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An Alternative Process Model of Preferential Contaminant Travel Times in the Unsaturated Zone: Application to Rainier Mesa and Shoshone Mountain, Nevada

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Abstract Simulating contaminant transport in unsaturated zones with sparse hydraulic property information is a difficult, yet common, problem. When contaminant transport may occur via preferential flow, simple modeling approaches can provide predictions of interest, such as the first arrival of contaminant, with minimal site characterization. The conceptual model for unsaturated zone flow at Rainier Mesa and Shoshone Mountain, Nevada National Security Site, establishes the possibility of preferential flow through lithologies between potential radionuclide sources and the saturated zone. After identifying preferential flow as a possible contaminant transport process, we apply a simple model to estimate first arrival times for conservatively transported radionuclides to reach the saturated zone. Simulated preferential flow travel times at Rainier Mesa are tens to hundreds of years for non-ponded water sources and 1 to 2 months for continuously ponded water sources; first arrival times are approximately twice as long at Shoshone Mountain. These first arrival time results should then be viewed as a worst-case scenario but not necessarily as a timescale for a groundwater-contamination hazard, because concentrations may be very low. The alternative approach demonstrated here for estimating travel times can be useful in situations where predictions are needed by managers for the fastest arrival of contaminants, yet budgetary or time constraints preclude more rigorous analysis, and when additional model estimates are needed for comparison (i.e., model abstraction).

Keywords Rainier mesa · Nevada Test Site · Radionuclide · Preferential flow · Fracture · Model abstraction

1 Introduction

Contaminant mobility through thick unsaturated zones within regolith and rock is a common concern for regulatory agencies. Various processes and pathways control downward contaminant transport, leading to a broad distribution of contaminant travel times with slow and fast extremes. The initial detectable arrival of contaminant carries particular regulatory significance for formulating the most conservative hazard-prevention scenarios. While unsaturated flow can occur diffusely through the rock or soil matrix, the initial arrival of a solute can often result from *preferential flow*, which is flow that bypasses portions of the porous media [29]. Preferential flow can be classified as (1) macropore flow, which consists of flow through well-defined pathways such as root channels and fractures, or (2) flow through a fraction of the matrix, typically divided into finger [3, 32, 82] or funnel flow [49, 50].

Preferential flow may transport contaminants at speeds considerably faster than matrix flow [31, 32, 38, 51]. Water-imbibition via capillary processes from preferential paths into the unsaturated matrix [65, 100] has been suggested to make arid and semi-arid environments less susceptible to macropore preferential flow. Some investigations, however, have shown that rapid solute migration via preferential paths can occur without being imbibed into the matrix, even in relatively dry climates [61, 70]. For example, localized recharge fluxes, fracture coatings that minimize imbibition, or subsurface conditions such as a nearly saturated matrix may have an elevated likelihood of contaminant transport via macropore flow.

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The most commonly employed approach for simulating unsaturated travel times is a combination of Richards' equation and the advection–dispersion equation. While this approach for simulating travel times of contaminants in unsaturated porous media has proven valuable, it requires a great deal of subsurface information for both parameterization (e.g., unsaturated hydraulic properties, lithologic geometries, macropore apertures, and macropore connectivities) and evaluation (e.g., saturation, matric potential, and solute concentration data). In cases where it is known or hypothesized that preferential flow is active and the prediction of interest is only the earliest contaminant arrival (and not concentration or flux), the opportunity exists to apply a simple model that minimizes the input information needed.

Here, we first present conceptual flow models for Rainier Mesa and Shoshone Mountain at the Nevada National Security Site (NNSS, formerly the Nevada Test Site) establishing the possibility of preferential flow from radionuclide sources associated with underground nuclear testing to the saturated zone in a carbonate aquifer. We then apply a relatively simple model to estimate the times of initial arrival of conservative radionuclides via preferential flow for an area of complex hydrogeology but limited parameterization and evaluation data. This model differs from more traditional unsaturated-zone models chiefly (1) in its emphasis on flow in preferential pathways as being of critical relevance to the earliest arrival of contaminant at a point of concern and (2) in its reliance on transport characteristics inferred from a large body of observational evidence concerning preferential transport, in general, as opposed to detailed unsaturated hydraulic property determinations. The main product presented here is a means of evaluating the first arrival time of contaminant via preferential unsaturated-zone flow that is useful in hazard assessment, whether basic unsaturated flow properties are quantitatively known or not.

This work expands from the work of Ebel and Nimmo [21] and builds on that previous work by adding independent testing of the Nimmo [64] model. The aim here is to develop a model to serve several purposes in an environmental assessment context, either apart from or supplemental to more traditional models. At the chosen site, independent efforts are in progress to predict the extent of radionuclide transport over 1,000 years by detailed simulation of unsaturated and saturated fluid flow and radionuclide fluxes at nested scales up to regional domains [91]. Purposes served by a simpler, independent model include the following. (1) It can establish preliminary bounds on the plausible ranges of travel times when rough estimates are needed quickly in an early stages of a comprehensive evaluation, or otherwise when an estimate is required in an unsaturated zone that has not been sufficiently characterized for traditional models. (2) It can permit effective model abstraction assessment, which utilizes different models of varying complexity answering the same scientific question at the same site [14, 26, 67], in which the simpler model has the role of augmenting understanding, rather than replacing more complex models [72]. (3) For purposes of accessing predictive uncertainty, it can provide one of the multiple independent alternative models required to evaluate conceptual uncertainties related to structure and process [62, 74].

2 Rainier Mesa and Shoshone Mountain

2.1 Study Site Location and History of Underground Nuclear Testing

The NNSS is located in Nye County, Nevada, United States of America, approximately 140 km northwest of Las Vegas (Fig. 1). The arid to semi-arid climate, deep regional saturated zone, and large surrounding unpopulated area made the NNSS favorable for underground nuclear testing. A total of 828 underground nuclear tests were conducted at the NNSS [16]. This investigation focuses on the Rainier Mesa and Shoshone Mountain Areas shown in Fig. 1. Rainier Mesa hosted 61 underground tests, and Shoshone Mountain hosted six underground tests from 1957–1992 [16]. The tests were conducted in volcanic rocks hundreds of meters above the regional saturated zone, which occurs in carbonate rock [6, 87] and introduced radionuclides into the unsaturated and perched saturated zones. Rainier Mesa and Shoshone Mountain are located within the Death Valley ground-water flow system, which provides water (via wells) for agricultural, livestock, industrial, and domestic use [52]. The transit time of selected radionuclides through the unsaturated zone at the NNSS is of interest to the US Department of Energy and certain regulatory agencies at the State and Federal levels [24].

With the exception of two borehole tests (U-12q and U-12r; see Fig. 2), all the underground nuclear tests at Rainier Mesa and Shoshone Mountain occurred within tunnels [59]. Figure 2 shows the tunnel locations; tunnel summary information is presented in Table 1. Here, the term *tunnel* or *tunnels* is used to denote both individual tunnels and complexes comprised of many connected tunnels. Construction of the six major (U12b, U12g, U12e, U12n, U12t, and U12p) and five minor (U12c, U12d, U12f, U12j, and U12k) tunnels used for nuclear testing occurred from the 1950s into the 1990s (Table 1). Shoshone Mountain underground tests occurred in the U16a tunnel between the 1960s and early 1970s [59]. The locations of the nuclear tests are referred to as working points. A downward tunnel slope from the working points to the tunnel portal facilitates drainage of water out of water-containing tunnel portals (i.e., U12e, U12n, and U12t), with discharge piped into unlined ponds. The location of the U12e, U12n, and U12t

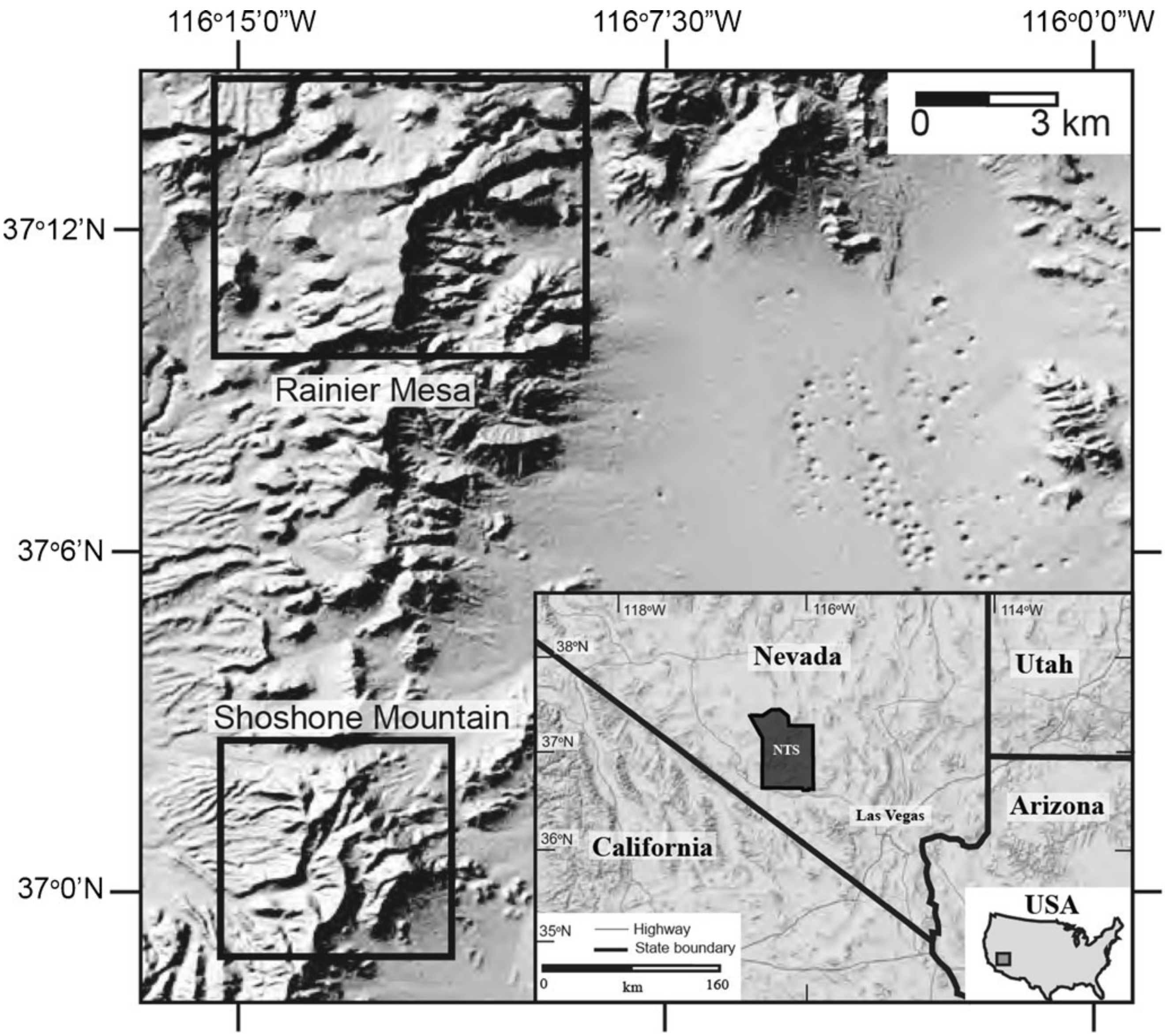

Fig. 1 *Shaded* relief map showing the location of the Nevada Test Site and the locations of Rainier Mesa and Shoshone Mountain

