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Water and Solute Travel Time Analysis for Soils Corrective Action Units 375, 411, 412, 413, 414, and 415

Navarro-Intera

Revision No.: 0

May 2013

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/s/ Joseph P. Johnston, N-I CO 05/30/2013

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WATER AND SOLUTE TRAVEL TIME ANALYSIS FOR SOILS CORRECTIVE ACTION UNITS 375, 411, 412, 413, 414, AND 415

Revision No.: 0
May 2013

Navarro-Intera, LLC
c/o U.S. DOE
P.O. Box 98952
Las Vegas, NV 89193-8952

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LIST OF ACRONYMS AND ABBREVIATIONS

AA	Alluvial aquifer
ATCU	Argillic tuff confining unit
CAS	Corrective action site
CAU	Corrective action unit
cm	Centimeter
DPWS	Distributed Parameter Watershed
DRI	Desert Research Institute
DVRFS	Death Valley Regional Flow System
EMAD	Engine Maintenance, Assembly, and Disassembly
ETS-1	Engine Test Stand No. 1
FCCM	Fortymile Canyon composite unit
FFACO	*Federal Facility Agreement and Consent Order*
ft	Foot
g/cm^3	Grams per cubic centimeter
HFM	Hydrostratigraphic framework model
HSU	Hydrostratigraphic unit
in.	Inch
K_d	Partition/distribution coefficient
km	Kilometer
L	Length
LFU	Lava-flow unit
m	Meter
mL/g	Milliliters per gram
mm/yr	Millimeter per year
NNSS	Nevada National Security Site
NTTR	Nevada Test and Training Range
OAA	Older alluvial aquifer
OSBCU	Oak Spring Butte confining unit
OVU	Older volcanic-rock unit
PET	Potential evapotranspiration
Pu	Plutonium
PVA	Paintbrush volcanic-rock aquifer
RCP	Reactor Control Point

LIST OF ACRONYMS AND ABBREVIATIONS (CONTINUED)

RMAD	Reactor Maintenance, Assembly, and Disassembly
SNJV	Stoller-Navarro Joint Venture
t	Time
TCA	Test Cell A
TCC	Test Cell C
TM-LVTA	Timber Mountain lower vitric-tuff aquifer
TM-WTA	Timber Mountain welded-tuff aquifer
TMVA	Thirsty Canyon-Timber Mountain volcanic-rock aquifer
TTR	Tonopah Test Range
TUBA	Tub Spring aquifer
UGTA	Underground Test Area
USAF	U.S. Air Force
USGS	U.S. Geological Survey
VSU_LOW	Volcanic- and sedimentary-rock lower unit
VSU_UP	Volcanic- and sedimentary-rock upper unit
WVU	Wahmonie volcanic-rock unit
WW	Water well
YAA	Younger alluvial aquifer
YMSCO	Yucca Mountain Site Characterization Office

EXECUTIVE SUMMARY

This document presents a water and solute (uranium and plutonium) travel analysis of the potential for residual radiological materials to impact groundwater at select Soils Activity sites. These sites comprise the following corrective action units (CAUs):

- CAU 375, Area 30 Buggy Unit Craters [Buggy and Test Cell A (TCA) sites]
- CAU 411, Double Tracks Plutonium Dispersion (Nellis)
- CAU 412, Clean Slate I Plutonium Dispersion (TTR)
- CAU 413, Clean Slate II Plutonium Dispersion (TTR)
- CAU 414, Clean Slate III Plutonium Dispersion (TTR)
- CAU 415, Project 57 No. 1 Plutonium Dispersion (NAFR)

The scope of this document is limited to these CAUs because the radionuclide inventories from the experiments conducted at these sites are not accounted for in the source term for the current Underground Test Area (UGTA) groundwater CAUs. Thus, this analysis was necessary to determine the time frame of potential impacts to groundwater by radionuclide contamination from these CAUs.

Because groundwater data are limited for these areas, the travel analysis uses conservative assumptions to answer the question of whether contaminant travel to the water table at each site will occur within 1,000 years. The 1,000-year time period is specified in the UGTA strategy contained in Appendix VI to the *Federal Facility Agreement and Consent Order* for determining groundwater contamination perimeter boundaries.

Assessing the contaminant travel time through the subsurface required estimating the state of the subsurface, including rock stratigraphy, water table depth, *in situ* volumetric water content, and recharge rate. Direct observations from boreholes at each site were not available, and these data were largely taken from UGTA modeling studies. The recharge rates used in this study are conservatively estimated to the highest possible likely from the reviewed data. Conservative simplifying assumptions and numerical input parameters were used to compensate for the uncertainties in the actual physical properties at each site, and to provide an upper bound of possible contaminant transport velocities and distances.

As a result of the travel analysis, the water and contaminant travel times through the unsaturated zone above the water table were calculated for each site. The expected estimated water travel time

to the water table exceeds 7,000 years at all of the sites evaluated. The sorptive processes associated with contaminant transport increase travel times by approximately 1 to 3 orders of magnitude for uranium and 2 to 5 orders of magnitude for plutonium. The calculated travel times greatly exceed the UGTA 1,000-year regulatory time period, indicating that the distance between residual contamination at each of the sites and the water table is sufficient for protecting the water resources below them.

1.0 Introduction

This document presents an analysis of the potential for residual radiological materials to impact groundwater at select Soils Activity sites. These sites comprise the following corrective action units (CAUs):

- CAU 375, Area 30 Buggy Unit Craters, which includes the Buggy and Test Cell A (TCA) sites
- CAU 411, Double Tracks Plutonium Dispersion (Nellis), referred to herein as Double Tracks
- CAU 412, Clean Slate I Plutonium Dispersion (TTR), referred to herein as Clean Slate I
- CAU 413, Clean Slate II Plutonium Dispersion (TTR), referred to herein as Clean Slate II
- CAU 414, Clean Slate III Plutonium Dispersion (TTR), referred to herein as Clean Slate III
- CAU 415, Project 57 No. 1 Plutonium Dispersion (NAFR), referred to herein as Project 57

These CAUs are located within Areas 25 and 30 of the Nevada National Security Site (NNSS), the Tonopah Test Range (TTR), and the Nevada Test and Training Range (NTTR), and involved experiments that used various amounts of plutonium and uranium (Figure 1). The experiments included evaluating plutonium dispersal resulting from the chemical detonation of nuclear devices (Clean Slate sites, Double Tracks, and Project 57); the testing of nuclear-propelled rockets (TCA); and trench excavation using nuclear explosions (Buggy), as discussed in Section 2.0. The experiments conducted at each of these sites resulted in releases of radioactive materials to surface soil.

The scope of this document is limited to these CAUs because the radionuclide inventories from the experiments conducted at these sites is not accounted for in the source term for the Underground Test Area (UGTA) groundwater CAUs on the NNSS. Thus, this independent analysis was necessary to determine the time frame of potential impacts to groundwater by radionuclide contamination from these CAUs.

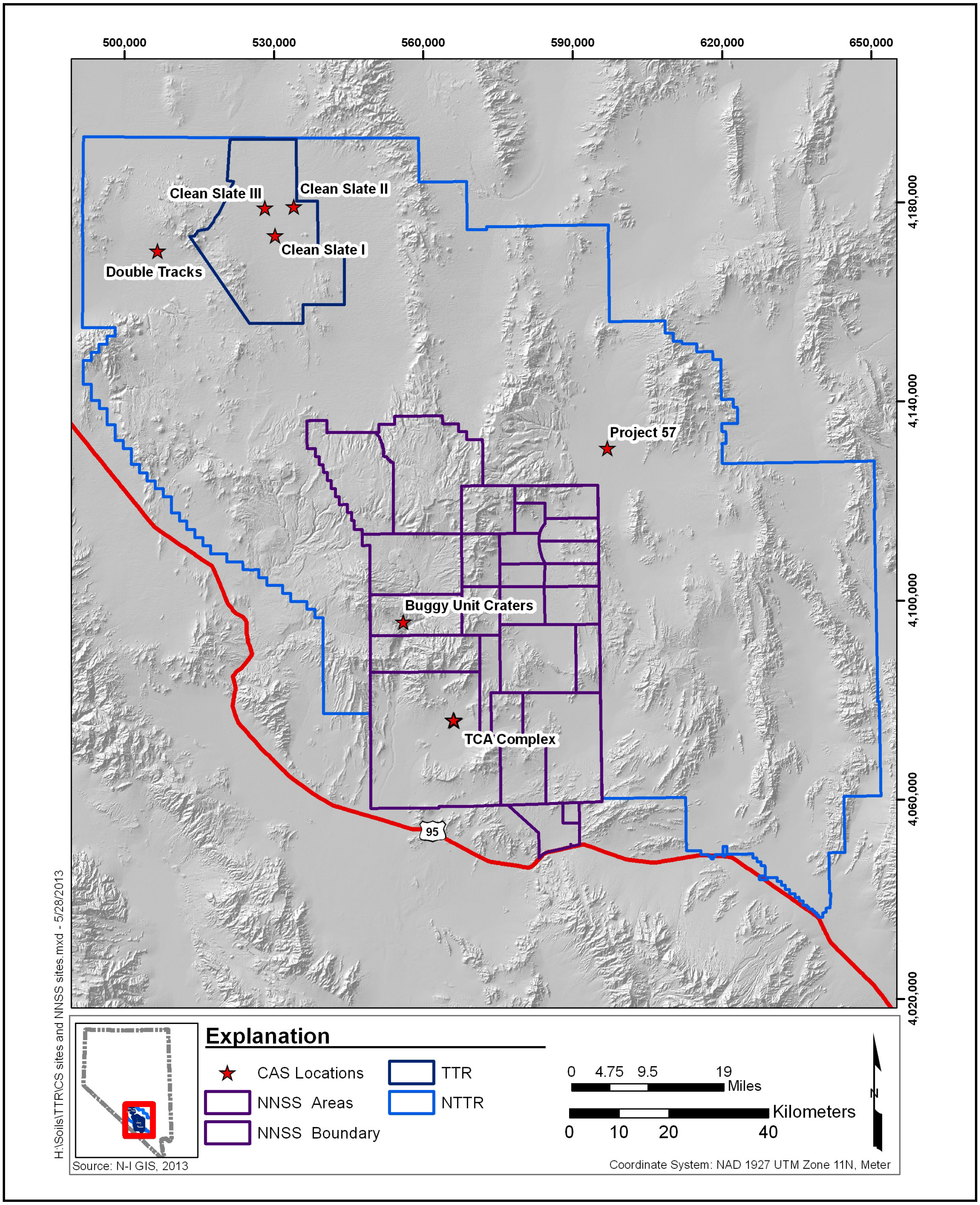

Figure 1
Location of CAUs 375, 411, 412, 413, 414, and 415

1.1 Evaluation Criteria

The following criterion is used to answer the study question "Will residual contaminants from the experiments conducted at CAUs 375, 411, 412, 413, 414, and 415 impact groundwater?":

- Does the estimated concentration of any contaminant exceed regulatory levels for drinking water at the groundwater interface within 1,000 years?

The 1,000-year time period is specified in the UGTA strategy contained in Appendix VI to the *Federal Facility Agreement and Consent Order* (FFACO) (1996, as amended) for determining groundwater contamination perimeter boundaries.

This document focuses on answering the simple question of whether contaminant travel to the water table at each site will occur within 1,000 years. Determining the contaminant concentrations upon arrival to the water table is not addressed in this document because the calculated arrival times exceed 1,000 years. The travel time to the water table is of primary concern because it is regionally extensive and serves as an important water resource for much of southern Nevada.

1.2 Evaluation Assumptions

This travel time analysis includes the following conservative and bounding assumptions:

- **Use of the highest estimated recharge rates.** The recharge rates used in this analysis are the highest obtained from available recharge models (see Section 2.0). Because transport of contaminants through the vadose zone is driven by the flow of infiltrating water to groundwater, higher net infiltration rates will result in faster contaminant travel rates.

