Approaches to Quantify Potential Contaminant Transport in the Lower Carbonate Aquifer from Underground Nuclear Testing at Yucca Flat, Nevada National Security Site, Nye County, Nevada – 12434

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ABSTRACT

Quantitative modeling of the potential for contaminant transport from sources associated with underground nuclear testing at Yucca Flat is an important part of the strategy to develop closure plans for the residual contamination. At Yucca Flat, the most significant groundwater resource that could potentially be impacted is the Lower Carbonate Aquifer (LCA), a regionally extensive aquifer that supplies a significant portion of the water demand at the Nevada National Security Site, formerly the Nevada Test Site. Developing and testing reasonable models of groundwater flow in this aquifer is an important precursor to performing subsequent contaminant transport modeling used to forecast contaminant boundaries at Yucca Flat that are used to identify potential use restriction and regulatory boundaries. A model of groundwater flow in the LCA at Yucca Flat has been developed. Uncertainty in this model, as well as other transport and source uncertainties, is being evaluated as part of the Underground Testing Area closure process.

INTRODUCTION

Contamination of groundwater resources has resulted from decades of underground nuclear testing conducted at Yucca Flat in the Nevada National Security Site (NNSS formerly the Nevada Test Site). Evaluation of the contamination migration is necessary to define use restriction and potential regulatory boundaries for each Corrective Action Unit (CAU) at the site. These boundaries are developed by joint agreement between the National Nuclear Security Administration/Nevada Site Office (NNSA/NSO) and the Nevada Division of Environmental Protection (NDEP) per requirements set forward in the Federal Facility Agreement and Consent Order (FFACO)[1]. These boundaries are based on models of expected contaminant migration that are developed based on available site hydrogeologic investigations [2]. These models include forecasts of contaminant migration from the underground nuclear test contaminant sources through the vadose zone and saturated alluvial/volcanic rock units to the Lower Carbonate Aquifer (LCA). The LCA is an extensive aquifer that underlies much of Nye County in southern Nevada and is the major source of water for the NNSS [3]. This study evaluates the potential for radionuclide contamination in the LCA and the impact of key conceptual and parameter uncertainties that influence the extent of contamination.

The Yucca Flat/Climax Mine CAU is located about 140 km northwest of Las Vegas, Nevada in the northeastern part of the NNSS. Yucca Flat is an intermontane valley in the northern portion of the Basin and Range physiographic province. Yucca Flat is a topographically closed basin with a playa at its southern end. The general topographic relief at Yucca Flat ranges from about 1,200 m amsl (above mean sea level) at the southern low point at Yucca Lake playa to more than 1,500 m amsl along the northwestern and northeastern margins of the basin.

Seven hundred and forty seven (747) underground nuclear detonations have been conducted in the Yucca Flat/Climax Mine CAU. Figure 1 identifies the location of the Corrective Action Sites (CASs) which represent these detonations. Of the total NNSS contaminant inventory of over 10^8 Curies, which is dominated by the tritium inventory, about 39 percent is within Yucca Flat. Many of the underground nuclear tests conducted in the area have resulted in surface craters and have significantly affected the area's topography [4].

The geology of the Yucca Flat/Climax Mine CAU consists of a thick Cenozoic volcanic and sedimentary section that unconformably overlies previously deformed rocks of Paleozoic age, including the regionally extensive LCA. The mapped geologic units within the CAU and surrounding areas have been grouped as hydrostratigraphic units (HSUs) on the basis of similar geologic and hydraulic properties [5]. Three general groupings of the most permeable HSUs have been classified as aquifers: basin-fill alluvial deposits, volcanic rocks consisting of welded tuffs and lava flows, and fractured carbonate rocks. The principal carbonate-rock aquifer consists of the thick sequence of Paleozoic carbonate rock that extends regionally throughout much of the subsurface of central and southeastern Nevada. The fractured Cenozoic volcanic rock and permeable Cenozoic basin-fill alluvium form local aquifers that contribute diffuse leakage or local drainage to the underlying Paleozoic carbonate-rock aquifer [6]. The Cenozoic aquifers are isolated from the deeper Paleozoic LCA by local confining units that consist of zeolitically altered tuffs within the Cenozoic volcanic section and fine-grained parts of the Cenozoic basin fill.