tunnel effluent ponds relative to the tunnel portals are shown in Fig. 3. In terms of conservative transport at Rainier Mesa and Shoshone Mountain, ^{14}C, ^{36}Cl, and ^{3}H are the principal radionuclides [91]; the radiologic source term is described by Smith et al. [85] and Zhao and Zavarin [105]. The distribution of radionuclides in the subsurface is complex, depending on detonation phenomenology [7, 34] and transport includes sorption [106] and colloidal [48] processes.

Residual contamination in the working points is the major radionuclide source at Rainier Mesa and Shoshone Mountain; distances to the saturated zone can be found in Department of Energy [15] and National Nuclear Security Administration [57]. Figure 4 presents a visual summary of potential radionuclide sources and the distances to the saturated zone in the carbonate rock. The observed hydraulic behavior during tunnel construction and modification provides information on the presence and flow behavior of water near the working points. The U12e, U12n, and U12t tunnels all began discharging water from the tunnel walls at the time of construction [59, 79] principally from fractures [79, 95]. Tunnel sealing stopped discharge from the portals for the U12n tunnel in 1994 [79] and the U12t tunnel in 1993. Prior to sealing, water flowed from the U12n and U12t tunnels into a sequence of effluent ponds via pipes (Fig. 3). These two tunnels have slowly filled with water [79]; flooding may enhance downward percolation and increase the connectivity of previously non-communicative fractures [73]. As noted by Stoller-Navarro Joint Venture [91], isolated fracture zones may now be connected by the extensive tunnel system (see Fig. 2) and test-induced fracturing and rubble chimneys from working point collapse [98], possibly creating hydraulic connections between

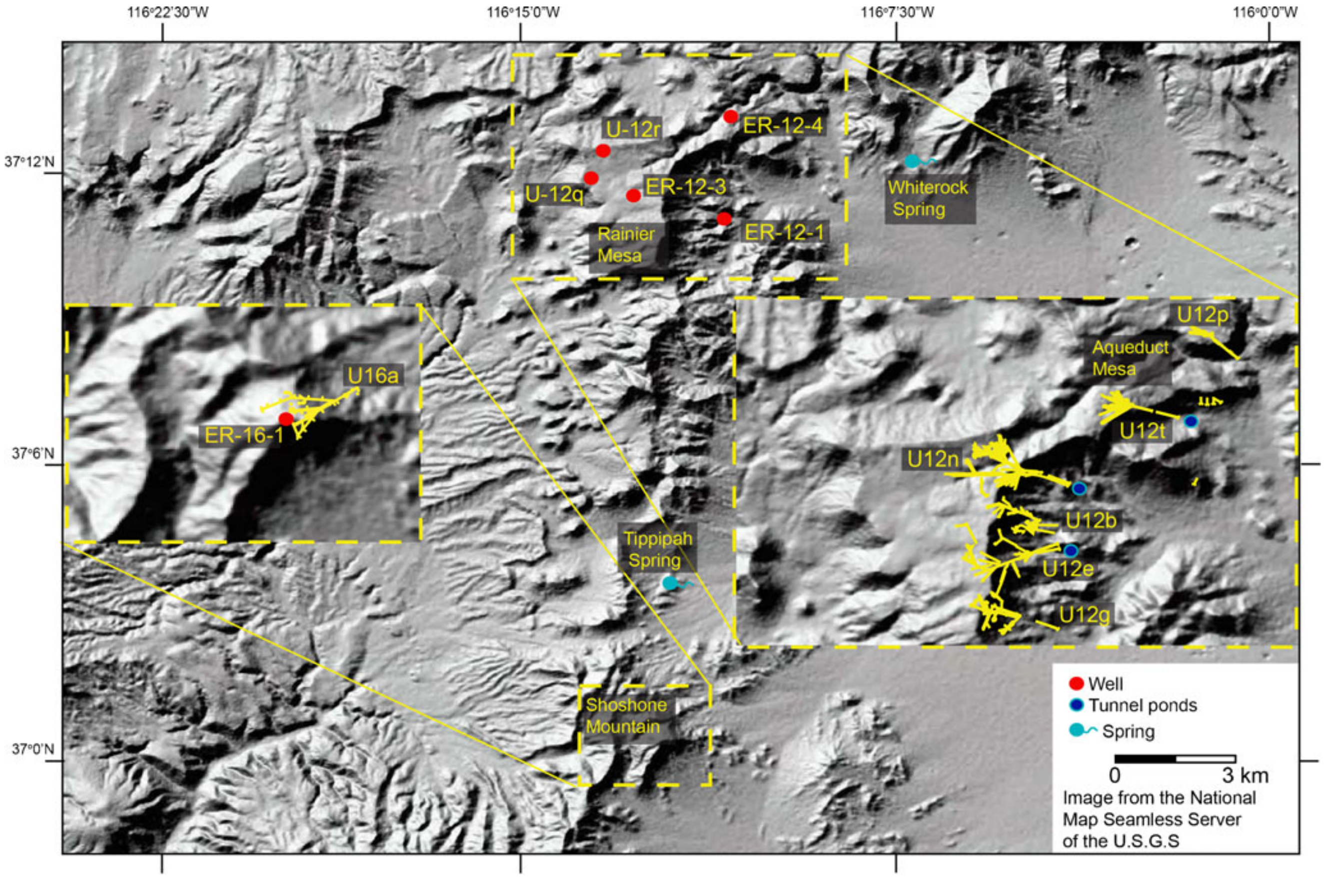

Fig. 2 Map of the major tunnels and selected boreholes at Rainier Mesa and Shoshone Mountain. See, Fenelon et al. [24] for a more complete map of Rainier Mesa boreholes

preferential paths. Attempts to seal the U12e tunnel failed [57], and water currently discharges, via pipes, into a sequence of tunnel effluent ponds (Fig. 3). Table 2 shows the periods of time that water draining through the U12e, U12n, and U12t tunnels and into the associated tunnel ponds was observed to be radionuclide-contaminated during sparse monitoring from 1970 through 1996. Tunnel invert (i.e., floor) seepage also serves as a potential source.

2.2 Potentially Active Flow Processes in the Unsaturated Zone

Flow through the unsaturated subsurface at Rainier Mesa and Shoshone Mountain is considered here as either stable matrix or preferential flow. Stable matrix flow will dominate when paths or conditions for macropore flow are absent, and factors that favor finger and funnel flow are minimal. The presence of fractures in rock at Rainier Mesa and Shoshone Mountain promotes macropore flow in some lithologic units. Finger flow has not been documented at Rainier Mesa or Shoshone Mountain, and the conditions necessary for its persistence [33] across such large travel distances are absent. For example, the heterogeneity of the primarily volcanic rocks likely does not provide the extreme homogeneity required to generate and sustain wetting front instability [5, 33, 101]. Funnel flow at Rainier Mesa and Shoshone Mountain could be promoted by areas of surface and lithologic-contact topography that can concentrate infiltration and subsurface flow but has not been documented at either site. A capillary barrier [40, 92] could be an additional flow-affecting feature at Rainier Mesa and Shoshone Mountain. A permeability barrier may also impede flow at lithologic contacts, where the underlying layer is less permeable and flow is impeded at the interface. The hydraulic conductivity contrast can be either in terms of effective hydraulic conductivity (including preferential paths) or in terms of matrix hydraulic conductivity alone, depending on the preferential path spacing relative to the scale of interest.

2.3 Climate and Groundwater Recharge

The average annual precipitation on the top of Rainier Mesa is 319 mm (record from 1960–2007) with snow constituting less than half of the total [58]. Rainier Mesa is estimated to have some of the highest recharge rates within the arid to semi-arid NNSS, ranging from 10–50 mm year^{-1} [76, 90].