- **Restricted lateral water movement.** Lateral water movement will occur within the vadose zone if low permeability layers are present to create perched water and lateral gradients. However, the hydrogeologic data presented in Sections 2.0 and 3.0 suggest that the subsurface hydraulic conductivity is much greater than the net infiltration rate, and flow is primarily vertical. Restricting lateral movement is conservative in that it will underestimate the water travel distance as well as contaminant dilution and dispersion. This will result in underestimating the time needed to reach groundwater and overestimating contaminant concentrations.

- **Unlimited source term.** These calculations assume that the amount of contaminant is not limited throughout the evaluated time period (1,000 years). This is a conservative assumption.

- **Representative groundwater levels.** The actual water-level depth at each CAS is unknown because there are no wells at these locations. Data from existing wells within a 15-kilometer (km) radius of each site were reviewed to determine the water-level depth that would best represent conditions at each site. These data, together with relevant regional groundwater model data and professional judgment, were used to select a water-level depth for use in calculating water and solute travel times for each site.

1.3 Basis for Evaluating Contaminant Transport

This evaluation uses established numerical relationships that describe the natural physical processes involved in the transport of radionuclides to groundwater. Conservative simplifying assumptions and conservative numerical input parameters are used in these numerical relationships that overestimate predictions of contaminant transport. This is done to compensate for uncertainties in the actual physical properties at each site and to provide an upper bound of possible contaminant transport velocities and distances.

This evaluation approach used a one-dimensional (downward only with no dispersion, diffusion, or dilution) analysis of water and solute travel rates through the unsaturated subsurface hydrological environment (i.e., vadose zone material) to groundwater. It was conducted by establishing a vertical velocity of infiltrating water through the vadose zone (based on the steady-state aquifer recharge). The movement of infiltrating water through the vadose zone is the driver for contaminant transport. However, contaminants move through the vadose zone material at a slower rate than does water due to physical and chemical interaction with the vadose zone material. The ratio of the water velocity to the contaminant velocity is defined as the retardation factor. Therefore, the vertical velocity of the contaminant will depend on the vertical velocity of infiltrating water (i.e., pore water) through the vadose zone and the retardation factor. The potential vertical velocity of infiltrating water through the vadose zone under saturated conditions is calculated in Equation (1) as

$$v_w = \frac{q}{n_e} \tag{1}$$

where
- v_w = vertical velocity of pore water (length [L]/time [t])
- q = steady-state recharge rate (L/t)
- n_e = effective porosity (dimensionless [–])

The effective porosity is defined as the interconnected water-filled pore spaces that can conduct water through the geologic matrix. The interconnected water-filled pore space can be grossly estimated as the entire volume of soil water (i.e., volumetric) under saturated conditions. Within the vadose zone, air occupies a fraction of the pore space, and the water vertical velocity can be faster than that identified for saturated flow.

The water vertical velocity for unsaturated flow is calculated in Equation (2) as

$$v_w = \frac{q}{\theta} \tag{2}$$

where

v_w = vertical velocity of pore water (L/t)
q = steady-state recharge rate (L/t)
θ = volumetric water content (dimensionless [–])

The potential vertical contaminant velocity is calculated in Equation (3) as

$$v_c = \frac{v_w}{R_f} \tag{3}$$

where

v_c = vertical velocity of the contaminant (L/t)
v_w = vertical velocity of pore water (L/t)
R_f = retardation factor (dimensionless [–])

Combining these two equations results in Equation (4), which calculates the vertical contaminant velocity as

$$v_c = \frac{q}{\theta \; x \; R_f} \tag{4}$$

where

v_c = vertical velocity of the contaminant (L/t)
q = steady-state recharge rate (L/t)
θ = volumetric water content (dimensionless [–])
R_f = retardation factor (dimensionless [–])

The distance a contaminant will migrate through geologic material is defined in Equation (5) as the vertical contaminant velocity multiplied by a specified time interval

$$d_i = v_c \times t \tag{5}$$

where

d_i = distance of the contaminant into the geologic layer (L)
v_c = vertical velocity of the contaminant (L/t)
t = specified time interval to be evaluated (t)

The time required for a contaminant to migrate through geologic material is defined in Equation (6) as the thickness of the geologic layer divided by the vertical velocity of the contaminant

$$t = \frac{d_i}{v_c} \tag{6}$$

where

t = time required for a contaminant to migrate through a geologic layer (t)
d_i = thickness of the geologic layer (L)
v_c = vertical velocity of the contaminant (L/t)

The information needed to resolve these equations is developed and discussed in Sections 2.0 and 3.0. Because the geologic material overlying the regional aquifer comprises several layers with differing physical properties, potential contaminant migration times are calculated for each stratigraphic layer. The resulting contaminant migration times to reach groundwater and the contaminant migration depths in 1,000 years are calculated in Section 4.0. Because there are uncertainties associated with the input parameters, a sensitivity assessment of the most uncertain parameters is presented in Section 5.0. Section 6.0 presents the conclusions of this water and solute travel time analysis.

2.0 HYDROGEOLOGIC DATA

2.1 Clean Slate Sites

The TTR is located in the western part of the Basin-and-Range physiographic province, and the Clean Slate sites are located in the central portion of the TTR within a broad valley known as Cactus Flat. The Clean Slate sites comprise three of the four Operation Roller Coaster experiments. These experiments evaluated the dispersal of plutonium in the environment from the chemical explosion of a plutonium-bearing device (DOE/NV, 1996a). The surface residual soil contamination created by the experiments is being evaluated as a potential contamination source to the groundwater. The evaluation consists of calculating water and solute travel times through the unsaturated zone at each site. If the travel times greatly exceed a 1,000-year time period, no further analysis of groundwater impacts will be required. However if the travel times are likely less than 1,000 years, further analysis is needed (e.g., calculation of solute concentration at the water table). A 1,000-year time period is specified in the UGTA FFACO guidance for determining groundwater contamination perimeter boundaries (FFACO, 1996 as amended).

The Clean Slate sites comprise the following CAUs and corrective action sites (CASs):

- CAU 412, CAS TA-23-01CS, Pu Contaminated Soil (Clean Slate I)
- CAU 413, CAS TA-23-02CS, Pu Contaminated Soil (Clean Slate II)
- CAU 414, CAS TA-23-03CS, Pu Contaminated Soil (Clean Slate III)

2.1.1 Depth to Groundwater

There are no wells located at the Clean Slate sites, and the hydrogeologic data are limited to water wells drilled to support activities on the TTR. The depth to groundwater in the vicinity of Cactus Flat varies from land surface at springs located in the Cactus and Kawich mountains bordering the Cactus Flat, to more than 120 meters (m) on the valley floor (Ekren et al., 1971). Figure 2 illustrates the wells within a 15-km distance of the three Clean Slate sites and the water elevation at each well. The Kawich Mountains can be seen in the northeast, and the Cactus Range can be seen in the southwest. Several springs are located within 15 km of the Clean Slate sites but are located at much higher

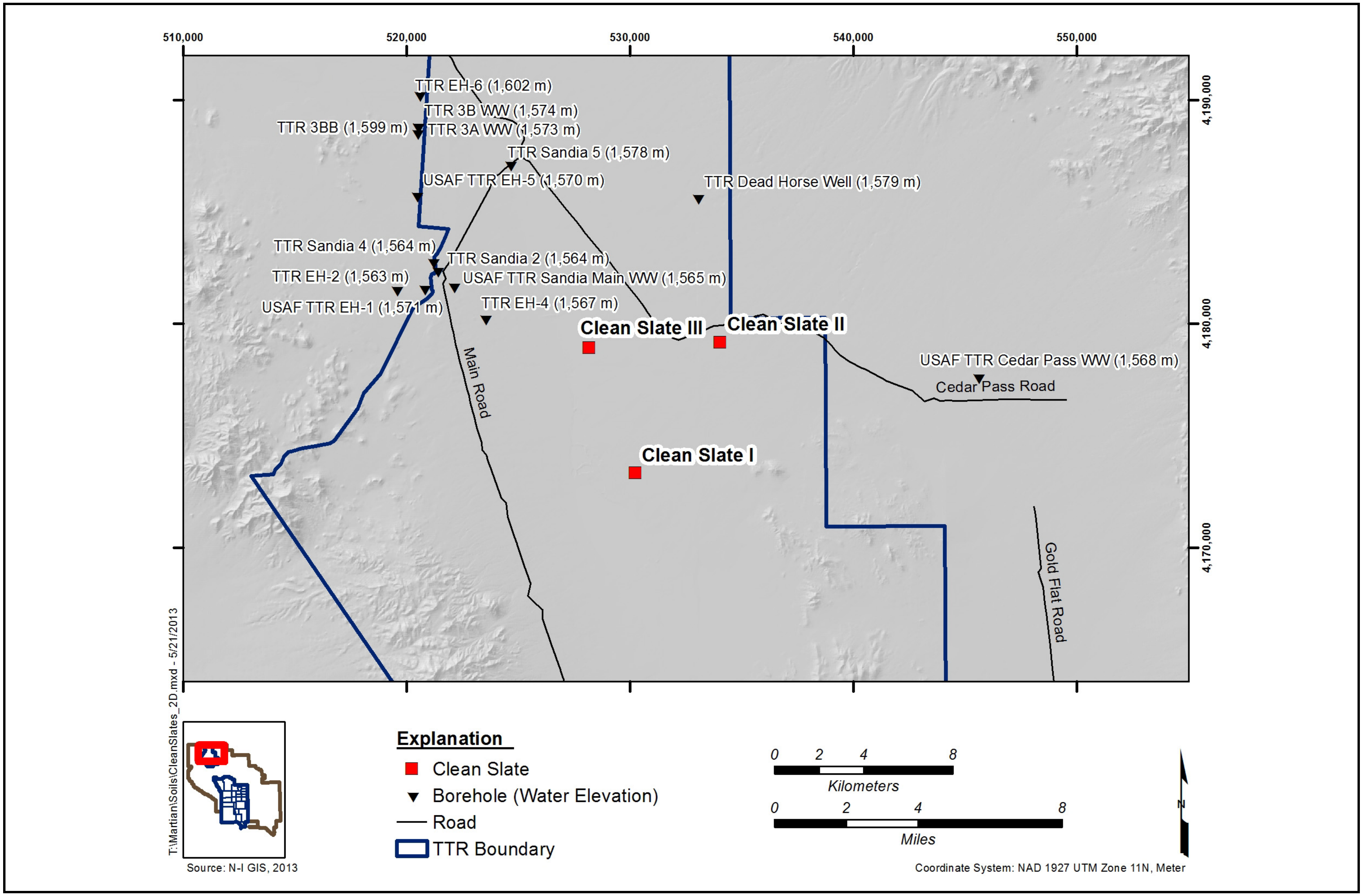

Figure 2
Wells Near the Clean Slate Sites

elevations within the Cactus Range, and there is no potential for groundwater contaminants to surface at the springs.

Tables 1, 2, and 3 provide the depth to groundwater at all wells within 15 km of each of the Clean Slate I, II, and III sites, respectively. The groundwater elevation within Cactus Flat varies from 1,602 m at TTR EH-6 to 1,563 m at TTR EH-2. The average depth to the groundwater is estimated from the three wells nearest each site and is 70.2 m, 118.7 m, and 79.7 m for Clean Slate I, II, and III, respectively.

