output of interest from the TSPA model is the cumulative release of the selected radionuclide 10,000 years after closure of the repository. For the sub-system level, the median transport time from the breakthrough curve for the selected radionuclide is used.

The contribution of the input parameter to the change in coefficient of determination of the regression model (ΔR^2) is reported. A ratio of the ΔR^2 values at system level and sub-system level is calculated. This ratio gives an informal measure of the importance of the saturated zone model in the uncertainty of the selected output at the system level.

The results of the stepwise regression at the system level and sub-system level for technetium are presented in Table 2. Technetium does not exhibit sorption under oxidizing chemical conditions and is transported relatively rapidly in the saturated zone. For the TSPA model (system level) output of cumulative technetium release at 10,000 years, the major contributor to uncertainty in the model results is the mass of commercial spent nuclear fuel (CSNFMASS) in the repository, which is not an input parameter to the saturated zone flow and transport abstraction model. The second most important parameter at the system level and the most important parameter at the sub-system level is GWSPD, which contributes about 17% of the uncertainty in the TSPA model results and about 55% of the uncertainty in the median transport time from the saturated zone model results, based on the values of ΔR^2 given in Table 2. The ratio of the ΔR^2 values for the system model to the values for the sub-system model is 0.31 for the GWSPD parameter. The FISVO and DCVO parameters also have significant, but lesser, importance to the uncertainty in the results from the system model and sub-system model. The sum of the ΔR^2 values for the parameters GWSPD, FISVO, and DDCVO in the system model is 0.27, which is similar to the ratio between the ΔR^2 values from the system and sub-system models (0.31) for GWSPD. Using these two methods of estimating the importance of uncertainty in the saturated zone model results to the TSPA model results, it is concluded that the saturated zone model accounts for about 30% of the variance in the TSPA model output with regard to technetium release in the igneous intrusive scenario. It is also relevant to note that the three most important input parameters with regard to technetium transport times in the saturated zone shown in Figure 2 also appear among the five most important parameters identified by the stepwise regression analysis of the TSPA model given in Table 2.

Table 2. Stepwise regression results for technetium.

Parameter	ΔR^2 (system model	ΔR^2 (sub-system model	Ratio (system/ subsystem)
CSNFMASS	0.47	-	-
SZGWSPDM (GWSPD)	0.17	0.55	0.31
INFIL	0.11	-	-
SZFISPVO (FISVO)	0.06	0.16	0.38
SZDIFCVO (DCVO)	0.04	0.07	0.57
SEEPCOND	0.01	-	-

Note: Parameter names are from the TSPA model and corresponding parameter names from the saturated zone model are in parentheses.

A similar comparison of stepwise regression results for the system model and sub-system model is shown in Table 3 for neptunium, which is not a major contributor to dose for the first 10,000 years. The ratio of the ΔR^2 values from the system and sub-system models for the GWSPD parameter is 0.18, which is approximately equal to the sum of the ΔR^2 values for the three saturated zone parameters included in the regression for the system model (0.19). As with technetium, the order of importance of the three saturated zone parameters is consistent between the sub-system analysis results shown in Figure 2 and the system level results in Table 3.

The role of the saturated zone model with regard to dissolved plutonium in the TSPA model is greater than for technetium and neptunium, as shown in Table 4. The ratio of the ΔR^2 values from the system and sub-system models for the GWSPD parameter is 0.40. This is approximately equal to the sum of the ΔR^2 values for the five saturated zone parameters that significantly contribute to the uncertainty of the system model predictions (GWSPD, FISVO, KDPUVO, CONCCOL, and NVF26). As with the other radionuclides, the ratios of the ΔR^2 values from the system and sub-system models for the less important parameters (e.g., FISVO and KDPUVO) are not very accurate and differ from the ratio for the GWSPD parameter. This is expected because the lower the contribution to uncertainty by a given parameter, the more the value of ΔR^2 is perturbed by noise in the sampling and regression analysis.