Table 1 Summary of tunnel characteristics at Rainier Mesa and Shoshone Mountain (see Fig. 2)

Tunnel	Dates of construction	Total length (m)	Portal elevation (m)	Lithologic unit	Presence of water	Number of nuclear detonations
Rainier Mesa						
U12a (USGS)	1956	187	1,702	Zeolitic tuff (TB3-4)	None	0
U12b	1956–1963	4,903	2,016	Vitric tuff (Upper GC)	Little	6
U12c	1957–1958	91	2,046	Vitric tuff (lower GC; R/GC)	–	3
U12d	Pre-1958	61	2,050	Vitric tuff (lower GC; R/GC)	–	1
U12e	1957–1977	15,149	1,865	Zeolitic tuff (TB1-4; TS; C)	Yes	9
U12f	Pre-1958	351	2,046	Vitric tuff (lower GC; R/GC)	–	2
U12g	1961–1989	11,667	1,864	Vitric tuff (TB2-4; GC)	Little	5
U12i	1959	760	1,718	Vitric tuff (R/GC)	None	0
U12j	1959	760	1,718	Vitric tuff (R/GC)	None	1
U12k	1959	760	1,718	Vitric tuff (R/GC)	None	1
U12n	1964–1993	25,000	1,840	Zeolitic tuff (TB1-2; GC; TS)	Yes	22
U12p	1962–1984	7,192	1,677	Vitric tuff (R/GC)	None	4
U12t	1968–1988	10,642	1,707	Zeolitic tuff (TB2-4; TS)	Yes	6
Shoshone Mountain						
U16a	1961–1971	1,105	1,649	Zeolitic tuff (TB)	None	6

Information from Diment et al. [18]; Dickey et al. [17]; Thordarson [95]; Fernandez and Freshley [25]; Russell et al. [78], [79]; National Nuclear Security Administration [57]; National Security Technologies, LLC [59]

TB Tunnel Bed, *GC* Grouse Canyon, *R/GC* pre Rainier/post-Grouse Canyon, *TS* tub spring, *C* Paleozoic carbonate

En dash denotes unknown or unmeasured

Maxwell [56] estimated 20 mm year^{-1} of recharge at Rainier Mesa but with a high spatial and temporal variability. Precipitation at Shoshone Mountain was estimated to be 200 mm year^{-1} by Winograd and Thordarson [104] and

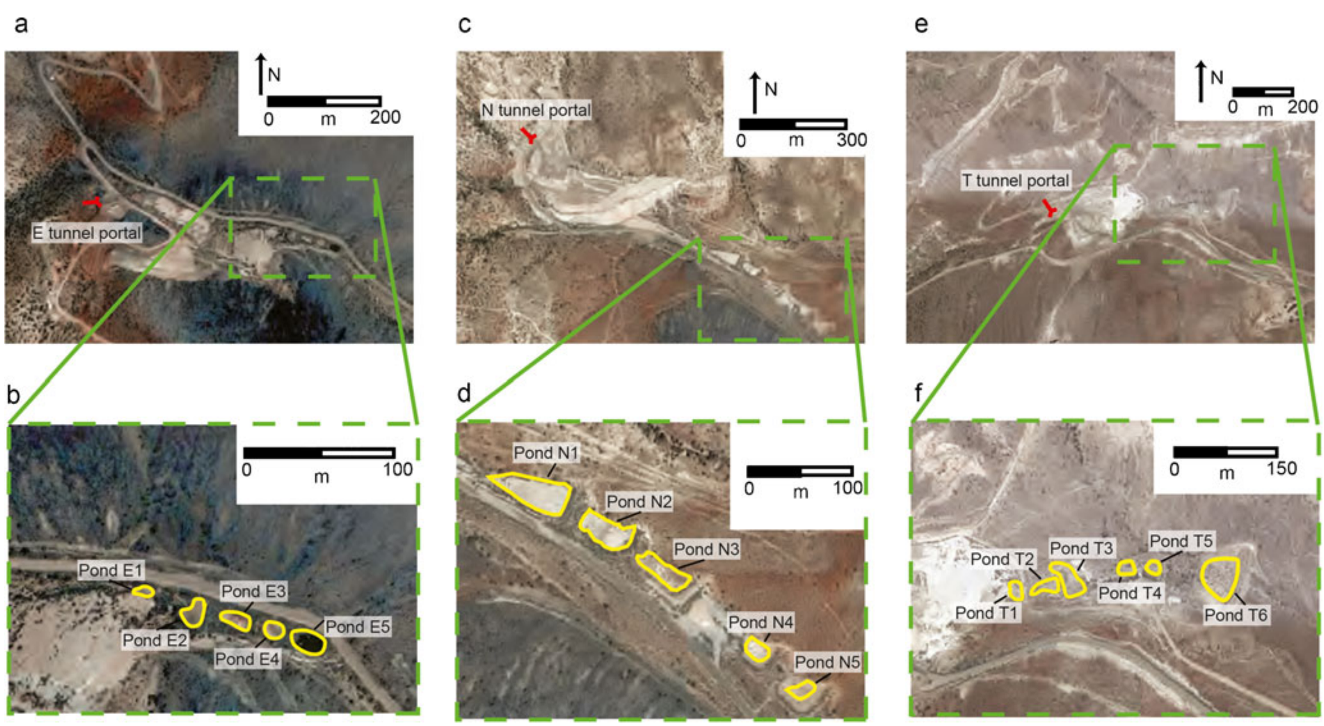

Fig. 3 Satellite images of the Rainier Mesa tunnel effluent ponds **a** U12e tunnel portal, **b** U12e tunnel ponds, **c** U12n tunnel portal, **d** U12n tunnel ponds, **e** U12t tunnel portal, **d** U12t tunnel ponds

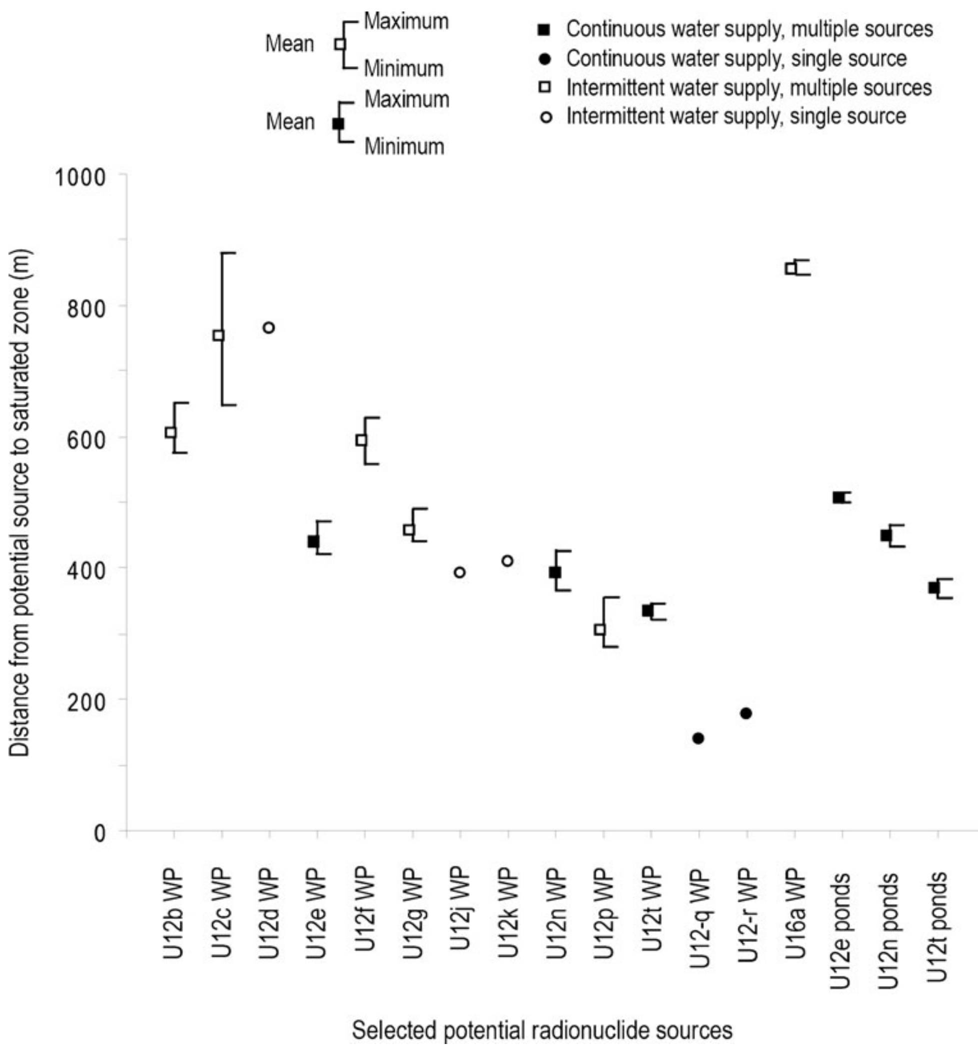

Fig. 4 Distances to the saturated zone in the carbonate rock from selected potential radionuclide sources, including working points (WP) and tunnel effluent ponds (based on information contained in Department of Energy [15]; National Nuclear Security Administration [57]; Fenelon et al. [24]). Potential sources are distinguished into continuous versus intermittent water supply. Multiple sources denote that more than one WP or effluent pond is represented by a point in the figure; single sources have only one WP

Table 2 Summary of observed radionuclide concentrations (in aqueous solution) in potential contamination sources at Rainier Mesa

Concentration					
Source name	Date range	Contaminant	Mean [pCi L^{-1}]	Maximum [pCi L^{-1}]	[pCi L^{-1}]
U12e effluent	1991–1992	^{3}H	-2.0×10^{6a}	–	–
U12e pond	2007	^{3}H	$2.0\times10^{6\ b}$	–	–
U12e pond	1990–1996	Gross beta activity	–	161^{c}	8.1^{c}
U12n pond	1976–1993	^{3}H	2.0×10^{6d}	1.1×10^{7d}	2.2×10^{5d}
U12n pond	1976–1993	Gross beta activity	602^{d}	$6{,}700^{\ d}$	$5.3^{\ d}$
U12t pond	1970–1993	^{3}H	4.0×10^{7d}	3.0×10^{8d}	5.0×10^{4d}
U12t pond	1970–1993	Gross beta activity	9.1×10^{4d}	1.1×10^{6d}	10^{d}

1 pCi equals 0.037 Bq

En dash denotes unknown or unmeasured

[a] Russell et al. [77]

[b] National Security Technologies, LLC [60]

[c] National Nuclear Security Administration [57]

[d] Russell et al. [79]

approximately 265 mm year^{-1} by Hevesi et al. [39]. Russell and Minor [76] estimated that the Shoshone Mountain recharge rates in the tunnel area are on the order of 2–10 mm year^{-1}. There are also topographic differences between Rainier Mesa and Shoshone Mountain that affect groundwater recharge; Rainier Mesa has relatively flat, soil-mantled topography with some convergence into drainages (see Fig. 2) that may enhance infiltration and groundwater recharge, while Shoshone Mountain has steep slopes that probably do not promote groundwater recharge above the U16a tunnel area.