Table 1
Wells Near the Clean Slate I Site

Well Name	Easting (m)	Northing (m)	Distance from Clean Slate I Site (m)	Water Elevation (m)	Estimated Water Depth at Clean Slate I Site (m)	Water Depth at Well Location (m)
TTR EH-4	523,504	4,180,252	9,656.4	1,567.3	70.7	96.3
USAF TTR Sandia Main WW	522,087	4,181,693	11,677.3	1,564.9	73.1	107.0
USAF TTR EH-1	520,767	4,181,597	12,570.7	1,571.2	66.8	117.3
TTR Dead Horse Well	533,005	4,185,643	12,620.6	1,578.8	59.2	109.8
TTR Sandia 2	521,352	4,182,380	12,682.2	1,563.6	74.4	106.0
TTR Sandia 4	521,174	4,182,785	13,096.9	1,563.6	74.4	103.1
TTR EH-2	519,544	4,181,532	13,476.9	1,563.3	74.7	142.1
TTR Sandia 5	524,615	4,187,125	14,896.4	1,577.9	60.1	47.9

Source: UGTA Borehole Index Database (N-I, 2013)

Table 2
Wells Near the Clean Slate II Site
(Page 1 of 2)

Well Name	Easting (m)	Northing (m)	Distance from Clean Slate II Site (m)	Water Elevation (m)	Estimated Water Depth at Clean Slate II Site (m)	Water Depth at Well Location (m)
TTR Dead Horse Well	533,005	4,185,643	6,541.7	1,578.8	111.2	109.8
TTR EH-4	523,504	4,180,252	10,590.9	1,567.3	122.7	96.3
USAF TTR Cedar Pass WW	545,568	4,177,629	11,631.2	1,567.8	122.2	178.7
USAF TTR Sandia Main WW	522,087	4,181,693	12,214.2	1,564.9	125.1	107.0

Table 2
Wells Near the Clean Slate II Site
(Page 2 of 2)

Well Name	Easting (m)	Northing (m)	Distance from Clean Slate II Site (m)	Water Elevation (m)	Estimated Water Depth at Clean Slate II Site (m)	Water Depth at Well Location (m)
TTR Sandia 5	524,615	4,187,125	12,325.1	1,577.9	112.1	47.9
TTR Sandia 2	521,352	4,182,380	13,085.2	1,563.6	126.4	106.0
TTR Sandia 4	521,174	4,182,785	13,361.1	1,563.6	126.4	103.1
USAF TTR EH-1	520,767	4,181,597	13,491.8	1,571.2	118.8	117.3
TTR EH-2	519,544	4,181,532	14,686.3	1,563.3	126.7	142.1

Source: UGTA Borehole Index Database (N-I, 2013); FFACO database (NNSA/NFO, 2013)

Table 3
Wells Near the Clean Slate III Site

Well Name	Easting (m)	Northing (m)	Distance from Clean Slate III Site (m)	Water Elevation (m)	Estimated Water Depth at Clean Slate III Site (m)	Water Depth at Well Location (m)
TTR EH-4	523,504	4,180,252	4,842.3	1,567.3	77.7	96.3
USAF TTR Sandia Main WW	522,087	4,181,693	6,672.0	1,564.9	80.1	107.0
TTR Sandia 2	521,352	4,182,380	7,631.7	1,563.6	81.4	106.0
USAF TTR EH-1	520,767	4,181,597	7,860.8	1,571.2	73.8	117.3
TTR Sandia 4	521,174	4,182,785	7,977.8	1,563.6	81.4	103.1
TTR Dead Horse Well	533,005	4,185,643	8,264.9	1,578.8	66.2	109.8
TTR Sandia 5	524,615	4,187,125	8,919.0	1,577.9	67.1	47.9
TTR EH-2	519,544	4,181,532	9,002.8	1,563.3	81.7	142.1
USAF TTR EH-5	520,438	4,185,756	10,302.3	1,570.0	75.0	81.7
TTR 3A WW	520,467	4,188,548	12,309.6	1,573.0	72.0	61.3
TTR 3B WW	520,473	4,188,823	12,521.6	1,573.7	71.3	60.0
TTR 3BB	520,480	4,188,844	12,534.0	1,599.3	45.7	33.8
TTR EH-6	520,557	4,190,239	13,619.9	1,601.9	43.1	30.3

Source: UGTA Borehole Index Database (N-I, 2013)

2.1.2 Subsurface Lithology

The Clean Slate sites are located in the central portion of the Cactus Flat valley, and the unsaturated subsurface is mostly valley-fill alluvium. The nearest well with lithologic data recorded is USAF TTR Roller Coaster WW, which is located approximately 7 to 12 km north of the three Clean Slate sites. The lithologic log recorded alternating clay, gravel, sand, and basalt to a depth of 242 m. Because USAF TTR Roller Coaster WW is plugged and water levels are not available, it is absent from Tables 1 through 3.

Because there are no wells located at the Clean Slate sites, the estimation of lithology must rely on geologic models incorporating geologic data, geophysical data, and the knowledge of geoscientists. The Death Valley Regional Flow System (DVRFS) hydrostratigraphic framework model (HFM) and flow model (Belcher et al., 2004) incorporates decades of groundwater flow studies performed by programs at the NNSS and Yucca Mountain Project. The model area includes the entire DVRFS and extends over a large area of southern Nevada and the adjacent area of California, encompassing approximately 100,000 square kilometers. Table 4 summarizes the lithologic layers, contact depths, and unsaturated zone travel thickness at Clean Slate I, II, and III.

Table 4
Clean Slate I, II, and III Lithology from the DVRFS HFM
(Page 1 of 2)

Site HSU	Rainier Mesa HSU Analog	Contact Depth from Surface (m)	Unsaturated Zone Travel Thickness in Each HSU Layer (m)
Clean Slate I			
YAA	Yucca Flat AA	0	10.6
OAA	Yucca Flat AA	10.6	43.1
TMVA	TM-WTA	53.7	16.5
Clean Slate II			
YAA	Yucca Flat AA	0	24.0
OAA	Yucca Flat AA	24.0	49.8
VSU_UP	ATCU	73.8	44.9

Table 4
Clean Slate I, II, and III Lithology from the DVRFS HFM
(Page 2 of 2)

Site HSU	Rainier Mesa HSU Analog	Contact Depth from Surface (m)	Unsaturated Zone Travel Thickness in Each HSU Layer (m)
Clean Slate III			
YAA	Yucca Flat AA	0	26.0
OAA	Yucca Flat AA	26.0	47.2
VSU_UP	ATCU	73.2	6.5

Source: Modified from Belcher et al. (2004)

AA = Alluvial aquifer
ATCU = Argillic tuff confining unit
HSU = Hydrostratigraphic unit
OAA = Older alluvial aquifer
TMVA = Thirsty Canyon-Timber Mountain volcanic-rock aquifer
TM-WTA = Timber Mountain welded-tuff aquifer
VSU_UP = Volcanic- and sedimentary-rock upper unit
YAA = Younger alluvial aquifer

2.1.3 Net Infiltration

The climate at the Clean Slate sites, and at the NNSS and NTTR sites, is one of the most arid within the United States. The potential evapotranspiration (PET) is the maximum water loss to the atmosphere that can occur. The PET greatly exceeds the average annual precipitation, and the net infiltration (aquifer recharge) is a small fraction of precipitation. Processes such as runoff and evapotranspiration reduce the quantity of precipitation that flows through the unsaturated geologic material (vadose zone) to recharge groundwater. Precipitation-derived recharge is the driving mechanism that moves contamination down toward the water table.

Orographic effects result in a strong correlation between elevation and precipitation, thereby increasing recharge rates at higher elevations. The greater precipitation in the mountains provides most of the recharge to the groundwater system, and any water that reaches the desert floor, such as that at Cactus Flat, is lost primarily through evaporation. Evaporation greatly exceeds precipitation rates, and the annual PET at the site is approximately 150 centimeters (cm) (59 inches [in.].) (French, 1983).

Recharge models take into account the processes that influence precipitation and recharge. The highest recharge occurs in high elevation areas with shallow soils. A total of seven alternative recharge models were created for use with either UGTA or the U.S. Geological Survey (USGS) groundwater modeling studies. The Rainier Mesa/Shoshone Mountain hydrologic data document (SNJV, 2008) examines the following four recharge models used by UGTA utilizing the most realistic assumptions:

1. **The UGTA Revised Model** uses the empirical Maxey-Eakin recharge method. This method relies on the concept that fixed percentages of precipitation become recharge in different elevation or precipitation zones. The UGTA Revised Model also allows some fraction of the estimated recharge in upland areas to be redistributed along adjacent downstream washes (SNJV, 2004).

2. **The USGS Distributed Parameter Watershed (DPWS) Model** uses a spatially distributed soil-water-budget method. This method considers physical processes affecting soil drainage, runoff and evapotranspiration. The USGS DPWS model presented in SNJV(2008) includes re-infiltration of runoff (Hevesi et al., 2003).

3. **The Death Valley Regional Groundwater Flow System (DVRFS) Model** is the USGS DPWS model with infiltration values scaled during calibration of the DVRFS model (Belcher et al., 2004).

4. **The Desert Research Institute (DRI) Chloride Mass-Balance Model** uses an elevation-dependent chloride mass-balance method. This method estimates recharge from the increase in the soil water or spring discharge water chloride concentration relative to the chloride concentration in precipitation. The model was calibrated and verified against regional spring measurements and superimposes additional limits on infiltration based on observations that infiltration is negligible in thick alluvium or below a certain elevation (Russell and Minor, 2002).

Each of the four recharge models examined by the Rainier Mesa/Shoshone Mountain hydrologic data document (SNJV, 2008) predicted that no recharge is occurring within a 1-km radius of the three Clean Slate sites. Although the recharge models predicted that no recharge is occurring at the Clean Slate sites, the models predicted recharge is generally 0.1 to 1.0 millimeter per year (mm/yr) at nearby areas within Cactus Flat. Thus, a conservative value of 1 mm/yr is used to assess the unsaturated travel times at the Clean Slate sites.

2.2 Double Tracks Site

The Double Tracks site is the location of the first experiment of Operation Roller Coaster. This experiment evaluated the dispersal of plutonium in the environment from the chemical explosion of a plutonium-bearing device (DOE/NV, 1996b). This site is designated CAU 411, CAS NAFR-23-01, Pu Contaminated Soil. The Double Tracks site is located in Stonewall Flat on Range 71 of the NTTR and is approximately 10 km west of the TTR. The town of Goldfield is located approximately 22 km west of the site.

2.2.1 Depth to Groundwater

There are no wells located at the Double Tracks site, and hydrogeologic data are limited to one well on the NTTR and one private water well near the town of Ralston. Several springs are located in the Cactus Range northeast of the Double Tracks site and in the Cole Mountain area west of the Double Tracks site. Because these springs are located at much higher elevations, there is no potential for groundwater contaminants to surface at the springs.

There is only one well within 15 km of the Double Tracks site. The depth to groundwater in the vicinity of Stonewall Flat is estimated to be 123 m as provided by the Unknown 83 well, located approximately 12 km south of the Double Tracks site (Figure 3). The Ralston well, located approximately 22 km southwest of the site, would provide a depth of 163 m, although the excessive distance downgradient between this well and the Double Tracks site would result in overestimating depth to groundwater. Table 5 provides the depth to groundwater for these two wells.

2.2.2 Subsurface Lithology

The Double Tracks site is located in the northern portion of the Stonewall Flat Valley, and unsaturated zone subsurface is mostly valley-fill alluvium. The nearest well with lithologic data recorded is USAF TTR Roller Coaster WW, which is located approximately 22 km northeast of the site within the Cactus Flat Valley. The lithologic log recorded alternating clay, gravel, sand, and basalt to a depth of 242 m.

Because there are no wells located at the Double Tracks site, the estimation of lithology must rely on the DVRFS HFM (Belcher et al., 2004). Table 6 summarizes the lithologic layers, contact depths, and unsaturated zone travel distances at the Double Tracks site.

