Hydrol. Earth Syst. Sci. Discuss., 7, 3879–3930, 2010
www.hydrol-earth-syst-sci-discuss.net/7/3879/2010/
doi:10.5194/hessd-7-3879-2010

Hydrology and Earth System Sciences Discussions

Simple estimation of fastest preferential contaminant travel times in the unsaturated zone: application to Rainier Mesa and Shoshone Mountain, Nevada

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Received: 27 May 2010 – Accepted: 1 June 2010 – Published: 28 June 2010

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Published by Copernicus Publications on behalf of the European Geosciences Union.

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 two areas within the Nevada Test Site, Rainier Mesa and Shoshone Mountain, establishes the possibility of preferential flow through lithologies between potential radionuclide sources and the saturated zone. Lithology, saturated or near-saturated conditions in portions of the rock matrix, and relatively high recharge rates may act in concert at Rainier Mesa to promote preferential flow, despite the semi-arid climate. After identifying preferential flow as a possible contaminant transport process at Rainier Mesa and Shoshone Mountain, we apply a simple model to estimate fastest unsaturated travel times for conservatively-transported radionuclides to initially reach the saturated zone. Preferential flow travel times at Rainier Mesa are tens to hundreds of years for non-ponded water sources and one to two months for continuously-ponded water sources. If preferential flow occurs at Shoshone Mountain, the fastest travel times are approximately twice the Rainier Mesa estimates. A siliceous rock unit is present at Shoshone Mountain that may provide a barrier to preferential flow; if so, estimated transport times increase to more than a thousand years. Our analysis of unsaturated transport of radionuclides via preferential flow, using a relatively simple model, suggests that contaminated locations associated with continuously-supplied water sources, such as effluent ponds and water-filled tunnels, may have significantly shorter radionuclide travel times than locations not associated with such sources. The simple 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).

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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. Although most of the mobile contaminant mass arrives between the timescale end members, the fastest transport speed 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 fastest flow will likely occur by *preferential flow*, which is flow that bypasses portions of the porous media (Gerke, 2006). Preferential flow can be classified as (i) macropore flow, which consists of flow through well defined pathways such as root channels and fractures, or (ii) flow through a fraction of the matrix, typically divided into finger or funnel flow. Unstable finger flow (Glass et al., 1988; Baker and Hillel, 1990; Selker et al., 1992) refers to flow preferentially-occurring in finger-shaped regions through the unsaturated media and usually associated with layered media having different pore-size distributions. Funnel flow occurs when hydraulic-property contrasts within the medium focus unsaturated flow preferentially into zones that are more permeable, either intrinsically or as a result of higher soil-water content (Kung, 1990a,b).

Preferential flow via macropore, finger, and funnel mechanisms may transport contaminants at speeds considerably faster than matrix flow (Glass et al., 1988; Hendrickx et al., 1993; Kung, 1993; Gjettermann et al., 2004). Water-imbibition via capillary processes from preferential paths into the unsaturated matrix (Nitao and Buscheck, 1991; Wang and Narasimhan, 1993) 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 (Nativ et al., 1995; Pruess, 1998). For example, localized recharge fluxes, fracture coatings that minimize imbibition, or subsurface conditions such as a nearly-saturated matrix may have an elevated

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likelihood of contaminant transport via macropore flow.

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 transport 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 Test Site (NTS) 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 fastest radionuclide transport times via preferential flow for an area of complex hydrogeology but limited parameterization and evaluation data; this is not an attempt to validate the simple model. The main product presented here is a means of evaluating contaminant transport via preferential unsaturated-zone flow that is useful in hazard assessment, whether basic unsaturated flow properties are quantitatively known or not. This work expands and clarifies issues from Ebel and Nimmo (2009) while building on that previous work.

There are ongoing efforts at Rainier Mesa and Shoshone Mountain to predict the extent of radionuclide transport within the next 1000 yr by simulating unsaturated and saturated fluid flow and solute transport at nested scales from individual sources up to regional domains, with detailed estimates of radionuclide fluxes, as mentioned by Stoller-Navarro Joint Venture (2008b). The estimates in this effort are presented in the context of model abstraction, which advocates considering different models of varying complexity answering the same scientific question at the same site (Davis and Bigelow, 2003; Fishwick, 1995; Pachepsky et al., 2006), in which the simpler model has the role of augmenting understanding, rather than replacing more complex models (Pruess et al., 1999).

2 Rainier Mesa and Shoshone Mountain

2.1 Study site location and history of underground nuclear testing

The NTS 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 NTS favorable for underground nuclear testing. A total of 828 underground nuclear tests were conducted at the NTS (Department of Energy, 2000). 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 (Department of Energy, 2000). 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 (Laczniak et al., 1996). The transit time of selected radionuclides through the unsaturated zone at the NTS is of interest to the US Department of Energy and certain regulatory agencies at the State and Federal level (Fenelon et al., 2008).

With the exception of two tests conducted in vertical boreholes U-12q and U-12r (see Fig. 2) at Rainier Mesa, all the underground nuclear tests at Rainier Mesa and Shoshone Mountain occurred within tunnels excavated into the subsurface (National Security Technologies, LLC, 2007). 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

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from the 1950s into the 1990s (Table 1). Shoshone Mountain underground tests occurred in the U16a tunnel between the 1960s and early 1970s (National Security Technologies, LLC, 2007). 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 tunnel effluent ponds relative to the tunnel portals are shown in Fig. 3.