2.4 Rainier Mesa Conceptual Model

Figure 5 shows a simplified lithologic model of Rainier Mesa, based on borehole ER-12-4 (Fig. 2). The non-perched saturated zone beneath Rainier Mesa is in an isolated Paleozoic carbonate aquifer, which is structurally and hydrologically separated from a deeper more regionally extensive carbonate aquifer [24]. A thin layer of argillic paleocolluvium separates the upper carbonate aquifer from overlying zeolitic tuff [95]. A perched zone of saturation or near-saturation occurs within the zeolitic tuff at Rainier Mesa. Vitric tuff (nonwelded and sparsely fractured) and densely welded and fractured tuff overlie the zeolitic tuff. Infiltration measurements [21] suggest that the soils atop Rainier Mesa are permeable and promote infiltration. A depositional syncline that has dips of 2–12° in the limbs greatly affects the thickness of the tuff units across Rainier Mesa [41, 95]. Cooling joints, fractures, and steeply dipping normal faults that trend north–south are typical in the volcanic rocks of Rainier Mesa [37]. Here, the term *fracture* is used to encompass fractures, faults, and joints. A more detailed characterization of the complex three-dimensional unsaturated and saturated transport at Rainier Mesa is presented in National Security Technologies, LLC [59].

Hydraulic properties for the matrix of the lithologic units at Rainier Mesa are summarized in Table 3, and further information can be found in Stoller-Navarro Joint Venture [90]. Large differences in Table 3 for saturated hydraulic conductivity values at the pump test versus lab scale may indicate larger-scale fracture conductivity. Table 3 suggests that the welded tuff, the zeolitic tuff, and the carbonate rock have low matrix permeability but have higher saturated hydraulic conductivity at larger scales where fractures are active. The vitric tuff (the Paintbrush Group) has higher matrix permeability and has been considered to be the only lithology at Rainier Mesa that transmits water primarily by matrix flow [95].

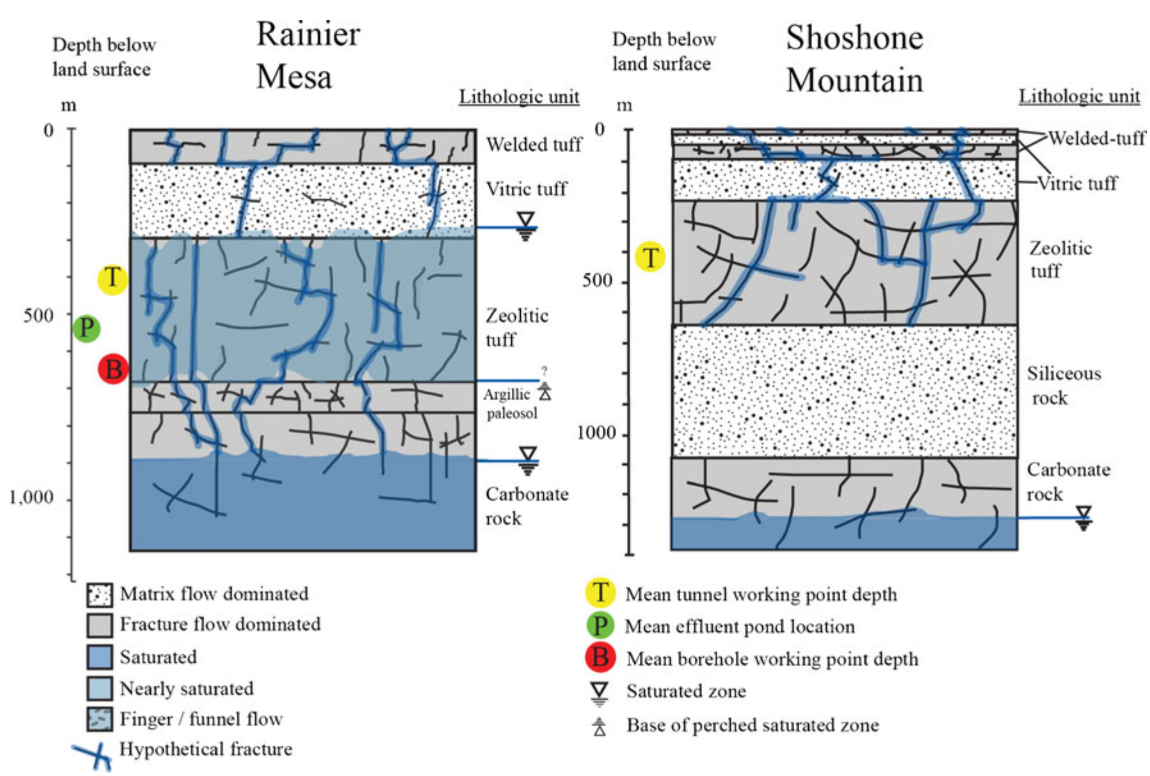

Fig. 5 Conceptual models of unsaturated flow, showing possible preferential flow in fractures, for Rainier Mesa and Shoshone Mountain at the Nevada Test Site, USA. Tunnel and borehole working point depths are to detonation cavity bottoms; the mean depths of working points and effluent ponds are approximate. The fracture geometries, lithologic configurations, and water table locations shown are for schematic purposes

Table 3 Hydraulic properties for the matrix of lithologic units at Rainier Mesa, after Russell [75] with data from Thordarson [95] and National Security Technologies, LLC [59]

Lithologic unit	Matrix property		
	Saturated hydraulic conductivity [$m s^{-1}$]	Porosity [$m^3 m^{-3}$]	Saturation [$m^3 m^{-3}$]
Welded tuff [b]	4.72×10^{-9a}	0.14	–
Vitric tuff [c]	1.75×10^{-6a}	0.40	0.64
Vitric tuff [d]	2.80×10^{-10a}	0.19	–
Zeolitic tuff [e]	9.44×10^{-9a}	0.38	~1.0
Zeolitic tuff [f]	1.40×10^{-9a}	0.35	~1.0
Zeolitic tuff [g]	–	0.32	~1.0
Zeolitic tuff [h]	–	0.25	~1.0
Carbonate rock	$3.30–9.43\times10^{-11a}$	0.04	–
Welded tuff	3.66×10^{-5i}		
Carbonate rock [j]	2.31×10^{-6i} ; $9.0 \text{ x} 10^{-11k}$		

En dash denotes unknown or unmeasured

[a] Saturated hydraulic conductivity based on per meter measurements of core samples [95]

[b] Rainier Mesa tuff

[c] Paintbrush Group

[d] Grouse Canyon tuff member, possibly welded and thus of lower saturated hydraulic conductivity

[e] Tunnel bed 4, tunnel formation

[f] Tunnel bed 3, tunnel formation

[g] Tunnel bed 2, tunnel formation

[h] Tunnel bed 1, tunnel formation

[i] Mean value from pumping tests National Security Technologies, LLC [59]

[j] LCA3 in National Security Technologies, LLC [59]

[k] Mean value from lab scale measurements National Security Technologies, LLC [59]

The conceptual model (Fig. 5) suggests the possibility of limited fracture preferential flow at Rainier Mesa in the vitric tuff but that most flow through the vitric tuff will be stable matrix flow. The occurrence of preferential flow in the vitric tuff at Rainier Mesa is supported by the observations from Clebsch [12] and Clebsch and Barker [13], who reported transport of the elevated ^3H levels from atmospheric nuclear testing taking 1–6 years to travel from the surface to tunnel level (approximately 500 m) at Rainier Mesa, through the welded and vitric tuff.

Table 3 shows the large saturated hydraulic conductivity contrast between the zeolitic tuff matrix and the overlying vitric tuff matrix for the Paintbrush Group, with the zeolitic tuff potentially acting as a permeability barrier to vertical unsaturated matrix flow. A second saturated hydraulic conductivity value given in Table 3 is for the Grouse Canyon tuff, which may be welded and thus far less permeable. Russell [75] suggested that groundwater percolating through the vitric tuff perches on the zeolitic tuff and then drains slowly through fractures in the zeolitic tuff and potentially into the tunnel system. Previous investigations have assumed that macropore preferential flow through fractures is the dominant pathway for downward movement of water in the zeolitic tuff [28, 75, 95]. Observational evidence suggests that there is some lateral hydrologic connectivity between the fractures in the zeolitic tuff. For example, Thordarson [95] noted that breaching a fracture in the U12e tunnel flooded the tunnel and caused the nearby Hagestad 1 well (screened in the zeolitic tuff from 580 to 490 m below land surface; see Fig. 3), which is 30 m from the tunnel, to drop 37 m in 1962.

Water age estimates at Rainier Mesa in the fractures and matrix of the zeolitic tuff, where the majority of nuclear tests were conducted, exist from a variety of techniques, including bacterial ecology [2, 35], stable isotopes [78], isotopes from atmospheric nuclear testing [13, 66], water chemistry [42], and temporal patterns in fracture discharge [18, 42]. These age observations suggest that the residence time of water in the zeolitic tuff matrix is on millennial timescales and the fracture water is much younger, on the order of 1–30 years [20] and may be recharged by modern waters, suggesting fracture connectivity from the zeolitic tuff to the surface.

Nuclear testing has potentially altered flow in the zeolitic tuff and other lithologies in which testing occurred at Rainier Mesa by enhancing fractures. Elevated sulfate concentrations in impounded water behind the U12t tunnel seal [79] could indicate a release of relict water from the matrix into the fractures that discharge into the tunnel, providing possible evidence for this local alteration. Matrix–fracture water exchange may have been enhanced by underground nuclear testing. This enhanced exchange in combination with water-filled tunnels may enable the rerouting of water across large distances through hydrologically connected fractures. Ongoing modeling efforts that simulate fracture flow near the U12t tunnel by Reeves et al. [73] and Parashar and Reeves [68] will shed light on this topic. The present state of knowledge at Rainier Mesa suggests that preferential flow in fractures is a substantial flow process in the zeolitic tuff.