Although the Paleozoic rocks show contractional deformation related to both east- and west-directed thrusting during the Mesozoic, this contractional deformation has been overprinted by extensive extensional deformation related to basin-and-range extension during the late Cenozoic [5,7]. This deformation has resulted in numerous normal faults that extend from the deep Paleozoic LCA into and through the Cenozoic tuff confining units. These faults provide for local drainage and associated contaminant transport between the contaminant sources in the overlying units to the underlying LCA.

Testing in Yucca Flat can be divided into those detonations with working points above and below the regional water table [4]. Most of these detonations were conducted in the unsaturated alluvial deposits and volcanic tuffs with the bulk of the remainder detonated in or above the thick tuff confining units above the LCA. While most of the contamination is determined to be retained and decay in the unsaturated alluvial deposits and volcanic tuffs or the saturated tuff confining units for the 1,000 year period of regulatory interest, a fraction of that contamination can migrate downward through the hydraulically transmissive faults and result in contaminant flux to the underlying LCA. Additionally, a small fraction of the detonations have a portion of their contamination that extends into saturated portions of the LCA. That contamination, when combined with contamination that migrates into the LCA from the detonations conducted in the overlying saturated alluvial deposits and tuff aquifers, can result in contamination of the LCA.

As a result of the above sources of potential contamination and the commitments documented in the FFACO, developing models of groundwater flow and contaminant transport in the LCA is an important part of the Corrective Action Investigation Plan for the Yucca Flat/Climax Mine CAU [2]. This paper summarizes a portion of the ongoing investigation to develop and evaluate the groundwater flow system in the LCA at Yucca Flat. Additional modeling of contaminant transport is ongoing and is expected to be used to forecast contaminant boundaries that can be used to identify use restriction boundaries and institutional controls.