2.2 Radionuclides of concern

The Rainier Mesa and Shoshone Mountain tests were detonated in volcanic rocks hundreds of meters above the regional saturated zone, which occurs in carbonate rock (Bechtel Nevada, 2006; Stoller-Navarro Joint Venture, 2006a), and introduced radionuclides into the unsaturated and perched saturated zones. One of the principal radionuclides of concern at Rainier Mesa and Shoshone Mountain is tritium (^{3}H) (Department of Energy, 1997), which is highly soluble and conservative when incorporated into water molecules. Other radionuclides of concern in the unsaturated and perched saturated zones at Rainier Mesa and Shoshone Mountain include longer-lived radionuclides (e.g. ^{14}C, ^{36}Cl, ^{99}Tc, ^{106}Ru, ^{129}I, ^{85}Kr) that have been found in groundwater at the NTS (Smith, 1998). The mass of these radionuclides comprise the radiologic source term, described by Smith et al. (2003) and Zhao and Zavarin (2008) for the Rainier Mesa and Shoshone Mountain area. In terms of conservative transport at Rainier Mesa and Shoshone Mountain, ^{14}C, ^{36}Cl, and ^{3}H are the principal radionuclides to consider (Stoller-Navarro Joint Venture, 2008b). Radionuclide distributions depend on the phenomenology of underground nuclear detonations, detailed descriptions of which can be found in Borg et al. (1976) and Guell and Hunt (2003). While the radiologic source term is important to radionuclide transport, only a small fraction of radionuclides are readily mobile in an aqueous solution, termed the hydrologic source term. Radionuclide cations can be affected by complex sorption processes (e.g., Zhao et al., 2007) which reduce mobility. Alternatively, radionuclides can be aqueously transported with

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colloids at the NTS (e.g., Kersting et al., 1999) experiencing minimal sorption.

2.3 Potential radionuclide sources

The issue of groundwater contamination from radionuclides at the NTS was recognized as early as 1959 (Batzel, 1959) and the first studies of the potential for groundwater contamination beneath Rainier Mesa were conducted in 1959–1960 (Clebsch, 1960). Working-point elevations, water-table elevations in the carbonate rock, and distances to the saturated zone in the carbonate rock for underground nuclear tests at Rainier Mesa and Shoshone Mountain can be found in Department of Energy (1997) and National Nuclear Security Administration (2004), thus providing distances from the potential radionuclide sources to the saturated zone in the carbonate rock. Percolation through the working points may constitute a source of radionuclide-contaminated water.

The U12e, U12n, and U12t tunnels all began discharging water from the tunnel walls at the time of construction (Russell et al., 2003; National Security Technologies, LLC, 2007), principally from fractures (Thordarson, 1965; National Security Technologies, LLC, 2007). Tunnel sealing stopped discharge from the portals for the U12n tunnel in 1994 (Russell et al., 2003) 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 (Russell et al., 2003). This flooding may enhance percolation of radionuclide-contaminated water downward. Reeves et al. (2007) raised the possibility that the flooded U12t tunnel may enhance the connectivity of previously non-communicative fractures. As noted by Stoller-Navarro Joint Venture (2008b), 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 (see US Congress, 1989), possibly creating hydraulic connections between preferential paths. Attempts to seal the U12e tunnel failed (National Nuclear Security Administration, 2004) 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

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ponds was observed to be radionuclide-contaminated during sparse monitoring from 1970 through 1996.

The tunnel effluent ponds are a potential radionuclide source (see Table 2) with the possibility of affecting groundwater, despite the large potential evaporation rates at the NTS; the presence of ponded water can enhance recharge, even in semi-arid climates (Tyler et al., 1986). Currently, the U12n and U12t ponds are not water-filled, owing to tunnel sealing. While infiltration of the pond water may be a minor recharge source to the regional groundwater flow system, it could introduce a localized flux of radionuclide-contaminated water (Laczniak et al., 1996).

Water percolating through the U12b, U12c, U12d, U12f, U12g, U12j, U12k, and U12p tunnel inverts (i.e. floors) is likely intermittent, but could be a source of radionuclide contamination. The U16a tunnel at Shoshone Mountain has no observed tunnel invert drainage.

2.4 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 for macropore flow are absent and factors that favor finger and funnel flow are minimal. The preferential flow can exist as macropore, finger, or funnel flow. 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, but some factors that promote finger flow (see Scanlon and Goldsmith, 1997; Sililo and Tellam, 2000) are present, such as approximately horizontal stratification, overlying lithologies that have macropore preferential flow paths, and lithologic transitions from a less conductive to a more conductive matrix. For finger flow to be a substantial flow process, the matrix must have sufficient hydraulic conductivity to transmit significant quantities of water relative to the flux of water from competing processes. Funnel flow at Rainier Mesa and Shoshone Mountain could be promoted by areas of surface and lithologic-contact topography that can

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concentrate infiltration and subsurface flow.

A capillary barrier (see Hillel and Baker, 1988; Stormont and Anderson, 1999) could be an additional flow-affecting feature at Rainier Mesa and Shoshone Mountain. A permeability barrier may also impede flow at lithologic contacts, relying on a contrast in saturated hydraulic conductivity between two rock layers, 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. It is difficult to quantitatively estimate the fraction of water flux conveyed or impeded by these sorts of features at Rainier Mesa and Shoshone Mountain, given the limited unsaturated zone characterization. Within each lithologic unit, one or two modes of flow are expected to have the strongest influence on contaminant travel times, and therefore to have overriding importance in governing transport of conservative radionuclides.