Water may be transmitted via macropore preferential flow in fractures through the zeolitic tuff to the argillic paleocolluvium. National Security Technologies, LLC [59] and Fenelon et al. [24] classify the argillic paleocolluvium as a confining unit, and National Security Technologies, LLC [59] states that the argillized unit typically has greater than 30% clay, suggesting saturated hydraulic conductivity is relatively low. It is unknown if the argillic paleocolluvium is fractured, but, if so, then water may be transferred by macropore preferential flow in fractures between the zeolitic rock and the uppermost carbonate rock. The low saturated hydraulic conductivity of the matrix of the carbonate rock (Table 3) suggests that water may flow through fractures downward to the saturated zone in the carbonate rock under the portions of Rainier Mesa where the majority of testing occurred [78, 95]. Significant lateral flow may also occur above the carbonate rock to the volcanic aquifer to the west and southwest [24], but this does not preclude vertical preferential flow.

2.5 Shoshone Mountain Conceptual Model

Figure 5 also shows a simplified lithologic model of Shoshone Mountain based on the ER-16-1 borehole (see Fig. 2). The saturated zone, which is part of the regional flow system, lies within carbonate. The siliceous rock overlying the carbonate rock is mostly shale [88]. Several hundred meters of zeolitic tuff lie above the siliceous rock. Approximately 100 m of vitric tuff overlie the zeolitic tuff followed by a relatively thin welded tuff unit. Unlike Rainier Mesa, no perched water was observed during tunnel construction [57], which may result from recharge being less at this location, such that groundwater drains laterally and vertically at a rate greater than upgradient supply by recharge. Little hydraulic-property information is available for the lithologic units at Shoshone Mountain, but the properties can be approximated from the similar lithologic units at Rainier Mesa shown in Table 3.

The conceptual flow model for Shoshone Mountain is similar to that of Rainier Mesa, although the upper carbonate aquifer (i.e., the carbonate rock at Rainier Mesa) is absent at Shoshone Mountain, where the carbonate rock shown is the lower carbonate aquifer. Based on this conceptual model, preferential flow may be active in the welded tuff, zeolitic tuff, and carbonate rock. Stable matrix flow dominates in the vitric tuff and siliceous rock, with a small probability of preferential flow in these units. Percolation through the welded tuff at Shoshone Mountain probably occurs as preferential flow though fractures [88], similar to the welded tuff at Rainier Mesa. The lithologic boundary between the welded and vitric tuff at Shoshone Mountain appears similar to the same lithologic boundary at Rainier Mesa, and therefore the same unsaturated flow processes would prevail. The conceptual flow model shown in Fig. 5 considers preferential flow via fractures at Shoshone Mountain to be possible, but steady matrix flow is the dominant flow process. The possibility of preferential flow through faults and fractures in the vitric tuff is suggested by the observation from Sweetkind and Drake [93] that faults are more numerous and have larger displacements than at Rainier Mesa, although faults may be filled with fault gouge, reducing the permeability, possibly to the point of rendering the faults inoperable as macropore preferential flow paths.

The lithologic transition from the vitric tuff to the zeolitic tuff at Shoshone Mountain may have less permeability contrast than the same interface at Rainier Mesa as a result of more intense fracturing [93], which may explain why no perched saturated zone is evident at Shoshone Mountain, although reduced recharge is also a possible explanation. Macropore preferential flow in fractures through the zeolitic tuff is possible through this unit, as at Rainier Mesa. Groundwater percolates through the zeolitic tuff at Shoshone Mountain and reaches the interface defined by the contact with the siliceous rock. The fine-grained siliceous rock, comprised primarily of shale, has low effective porosity and minimal open fracturing [52, 104]. The siliceous rock was originally thought to act as a permeability barrier to vertical flow, possibly forming a perched saturated zone at the top of the shale [88], but the ER-16-1 well at Shoshone Mountain demonstrated no perched water at this interface below the U16a tunnel. Flow through the siliceous rock is stable and matrix-dominated, with macropore preferential flow considered improbable as shown in Fig. 5, based on the limited degree of fracturing and the improbability of fingered flow persisting through the several-hundred-meter thickness of the siliceous rock. The carbonate rock below the siliceous rock is fractured and has relatively low matrix permeability [52, 104], making it likely that some macropore preferential flow occurs through fractures, as water percolates downward to the saturated zone.

2.6 Likelihood of Preferential Flow at Rainier Mesa and Shoshone Mountain

Preferential flow must occur for the source-responsive preferential-flow (SRPF) model to be appropriate for estimating unsaturated-zone travel times at Rainier Mesa and Shoshone Mountain. At Rainier Mesa, it is probable that preferential flow occurs in all of the lithologic layers shown in Fig. 5, with the possible exception of the vitric tuff [78, 95]. Flow through Shoshone Mountain could be preferential throughout all the lithologies shown in Fig. 5 with the possible exception of the vitric tuff and the siliceous rock [88]. Most underground testing at Rainier Mesa and Shoshone Mountain was conducted in the zeolitic tuff, which is stratigraphically below the vitric tuff. Therefore, the downward transport of radionuclides from the majority of the working points, tunnel inverts, and effluent ponds at Rainier Mesa occurs in lithologies with possible preferential flow via fractures [95]. The same may be true for radionuclide transport at Shoshone Mountain but with the possibility that significant preferential flow may not occur through the layer of siliceous rock.

3 Source-Responsive Preferential-Flow Model

Analysis of data from 64 diverse field tests in the unsaturated zone with measured velocities of first arrival of solutes, $V_{FA,}$ by Nimmo [64] suggested that an unusually simple mathematical model can provide an estimate of the time of initial solute breakthrough where flow is predominately preferential. Figure 6 shows simulated versus measured V_{FA} for the 64 selected cases; sites of these tracer tests have a wide spectrum of porous media from fractured rocks to soils, climates ranging from arid to humid, and transport distances ranging over nearly four orders of magnitude to a maximum of 1,300 m. Note that no measured or simulated V_{FA} values from Rainier Mesa or Shoshone Mountain are included in Fig. 6. The spread about the 1:1 line of simulated versus measured fastest V_{FA} illustrates the approximate factor-of-ten agreement between simulated and observed V_{FA} for the Nimmo [64] approach.

The paradigm used in the travel time model by Nimmo [64] is that the primary control on preferential flow travel times is whether water supply to preferential paths is temporally continuous or intermittent, rather than soil-hydraulic properties. The first-arrival times correlate strongly with the nature of the water supply but not with the particular earth materials involved [64]. This model is described here as a SRPF model to emphasize the sensitivity to the temporal nature of the source of water to the preferential flow system. The SRPF model does not distinguish between different mechanisms of preferential flow. Numerous other studies also suggest that the development of preferential flow depends on the rate of water supply to preferential paths (i.e., a source-responsive paradigm). For example, higher rates of applied water flux at the surface increased the prevalence of preferential flow in studies by Gjettermann et al. [30] and Kasteel [46]; ponded water at the surface increased preferential flow, relative to non-ponded water application, in the work by Hamdi et al. [36], Flury et al. [27], and Scanlon and Goldsmith [80].

3.1 SRPF Model Output

The SRPF model estimates the first detectable arrival time of solute, which necessarily is shorter than the average travel time of the main bulk of transported material. It does not provide water or contaminant fluxes and therefore does not predict concentrations at the point of arrival. If there is a broad spread of travel times, the average travel time would be much longer, and substantially more time would elapse before enough contaminant has been transported to raise concentrations to a given level of significance (e.g., a drinking-water standard). The SRPF results should then be viewed as a worst-case scenario for the first arrival of a contaminant but not necessarily as a timescale for a groundwater-contamination hazard.

The SRPF model's quantitative output, used here to estimate radionuclide travel times, is an estimate of first

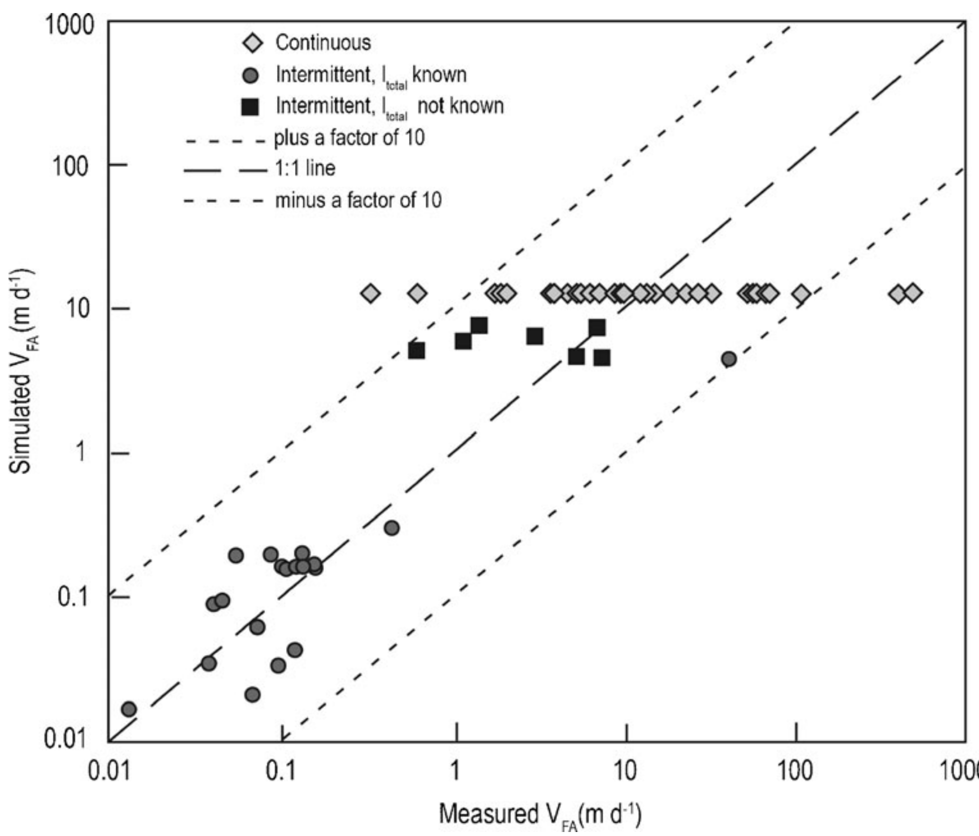

Fig. 6 Simulated versus measured velocity of initial arrival of solute via unsaturated zone preferential flow (V_{FA}) for the 64 selected tracer tests analyzed by Nimmo [64] demonstrating the factor-of-ten bounds of agreement for fastest travel-time estimates and the distinction between continuous and intermittent water-supply made by the Source Responsive Preferential Flow (SRPF) model (after Fig. 2 in Nimmo [64]). Note that this figure is for explaining the SRPF model origins and no Rainier Mesa or Shoshone Mountain data or transport speed estimates are included in this figure

arrival time t_t [T] (based on the transport velocity of the first physically detectable amount of solute, V_{FA} [LT^{-1}]) and is calculated as

$$t_t = \frac{D_{transport}}{V_{FA}}, \tag{1}$$

where $D_{transport}$ is the distance of solute transport. Two separate formulas described in the following sections provide estimates of first contaminant arrival velocities, depending on whether preferential flow supply is continuous in time or intermittent.