2.2.3 Net Infiltration

Each of the four recharge models examined by the Rainier Mesa/Shoshone Mountain hydrologic data document (SNJV, 2008) determined that no recharge is occurring within a 1-km radius of the Double Tracks site. Although the recharge models predicted that no recharge is occurring at the Double

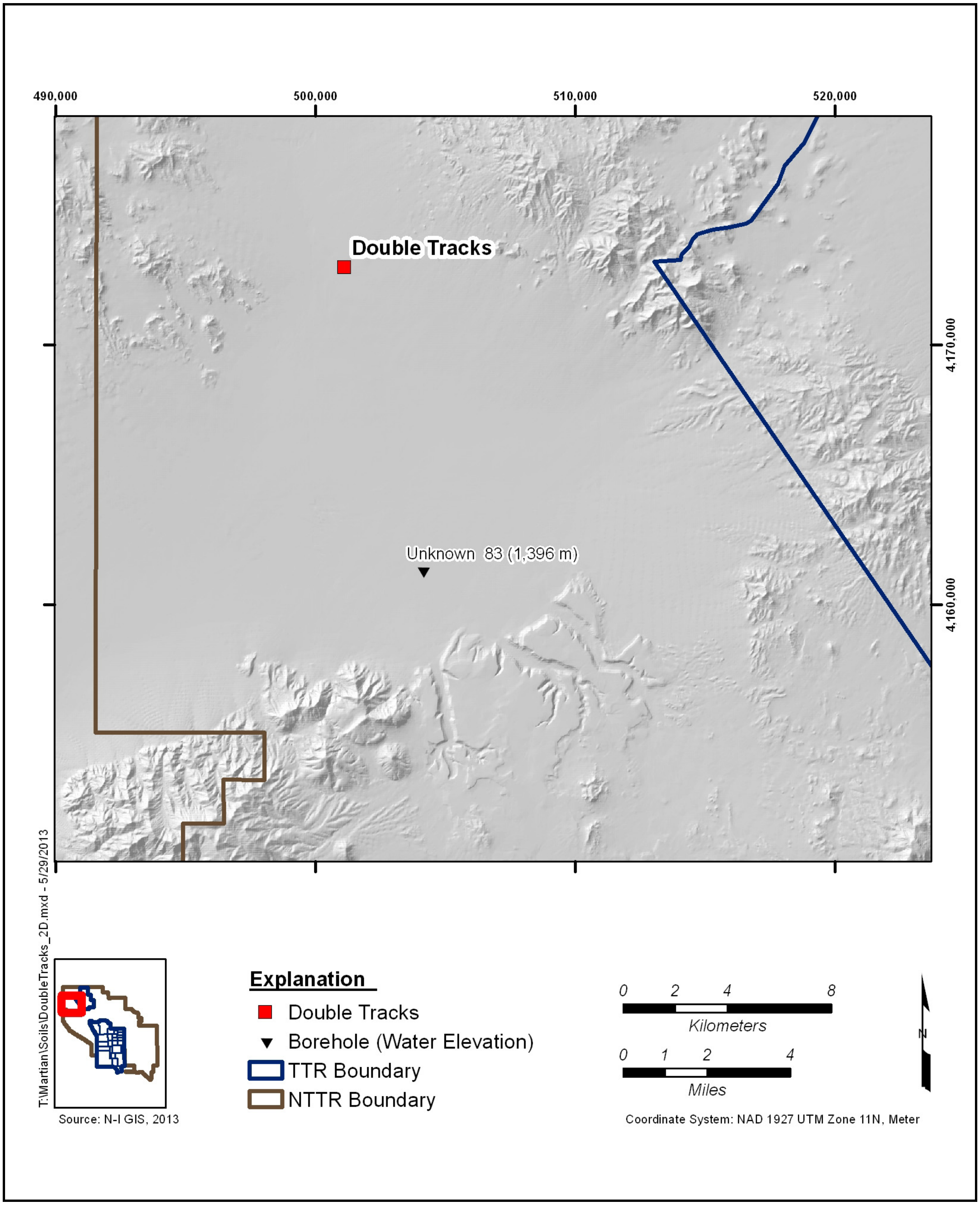

Figure 3
Wells Near the Double Tracks Site

Table 5
Wells Near the Double Tracks Site

Well Name	Easting (m)	Northing (m)	Distance from Double Tracks Site (m)	Water Elevation (m)	Estimated Water Depth at Double Tracks Site (m)	Water Depth at Well Location (m)
Unknown 83	504,120	4,161,324	12,062.7	1,396.0	123.5	33.5
Ralston Well	486,626	4,156,299	22,119.7	1,355.7	163.7	93.9

Source: UGTA Borehole Index Database (N-I, 2013)

Table 6
Double Tracks Site Lithology from the DVRFS HFM

Site HSU	Rainier Mesa HSU Analog	Contact Depth from Surface (m)	Unsaturated Zone Travel Thickness in Each HSU Layer (m)
YAA	Yucca Flat AA	0	15.0
OAA	Yucca Flat AA	15.0	45.7
OVU	OSBCU	60.7	44.1
VSU_LOW	ATCU	104.8	18.6

Source: Modified from Belcher et al. (2004)

OSBCU = Oak Spring Butte confining unit
OVU = Older volcanic-rock unit
VSU_LOW = Volcanic- and sedimentary-rock lower unit

Tracks site, the models predicted recharge is generally 0.1 to 1.0 mm/yr at nearby areas within Stonewall Flat. Thus, a conservative value of 1 mm/yr is used to assess the unsaturated travel time at the Double Tracks site.

2.3 Project 57 Site

Project 57 was a safety test conducted on the NTTR. The purpose of the test was to evaluate the dispersal of plutonium resulting from a chemical explosion of a simulated nuclear device. This site is designated CAU 415, CAS NAFR-23-02, Pu Contaminated Soil, and is located northeast of the NNSS boundary in Emigrant Valley. The Belted and Groom Ranges lie west and east of the Project 57 site, respectively.

2.3.1 Depth to Groundwater

There are no wells completed to groundwater at the Project 57 site, and the hydrogeologic data are limited to wells constructed in support of nuclear testing and environmental restoration activities on the NNSS, which are located within several kilometers of the site. The depth to groundwater within Emigrant Valley in the vicinity the Project 57 site is estimated at 66 m and is provided by the depth of the water table at the Stewart 2 (HTH) well, located 1.4 km southwest of the site. Figure 4 illustrates all wells and their water elevation within a 15-km distance of the site. Table 7 provides the depth to groundwater for the wells within 15 km of the site.

2.3.2 Subsurface Lithology

The Project 57 site is located in central Emigrant Valley, and unsaturated zone subsurface is mostly valley-fill alluvium. The nearest well with lithologic data recorded is Watertown 4 WW, which is located approximately 9 km southeast of the site. The lithologic log recorded alternating sand, clay, caliche, and rock conglomerate to a depth of 163 m.

Because there are no wells located at the Project 57 site, the estimation of lithology must rely on the DVRFS HFM (Belcher et al., 2004). Table 8 summarizes the lithologic layers, contact depths, and unsaturated zone travel distances at the Project 57 site.

2.3.3 Net Infiltration

The four recharge models examined by the Rainier Mesa/Shoshone Mountain hydrologic data document (SNJV, 2008) determined that no recharge is occurring within a 1-km radius of the Project 57 site. Although the recharge models predicted that no recharge is occurring at the Project 57 site, the models predicted recharge is generally 0.1 to 1.0 mm/yr at nearby areas within Emigrant Valley. Thus, a conservative value of 1 mm/yr is used to assess the unsaturated travel time at the Project 57 site.

2.4 TCA Complex and Bunker

The TCA Complex is located in Area 25 of the NNSS within the Jackass Flats basin. The TCA Complex was used to test and develop nuclear rocket motors as part of the Nuclear Rocket Development Station from its construction in 1958 until 1966, when rocket testing began at

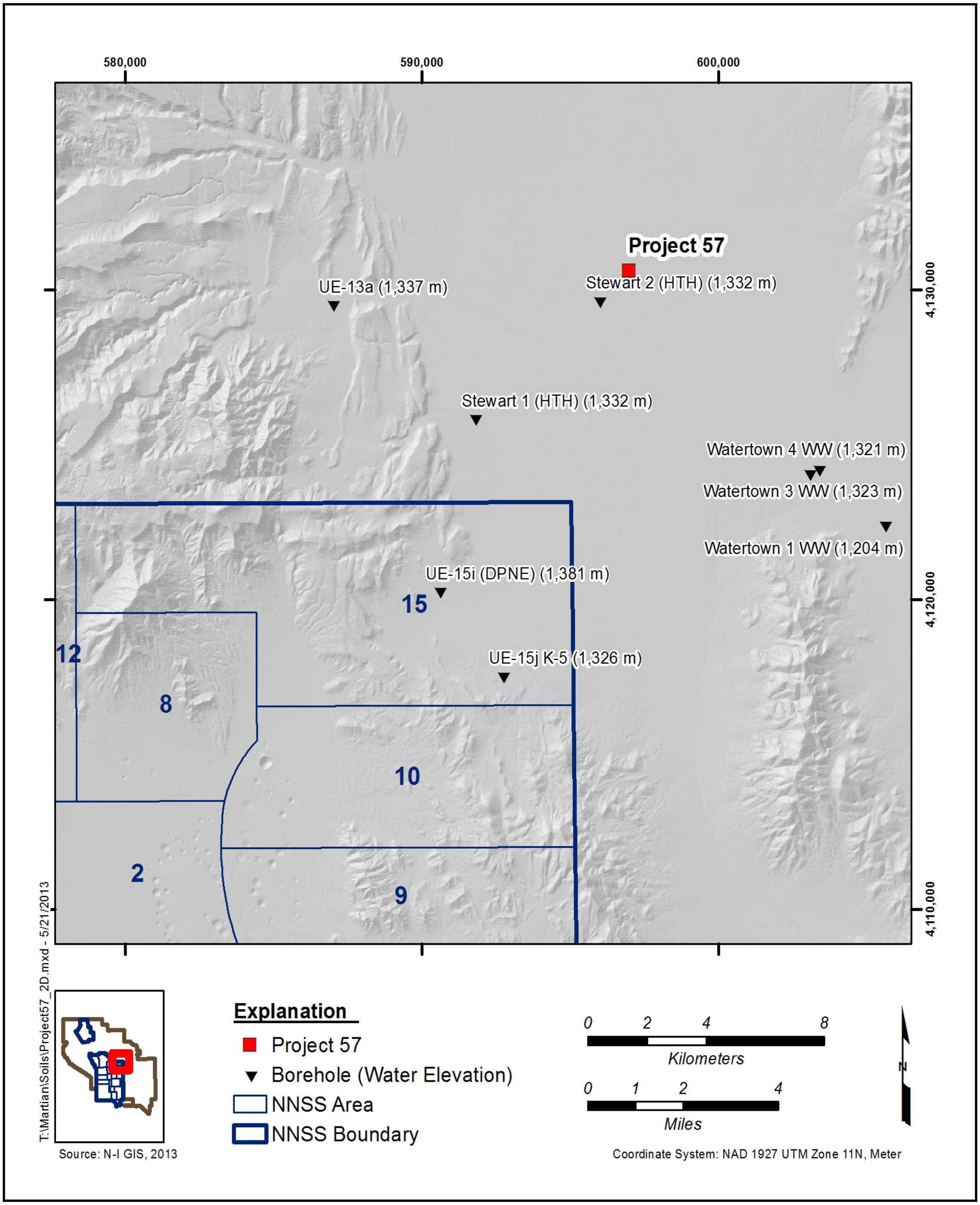

Figure 4
Wells Near the Project 57 Site

Table 7
Wells Near the Project 57 Site

Well Name	Easting (m)	Northing (m)	Distance from Project 57 No. 1 Site (m)	Water Elevation (m)	Estimated Water Depth at Project 57 No. 1 Site (m)	Water Depth at Well Location (m)
Stewart 2 (HTH)	595,980	4,129,685	1,390.6	1,331.7	65.8	61.9
Stewart 1 (HTH)	591,782	4,125,879	7,057.1	1,332.3	65.2	80.2
Watertown 4 WW	603,063	4,124,102	8,933.1	1,320.7	76.8	34.7
Watertown 3 WW	603,382	4,124,241	9,054.7	1,322.6	74.9	32.6
UE-13a	586,981	4,129,563	10,060.8	1,336.7	60.8	129.7
Watertown 1 WW	605,605	4,122,437	11,906.0	1,203.8	193.7	149.5
UE-15i (DPNE)	590,587	4,120,305	12,161.4	1,381.5	16.0	39.8
UE-15j K-5	592,725	4,117,572	13,751.9	1,325.7	71.8	125.2

Source: UGTA Borehole Index Database (N-I, 2013)

Table 8
Project 57 Site Lithology from the DVRFS HFM

Site HSU	Rainier Mesa HSU Analog	Contact Depth from Surface (m)	Unsaturated Zone Travel Thickness in Each HSU Layer (m)
YAA	Yucca Flat AA	0	25.0
OAA	Yucca Flat AA	25.0	40.8

Source: Modified from Belcher et al. (2004)

Test Cell C. The rocket motors were built with an unshielded nuclear reactor that produced as much as 1,100 kilowatts to heat liquid hydrogen to 4,000 degrees Fahrenheit, at which time the expanded gases were focused out a nozzle to produce thrust. The fuel rods in the reactor were not clad and were designed to release fission fragments to the atmosphere, but due to vibrations and loss of cooling during some operational tests, fuel fragments in excess of planned releases became entrained in the exhaust and spread in the immediate area surrounding the testing location (NNSA/NSO, 2010).