2.5 Climate and groundwater recharge

The average annual precipitation on the top of Rainier Mesa is 319 mm, based on a record from 1960–2007, with snow constituting less than half of the total (National Oceanic and Atmospheric Administration, 2006). Rainier Mesa is estimated to have some of the highest recharge rates within the arid to semi-arid NTS. Russell and Minor (2002), who used the chloride mass-balance approach of Dettinger (1989), indicate recharge rates from 10–50 mm yr^{-1} for Rainier Mesa. Stoller-Navarro Joint Venture (2008a) presented estimates of 20–50 mm yr^{-1} based on a modified Maxey–Eakin method. Precipitation at Shoshone Mountain was estimated to be 200 mm yr^{-1} by Winograd and Thordarson (1975) and approximately 265 mm yr^{-1} by Hevesi et al. (1992); the annual precipitation for nearby Tippipah Spring (see Fig. 2) was reported by Hevesi et al. (1992) to be 245 mm yr^{-1}. Russell and Minor (2002) estimated that the Shoshone Mountain recharge rates in the tunnel area are on the order of 2–10 mm yr^{-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.

2.6 Rainier Mesa lithology and hydraulic properties

Figure 4 shows a simplified lithologic model of Rainier Mesa, based on borehole ER-12-4 (see Fig. 2). This one-dimensional conceptual model is designed to be used by the simplified contaminant transport model employed in this work, whereas it does not capture the full complexity of the geology at Rainier Mesa. The knowledge of the subsurface lithology at Rainier Mesa is derived primarily from geologic mapping and geophysical measurements in boreholes (see Fig. 2 and Fenelon et al., 2008) and tunnels (Fig. 2 and Table 1). 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 (Fenelon et al., 2008). A thin layer of argillic paleocolluvium separates the upper carbonate aquifer from overlying zeolitic tuff (Thordarson, 1965). A perched or semi-perched zone of saturation occurs within the zeolitic tuff at Rainier Mesa. Vitric tuff (which is nonwelded and sparsely fractured) and densely welded and fractured tuff overlie the zeolitic tuff. A depositional syncline that has dips of 2–12° in the limbs greatly affects the thickness of the tuff units across Rainier Mesa (Thordarson, 1965; Hoover and Magner, 1990). Cooling joints, fractures, and steeply dipping normal faults that trend north-south are typical in the volcanic rocks of Rainier Mesa (Hansen et al., 1963). Here the term *fracture* is used to encompass fractures, faults, and joints. Clearly there is a difference in scale between a major through-cutting feature such as a large fault versus a small fracture, but for the purposes of a basic evaluation of macropore preferential flow our simplification of terminology is sufficient.

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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 (2008a). The shallowest portion of the regional saturated zone at Rainier Mesa is located within carbonate rock (Fenelon et al., 2008). Pumping tests in deep wells demonstrate that this carbonate rock is more hydraulically conductive than the overlying zeolitic tuff (Thordarson, 1965), despite the low saturated hydraulic conductivity of the carbonate-rock matrix given in Table 3. Thordarson (1965) attributed the higher saturated hydraulic conductivity to a connected fracture network. This conclusion is supported by the five order of magnitude difference in saturated hydraulic conductivity values at the pump test versus lab scale shown in Table 3 (i.e. the pump tests include fracture influence while the lab scale tests do not). The zeolitic tuff also has low matrix permeability (Table 3). Numerous fractures occur in the zeolitic tuff, these preferential flow paths irregularly drain the tuff to create a hummocky perched saturated zone. The perched saturated zone may have declined locally in the last 50 yr as a result of drainage by tunnel-mining activities and nuclear testing (Russell, 1987). Byers (1962) and Keller (1960, 1962) observed fully or nearly saturated conditions in the zeolitic tuff.

Inspection of Table 3 indicates that the Paintbrush Group vitric tuff has the largest matrix permeability of any of the lithologies for which permeameter tests were conducted at Rainier Mesa (i.e. excluding the larger support volume pump tests in Table 3). While no fracture permeability data are available for the vitric tuff, the friable nature of the tuff suggests that fractures are not readily preserved. The few fractures observed in the vitric tuff tend to be filled with a clayey fault-gouge material (Laraway and Houser, 1962). The vitric tuff has been considered to be the only lithology at Rainier Mesa that transmits water primarily by matrix flow (Thordarson, 1965). The welded tuff has relatively low matrix permeability (Table 3), but is permeable because of well-connected fracture networks (Poole and Rooler, 1959). The four order of magnitude difference in saturated hydraulic conductivity values at the pump test versus lab scale, shown in Table 3, support this conclusion.

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2.7 Rainier Mesa conceptual flow model

Figure 4 presents a conceptual model of the unsaturated flow processes most pertinent to contaminant transport through each major lithologic unit at Rainier Mesa down to the carbonate aquifer. The contaminant transport model used in this work does not rely heavily on specific quantitative properties like unsaturated hydraulic conductivity and water retention as is typical of most unsaturated-zone flow models. Instead it puts much emphasis on the character of the unsaturated-zone media with respect to tendency to promote or inhibit general qualitative types of flow (i.e. diffuse versus preferential). Accordingly, the conceptual model in Fig. 4 emphasizes the evaluation of the subsurface media in these respects, which is in essence a decision as to whether preferential flow occurs or not. A more detailed characterization of the complex three-dimensional unsaturated and saturated flow and transport at Rainier Mesa is presented in National Security Technologies, LLC (2007).

Sections 2.7.1 through 2.7.4 below present site-specific hydrogeologic information and basic understanding of unsaturated-zone flow for each major lithologic unit, providing evidence, in terms of the qualitative likelihood of preferential flow, to support the following conclusions regarding unsaturated flow through Rainier Mesa: (i) macropore preferential flow via fractures is likely through the welded tuff, zeolitic tuff, and carbonate rock units, and (ii) stable matrix flow dominates through the vitric tuff, although observed short travel times of hydrologic tracers from the surface to tunnel level suggest very limited preferential flow as macropore preferential flow through fractures or finger flow below areas where fractures discharge water from the overlying welded tuff.