Table 3. Stepwise regression results for neptunium.

Parameter	ΔR^2 (system model	ΔR^2 (sub-system model	Ratio (system/ subsystem)
PHCSS	0.22	-	-
INFIL	0.17	-	-
SZGWSPDM (GWSPD)	0.12	0.65	0.18
SZFISPVO (FISVO)	0.05	0.14	0.36
EP1NPO2	0.03	-	-
DELPPCO2	0.03	-	-
EP1LOWAM	0.03	-	-
SZDIFCVO (DCVO)	0.02	0.05	0.40
CORRATSS	0.02	-	-
EP1LOWNU	0.02	-	-

Table 4. Stepwise regression results for plutonium reversibly sorbed on colloids.

Parameter	ΔR^2 (system model	ΔR^2 (sub-system model	Ratio (system/ subsystem)
SZGWSPDM (GWSPD)	0.22	0.55	0.40
INFIL	0.17	-	-
SZFISPVO (FISVO)	0.12	0.16	0.76
EP1LOWPU	0.05	-	-
SZKDPUVO (KDPUVO)	0.03	0.04	0.75
SZCONCOL (CONCCOL)	0.03	0.0	-
SZPORUAL (NVF26)	0.03	0.0	-
DELPPCO2	0.02	-	-

IV. CONCLUSIONS

Sensitivity analyses of uncertainty in groundwater flow and radionuclide transport in the saturated zone at Yucca Mountain have been updated for the current modeling using stepwise rank regression. In addition, these analyses have been compared to similar analyses of parameter uncertainty in the TSPA model. The results are similar to those reported for previous modeling of radionuclide transport in the saturated zone in Ref. 1. For most radionuclides, except some subject to colloid-facilitated transport, uncertainty in groundwater specific discharge dominates uncertainty in simulated radionuclide transport times in the saturated zone and is one of the most important input parameters in the TSPA model with regard to cumulative radionuclide release at 10,000 years in the igneous intrusion scenario. In comparison to the results in Ref. 1, the importance of the flowing interval spacing and effective diffusion coefficient parameters is somewhat higher for most radionuclides in the current modeling. This result indicates a somewhat more important role for matrix diffusion in the fractured volcanic rocks of the saturated zone in the current modeling. For sorbing radionuclides, there is an enhanced retardation effect in which greater matrix diffusion leads to greater sorption of radionuclide mass on the volcanic rock matrix.

The importance of input parameters for sorption coefficients in the volcanic rock matrix and alluvium, colloid retardation factors, colloid concentration, sorption onto colloids, and flowing interval porosity is generally secondary to the importance of the groundwater specific discharge multiplier and matrix diffusion parameters, but is highly variable among radionuclides. Uncertainty in the colloid retardation factor in alluvium is the dominant contributor to uncertainty in the transport of plutonium and americium irreversibly attached to colloids. The flowing interval porosity parameter is the most important parameter in the transport times for the fast fraction of colloids with irreversibly attached radionuclides. Another notable exception is that the concentration of colloids and the sorption coefficient of americium onto colloids are the most important parameters in the transport of americium that is reversibly sorbed on colloids.

It is interesting to note that several input parameters have relatively small or insignificant impacts on uncertainty at the sub-system and system levels. These parameters include longitudinal dispersivity, horizontal anisotropy in permeability, the northwestern boundary of the alluvial uncertainty zone, source location, and alluvium bulk density.

The generally good consistency between the results of the sensitivity analyses at the sub-system and system levels supports the overall conclusions. This consistency suggests that the median radionuclide transport time for the breakthrough curves from the saturated zone flow and transport abstraction model is an appropriate proxy for relative sensitivity at the system level, with regard to cumulative release on a radionuclide specific basis. Overall sensitivity of saturated zone parameters in the TSPA model predictions of dose is more complexly related to the importance of other sub-system parameters, radioactive decay, and the relative values of biosphere dose conversion factors for different radionuclides.

ACKNOWLEDGMENTS

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

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