The TCA Complex is within CAU 375 and comprises two CASs: (1) CAS 25-23-22, Contaminated Soils Site, which contains soil contamination resulting from fuel fragments being ejected from the rocket motors; and (2) CAS 25-34-06, Test Cell A Bunker, which contains contamination associated with material stored in the TCA Complex bunker. The bunker is located within the TCA Complex, so the two sites are indistinguishable from one another in terms of depth to groundwater, net infiltration, and lithology. A single unsaturated zone travel time is calculated for both CASs.

2.4.1 Depth to Groundwater

There are no wells completed to groundwater at the TCA Complex, and the hydrogeologic data are limited to wells constructed in support of nuclear testing and environmental restoration activities on the NNSS. The depth to groundwater within Jackass Flats, in the vicinity of the TCA Complex, is estimated to be 392 m as provided by the second-nearest well to the site (UE-25a3), which is located approximately 6.2 km west of the site. The nearest well to the site is J-11, which is located approximately 5.5 km south of the site. Fenelon et al. (2010) describes the flow systems at the NNSS and places J-11 downgradient of the TCA Complex. Although J-11 is the nearest well to the TCA Complex, it would overestimate the depth to groundwater at the TCA Complex. Well UE-25a3 is located more parallel to the groundwater gradient at the TCA Complex. Figure 5 illustrates the wells that are within a 15-km distance of the TCA Complex. Table 9 provides the depth to groundwater for all wells within 15 km of the site.

2.4.2 Subsurface Lithology

The TCA Complex is located in the northeast part of Jackass Flats and unsaturated zone subsurface is valley-fill alluvium near land surface and ash-flow tuff at deeper depths. The nearest well with lithologic data recorded is UE-25a3, which is located approximately 6 km west of the TCA Complex within the Calico Hills. The lithologic log from UE-25a3 recorded argillite to a depth of 771 m. Well UE-25a3 is located in an isolated area of Paleozoic and Precambrian sedimentary rocks within the Calico Hills north of Jackass Flats and is likely unrepresentative of the TCA subsurface (BN, 2002). The second-nearest well with a lithologic log is UE-25 WT 13, located 12 km southwest of the TCA Complex. This well recorded alluvium near the surface and ash-flow tuffs at deeper depths.

Because there are no wells located at the TCA Complex, the estimation of lithology must rely on the DVRFS HFM (Belcher et al., 2004). Table 10 summarizes the lithologic layers, contact elevations, and unsaturated zone travel distances for each layer at the TCA Complex.

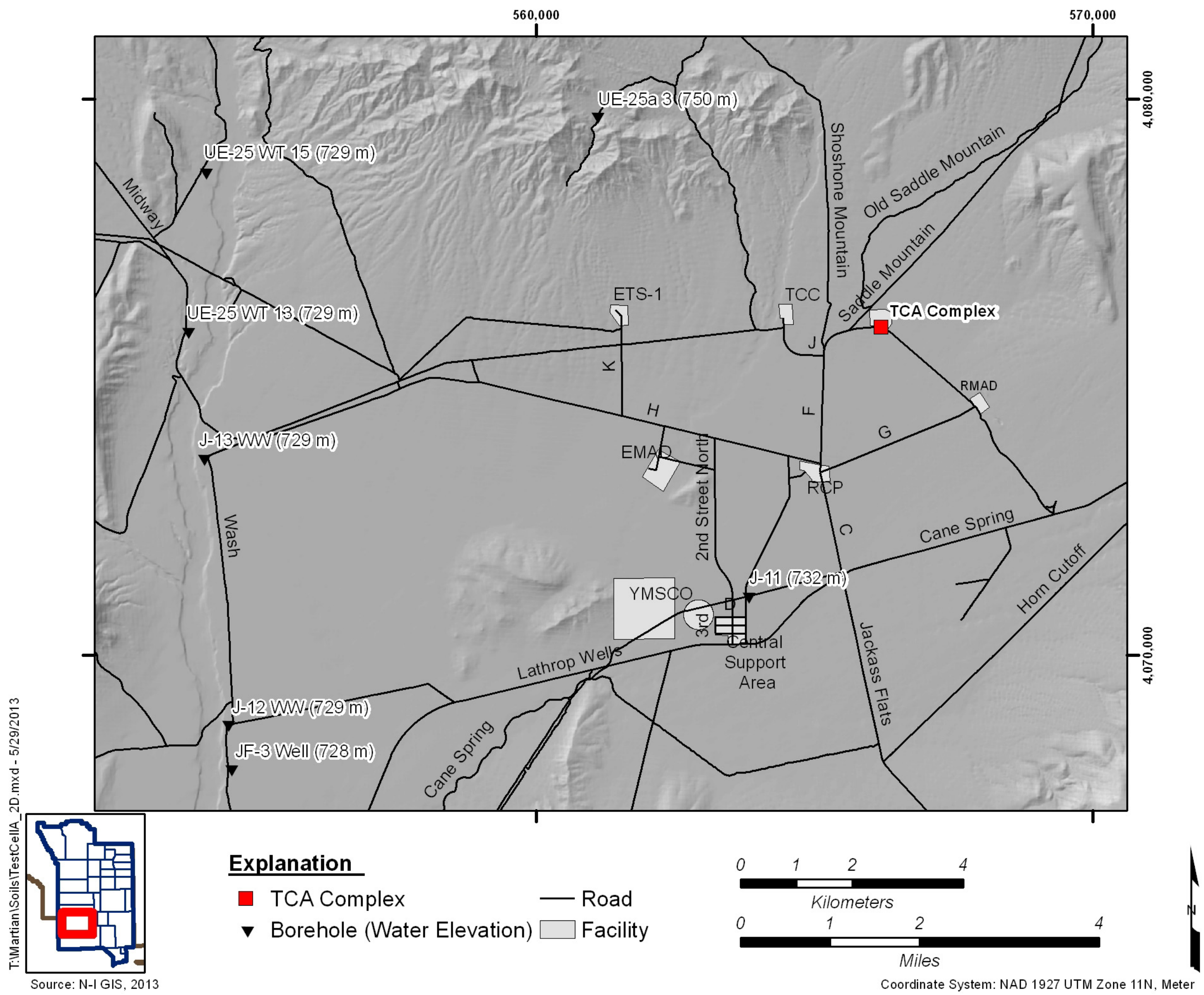

Figure 5
Wells Near the TCA Complex

Table 9
Wells Near the TCA Complex

Well Name	Easting (m)	Northing (m)	Distance from TCA Complex (m)	Water Elevation (m)	Estimated Water Depth at TCA Complex (m)	Water Depth at Well Location (m)
J-11	563,799	4,071,073	5,402.5	732.2	432.5	317.1
UE-25a 3	561,079	4,079,703	6,424.7	749.6	392.4	636.1
J-13 WW	554,004	4,073,550	12,465.3	728.8	435.9	282.5
UE-25 WT 13	553,724	4,075,836	12,524.6	729.1	435.6	302.9
UE-25 WT 15	554,034	4,078,702	12,534.8	729.5	435.2	353.5
J-12 WW	554,436	4,068,767	13,793.0	728.7	436.0	225.3
JF-3 Well	554,499	4,067,974	14,166.6	728.2	436.5	216.1

Source: UGTA Borehole Index Database (N-I, 2013)

Table 10
TCA Complex Lithology from the DVRFS HFM

Site HSU	Rainier Mesa HSU Analog	Contact Depth from Surface (m)	Unsaturated Zone Travel Thickness in Each HSU Layer (m)
YAA	Yucca Flat AA	0	13.3
OAA	Yucca Flat AA	13.3	19.9
LFU	TUBA	33.2	47.7
TMVA	TM-WTA	80.9	116.0
PVA	TM-LVTA	196.9	129.4
WVU	OSBCU	326.2	66.2

Source: Modified from Belcher et al. (2004)

LFU = Lava-flow unit
PVA = Paintbrush volcanic-rock aquifer
TM-LVTA = Timber Mountain lower vitric-tuff aquifer
TUBA = Tub Spring aquifer
WVU = Wahmonie volcanic-rock unit

2.4.3 Net Infiltration

Only the UGTA Revised Model infiltration determined that recharge is occurring at the TCA Complex (SNJV, 2004). The range of net infiltration rates within a 1-km radius of the TCA Complex sites is 2.1 to 2.7 mm/yr. The maximum value from UGTA Revised Model is used for the unsaturated zone travel time calculation at the TCA Complex (2.7 mm/yr).

2.5 Buggy Site

The Buggy site is located within Area 30 on Chukar Mesa on the NNSS. Five nuclear devices were detonated in a row at 150-foot intervals at a depth of 140 feet (ft). The devices produced a trench 254 ft wide, 865 ft long, and 70 ft deep. The Buggy test was part of Operation Crosstie to demonstrate the use of nuclear explosions for trench excavation. The Buggy site is within CAU 375 and is designated CAS 30-45-01, U-30a, b, c, d, e Craters (NNSA/NSO, 2010).

2.5.1 Depth to Groundwater

There are no wells completed to groundwater at the Buggy site, and the hydrogeologic data are limited to wells constructed in support of nuclear testing and environmental restoration activities on the NNSS. The depth to groundwater on Chukar Mesa in the vicinity the Buggy site is estimated at 287 m. This value is the Buggy site land surface depth to the water table estimated from the well nearest the site (ER-30-1-2) less the crater depth of 21.3 m (70 ft). Figure 6 illustrates all wells and their water elevation within a 15-km distance of the Buggy site. Table 11 provides the depth to groundwater and water-level elevations for all wells within 15 km of the site.

2.5.2 Subsurface Lithology

The Buggy site is located on Chukar Mesa, with deep ravines located on three sides of the crater area. The unsaturated zone subsurface is mostly volcanic rock (BN, 2002). The nearest well with lithologic data recorded is ER-30-1, which is located approximately 6.8 km northeast of the site within Upper Fortymile Canyon. The lithologic log of ER-30-1 recorded alluvium to a depth of 67.67 m (222 ft), followed by volcanic rock to a depth of 434.64 m (1,426 ft). The location of ER-30-1 within Fortymile Canyon likely results in an alluvium depth much greater than what is expected at the Buggy site on Chukar Mesa.

Because there are no wells located at the Buggy site, the estimation of lithology must rely on the Pahute Mesa Phase I HFM (BN, 2002). Table 12 summarizes the lithologic layers, contact elevations, and unsaturated zone travel distances at the Buggy site.