2.7.1 Flow through the welded tuff

Infiltration measurements reported by Ebel and Nimmo (2010) suggest that the soils atop Rainier Mesa are permeable and promote infiltration; when water passes through the soil, it enters the Rainier Mesa welded tuff. The Rainier Mesa welded tuff has relatively low saturated hydraulic conductivity in the matrix (Table 3). The welded tuff is

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heavily fractured, which in combination with the low matrix saturated hydraulic conductivity favors macropore preferential flow through fractures as a substantial flow process (Thordarson, 1965).

2.7.2 Flow into and through the vitric tuff

The vitric tuff has a matrix with a much larger saturated hydraulic conductivity and porosity than the overlying welded tuff (Table 3), which suggests that this lithologic boundary marks a transition from preferential flow in fractures through the welded tuff to matrix-dominated flow through the vitric tuff, where fractures may not be well preserved (Thordarson, 1965; Russell, 1987). There is limited evidence, however, that minor quantities of preferential flow occur through the vitric tuff at Rainier Mesa, possibly as macropore preferential flow via fractures, as suggested by Wang et al. (1993) and Gauthier (1998). Alternatively, preferential flow through the matrix may occur as either finger flow beneath points of focused discharge below fractures in the welded tuff, although it is questionable whether finger flow can be sustained over a hundred meters of unsaturated porous material. The occurrence of preferential flow in the vitric tuff at Rainier Mesa is supported by the observations from Clebsch (1960) and Clebsch and Barker (1960), who reported transport of the elevated ^{3}H levels from atmospheric nuclear testing taking 1–6 yr to travel from the surface to tunnel level (approximately 500 m) at Rainier Mesa, through the welded and vitric tuff. Philips et al. (1988) noted that anthropogenic ^{3}H production began in 1952 with a peak in 1963–1964. This is corroborated by Fig. 1 in Guerin (2001) for a graph of ^{3}H concentrations over time in atmospheric moisture showing values well above the 10 ^{3}H unit pre-atmospheric testing concentrations beginning in the mid 1950's. Philips et al. (1988) also noted that ^{3}H from atmospheric nuclear testing is "considered to be an excellent tracer for the movement of water itself".

The conceptual model, therefore, shown in Fig. 4 shows both fracture and finger preferential flow as possibilities at Rainier Mesa in the vitric tuff, but the majority of flow through the vitric tuff will be stable matrix flow and therefore slower than preferential

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processes.

2.7.3 Flow into and through the zeolitic tuff

Table 3 shows the large saturated hydraulic conductivity contrast between the zeolitic tuff matrix and the overlying vitric tuff matrix, with the zeolitic tuff potentially acting as a permeability barrier to vertical unsaturated matrix flow. Russell (1987) 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. The lithologic transition between the zeolitic and vitric tuff is approximately at the upper extent of the hummocky perched saturated zone at Rainier Mesa (Russell et al., 2003). Previous investigations have assumed that macropore preferential flow through fractures is the dominant pathway for downward movement of water in the zeolitic tuff (Thordarson, 1965; Russell, 1987; Gauthier, 1998). Observational evidence suggests that there is some lateral hydrologic connectivity between the fractures in the zeolitic tuff. For example, Thordarson (1965) noted that breaching a fracture in the U12e tunnel flooded the tunnel and caused the nearby Hagestad 1 well (see Fig. 2), which is 30 m from the tunnel, to drop 37 m in 1962. The Hagestad 1 well is screened in the zeolitic tuff from 580 to 490 m below land surface.

Differences in the ages of water in the matrix and fractures of the zeolitic tuff elucidate the degree of hydrologic connection between the saturated matrix of the zeolitic tuff and the fractures. 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 age-estimation techniques, including bacterial ecology (Amy et al., 1992; Haldeman and Amy, 1993), stable isotopes (Russell et al., 2001), isotopes from atmospheric nuclear testing (Clebsch and Barker, 1960; Norris, 1989), water chemistry (Jacobson et al., 1986), and temporal patterns in fracture discharge (Diment et al., 1959; Jacobson et al., 1986). These age observations suggest that the residence time of water in the zeolitic tuff matrix is on millennial timescales and the fracture water has a much smaller residence time and appears to be recharged by modern waters.

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Nuclear testing has potentially altered flow in the zeolitic tuff and other lithologies in which testing occurred at Rainier Mesa by enhancing fractures. One possible line of evidence for this local alteration is the observation of high sulfate concentrations in impounded water behind the U12t tunnel seal observed by Russell et al. (2003). These elevated sulfate concentrations could indicate a release of relict water from the matrix into the fractures that discharge into the tunnel. It is conceivable that matrix-fracture water exchange has 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. (2007) and Parashar and Reeves (2008) will shed light on this topic. The present state of knowledge at Rainier Mesa suggests that macropore preferential flow in fractures is a substantial flow process in the zeolitic tuff.

2.7.4 Flow into and through the carbonate rock

Groundwater may be transmitted via macropore preferential flow in fractures through the zeolitic tuff to the argillic paleocolluvium. The presence of argillic paleocolluvium above the carbonate rock may affect how groundwater discharging from the zeolitic tuff moves into the underlying carbonate rock, although little information is available regarding the hydraulic properties of the argillic paleocolluvium. National Security Technologies, LLC (2007) and Fenelon et al. (2008) classify the argillic paleocolluvium as a confining unit and National Security Technologies, LLC (2007) 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 (Thordarson, 1965; Russell et al., 2001).

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Significant lateral flow may also occur at the top of the carbonate rock to the volcanic aquifer to the west and southwest (Fenelon et al., 2008); but this does not preclude vertical preferential flow.