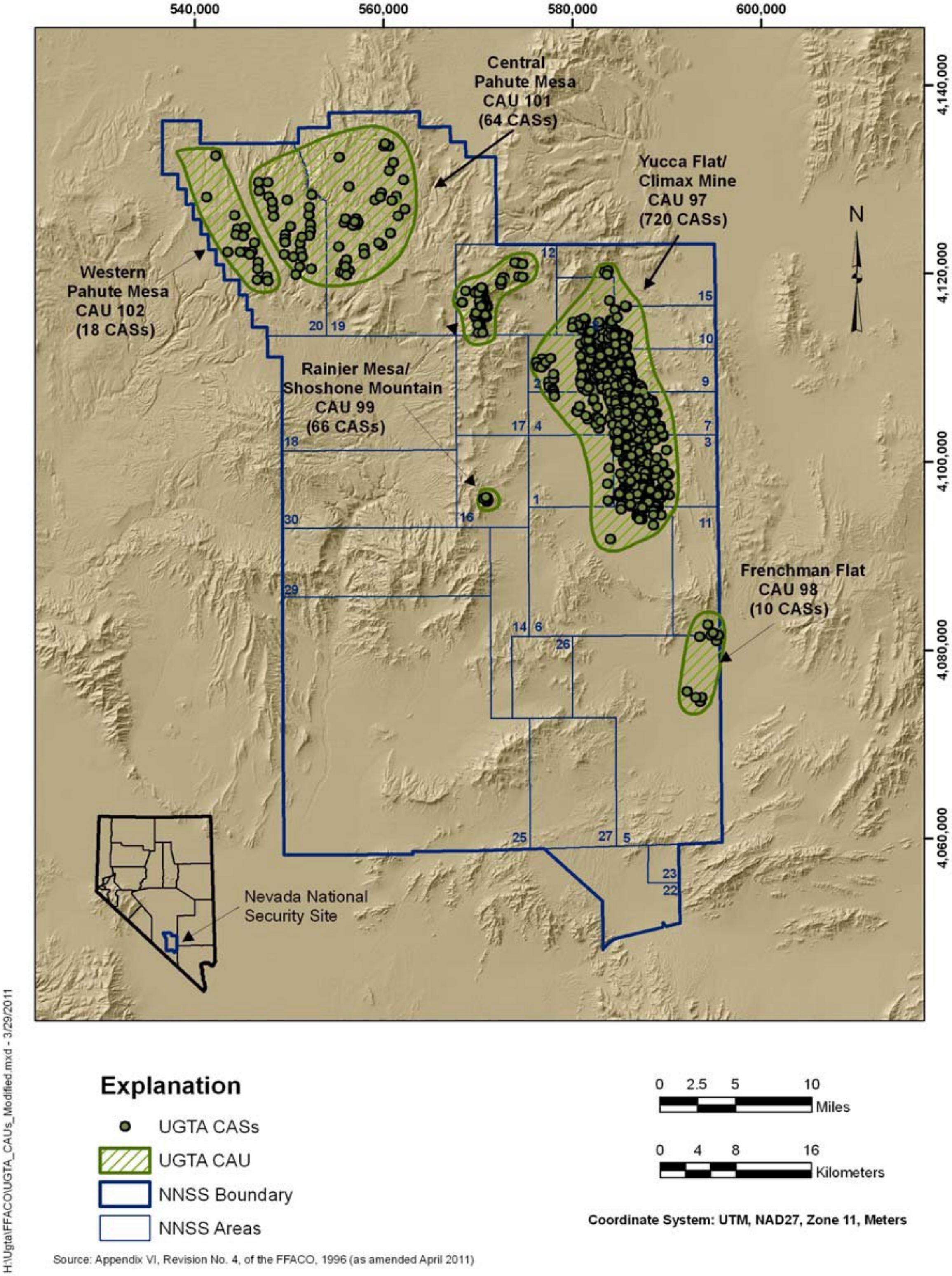


Fig. 1. Location of Underground Nuclear Detonations and Corresponding Corrective Action Sites (CASs) and Corrective Action Units (CAU) at the Nevada National Security Site (NNSS)

METHOD

Quantitative groundwater flow and contaminant transport modeling techniques have been used to evaluate the possible contaminant migration in the LCA over the next 1,000 years. These techniques have included automated parameter estimation approaches to calibrate the flow model within the constraints of the observed steady state and transient flow conditions. Multiple independent lines of evidence have been used to support the flow conceptual model, including geochemical observations, radiotracer information and thermal data. To account for conceptual and parametric uncertainty, alternative flow models have been developed and calibrated using automated parameter estimation techniques and the Null Space Monte Carlo method [8].

The approach taken to simulate groundwater flow within the LCA has been to first develop a representation of the hydrostratigraphic framework. The hydrostratigraphic framework model (HFM) includes significant faults that are known or inferred to provide significant pathways for groundwater flow and contaminant transport. The HFM is used to develop a 3-dimensional groundwater flow and transport model. The initial parameter estimates are based on observations of hydraulic properties from well tests conducted in numerous wells that penetrate the LCA in the NNSS [9] as well as boundary and recharge fluxes that are estimated from regional models [10, 11] developed to evaluate flow in the region.

The LCA groundwater flow model is developed using the FEHM software which was also used in evaluations of other CAUs at the NNSS and the saturated zone flow model at Yucca Mountain [12]. This finite element model consists of over 2,900,000 elements and 500,000 nodes with discrete elements representing the core and damage zones of the major faults in the area (Figure 2). The LCA flow model was calibrated using the PEST automated parameter estimation software [13] by using both steady-state and transient observed heads, the latter derived from a 6-month long multi-well aquifer and tracer test.

Multiple lines of evidence were used to support the evaluation of the flow model, including comparisons to models of the observed borehole temperature distributions and geochemical flow paths as well as to inferred flow regimes developed by the USGS [9, 14 and15]. The sensitivity and uncertainty in the calibrated flow model has been evaluated using a range of global and local sensitivity analyses and one-off uncertainty analyses to investigate a reasonable range of possible flow conditions. The range of reasonable alternative flow conceptual models and flow parameter uncertainties has been propagated to the transport assessment in order to evaluate the affect of flow model uncertainty on contaminant transport.