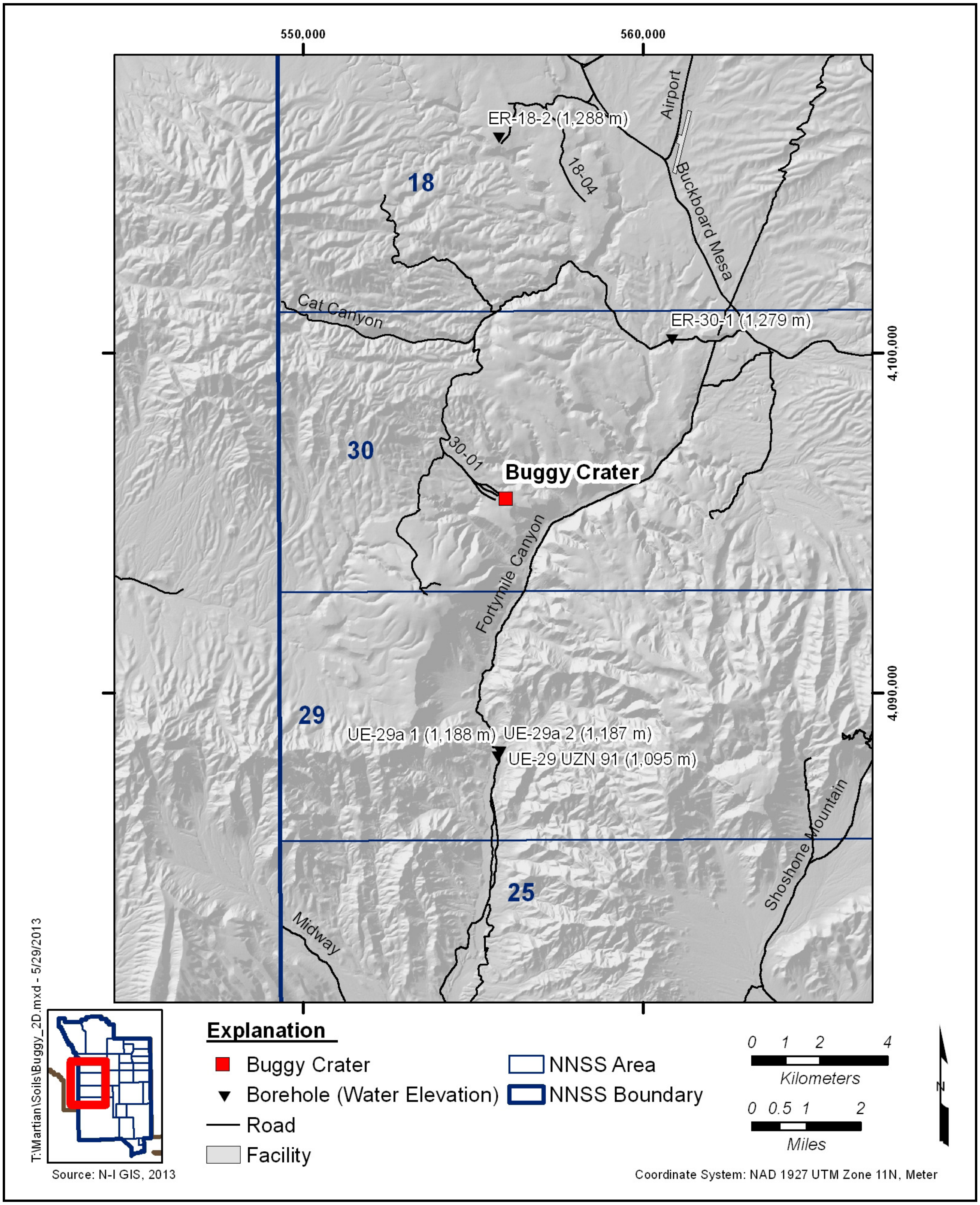

Figure 6
Wells Near the Buggy Site

2.5.3 Net Infiltration

Each of the four recharge models examined by the Rainier Mesa/Shoshone Mountain hydrologic data document (SNJV, 2008) predicted that recharge is occurring within a 1-km radius of the Buggy site. The range of net infiltration rates within a 1-km radius of the site is 0 to 9.8 mm/yr. Table 13 summarizes the recharge rates predicted by the four models. The maximum value from the four infiltration models is used for the unsaturated zone travel time calculation at the Buggy site (9.8 mm/yr).

Table 11
Wells Near the Buggy Site

Well Name	Easting (m)	Northing (m)	Distance from Buggy Site (m)	Water Elevation (m)	Estimated Water Depth at Buggy Site (m)	Water Depth at Well Location (m)
ER-30-1-2 shallow [a]	560,805	4,100,463	6,776.2	1,279.2	308.9	137.3
UE-29a 2	555,749	4,088,346	7,374.4	1,186.8	401.2	28.4
UE-29a 1	555,758	4,088,341	7,379.0	1,188.1	399.9	27.1
UE-29 UZN 91	555,687	4,088,203	7,519.8	1,094.6	493.4	17.0
ER-18-2	555,725	4,106,389	10,674.3	1,288.4	299.6	368.8

Source: UGTA Borehole Index Database (N-I, 2013)

[a] Shown as ER-30-1 on Figure 6.

Table 12
Buggy Site Lithology from the Pahute Mesa Phase I HFM

Site HSU	Rainier Mesa HSU Analog	Contact Depth from Surface (m)	Unsaturated Zone Travel Thickness in Each HSU Layer (m)
FCCM	ATCU	0	287.5

Source: Modified from BN (2002)

FCCM = Fortymile Canyon composite unit

Table 13
Buggy Site Recharge Rates Predicted by Recharge Models

Model	Net Infiltration (mm/yr)	
	Minimum	Maximum
UGTA Revised Model[a]	2.5	2.5
USGS DPWS Model[b]	0	9.8
USGS DVRFS Model[c]	4.1	4.1
DRI Chloride Mass-Balance Model[d]	4.2	4.2

[a] SNJV, 2004
[b] Hevesi et al., 2003
[c] Belcher et al., 2004
[d] Russell and Minor, 2002

3.0 HYDRAULIC AND TRANSPORT PROPERTY DATA

Hydraulic and transport data needed to resolve the contaminant transport calculations are listed in Table 14 with the corresponding sections that define the values for these parameters. The rationale used in developing a value for each parameter is also explained in the referenced section. The effect that changes in these input parameter values have on contaminant travel distances and times (sensitivity analysis) is presented in Section 5.0.

Table 14
Contaminant Transport Calculation Input Parameters

Parameter	Definition	Section
d_i	Distance (L)	2.0
q	Steady-state recharge rate (L/t)	2.0
θ	Volumetric water content (dimensionless [-])	3.1
V_w	Vertical velocity of pore water (L/t)	3.2
R_f	Retardation factor (dimensionless [-])	3.3

3.1 Volumetric Water Content

This section develops the values to be used for the volumetric water content (θ) input parameter. Because the geological material between the contaminant source and the underlying aquifers comprises several layers of differing material, volumetric water content values are established for each layer.

Under unsaturated conditions, relative hydraulic conductivity ($K(h)$), volumetric water content (θ), and matric potential head (h) are interrelated. The matric potential head is negative relative to saturated conditions due to the surface tension of water in pore capillaries and on grain surfaces. Characterization of unsaturated flow requires two constitutive relationships for each material type identified in the subsurface: (1) the moisture characteristic curve, which is the relationship between the matric potential and volumetric water content; and (2) the hydraulic conductivity curve, which is the relationship between the matric potential and the unsaturated hydraulic conductivity.

The van Genuchten (1980) equation was used to represent the constitutive relationships between the hydraulic properties. The equation for the moisture characteristic curve (Equation [7]) is

$$\theta = \theta_r + \frac{(\theta_s - \theta_r)}{[1 + (\alpha h)^n]^{1 - \frac{1}{n}}} \tag{7}$$

where
- θ = volumetric water content (dimensionless [–])
- θ_r = residual volumetric water content (–)
- θ_s = saturated volumetric water content (–)
- α = inverse air-entry potential (L^{-1})
- h = matric potential head (length [L])
- n = pore-size distribution index parameter (–)

When the van Genuchten function is combined with the Mualem conductivity model (Mualem, 1976), the equation for the hydraulic conductivity curve (Equation [8]) is

$$K(h) = K_s \frac{\{1 - (\alpha h)^{n-1}[1 + (\alpha h)^n]^{1 - 1/n}\}^2}{[1 + (\alpha h)^n]^{0.5(1 - 1/n)}} \tag{8}$$

where
- $K(h)$ = unsaturated hydraulic conductivity (L/t)
- K_s = saturated hydraulic conductivity (L/t)

Equations (7) and (8) illustrate that volumetric water content and matric potential head in the unsaturated zone are nonlinear functions of the recharge passing through them. Under steady-state flow conditions, the volumetric water content will correspond to an unsaturated hydraulic conductivity that is equivalent to the recharge rate. The volumetric water content for each rock layer is calculated by solving Equation (8) for matric potential head and then solving equation Equation (7) for volumetric water content.

In general, there are very few or no measurements of subsurface moisture characteristics for the NNSS, TTR, or NTTR. Site-specific unsaturated flow data are not available for each CAU, and analog data from sites with similar lithology must be used to calculate the unsaturated zone travel times. The alluvium data are from Yucca Flat on the NNSS (SNJV, 2009; BN, 1998), and the volcanic rock data are from Rainier Mesa on the NNSS (Kwicklis et al., 2008). The analog HSU moisture characteristics of Kwicklis et al. (2008) represent the rock matrix. These moisture characteristics are appropriate for each site because the recharge rates predicted by the models are less than the saturated hydraulic conductivity of the analog HSUs rock matrix, which prohibits substantial fracture flow. Table 15 summarizes the hydraulic properties and Rainier Mesa analog HSUs assigned to the stratigraphic layers for each site.

Table 15
Hydraulic Properties

Site HSU	Yucca Flat/ Rainier Mesa HSU Analog	K_s (mm/yr)	θ_s (–)	θ_r (–)	α (1/m)	*n* (–)	Calculated Volumetric Water Content at Max Recharge Rate (–)
Clean Slate I							
YAA[a]	Yucca Flat AA	195,689	0.412	0.142	1.03	1.789	0.175
OAA[a]	Yucca Flat AA	195,689	0.412	0.142	1.03	1.789	0.175
TMVA[b]	TM-WTA	3,700	0.208	0.0017	0.216	1.38	0.100
Clean Slate II							
YAA[a]	Yucca Flat AA	195,689	0.412	0.142	1.03	1.789	0.175
OAA[a]	Yucca Flat AA	195,689	0.412	0.142	1.03	1.789	0.175
VSU_UP[b]	ATCU	212	0.264	0.0	0.006	1.194	0.224
Clean Slate III							
YAA[a]	Yucca Flat AA	195,689	0.412	0.142	1.03	1.789	0.175
OAA[a]	Yucca Flat AA	195,689	0.412	0.142	1.03	1.789	0.175
VSU_UP[b]	ATCU	212	0.264	0.0	0.006	1.194	0.224
Double Tracks							
YAA[a]	Yucca Flat AA	195,689	0.412	0.142	1.03	1.789	0.175
OAA[a]	Yucca Flat AA	195,689	0.412	0.142	1.03	1.789	0.175
OVU[b]	OSBCU	66.1	0.292	0.005	0.005	1.368	0.230
VSU_LOW[b]	ATCU	212	0.264	0.0	0.006	1.194	0.224
Project 57							
YAA[a]	Yucca Flat AA	195,689	0.412	0.142	1.03	1.789	0.175
OAA[a]	Yucca Flat AA	195,689	0.412	0.142	1.03	1.789	0.175
TCA							
YAA[a]	Yucca Flat AA	195,689	0.412	0.142	1.03	1.789	0.182
OAA[a]	Yucca Flat AA	195,689	0.412	0.142	1.03	1.789	0.182
LFU[b]	TUBA	20.3	0.042	0.0	0.0	1.486	0.038
TMVA[b]	TM-WTA	3700	0.208	0.002	0.216	1.384	0.113
PVA[b]	TM-LVTA	8960	0.366	0.023	0.471	1.911	0.106
WVU[b]	OSBCU	66.1	0.292	0.005	0.052	1.368	0.253
Buggy							
FCCM[b]	ATCU	212	0.264	0.0	0.055	1.194	0.254

[a] Alluvial aquifer and older aquifer hydraulic properties are from the Yucca Flat/Climax Mine source term document (SNJV, 2009) and are composite of all alluvium data in the Radioactive Waste Management Site characterization study (BN,1998).
[b] All other properties are from Rainier Mesa core analysis by Los Alamos National Laboratory (Kwicklis et al., 2008).