2.8 Shoshone Mountain lithology and hydraulic properties

Figure 4 shows a simplified lithologic model of Shoshone Mountain based on the ER-16-1 borehole (see Fig. 2). This one-dimensional conceptual model is intended for use with the simplified contaminant transport model employed here and does not capture the full geologic complexity. The saturated zone, which is part of the regional flow system, lies within carbonate rock. The siliceous rock overlying the carbonate rock is mostly shale (Stoller-Navarro Joint Venture, 2006b). 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 (National Nuclear Security Administration, 2004). The absence of perched water may be the result of lower recharge fluxes in the portion of Shoshone Mountain above the U16a tunnel, relative to Rainier Mesa (Russell and Minor, 2002), such that groundwater drains laterally and vertically at a rate greater than upgradient supply by recharge, thus preventing perched water. 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.

2.9 Shoshone Mountain conceptual flow model

This section presents a simplified conceptual model of the flow of water from the land surface to the lower carbonate aquifer below Shoshone Mountain, which is illustrated in Fig. 4. The conceptual flow model for Shoshone Mountain is similar to the Rainier Mesa conceptual model owing to the similar geology, although the upper carbonate aquifer is absent at Shoshone Mountain. Based on the conceptual model in Fig. 4, the qualitative likelihoods of preferential flow in each major lithologic unit at Shoshone Mountain for

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flow through the vadose zone to the saturated zone in the carbonate rock, for which the evidence is presented in Sects. 2.9.1 through 2.9.5, are: (i) preferential flow is active in the welded tuff, zeolitic tuff, and carbonate rock, and (ii) stable matrix flow dominates in the vitric tuff and siliceous rock, with a very small probability of preferential flow in these units.

2.9.1 Flow through the welded tuff

Percolation through the welded tuff at Shoshone Mountain probably occurs as preferential flow though fractures (Stoller-Navarro Joint Venture, 2006b), similar to the welded tuff at Rainier Mesa.

2.9.2 Flow into and through the vitric tuff

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 be prevalent. The transition from the fine-grained, low hydraulic conductivity matrix of the welded tuff to the coarser-grained higher hydraulic conductivity matrix of the vitric tuff is unlikely to serve as a capillary barrier, given that flow occurs predominantly in fractures in the welded tuff, despite the smaller recharge fluxes at Shoshone Mountain, relative to Rainier Mesa.

Flow through the vitric tuff is probably predominantly steady, diffuse flow through the collective pore space of the matrix. Preferential flow as unstable finger flow is possible below fractures discharging from the welded tuff into the vitric tuff. Sweetkind and Drake (2007) observed that faults are more numerous and have larger displacements at Shoshone Mountain relative to Rainier Mesa. The more intensive faulting at Shoshone Mountain may form macropore flow paths within the vitric tuff, which may facilitate preferential flow, as proposed for the vitric tuff at Rainier Mesa by Wang et al. (1993) and Gauthier (1998). Alternatively, faults may be filled with fault gouge, drastically reducing the permeability and potentially rendering the faults inoperable as macropore preferen-

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tial flow paths. The conceptual flow model shown in Fig. 4 considers preferential flow via fractures or fingers at Shoshone Mountain to be possible, but steady matrix flow is the dominant flow process.

2.9.3 Flow into and through the zeolitic tuff

The lithologic transition from the vitric tuff to the zeolitic tuff at Shoshone Mountain may have less of a permeability contrast than the same interface at Rainier Mesa if the more intense fracturing at Shoshone Mountain (Sweetkind and Drake, 2007) increases the effective permeability of the zeolitic tuffs. If a reduced permeability contrast exists, it may explain why no perched saturated zone is evident at Shoshone Mountain near the U16a tunnel, 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.

2.9.4 Flow into and through the siliceous rock

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 (Winograd and Thordarson, 1975; Laczniak et al., 1996). 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 (Stoller-Navarro Joint Venture, 2006b) 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. 4. This conclusion is based on the limited degree of fracturing and the improbability of fingered flow persisting through the several-hundred-meter thickness of the siliceous rock.

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2.9.5 Flow into and through the carbonate rock

If the permeability of the carbonate rock matrix is less than that of the siliceous rock matrix and unsaturated flow through the siliceous rock is stable and matrix-dominated, a permeability barrier at this lithologic interface could cause flow to enter the fractures in the carbonate rock and become macropore preferential flow. Given that the carbonate rock below the siliceous rock is heavily fractured and has relatively low matrix permeability (Winograd and Thordarson, 1975; Laczniak et al., 1996), it is reasonable to assume that at least some macropore preferential flow occurs through fractures, as water percolates downward to the saturated zone.

3 Source-responsive preferential-flow model

The following section explains the development and application of the relatively simple contaminant transport model used to estimate radionuclide travel times from potential sources to the saturated zones at Rainier Mesa and Shoshone Mountain.

3.1 Source-responsive preferential-flow model development

Analysis of data from 64 diverse field tests in the unsaturated zone with measured fastest solute transport velocities, V_{max}, by Nimmo (2007) suggested that an unusually simple mathematical model can provide an estimate of the fastest solute travel times where flow is predominately preferential. Figure 5 shows simulated versus measured V_{max} 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 1300 m. Note that no measured or simulated V_{max} values from Rainier Mesa or Shoshone Mountain are included in Fig. 5. The spread about the 1:1 line of simulated versus measured fastest V_{max} illustrates the approximate factor-of-ten accuracy of the Nimmo (2007) approach, and indicates definite uncertainty bounds.

The paradigm used in the travel time model by Nimmo (2007) 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, a distinction supported by examination of Fig. 5. The fastest travel times correlate strongly with the nature of the water supply but not with the particular earth materials involved (Nimmo, 2007). This model is described here as a *Source-Responsive Preferential-Flow* (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. (1997) and Kasteel (1997); ponded water at the surface increased preferential flow, relative to non-ponded water application, in the work by Hamdi et al. (1994), Flury et al. (1994), and Scanlon and Goldsmith (1997).