For the case of continuous water supply to preferential flow paths, typically as infiltration of ponded water, the velocity of the initial arrival of contaminant, V_{FA}, is estimated to equal V_0=13 m day^{-1}, the geometric mean of the measured V_{FA} for the 34 continuous-supply cases examined by Nimmo [64]. Then the SRPF-estimated travel time for continuous supply is

$$t_t = \frac{D_{transport}}{V_o} \tag{2}$$

For the case of intermittent water supply to preferential paths (e.g., natural precipitation), estimation of preferential travel times requires additional assumptions. The V_{FA} for intermittent water supply is estimated in the SRPF model by assuming that the preferential solute transport is pulsed in an *on–off* mode, with a constant tracer velocity of V_0 when *on* and zero when *off*. In the simplest situation of known *on* and *off* times, as when observed ponded and nonponded states alternate at the land surface, the total duration t_p [T] of pulsed input can be calculated. Given the total duration of the transport process, t_f [T], the effective V_{FA} over that period is

$$V_{FA} = V_o\left[\frac{t_p}{t_f}\right] \tag{3}$$

For natural precipitation or other inputs supplied at irregular rates, if one considered the total *on* time to be the time during which the input rate was measurably nonzero, it would overestimate V_{FA} because low rates presumably would not always support preferential flow. Typically, information is available on the average rate of water supply over time, i_{avg} [LT^{-1}], for example average annual precipitation. To apply the model in such cases, a universal effective rate, i_0 [LT^{-1}], is hypothesized. Apportioning the total amount of precipitation into effective *on* pulses during which the input rate is consistently i_0 gives a more realistic estimate of preferentially active *on* time. The cumulative duration of all such hypothetical pulses within the total time t_f is

$$t_p = \frac{t_f i_{avg}}{i_0} \tag{4}$$

Over the long-term, the transport speed of the first detectable solute parcel is

$$V_{FA} = V_0\frac{i_{avg}}{i_0}, \tag{5}$$

giving a total travel time over distance $D_{transport}$ of

$$t_t = \frac{i_0 D_{transport}}{i_{avg} V_0}, \tag{6}$$

for the intermittent case with i_{avg} known.

Nimmo [64] estimated i_0 by optimizing its value for minimum deviation of computed from measured V_{FA}. The optimized i_0 is 0.73 m day^{-1} (30 mm hour^{-1}) based on the 23 examined intermittent supply cases where average input rate is known.

3.2 Site-Specific Implementation of the SRPF Model

In cases where the precise character of the water supply at the source of contamination is not known, we have applied the SRPF model for two plausible bracketing scenarios representing the fast-extreme case (continuous supply) and the slow-extreme case (intermittent supply). The continuous-supply scenario construes the source as perched water available at the point of contamination. Its adoption also implies the existence of a continuously operating preferential flow path between that perched water and the carbonate aquifer. The intermittent-supply scenario construes the source as deriving from precipitation at the land surface as if it were transmitted to the point of contamination and through the rest of the unsaturated zone as intermittent percolation. That is, taking i_{avg} in Eq. 6 to equal average annual precipitation. The intermittent-supply SRPF calculations are based on the assumptions that natural rainfall is the only source of water, that it is not supplemented by streamflow or runoff, and that the intermittency is unchanged in time by passage through working points and tunnels. SRPF model calculations use Eqs. 2 or 6 as appropriate, with V_0=13 m day^{-1} and i_0= 0.73 m day^{-1} as estimated by Nimmo [64]. The scales and the general types of media in Rainier Mesa and Shoshone Mountain initial contaminant arrival problems have significant representation in the model-development data set used by Nimmo [64], so the use of these parameter values is appropriate.

Travel-time estimates for both continuous and intermittent water supply, as appropriate, are calculated for the different types of contaminant sources at Rainier Mesa and Shoshone Mountain: working points, tunnel inverts, and ponds. The known positions of these and the known depth of the carbonate-aquifer water table lead to values of $D_{transport}$. The inclusion of the test cavity radius in the working point distances to the saturated zone in the carbonate rock makes the minimum travel time in some cases slightly less for the working points than for the invert. The i_{avg} value used in Eq. 6 for intermittent infiltration is the average annual precipitation—319 mm year^{-1} at Rainier Mesa and 200 mm year^{-1} at Shoshone Mountain.

4 SRPF Travel-Time Results

Figure 7 presents the SRPF travel-time estimates for potential radionuclide sources at Rainier Mesa and Shoshone Mountain. Error bars indicate the factor-of-ten uncertainty of individual SRPF model travel-time estimates.

4.1 First-Arrival Estimates for Rainier Mesa Working Points and Tunnel Inverts—Fast-Extreme

The working point travel times from the SRPF model suggest preferential radionuclide transmission to the saturated zone in the carbonate rock, on the order of 1 month (0.08 years) for the U12e, U12n, and U12t tunnel working points, if the preferential paths are continuously supplied (see Fig. 7). For borehole working points, the U-12q test travel times are 11 days for continuous water supply; the U-12r test travel times are 14 days for continuous water supply (see Fig. 7). Fenelon [23] noted that the U-12q borehole filled with water immediately after construction but that the current water level in the U-12q borehole is unknown because the test damaged the borehole. The U-12r borehole is emplaced in a low hydraulic conductivity confining unit (Randy Laczniak, personal communication, 2008) that may significantly impede advective solute transport.

The U12e tunnel currently has continuous water discharge, and the U12n and U12t tunnels had continuous discharge until they were sealed and flooded. Thus, it is plausible that continuously flowing water along inverts or flooded tunnels can be treated as continuous supply to preferential paths. The transport distance for the tunnel inverts is based on the elevation at the tunnel portal; the mean invert location is higher than the portal, which results in a shorter (i.e., worst case) transport distance and SRPF model travel time. The estimated fastest travel times to the saturated zone for the Rainier Mesa U12e, U12n, and U12t tunnel inverts suggest that after sealing and flooding, the fastest traveling water reached the saturated zone in the carbonate rock in approximately 1 month (see Fig. 7).

4.2 First-Arrival Estimates for Rainier Mesa Working Points and Tunnel Inverts—Slow-Extreme

The U12a, U12b, U12c, U12d, U12f, U12g, U12i, U12j, U12k, and U12p tunnels have little or no drainage outside the portal and, therefore, no tunnel effluent ponds; this

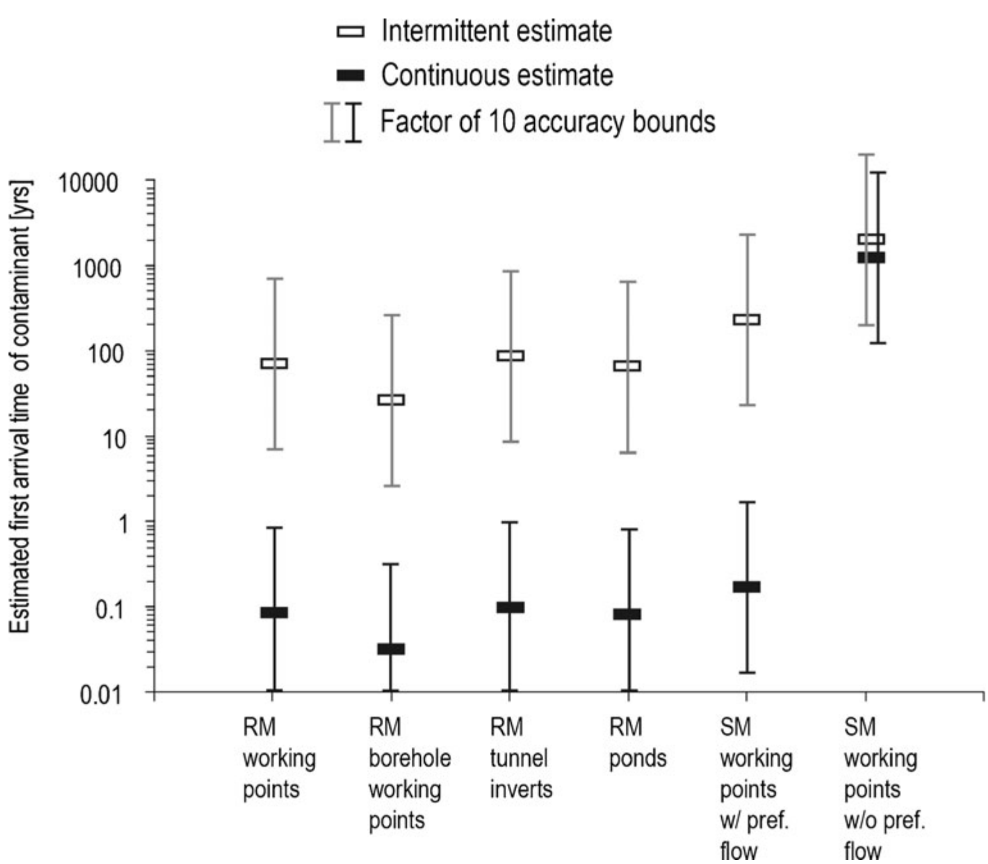

Fig. 7 Range of unsaturated first arrival time estimates for Rainier Mesa and Shoshone Mountain using a source-responsive preferential flow (SRPF) model [64] for continuous and intermittent water supply. The Shoshone Mountain travel-time estimates are given for the cases with and without preferential flow in the siliceous rock. The *bracketed lines* provide uncertainty estimates based on the approximate factor-of-ten agreement of the SRPF model

suggests intermittent water discharge and use of Eq. 6. The U12a and U12i tunnels have no working points and, therefore, are not considered potential sources of radionuclide contamination. Further information regarding the number of tests in each tunnel is given in Table 1. The working point travel times and summary statistics of travel times from the SRPF model for intermittent water supply suggest initial conservative radionuclide arrivals to the carbonate aquifer at timescales on the order of 35 to 155 years for these tunnel working points (see Fig. 7). The estimated fastest travel times to the saturated zone shown in Fig. 7 for these tunnel inverts are similar to the working points, ranging from 70 to 120 years (see Fig. 7).