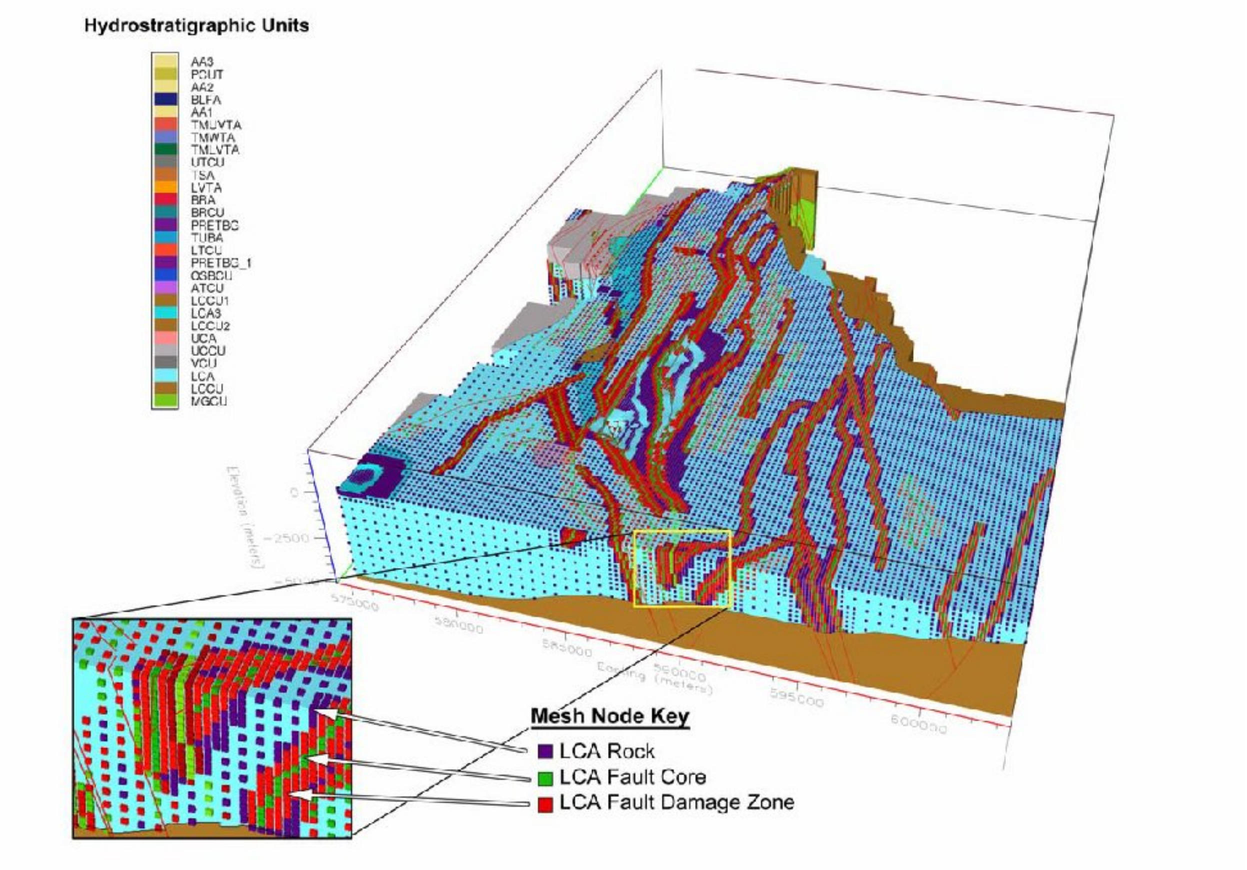
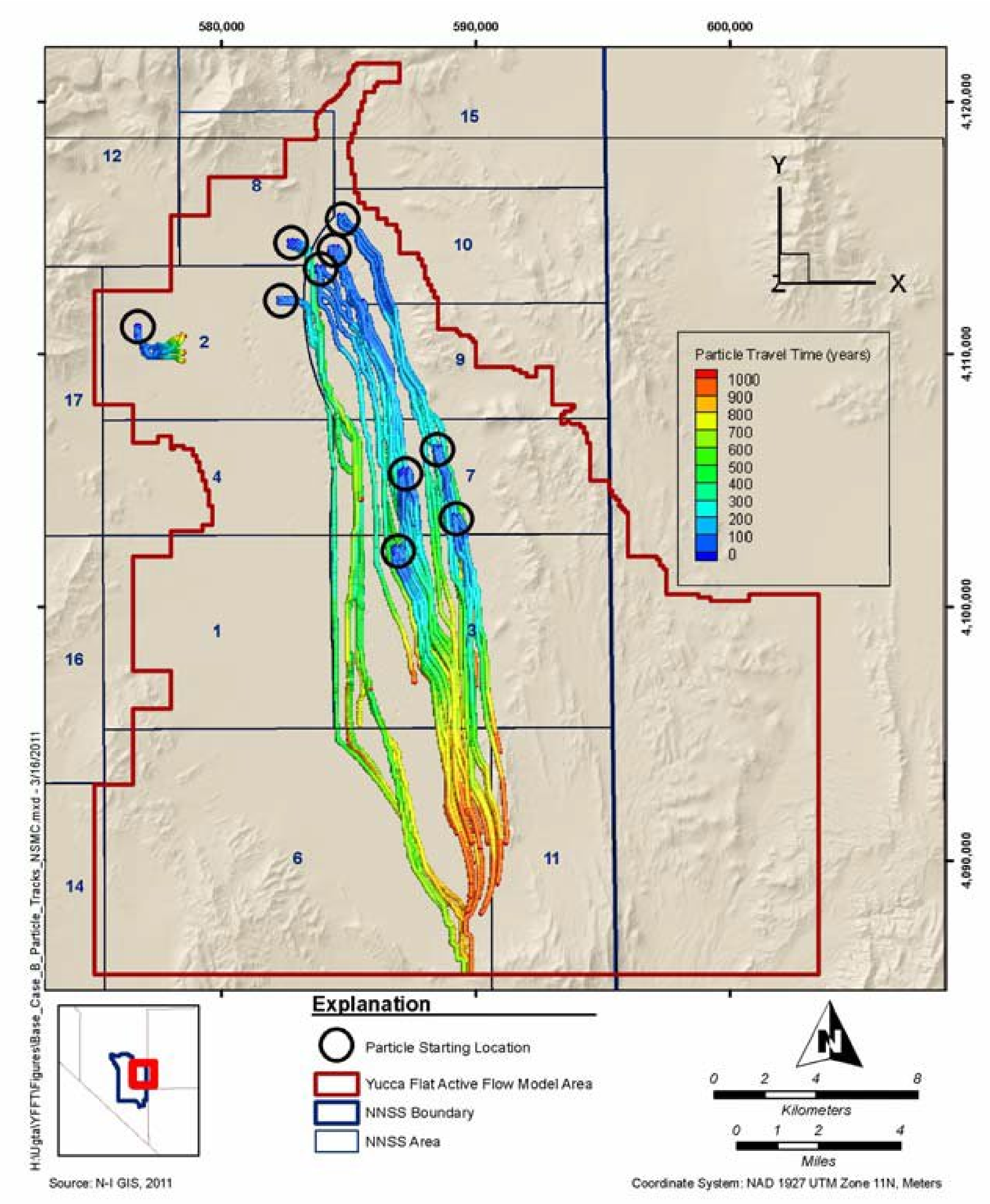