3.2 SRPF model output

The SRPF model estimates the fastest travel time, 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. Viewed in a particle-tracking framework, it would indicate the estimated arrival time of the first particle. If there is a broad spread of travel times for the other particles, the average travel time of those particles 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 shortest travel time t_t [T] (based on the fastest solute transport

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velocity, V_{max} [L T^{-1}]) and is calculated as

$$t_t = \frac{D_{transport}}{V_{max}}, \quad (1)$$

where $D_{transport}$ is the distance of solute transport. The effects of tortuosity of preferential flow paths are not explicitly accounted for, though for the earliest arrival of a tracer, the shortest preferential path may not differ appreciably from the straight line distance used in Eq. (1), depending on the preferential path connectivity and tortuosity. Two separate formulas described in the following sections provide estimates of fastest contaminant transport velocities, depending on whether preferential flow supply is continuous in time or intermittent.

3.3 Continuous water supply

For the case of continuous water supply to preferential flow paths, typically as infiltration of ponded water, the fastest contaminant transport velocity, V_{max}, is estimated to equal V_0=13 m d^{-1}, the geometric mean of the measured V_{max} for the 34 continuous-supply cases examined by Nimmo (2007). Then the SRPF-estimated travel time for continuous supply is

$$t_t = \frac{D_{transport}}{V_0}. \quad (2)$$

3.4 Intermittent water supply

For the case of intermittent water supply to preferential paths (e.g. natural precipitation), estimation of preferential travel times requires additional assumptions. The V_{max} 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,

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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_{max} over that period is

$$V_{max} = V_0 \left[\frac{t_p}{t_f}\right]. \quad (3)$$

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_{max} 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} [L T^{-1}], for example average annual precipitation. To apply the model in such cases, a universal effective rate, i_0 [L T^{-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

$$t_p = \frac{t_f i_{avg}}{i_0}. \quad (4)$$

Over the long term the maximum transport speed is

$$V_{max} = V_0 \frac{i_{avg}}{i_0}, \quad (5)$$

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

$$t_t = \frac{i_0 D_{transport}}{i_{avg} V_0}, \quad (6)$$

for the intermittent case with i_{avg} known.

Nimmo (2007) estimated i_0 by optimizing its value for minimum deviation of computed from measured V_{max}. The optimized i_0 is 0.73 m d^{-1} (30 mm h^{-1}) based on the 23 examined intermittent supply cases where average input rate is known.

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3.5 Site-specific implementation of the SRPF model

Precise estimation of unsaturated-zone travel times is impossible without spatially detailed knowledge of materials and conditions within the great volume of unsaturated zone. Given what is known about subsurface water conditions at Rainier Mesa and Shoshone Mountain, a feasible alternative is to establish a range of plausible values for the fastest travel time using continuous- and intermittent-supply scenarios with the SRPF model to generate end members of the range.

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 $V_0=13\,\mathrm{m\,d^{-1}}$ and $i_0=0.73\,\mathrm{m\,d^{-1}}$ as estimated by Nimmo (2007). The scales and the general types of media in Rainier Mesa and Shoshone Mountain contaminant-transport problems have significant representation in the model-development data set used by Nimmo (2007), so the use of these parameter values is appropriate.

Travel-time estimates for both continuous and intermittent water supply 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 detonation cavity radius in the working point distances to the saturated zone in the carbonate rock makes the minimum travel time in some cases slightly

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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 noted in Sect. 2.5: 319 mm yr^{-1} at Rainier Mesa and 200 mm yr^{-1} at Shoshone Mountain.

4 SRPF travel-time results

Figure 6 presents the SRPF travel time estimates for potential radionuclide sources at Rainier Mesa and Shoshone Mountain. Error bars span the factor-of-ten uncertainty range of SRPF model travel time estimates. The results are summarized by continuous versus intermittent water-source classification, consistent with the SRPF concept, in the following sections.

4.1 Continuous-supply fastest travel-time estimates for working points and tunnel inverts at Rainier Mesa

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 one month (0.08 yr) for the U12e, U12n, and U12t tunnel working points, if the preferential paths are continuously supplied (see Fig. 6). For borehole working points, the U-12q test travel times are 11 d for continuous water supply; the U-12r test travel times are 14 d for continuous water supply (see Fig. 6). Fenelon (2006) 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 (R. 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

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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 one month (see Fig. 6).

4.2 Intermittent-supply fastest travel-time estimates for working points and tunnel inverts at Rainier Mesa

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 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 radionuclide transport to the carbonate aquifer at timescales on the order of 35 to 155 yr for these tunnel working points (see Fig. 6). The estimated fastest travel times to the saturated zone shown in Fig. 6 for these tunnel inverts are similar to the working points, ranging from 70 to 120 yr (see Fig. 6).

4.3 Tunnel pond fastest travel-time estimates for Rainier Mesa

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 (Russell et al., 2003) and 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

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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 yr (one month) and for intermittent supply are considerably longer, on the order of 60 to 90 yr.

4.4 Intermittent-supply fastest travel-time estimates for the working points and tunnel invert at Shoshone Mountain

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 yr for the U16a tunnel working points (see Fig. 6) and 250 yr for the U16a tunnel invert at Shoshone Mountain.

4.5 Possibility of non-preferential flow at Rainier Mesa and Shoshone Mountain

Preferential flow must occur for the 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. 4, with the possible exception of the vitric tuff (Russell et al., 2001; Thordarson, 1965). Flow through Shoshone Mountain could be preferential throughout all the lithologies shown in Fig. 4 with the possible exception of the vitric tuff and the siliceous rock (Stoller-Navarro Joint Venture, 2006b). 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 the potential to have preferential flow via fractures (Thordarson, 1965).