3.2 Vertical Velocity of Pore Water

This section develops the vertical velocity of pore water (v_w) values that are used to calculate contaminant travel distances and arrival times. As the geological material between the contaminant source and the underlying aquifers comprises varying layers of differing material, vertical velocities of pore water are established for each layer.

As described in Equation (2), the vertical velocity of pore water is calculated as the steady-state recharge rate (as developed in Section 2.0) divided by the volumetric water content (as developed in Section 3.1). The vertical velocity for each stratigraphic layer for each site is presented in Table 16, with the calculated or volumetric water content.

Table 16
Vertical Velocity of Pore Water
(Page 1 of 2)

Site HSU	Yucca Flat/ Rainier Mesa HSU Analog	Calculated Volumetric Water Content at Max Recharge Rate (–)	Pore Water Vertical Velocity (mm/yr)
Clean Slate I			
YAA	Yucca Flat AA	0.175	5.7
OAA	Yucca Flat AA	0.175	5.7
TMVA	TM-WTA	0.100	10.0
Clean Slate II			
YAA	Yucca Flat AA	0.175	5.7
OAA	Yucca Flat AA	0.175	5.7
VSU_UP	ATCU	0.224	4.5
Clean Slate III			
YAA	Yucca Flat AA	0.175	5.7
OAA	Yucca Flat AA	0.175	5.7
VSU_UP	ATCU	0.224	4.5
Double Tracks			
YAA	Yucca Flat AA	0.175	5.7
OAA	Yucca Flat AA	0.175	5.7
OVU	OSBCU	0.230	4.3
VSU_LOW	ATCU	0.224	4.5
Project 57			
YAA	Yucca Flat AA	0.175	5.7
OAA	Yucca Flat AA	0.175	5.7

Table 16
Vertical Velocity of Pore Water
(Page 2 of 2)

Site HSU	Yucca Flat/ Rainier Mesa HSU Analog	Calculated Volumetric Water Content at Max Recharge Rate (–)	Pore Water Vertical Velocity (mm/yr)
TCA			
YAA	Yucca Flat AA	0.182	14.8
OAA	Yucca Flat AA	0.182	14.8
LFU	TUBA	0.038	70.3
TMVA	TM-WTA	0.113	23.8
PVA	TM-LVTA	0.106	25.5
WVU	OSBCU	0.253	10.7
Buggy			
FCCM	ATCU	0.254	38.7

3.3 Retardation Factor

This section develops the values to be used for the retardation factor (R_f) input parameter. Because the geological material between the contaminant source and the underlying aquifers comprises several layers of differing material, retardation factors are established for each layer.

Sorption is a physiochemical process at the mineral-water interfaces that retard contaminant mobility within the geologic matrix. Calculating the contaminant retardation factors requires knowledge of the bulk density and volumetric water content of the matrix along with a partition (or distribution) coefficient (K_d) parameter. The K_d parameter combines a variety of molecular-scale processes (e.g., surface complexation and ion exchange) into an effective relationship between the amount of contaminant sorbed to the rock and the amount of contaminant in solution. The K_d parameter value is defined in Equation (9) as

$$K_d = \frac{\text{Mass of adsorbed solute per gram of solid phase}}{\text{Mass of solute per milliliter of solution}} \tag{9}$$

The contaminant retardation factor is related to bulk density, volumetric water content, and the K_d parameter as indicated in Equation (10)

$$R_f = 1 + \frac{K_d \rho_b}{\theta} \tag{10}$$

where

R_f = retardation factor (–)
ρ_b = bulk density (grams per cubic centimeter [g/cm^3])
θ = volumetric water content (dimensionless [–])

The K_d parameter values for the volcanic rock are taken from a Rainier Mesa hydrologic source term study (Tompson et al., 2011, Table 2-14) for each analog HSU. The K_d parameter values provided by Tompson et al. (2011) included uncertainty in surface complexation and ion exchange constants and are presented as distributions. The volcanic rock bulk density values are taken from a core-scale data analysis performed for Rainier Mesa by Kwicklis et al. (2008, Table 6). The alluvium K_d distributions are from Frenchman Flat alluvium data presented in the Yucca Flat transport data document (SNJV, 2007, Table 11-6). The alluvium bulk density is calculated from the matrix porosity and particle density in Equation (11) as

$$\rho_b = (1 - \theta_s) \times \rho_p \tag{11}$$

where

ρ_b = bulk density (g/cm^3)
θ_s = saturated volumetric water content (dimensionless [–])
ρ_p = particle density (g/cm^3)

The bulk density along with the log10 K_d distribution for each stratigraphic layer at each site is presented in Table 17. The transport of actinides can be more rapid than the K_d parameter suggests. Sorption onto inorganic colloids can facilitate unretarded plutonium transport with the bulk water

Table 17
Solute Transport Properties
(Page 1 of 2)

Site HSU	Bulk Density ρ_b (g/cm^3)[a]	Uranium		Plutonium	
		Log10 K_d Distribution (mL/g)[b,c]			
		Average	Standard Deviation	Average	Standard Deviation
Clean Slate I					
YAA	1.46	-0.11	0.33	0.23	0.30
OAA	1.46	-0.11	0.33	0.23	0.30
TMVA	2.01	-0.83	0.27	1.13	0.37

Table 17
Solute Transport Properties
(Page 2 of 2)

Site HSU	Bulk Density ρ_b (g/cm^3)[a]	Uranium		Plutonium	
		Log10 K_d Distribution (mL/g)[b,c]			
		Average	Standard Deviation	Average	Standard Deviation
Clean Slate II					
YAA	1.46	-0.11	0.33	0.23	0.30
OAA	1.46	-0.11	0.33	0.23	0.30
VSU_UP	2.14	1.37	0.28	3.28	0.37
Clean Slate III					
YAA	1.46	-0.11	0.33	0.23	0.30
OAA	1.46	-0.11	0.33	0.23	0.30
VSU_UP	2.14	1.37	0.28	3.28	0.37
Double Tracks					
YAA	1.46	-0.11	0.33	0.23	0.30
OAA	1.46	-0.11	0.33	0.23	0.30
OVU	1.80	0.9	0.28	2.82	0.37
VSU_LOW	2.14	1.37	0.28	3.28	0.37
Project 57					
YAA	1.46	-0.11	0.33	0.23	0.30
OAA	1.46	-0.11	0.33	0.23	0.30
TCA					
YAA	1.46	-0.11	0.33	0.23	0.30
OAA	1.46	-0.11	0.33	0.23	0.30
LFU	2.43	-0.20	0.27	1.76	0.37
TMVA	2.01	-0.83	0.27	1.13	0.37
PVA	1.37	0.05	0.27	2.01	0.37
WVU	1.80	0.90	0.28	2.82	0.37
Buggy					
FCCM	2.14	1.37	0.28	3.28	0.37

[a] Kwicklis et al., 2008
[b] Alluvium K_d values are from the Yucca Flat/Climax Mine transport data document (SNJV, 2007, Table 2-14).
[c] Tertiary volcanic rock HSU K_d values are from the Rainier Mesa hydrologic source term document (Tompson et al., 2011, Table 11-6).

mL/g = Milliliters per gram

movement (Tompson et al., 2011). Colloid sorption and transport can reduce the apparent K_d by one to 2 orders of magnitude (Tompson et al., 2011). The alluvium plutonium K_d values are reduced by a factor of 10 to reflect the guidance provided by Tompson et al. (2011) that 90 percent of aqueous plutonium may be colloid associated and not truly aqueous. Flow within the volcanic rock is likely predominantly within the rock matrix due to the infiltration rates being less than the rock matrix hydraulic conductivity. The combination of fine grain structure and predominantly matrix flow likely prohibits colloid-facilitated plutonium transport in the volcanic rock. Retardation factors for uranium and plutonium are presented in Table 18.

Table 18
Retardation Factors
(Page 1 of 2)

Site HSU	Calculated Volumetric Water Content	Uranium		Plutonium	
		K_d [a,b]	Retardation Factor (R_f)	K_d [a,b]	Retardation Factor (R_f)
Clean Slate I					
YAA	0.175	0.78	7.5	1.7	15.2
OAA	0.175	0.78	7.5	1.7	15.2
TMVA	0.100	0.15	4.0	13.49	271.8
Clean Slate II					
YAA	0.175	0.78	7.5	1.7	15.2
OAA	0.175	0.78	7.5	1.7	15.2
VSU_UP	0.224	23.44	224.7	1,905.46	18,181.0
Clean Slate III					
YAA	0.175	0.78	7.5	1.7	15.2
OAA	0.175	0.78	7.5	1.7	15.2
VSU_UP	0.224	23.44	224.7	1,905.46	18,181.0
Double Tracks					
YAA	0.175	0.78	7.5	1.7	15.2
OAA	0.175	0.78	7.5	1.7	15.2
OVU	0.230	7.94	63.1	660.69	5,168.8
VSU_LOW	0.224	23.44	224.7	1,905.46	18,181.2

Table 18
Retardation Factors
(Page 2 of 2)

Site HSU	Calculated Volumetric Water Content	Uranium		Plutonium	
		K_d [a,b]	Retardation Factor (R_f)	K_d [a,b]	Retardation Factor (R_f)
Project 57					
YAA	0.175	0.78	7.5	1.7	15.2
OAA	0.175	0.78	7.5	1.7	15.2
TCA					
YAA	0.182	0.78	7.2	1.7	14.6
OAA	0.182	0.78	7.2	1.7	14.6
LFU	0.038	0.63	40.9	57.54	3,642.9
TMVA	0.113	0.15	3.6	13.49	240.5
PVA	0.106	1.12	15.5	102.33	1,326.2
WVU	0.253	7.94	57.5	660.69	4,698.5
Buggy					
FCCM	0.254	23.44	198.9	1,905.46	16,088.2

[a] Alluvium K_d values are from the Yucca Flat/Climax Mine transport data document (SNJV, 2007, Table 2-14).
[b] Tertiary volcanic rock HSU K_d values are from the Rainier Mesa hydrologic source term document (Tompson et al., 2011, Table 11-6).

4.0 Contaminant Transport Calculations

This section presents the travel times to the water table, and the 1,000-year travel distances calculated using the equations presented in Section 1.1 and the data presented in Sections 2.0 and 3.0.

4.1 Contaminant Travel Times

The travel time required for pore water to migrate through each HSU is defined as the thickness of the geologic layer (Section 1.3) divided by the vertical velocity of the pore water (Section 3.2), in addition to the travel time through any upper geologic layer. Based on the thicknesses of the HSUs and the conservatively high estimates of vertical velocities of the pore water, the estimated time for pore water (i.e., infiltration water) to reach the water table is greater than 1,000 years at all sites.

Using the conservative estimates of the vertical water velocities of pore water presented in Section 3.2 and the retardation factors presented in Section 3.3, the potential vertical velocity of the contaminant in each HSU is defined in Equation (3) as the vertical velocity of the pore water divided by the retardation factor. The travel time required for a contaminant to migrate through each HSU is defined in Equation (6) as the thickness of the geologic layer divided by the vertical velocity. The cumulative time for a contaminant to pass through an HSU is the individual HSU travel time in addition to the travel time through any higher geologic layer. The vertical velocities and travel times for each site are presented in Table 19.

4.2 Contaminant 1,000-Year Travel Distances

The distance a contaminant will migrate through each HSU is defined as the vertical velocity of the contaminant multiplied by a specified time interval (Equation [5]). The potential travel distances of infiltrating water and the contaminants within the 1,000-year time period are presented in Table 20. Table 19 shows that the calculated travel times to the water table greatly exceed the UGTA 1,000-year regulatory time period.