Fig. 2. Perspective Plot of LCA Flow Model Grid and Distribution of Modeled Fault Core and Damage Zones

RESULTS

The calibrated LCA groundwater flow models confirm the generally southerly flow direction in the Yucca Flat area, with the ultimate discharge, based on regional model studies being to the Ash Meadows area in southern Nevada. The Darcy velocities resulting from the calibrated flow model are spatially variable but are generally on the order of 3×10^{-10} to 1×10^{-8} m/sec, which is consistent with the regional geochemical radiotracer interstitial velocity estimates of 1.3 to 1.9 m/yr [14] based on assumed unretarded C-14 ages and the estimates developed from the MWAT tracer test of 24 m/yr [15] when considering effective porosities of the order of 10^{-3} to 10^{-2} [16].

Using the calibrated LCA groundwater flow model and the midpoint of the effective porosity range of 4×10^{-3}, particle trajectories and advective transport times applicable to unretarded radionuclides from several representative underground nuclear detonation locations are illustrated in Figure 3. These locations are selected because their exchange volumes either directly intersect the saturated LCA (BOURBON, LAMPBLACK, CORDUROY, NASH and TORRIDO), their exchange volumes are mostly in the tuff confining units but near faults that are assumed to provide hydraulic communication with the LCA (LAMPBLACK, BILBY, and CORDUROY), or their exchange volumes are in the unsaturated zone just above the water table in the LCA (BOURBON, HANDCAR, KANKAKEE, and TORRIDO). These transport times do not consider the important effects of matrix diffusion which significantly retards the contaminant migration.