4.3 First-Arrival Estimates for Rainier Mesa Tunnel Ponds

The U12e, U12n, and U12t tunnel ponds are potential continuously supplied sources of water to preferential flow paths when filled and an intermittently supplied source when considered over long time periods that include empty intervals. Discharge from the U12n tunnel stopped upon sealing in 1994 [79] and is the same for the U12t tunnel in 1993, which ended continuous water supply to the U12n and U12t ponds. It is unknown whether all the ponds contained water simultaneously prior to tunnel sealing, but the tunnel discharge history suggests that at least some of the U12n and U12t ponds contained effluent until tunnel sealing while at least some of the U12e tunnel ponds consistently contain water at the present time. After sealing, intermittent travel times would apply for the U12n and U12t tunnel ponds. The estimated travel times for continuous supply from U12e, U12n, and U12t tunnel ponds are about 0.09 years (1 month) and for intermittent supply are considerably longer, on the order of 60 to 90 years.

4.4 First-Arrival Estimates for the Shoshone Mountain Working Points and Tunnel Invert

The U16a tunnel has no recorded drainage in tunnel inverts, and any tunnel discharge that may have occurred is assumed to be intermittent in space and time; therefore, the intermittent supply equation from the SRPF model would apply. Estimated fastest travel times are 240 years for the U16a tunnel working points (see Fig. 7) and 250 years for the U16a tunnel invert at Shoshone Mountain.

4.5 Possible Non-preferential Flow at Shoshone Mountain

If through-flowing preferential flow paths are absent from one or more of the lithologies beneath the contaminant sources, then the estimated fastest travel times presented above will be too short. An estimate of the tracer velocity v for steady, matrix-dominated flow can be approximated using

$$v = \frac{i}{\theta} \tag{7}$$

where i is the input rate [L T^{-1}] and θ is the soil-water content [L^{3}L^{-3}] within the porous medium.

At Shoshone Mountain, the low-permeability, unfractured siliceous rock [88] could inhibit preferential flow. The flux and water content at the top of the siliceous rock is unknown, although the estimated recharge rate can be used as a flux estimate if steady flow is assumed. Using Eq. 7 with θ of 0.03 m^{3}m^{-3}, which is a saturation of 0.5 based on a 0.06 m^{3}m^{-3} porosity [69, 94], and a flux estimate of 9 mmyear^{-1}, which is the mean of the recharge estimates from Shoshone Mountain (2 to 16 mmyear^{-1}), provides a contaminant velocity estimate of 0.3 myear^{-1}. The travel time through the 450 m of siliceous rock [88] can be calculated using Eq. 1 to give 1,500 years. Using the mean distance from the Shoshone Mountain working points to the saturated zone in the carbonate rock, preferential flow through the 400 m that is non-siliceous rock takes approximately 100 years, based on the intermittent-supply fastest travel-time estimates from the SRPF model, giving a total average travel time from the U16a working points of approximately 1,600 years. This estimate shows the profound influence that interruptions of preferential pathways have on travel times.

5 Discussion

5.1 Important Features of the SRPF Model

Rate-affecting quantities like the acceleration of gravity and the viscosity of water are implicit in the formulation of the SRPF model, and specific porous media properties do not enter explicitly into the V_{FA} calculation. De-emphasizing the porous media properties in the actual calculation of travel time is advantageous in unsaturated zones like those of Rainier Mesa and Shoshone Mountain, where the basic lithologic character is known but few measurements of unsaturated hydraulic properties exist.

The constant value for V_0 may seem to be an oversimplification, but there are physical reasons that support a possible minimal variability of velocity defined in this way, such as the first arrival velocity being sensitive to only the fastest path and the gravity-dominated nature of preferential flow, where gravity is a constant. The velocity dependence of frictional and viscous forces (retarding force increasing as velocity increases) limits the possible variation of transport. Bulk liquid that moves downward in a mostly air-filled conduit, like drops running down a fracture face, also can have relatively little velocity variation. If at a later time, additional data and information become available to support adjustments concerning the value or universality of V_0, such modifications are desirable. In the meantime, the approximation from Nimmo [64] used here can provide order-of-magnitude agreement.

For the case of intermittent supply derived from precipitation, the SRPF model utilizes precipitation rate where, at first glance, recharge rate estimates (accounting for runoff or evapotranspiration) might be considered more directly appropriate. Nimmo [64] formulated the original model this way because in most cases precipitation rates are known but infiltration or recharge rates are not. Therefore, precipitation rate was used as i_{avg} in SRPF model development, as it must be for use with the present calibrated value of i_o. The fact that only a fraction of annual precipitation moves deep in the unsaturated zone as recharge is already accounted for by the relatively large i_o value of Nimmo [64]. For use with actual recharge estimates instead of precipitation, the value of i_o could be reduced by multiplying by the recharge-to-precipitation ratio.

The development of the SRPF model by Nimmo [64] is an example of the "downward" or data-driven approach [83, 84], where a conceptual model of the problem is developed at a level consistent with the prediction of interest and the quantity and quality of parameterization and evaluation data. This frequently leads to a simple model with minimum data requirements. It contrasts with the traditional "upward" approach [43, 47] with highly complex models, for example, Richards' equation and the advection–dispersion equation, used to predict unsaturated solute transport. Both upward and downward modeling protocols are valuable in hydrologic science and management; upward models generally require much input data and tend toward predictions of "everything, everywhere" while downward models require less data and computation and can serve specific purposes. The application of the downward approach using the SRPF model at Rainier Mesa and Shoshone Mountain shows it can contribute to the suite of models used to ask and answer difficult questions regarding environmental problems, particularly in the context of model abstraction and in-depth uncertainty analysis [62, 67].

5.2 Examination of SRPF Results in Tuff Lithology

One way to assess of the appropriateness of the SRPF model for estimating the first contaminant arrival time at Rainier Mesa and Shoshone Mountain is to examine the SRPF model performance in similar lithologies. Among the 64 tracer tests considered by Nimmo [64], both Apache Leap, Arizona, and Yucca Mountain, Nevada, have tuff lithologies. For the six continuous-supply tracer tests in tuffs, the geometric mean of the observed V_{FA} is 12.3 $\mathrm{m\,day^{-1}}$, which is almost the same as the V_0 determined by Nimmo [64] from the 34 continuous supply examples. For the intermittent supply, examples in tuff lithologies (at Apache Leap and Yucca Mountain), using appropriate site-specific parameters for i_{avg}, the SRPF estimated V_{FA} for Yucca Mountain is $8.3\times10^{-3}\,\mathrm{m\,day^{-1}}$ and for Apache Leap is $1.8\times10^{-2}\,\mathrm{m\,day^{-1}}$; the observed V_{FA} values for Yucca Mountain are $3.0\times10^{-2}\,\mathrm{m\,day^{-1}}$, $6.0\times10^{-3}\,\mathrm{m\,day^{-1}}$, and $4.0\times10^{-3}\,\mathrm{m\,day^{-1}}$, and for Apache Leap is $1.0\times10^{-2}\,\mathrm{m\,day^{-1}}$ (see Nimmo [64] for further details on these tracer observations). The aforementioned tracer tests in tuff lithologies suggest that the Nimmo [64] model provides relatively accurate estimates of V_{FA} in tuff lithologies, such as those present at Rainier Mesa and Shoshone Mountain.

5.3 Additional Independent Testing of the SRPF Model

To test the first arrival times estimated by the Nimmo [64] model beyond the 64 cases of observed first arrival times of solute used in the original SRPF model development, we collected (from the literature) first-observed arrival times from 48 additional tracer tests. These tests, some with multiple tests and locations per study, are all cases where solute transport occurs in the unsaturated zone and preferential flow was identified as responsible for a rapid initial arrival of tracer [1, 4, 8–11, 19, 22, 55, 63, 81, 96, 97, 99, 101–103]. The geometric mean of the observed V_{FA} from the 46 continuous cases is 12.7 $\mathrm{m\,day^{-1}}$, which is close to the 13 $\mathrm{m\,day^{-1}}$ estimated by Nimmo [64] in model development. Figure 8 shows the approximate order-of-magnitude agreement between the simulated and observed V_{FA} for the independent testing data set. While there are only two test cases for intermittent supply, these two V_{FA} values lie close to the 1:1 line of agreement between simulated and observed. This additional testing provides additional support for the suitability of the Nimmo [64] model.

5.4 Comparisons Against Radionuclide Observations at Rainier Mesa and Shoshone Mountain

Instrumentation to detect preferential solute transport from tunnel or working point level to the carbonate aquifer at Rainier Mesa and Shoshone Mountain is sparse, and few data are available. Annual to multiannual monitoring at the Rainier Mesa wells ER-12-3 (near the U12e and U12n tunnel working points), and ER-12-4 (near the U12t tunnel working points), sampling the carbonate aquifer, has not detected radionuclides above NNSS background levels [6, 87]. Given the finite detection limits (about 330 $\mathrm{pCiL^{-1}}$; [90]) and the great degree of dilution that is likely for any contaminants that enter the carbonate aquifer, these data do not rule out preferential radionuclide transport through the unsaturated zone at the timescales estimated in this study.