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If flow is non-preferential in some of the lithologies beneath the contaminant sources, then the estimated fastest travel times presented here will be too short. An estimate of the tracer velocity v for steady, matrix-dominated flow can be approximated using the expression

$$v = \frac{i}{\theta}. \quad (7)$$

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 (Stoller-Navarro Joint Venture, 2006b) 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 (Plume, 1996; Sweetkind et al., 2007), and a flux estimate of 9 mm yr^{-1}, which is the mean of the recharge estimates from Shoshone Mountain (2 to 16 mm yr^{-1}), provides a contaminant velocity estimate of 0.3 m yr^{-1}. The travel time through the 450 m of siliceous rock (Stoller-Navarro Joint Venture, 2006b) can be calculated using Eq. (1) to give 1500 yr. 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 yr, based on the intermittent-supply fastest travel time estimates from the SRPF model, giving a total average travel time from the U16 a working points of approximately 1600 yr. This estimate shows the profound influence that interruptions of preferential pathways have on travel times.

4.6 Sensitivity analysis

To examine the sensitivity of the SRPF model to the input parameters, the effect of varying the values for i_0, V_0, and i_{avg} is considered using the U16a working points at Shoshone Mountain as an example. The other parameters are held constant while

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one is varied for each example. For a ±20% variation in the i_0 value of 0.73 m d^{-1}, the mean intermittent travel time (Eq. 6) would range from 192 to 288 yr. Considering a ±20% variation in the V_0 of value of 13 m d^{-1}, the mean intermittent travel time would range from 200 to 300 yr. Inspection of Eq. (6) shows that changing i_{avg} has the same effect as changing V_0 for estimated travel time. Alternatively, one could consider a different estimate of i_{avg} for Shoshone Mountain than the 200 mm yr^{-1} given by Winograd and Thordarson (1975). Hevesi et al. (1992) estimated annual precipitation at Shoshone Mountain to be approximately 265 mm yr^{-1} using a geostatistical approach, which when used as an alternative parameterization of i_{avg}, shortens the mean estimated intermittent travel time for the U16a working points at Shoshone Mountain to 181 yr, a difference of nearly 60 yr from the 200 mm yr^{-1} i_{avg} parameterization. All of these variations are small in consideration of the overall order-of-magnitude uncertainty of the SRPF travel-time estimates.

5 Discussion

5.1 Important features of the SRPF model

Rate-affecting quantities like the acceleration of gravity and the viscosity of water are contained implicitly in the formulation of the SRPF model, and specific porous media properties do not enter explicitly into the V_{max} calculation. Those properties are instead taken into account earlier in the travel-time estimating process, in a more qualitative manner, in the evaluation of preferential and diffuse flow possibilities at the given site. 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 SRPF model utilizes precipitation rate where recharge rate estimates might be considered to be more directly appropriate. Some fraction of incident precipitation be-

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comes runoff or evapotranspiration and so would not be active in driving preferential flow to the deep unsaturated zone. Nimmo (2007) used the precipitation rate to correlate with maximum preferential solute transport speed because, for the great majority of V_{max} measurements for intermittent supply, 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_0. If there were enough available cases of measured V_{max} with reliably estimated infiltration or recharge rates, it would be possible to reformulate the SRPF model, thus leading to a different (smaller) i_0 value for use in predicting travel times for these situations. 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_0 value of Nimmo (2007).

The development of the SRPF model by Nimmo (2007) is an example of the "downward" or data-driven approach (Sivapalan, 2003; Sivapalan et al., 2003), 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. A common progression of models based on the downward protocol is to begin with a simple model and then add complexity to achieve a better process representation, which is an ongoing effort for the SRPF model; additional source-responsive theory was developed by Nimmo (2010) but has yet to be fully implemented and tested. The downward approach is in stark contrast to the traditional "upward" approach, as defined by Klemeš (1983) and Jarvis (1993), where highly complex models are employed, for example using Richards' equation and the advection-dispersion equation to predict unsaturated solute transport. The upward approach is often described as "physically-based" and follows a mechanistic or reductionist protocol, where processes and interactions are specified a priori (Sivapalan et al., 2003) and the model predicts "everything, everywhere"; see examples by Ebel and Loague (2008) and Ebel et al. (2009; 2010). Clearly, both the upward and downward modeling protocols are valuable in the hydrologic sciences. The application of the downward approach using the SRPF model at Rainier

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Mesa and Shoshone Mountain demonstrates its role in the suite of models used to ask and answer difficult questions regarding environmental problems such as contaminant transport, particularly in the context of model abstraction.

5.2 Comparisons against radionuclide observations

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 NTS background levels (Bechtel Nevada, 2006; Stoller-Navarro Joint Venture, 2006a). Given the finite detection limits (about 330 pCi L^{-1}, Stoller-Navarro Joint Venture, 2008a) and 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. At Shoshone Mountain, neither well ER-16-1 nor Tippipah Spring has radionuclide concentrations above background NTS levels (Stoller-Navarro Joint Venture, 2006b; National Nuclear Security Administration, 2004). 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 (Winograd and Thordarson, 1975; Johannesson et al., 1997; Johannesson et al., 2000; Stetzenbach et al., 2001). Tippipah Spring is at 1585 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 1600 yr. Monitoring contaminants in wells at subsurface positions carefully targeted to locations of preferential flow would allow more thorough testing of travel time estimates.

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Fastest travel time estimates assume conservative contaminant behavior, which will not be true for all radionuclides such as sorbing cations (which would have much longer transport times) but is probably a valid assumption for certain radionuclides such as ^{3}H, ^{36}Cl, and ^{14}C. This distinction is important at locations like Rainier Mesa and Shoshone Mountain where non-conservative radionuclides may strongly sorb to zeolitized tuffs.