Source: N-I GIS, 2011

Coordinate System: NAD 1927 UTM Zone 11N, Meters

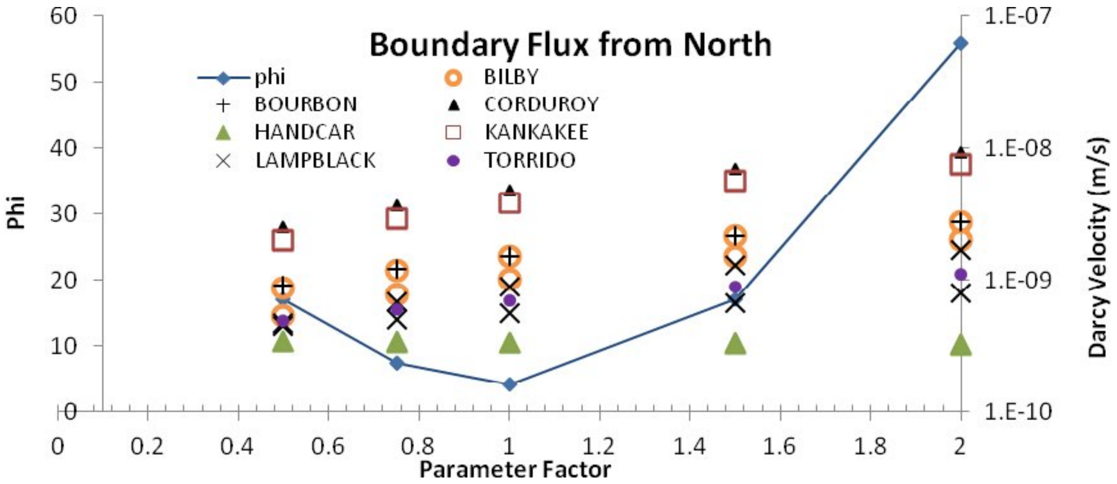
Fig. 3. Advective Particle Trajectories and Groundwater Travel Times in the LCA from Locations near Representative Underground Nuclear Detonations

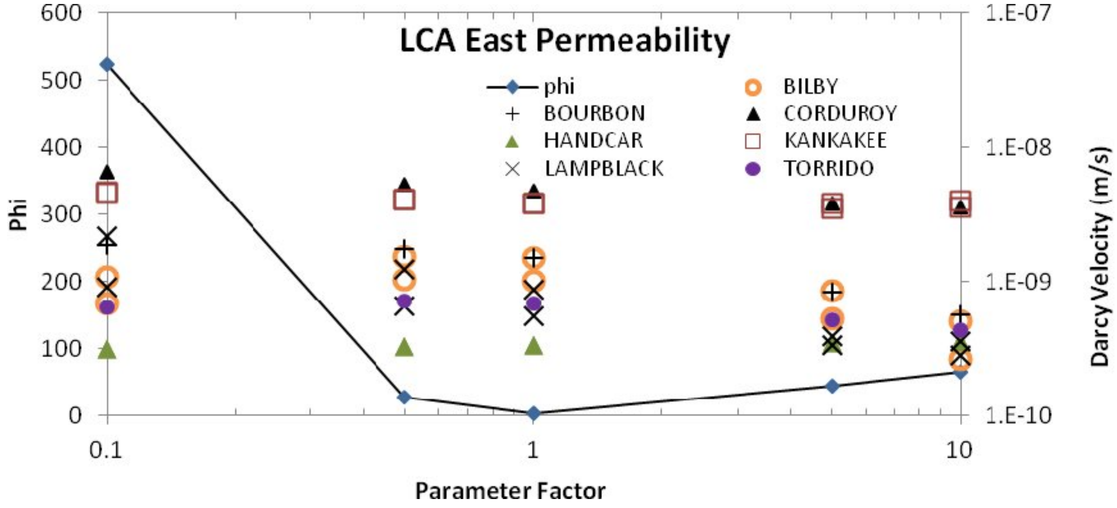
To evaluate the effect of parameter and conceptual model uncertainty, a range of alternative calibrated flow fields were developed. Both global and local uncertainty analyses were performed. An example of the local sensitivity analyses is illustrated in Figure 4 for three of the more significant discrete model parameters, notably (a) the boundary influx into the northern portion of the model domain, (b) the permeability of the LCA country rock in the eastern portion of the model domain and (c) the permeability of one of the major faults in the LCA; the Yucca Fault. These results indicate the relative significance of the parameter to the model calibration objective function (phi), with lower values indicating a more reasonably calibrated flow field, as well as the significance of the parameter to the local Darcy velocity in the vicinity of representative underground nuclear tests. As expected, the boundary flux and permeability of the country rock can be significantly constrained during the calibration process, while the fault permeability is less sensitive for this conceptual model. The modeled Darcy velocities are significantly affected by the boundary flux and the fault permeability.