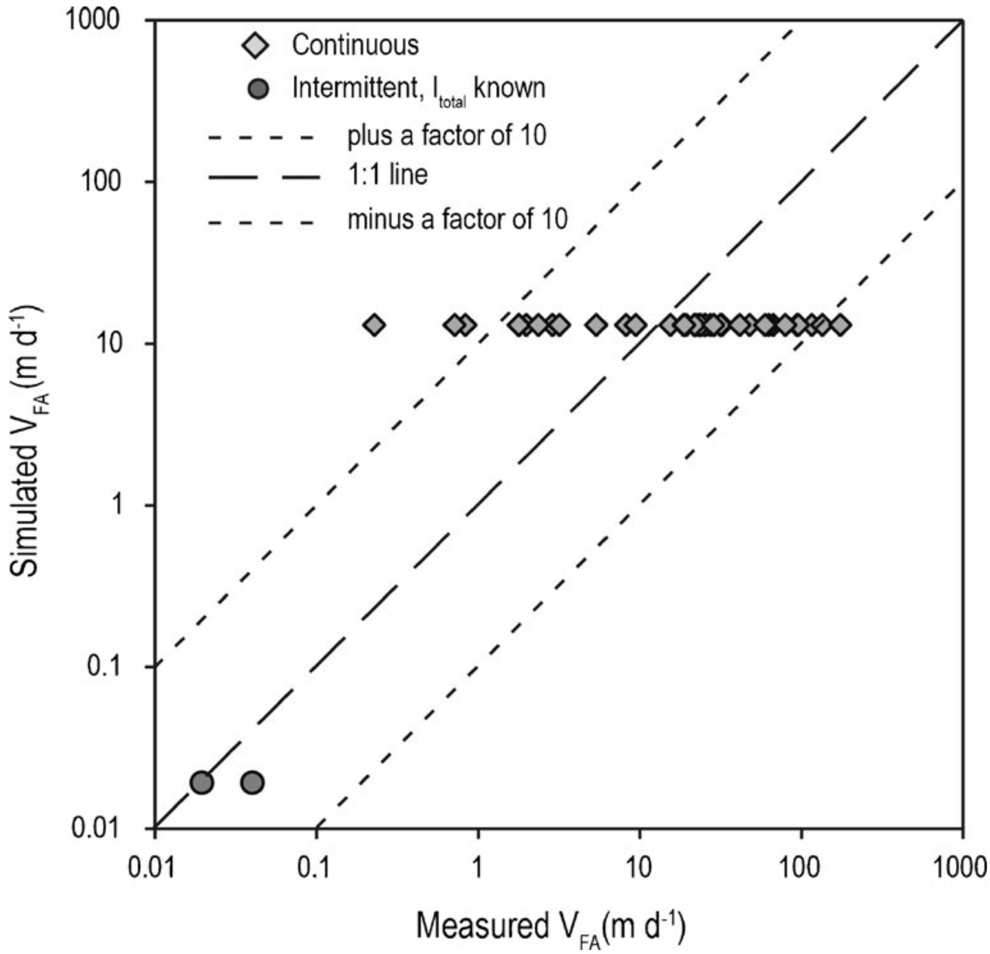

Fig. 8 Simulated versus measured velocity of initial arrival of solute via unsaturated zone preferential flow (V_{FA}) for the 48 selected tracer tests analyzed to test the SRPF approach using data which are independent of those used for model development by Nimmo [64]

Some geochemical data indicates that vertical flow occurs through the volcanic rocks into the carbonate rock. Lawrence Livermore National Laboratory [53, 54] analyzed Cl and Sr concentrations and ^{36}Cl/Cl and ^{87}Sr/^{86}Sr ratios and δ^{87}Sr from well ER-12-4 (see Fig. 2) in the carbonate aquifer, and the results suggested a contribution from the overlying perched volcanic waters [89], thus implying a vertical flux. Groundwater samples from ER-12-4 analyzed for major ions and stable isotopes (i.e., δ^{18}O and δD) suggest the carbonate aquifer water is a mixture of carbonate and volcanic rock sources, suggesting some vertical flow into the carbonates at Rainier Mesa

At Shoshone Mountain, neither well ER-16-1 nor Tippipah Spring has radionuclide concentrations above background NNSS levels [57, 88]. Groundwater recharge at Shoshone Mountain into perched or semi-perched zones, not necessarily from the vicinity of the U16a tunnel, is assumed to be the source of the discharge at Tippipah Spring [44, 45, 86, 104]. Tippipah Spring is at 1,585 m elevation, approximately 70 m below the working points in U16a, although not in close proximity (see Fig. 2). It may be the case, as suggested here, that the siliceous rock at Shoshone Mountain does not support substantial preferential flow, and therefore, the timescale for detecting aquifer contamination may be on the order of 1,600 years. Monitoring contaminants in wells at subsurface positions carefully targeted to locations of preferential flow would allow more thorough testing of travel-time estimates. Fastest travel-time estimates assume conservative contaminant behavior, an important distinction at locations like Rainier Mesa and Shoshone Mountain where non-conservative radionuclides may strongly sorb to zeolitized tuffs. This assumption is probably valid for certain radionuclides (i.e., ^{3}H, ^{36}Cl, and ^{14}C).

5.5 Implications for Travel-Time Estimation in Undercharacterized Unsaturated Zones

In unsaturated zones of significant thickness or complexity, the typical situation is that far fewer data are available than are needed for precise quantification of travel times with an unsaturated-zone flow model. For example, rigorous application of Richards' equation requires quantitative characterization of extremely heterogeneous unsaturated hydraulic properties and hydrogeologic features. In general, estimates may be possible only in terms of broad ranges. In arid regions, travel times may be extremely long if determined by minimal subsurface wetness and a lack of preferential flow and may be short if preferential flow possibilities arise from temporal and spatial concentrations of water flow [71]. The SRPF model has the strong advantage of not requiring site-specific unsaturated hydraulic properties, the general character of gravity-driven preferential flow in earth materials being already implicitly incorporated. The obvious cost of this simplicity is a fundamental limit on the accuracy of model predictions. More traditional models, though not limited in this fundamental way, are limited in a practical way because they require an extreme amount of quantitative unsaturated-zone characterization to achieve greater accuracy.

Although the broad ranges for most contaminant sources in Fig. 7 span about three orders of magnitude, for each case, there are known facts to suggest actual travel times are more likely to fall in one portion of the range than others. For Shoshone Mountain, intermittent supply is a more probable scenario than continuous supply, favoring the slower portion of the estimated travel-time range. For Rainier Mesa tunnels U12e, U12n, and U12t, the continuous case and short travel times are more likely and conversely for the other tunnels. For the ponds, the relative likelihood of short or long travel time depends on the duration of ponding relative to the travel-time estimates and the time period of interest; given the continuous-supply travel times of about 1 month, the shorter times would seem more appropriate for U12e and at least in the early period of the ponds' history for the other two sets of ponds.

If dominant flow modes can be established, then the single-order-of-magnitude agreement of the SRPF model would be comparable to uncertainties associated with predictive unsaturated zone flow modeling in general and so would have similar usefulness where management or investigational concerns require estimates of fastest travel times. Even if uncertainties are greater because little is known about unsaturated flow, SRPF travel-time estimates can have value, for example, to identify time scales to focus on in more detailed investigation. For the U12e tunnel for example, time scales of months or years, as well as longer periods, would be appropriate. If the distance of the tunnel from the saturated zone were much less, say 10 instead of 400 m, time scales of hours or days would have to be considered also, but SRPF results for the actual situation suggest these can be neglected. In this way, the highly approximate but easily obtained SRPF predictions can serve to limit the range of scenarios that require consideration, alert analysts and managers to ranges of predictive interest, and provide comparisons for ensemble-of-model approaches for complex environmental assessments.

6 Summary and Conclusions

The applicability of a highly simplified means of contaminant travel-time estimation hinges on two critical elements: (1) that the available evidence such as lithology, hydraulic properties, and other inputs suggests the likelihood of preferential transport and (2) that a prediction of interest is the earliest plausible arrival of contaminant rather than detailed estimates of concentrations or fluxes. For Rainier Mesa, our analysis suggests that preferential flow is possible from potential sources down to the carbonate aquifer, which implies that the SRPF model can be applied to estimate the fastest radionuclide travel times. SRFP model estimates for fastest travel times at Rainier Mesa are tens to hundreds of years for intermittently supplied preferential paths, as may be likely for contamination from those working points and tunnel inverts where there is no continuous discharge of water. The estimates at Rainier Mesa are approximately 1 month for continuously supplied preferential paths, appropriate for working points and tunnel inverts with continuous discharge, tunnel effluent ponds, or sealed-tunnel inverts. The SRPF travel times at Shoshone Mountain for intermittently supplied preferential paths, considered probable for all working points and tunnel inverts at that site, are hundreds of years. Continuous and intermittent estimates can be considered delimiters for the fastest travel time, within the factor-of-ten agreement of the SRPF model, for conservative contaminants (and not necessarily for sorbing cations, especially considering transport through zeolitized tuffs). The presence of a thick layer of siliceous rock under Shoshone Mountain may interrupt all preferential flow paths above the carbonate aquifer, potentially increasing estimated travel times to over a thousand years.

Even the shortest of these SRPF contaminant arrival times may not imply serious potential for radionuclide contamination of the regional flow system beneath Rainier Mesa, owing to the potential hydraulic isolation of the upper carbonate aquifer from the regional ground-water flow system [24]. It should also be noted that the SRPF estimates are fastest travel times, not fluxes, and do not indicate whether concentrations have exceeded or will exceed any standard of interest.

The application of the SRPF model to Rainier Mesa and Shoshone Mountain emphasizes the importance of radionuclide sources near both continuously supplied water and preferential flow paths. Its results may have utility for management decisions, for example, in evaluating the need for and likely efficacy of liners, barriers, hydraulic modifications, or remedial measures. The SRPF model is useful for hydrologic management questions where contaminant transport via preferential flow is of concern, yet limited characterization data are available.

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