Table 19
Vertical Velocities and Travel Times

Site HSU	Unsaturated Zone Thickness (m)	Water Velocity (V_w) (mm/yr)	Cumulative Water Travel Time (years)	Uranium Velocity (V_c) (mm/yr)	Cumulative Uranium Travel Time (years)	Plutonium Velocity (V_c) (mm/yr)	Cumulative Plutonium Travel Time (years)
Clean Slate I							
YAA	10.61	5.7	1.86E+03	0.76	1.39E+04	0.38	2.82E+04
OAA	43.12	5.7	9.41E+03	0.76	7.03E+04	0.38	1.43E+05
TMVA	16.45	10.0	1.11E+04	2.52	7.68E+04	0.04	5.90E+05
Clean Slate II							
YAA	23.98	5.7	4.20E+03	0.76	3.14E+04	0.38	6.37E+04
OAA	49.77	5.7	1.29E+04	0.76	9.65E+04	0.38	1.96E+05
VSU_UP	44.91	4.5	2.30E+04	0.02	2.36E+06	0.00	1.83E+08
Clean Slate III							
YAA	26.0	5.7	4.55E+03	0.76	3.40E+04	0.38	6.9E+04
OAA	47.25	5.7	1.28E+04	0.76	9.58E+04	0.38	1.94E+05
VSU_UP	6.48	4.5	1.43E+04	0.02	4.22E+05	0.00	2.66E+07
Double Tracks							
YAA	15.04	5.7	2.64E+03	0.76	1.97E+04	0.38	3.99E+04
OAA	45.68	5.7	1.06E+04	0.76	7.95E+04	0.38	1.61E+05
OVU	44.12	4.3	2.08E+04	0.07	7.20E+05	0.00	5.26E+07
VSU_LOW	18.60	4.5	2.50E+04	0.02	1.66E+06	0.00	1.28E+08
Project 57							
YAA	25.00	5.7	4.38E+03	0.76	3.27E+04	0.38	6.64E+04
OAA	40.84	5.7	1.15E+04	0.76	8.61E+04	0.38	1.75E+05
TCA							
YAA	13.30	14.8	8.99E+02	2.05	6.48E+03	1.01	1.31E+04
OAA	19.91	14.8	2.24E+03	2.05	1.62E+04	1.01	3.27E+04
LFU	47.71	70.3	2.92E+03	1.72	4.40E+04	0.02	2.50E+06
TMVA	115.96	23.8	7.79E+03	6.58	6.16E+04	0.10	3.67E+06
PVA	129.36	25.5	1.29E+04	1.64	1.40E+05	0.02	1.04E+07
WVU	66.21	10.7	1.91E+04	0.19	4.97E+05	0.00	3.96E+07
Buggy							
FCCM	287.52	38.7	7.44E+03	0.19	1.48E+06	0.00	1.20E+08

Table 20
Calculated Water and Solute 1,000-Year Travel Distances

Location	Travel Distance (m)		
	Water	Uranium	Plutonium
Clean Slate I	5.7	0.76	0.38
Clean Slate II	5.7	0.76	0.38
Clean Slate III	5.7	0.76	0.38
Double Tracks	5.7	0.76	0.38
Project 57	5.7	0.76	0.38
TCA	14.8	2.05	1.01
Buggy	38.7	0.19	0.00

5.0 PARAMETER SENSITIVITY

This section evaluates the travel time calculation sensitivity to the most uncertain parameters. The parameters with the most uncertainty are K_d and recharge rate, as K_d is the factor most affecting the retardation rates; the recharge rate is the driver for vertical flow velocities and volumetric water content. The other input parameters do not have as much uncertainty and do not have as much impact to contaminant travel times. Equation (11) illustrates that bulk density is strongly a function of porosity, and variability will be similar to the porosity variability.

5.1 Recharge Rate Travel Time Sensitivity

Equations (4) and (6) illustrate that the water travel time is inversely proportional to the recharge rate and will increase with lower recharge rates. Although this analysis uses the highest estimated recharge rate from the NNSS data, a range of recharge rates are used to demonstrate sensitivity of water travel time to the recharge rate; specifically, a “low,” “base,” and “high” recharge rate are evaluated. The low, base, and high values are the 5th, 50th, and 100th percentile value assuming that the recharge rates have a uniform distribution between the minimum and maximums from the infiltration models at each location (Section 2.0). Table 21 summarizes the water travel time sensitivity to recharge rate. For example, the water travel time to the water table at the Clean Slate I site increases from 11,060 to 221,194 years as the recharge rate is decreased from 1 to 0.05 mm/yr. The travel times do not directly scale to the change in recharge rate because the volumetric water content is a nonlinear function of recharge.

5.2 K_d Parameter Travel Time Sensitivity

Equations (4), (6), and (10) illustrate that the contaminant travel time will increase with larger K_d parameter values. The travel time sensitivity to the K_d parameter is evaluated by using a range of K_d values for uranium and plutonium. Specifically, a “low,” “base,” and “high” mobility cases are evaluated using the conservative recharge rate (highest value from the infiltration models). The base K_d values are the mean of the log K_d distribution, and the low and high values are one log-scale

Table 21
Water Travel Time Sensitivity

Location	Recharge Rate (mm/yr)	Travel Time (years)
		Water Table
Clean Slate I	0.05	1.95E+05
	0.50	2.14E+04
	1.00	1.11E+04
Clean Slate II	0.05	4.00E+05
	0.50	4.45E+04
	1.00	2.30E+04
Clean Slate III	0.05	2.58E+05
	0.50	2.78E+04
	1.00	1.43E+04
Double Tracks	0.05	4.08E+05
	0.50	4.76E+04
	1.00	2.50E+04
Project 57	0.05	2.11E+05
	0.50	2.25E+04
	1.00	1.15E+04
TCA	0.14	2.62E+05
	1.35	3.52E+04
	2.70	1.91E+04
Buggy	0.49	1.26E+05
	4.90	1.44E+04
	9.80	7.44E+03

standard deviation below and above the base K_d values. Table 22 summarizes the transport properties evaluated for each HSU. Table 23 summarizes the travel time and travel distance sensitivity to the K_d parameter.

Table 22
Transport Properties

Site HSU	Bulk Density ρ_b (g/cm^3)	Uranium			Plutonium		
		Mobility K_d (mL/g)[a,b]					
		Low	Base	High	Low	Base	High
Clean Slate I							
YAA	1.46	1.66	0.78	0.36	3.39	1.70	0.85
OAA	1.46	1.66	0.78	0.36	3.39	1.70	0.85
TMVA	2.01	0.28	0.15	0.08	31.62	13.49	5.75
Clean Slate II							
YAA	1.46	1.66	0.78	0.36	3.39	1.70	0.85
OAA	1.46	1.66	0.78	0.36	3.39	1.70	0.85
VSU_UP	2.14	44.67	23.44	12.30	4,466.84	1,905.46	812.83
Clean Slate III							
YAA	1.46	1.66	0.78	0.36	3.39	1.70	0.85
OAA	1.46	1.66	0.78	0.36	3.39	1.70	0.85
VSU_UP	2.14	44.67	23.44	12.30	4,466.84	1,905.46	812.83
Double Tracks							
YAA	1.46	1.66	0.78	0.36	3.39	1.70	0.85
OAA	1.46	1.66	0.78	0.36	3.39	1.70	0.85
OVU	1.80	15.14	7.94	4.17	1,548.82	660.69	281.84
VSU_LOW	2.14	44.67	23.44	12.30	4,466.84	1,905.46	812.83
Project 57							
YAA	1.46	1.66	0.78	0.36	3.39	1.70	0.85
OAA	1.46	1.66	0.78	0.36	3.39	1.70	0.85
TCA							
YAA	1.46	1.66	0.78	0.36	3.39	1.70	0.85
OAA	1.46	1.66	0.78	0.36	3.39	1.70	0.85
LFU[c]	2.43	1.17	0.63	0.34	134.90	57.54	24.55
TMVA	2.01	0.28	0.15	0.08	31.62	13.49	5.75
PVA	1.37	2.09	1.12	0.60	239.88	102.33	43.65
WVU	1.80	15.14	7.94	4.17	1,548.82	660.69	281.84
Buggy							
FCCM	2.14	44.67	23.44	12.30	4,466.84	1,905.46	812.83

[a] Volcanic rock K_d values are from the Rainier Mesa hydrologic source term document, Table 2-14 (Tompson et al., 2011). The alluvium Pu K_d is reduced by a factor of 10 to reflect that 90% of aqueous plutonium is colloid-associated and not truly aqueous as recommended in the Rainier Mesa hydrologic source term document.
[b] The low-mobility case assumes a one log-scale standard deviation increase from the average K_d value. The high-mobility case assumes a one log-scale decrease from the average K_d value.
[c] The K_d values provided for the LFU are from the Rainier Mesa/Shoshone Mountain hydrologic data document (SNJV, 2008).

Table 23
Calculated Water and Solute Travel Times

Location	Mobility Case	Water	Uranium	Plutonium
		Travel Time (years)		
		Water Table	Water Table	Water Table
Clean Slate I	Low	1.11E+04	1.50E+05	1.32E+06
	Base		7.68E+04	5.90E+05
	High		4.22E+04	2.68E+05
Clean Slate II	Low	2.30E+04	4.50E+06	4.30E+08
	Base		2.36E+06	1.83E+08
	High		1.24E+06	7.82E+07
Clean Slate III	Low	1.43E+04	8.11E+05	6.23E+07
	Base		4.22E+05	2.66E+07
	High		2.24E+05	1.14E+07
Double Tracks	Low	2.50E+04	3.15E+06	3.01E+08
	Base		1.66E+06	1.28E+08
	High		8.78E+05	5.48E+07
Project 57	Low	1.15E+04	1.71E+05	3.37E+05
	Base		8.61E+04	1.75E+05
	High		4.64E+04	9.33E+04
TCA	Low	1.91E+04	9.28E+05	9.27E+07
	Base		4.97E+05	3.96E+07
	High		2.71E+05	1.69E+07
Buggy	Low	7.44E+03	2.81E+06	2.80E+08
	Base		1.48E+06	1.20E+08
	High		7.80E+05	5.10E+07

6.0 Summary and Conclusions

An analysis was performed to determine whether residual contamination from the soil sites at CAUs 375, 411, 412, 413, 414, and 415 may impact the regional water resource. The water and contaminant travel time through the unsaturated zone above the water table was calculated using conservative and bounding assumptions.

Assessing the contaminant travel time through the subsurface required estimating the state of the subsurface, including rock stratigraphy, water table depth, volumetric water content, and recharge rate. Direct observations from boreholes at each site were not available, and these data were largely taken from UGTA modeling studies.

The recharge rates used in this study are conservatively estimated to the highest likely from the reviewed data. The estimated water travel time to the water table exceeds 7,000 years at all of the sites evaluated (Table 23). The sorptive processes associated with contaminant transport increase travel times by approximately 1 to 3 orders of magnitude for uranium and 2 to 5 orders of magnitude for plutonium. The calculated travel times greatly exceed the UGTA 1,000-year regulatory time period, indicating that the distance between residual contamination at each of the sites and the water table is sufficient for protecting the water resources below them.

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Mark C. Burmeister Navarro-Intera, LLC P.O. Box 98952, NSF 167 Las Vegas, NV 89193-8518	1 Hard Copy
Patricia L. Gallo Navarro-Intera, LLC P.O. Box 98952, NSF 167 Las Vegas, NV 89193-8518	1 Hard Copy

Raymond L. Kidman Navarro-Intera, LLC P.O. Box 98952, NSF 167 Las Vegas, NV 89193-8518	1 Hard Copy
Mark J. Krauss Navarro-Intera, LLC P.O. Box 98952, NSF 167 Las Vegas, NV 89193-8518	1 Hard Copy
Peter Martian Navarro-Intera, LLC P.O. Box 98952, NSF 167 Las Vegas, NV 89193-8518	1 Hard Copy
Patrick K. Matthews Navarro-Intera, LLC P.O. Box 98952, NSF 167 Las Vegas, NV 89193-8518	1 Hard Copy
Navarro-Intera, LLC Central Files P.O. Box 98952, NSF 156 Las Vegas, NV 89193-8518	1 Hard Copy
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