DISCUSSION

Several alternative flow models of the LCA in the Yucca Flat/Climax Mine CAU have been developed. These flow models are used in conjunction with contaminant transport models and source term models and models of contaminant transport from underground nuclear tests conducted in the overlying unsaturated and saturated alluvial and volcanic tuff rocks to evaluate possible contaminant migration in the LCA for the next 1,000 years.

Assuming the flow and transport models are found adequate by NNSA/NSO and NDEP, the models will undergo a peer review. If the model is approved by NNSA/NSO and NDEP, it will be used to identify use restriction and regulatory boundaries at the start of the Corrective Action Decision Document Corrective Action Plan (CADD/CAP) phase of the Corrective Action Strategy. These initial boundaries may be revised at the time of the Closure Report phase of the Corrective Action Strategy.


Boundary Flux from North
phi
BILBY
BOURBON
CORDUROY
HANDCAR
KANKAKEE
LAMPBLACK
TORRIDO
Phi
Darcy Velocity (m/s)
Parameter Factor
0
10
20
30
40
50
60
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
1.E-10
1.E-09
1.E-08
1.E-07


LCA East Permeability
phi
BILBY
BOURBON
CORDUROY
HANDCAR
KANKAKEE
LAMPBLACK
TORRIDO
Phi
Darcy Velocity (m/s)
Parameter Factor
0
100
200
300
400
500
600
0.1
1
10
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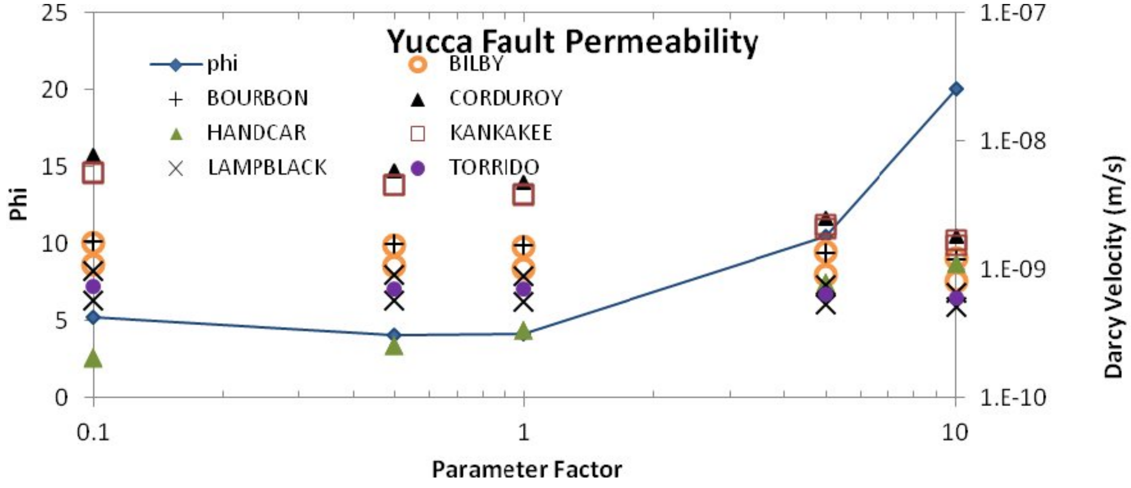
Yucca Fault Permeability
phi
BILBY
BOURBON
CORDUROY
HANDCAR
KANKAKEE
LAMPBLACK
TORRIDO
Phi
Darcy Velocity (m/s)
Parameter Factor
0
5
10
15
20
25
0.1
1
10
1.E-10
1.E-09
1.E-08
1.E-07

Fig. 4. Yucca Flat LCA Flow Model Local Sensitivity Analysis Results

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