5.3 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 concentration of water flow (Pruess, 1999). 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. 6 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 con-

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versely 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 one 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 uncertainty 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 .

5.4 The occurrence of vertical flow at Rainier Mesa

Some controversy exists regarding the proportion of flow at Rainier Mesa that is vertical versus lateral, with the lateral flow occurring to the west and south to the Pahute Mesa-Timber Mountain volcanic aquifer, see Fenelon et al. (2008) and Stoller-Navarro Joint Venture (2008b). The Rainier Mesa conceptual model shown in Fig. 4 does not preclude lateral flow, but instead requires that some of the flow must be occur vertically for radionuclides to be transported preferentially to apply the SRPF model. According to Stoller-Navarro Joint Venture (2008b), data from wells ER-12-3 and ER-12-4 indicate vertical gradients within the zeolitized tuffs down to the lower carbonate aquifer, suggesting a vertical flux of recharge, although sections of higher hydraulic conductivity from fractures or welded tuff sections may complicate exact interpretation (Bechtel Nevada, 2006; Stoller-Navarro Joint Venture, 2006a; Stoller-Navarro Joint

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Venture, 2008b). Lawrence Livermore National Laboratory (2006; 2007) 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 (Stoller-Navarro Joint Venture, 2006c), 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, although the flux is not sufficient enough to saturated the upper portions of the carbonate aquifer, possibly because of the low saturated hydraulic conductivity of the zeolitized tuff (Stoller-Navarro Joint Venture, 2006c).

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 one 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

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fastest travel time, within the factor-of-ten accuracy 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 transport 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 (see Fenelon et al., 2008). 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. Management options minimizing such radionuclide sources may reduce contamination potential, for example lining pond bottoms and tunnel inverts with impervious barriers. The SRPF model is useful for hydrologic management questions where contaminant transport via preferential flow is of concern yet limited characterization data are available.

Acknowledgements. The presentation here benefitted from comments from Joe Fenelon, Randy Laczniak, Paul Hsieh, Don Sweetkind, Ben Mirus, and eight anonymous reviewers. Prepared in cooperation with the US Department of Energy, National Nuclear Security Administration, Nevada Site Office under Interagency Agreement DE-AI52-07NV28100.

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Table 1. Summary of tunnel characteristics at Rainier Mesa and Shoshone Mountain (see Fig. 2). Information from (Diment et al., 1959; Dickey et al., 1962; Thordarson, 1965; Fernandez and Freshley, 1984; Russell et al., 2001; Russell et al., 2003; National Nuclear Security Administration, 2004; National Security Technologies, LLC, 2007).

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	1702	Zeolitic tuff (TB3-4)	None	0
U12b	1956–1963	4903	2016	Vitric tuff (Upper GC)	Little	6
U12c	1957–1958	91	2046	Vitric tuff (Lower GC; R/GC)	–	3
U12d	pre-1958	61	2050	Vitric tuff (Lower GC; R/GC)	–	1
U12e	1957–1977	15 149	1865	Zeolitic tuff (TB1-4; TS; C)	Yes	9
U12f	pre-1958	351	2046	Vitric tuff (Lower GC; R/GC)	–	2
U12g	1961–1989	11 667	1864	Vitric tuff (TB2-4; GC)	Little	5
U12i	1959	760	1718	Vitric tuff (R/GC)	None	0
U12j	1959	760	1718	Vitric tuff (R/GC)	None	1
U12k	1959	760	1718	Vitric tuff (R/GC)	None	1
U12n	1964–1993	25 000	1840	Zeolitic tuff (TB1-2; GC; TS)	Yes	22
U12p	1962–1984	7192	1677	Vitric tuff (R/GC)	None	4
U12t	1968–1988	10 642	1707	Zeolitic tuff (TB2-4; TS)	Yes	6
Shoshone Mountain						
U16a	1961–1971	1105	1649	Zeolitic tuff (TB)	None	6

(TB) Tunnel Bed; (GC) Grouse Canyon; (R/GC) pre Rainier/post Grouse Canyon; (TS) Tub Spring; (C) Paleozoic Carbonate; – denotes unknown or unmeasured

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

Source name	Date range	Contaminant	Concentration Mean [pCi L^{-1}]	Maximum [pCi L^{-1}]	Minimum [pCi L^{-1}]
U12e effluent	1991–1992	^3H	2.0×10^{6} [a]	–	–
U12e pond	2007	^3H	2.0×10^{6} [b]	–	–
U12e pond	1990–1996	Gross beta activity	–	161 [c]	8.1 [c]
U12n pond	1976–1993	^3H	2.0×10^{6} [d]	1.1×10^{7} [d]	2.2×10^{5} [d]
U12n pond	1976–1993	Gross beta activity	602 [d]	6.7×10^{3} [d]	5.3 [d]
U12t pond	1970–1993	^3H	4.0×10^{7} [d]	3.0×10^{8} [d]	5.0×10^{4} [d]
U12t pond	1970–1993	Gross beta activity	9.1×10^{4} [d]	1.1×10^{6} [d]	10 [d]

[a] Russell et al. (1993); [b] National Security Technologies, LLC (2008); [c] National Nuclear Security Administration (2004); [d] (Russell et al., 2003); – denotes unknown or unmeasured.

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Table 3. Hydraulic properties for the matrix of lithologic units at Rainier Mesa (after Russell, 1987; data from Thordarson, 1965; National Security Technologies, LLC, 2007).

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^{-9} [a]	0.14	–
Vitric tuff[c]	1.75×10^{-6} [a]	0.40	0.64
Vitric tuff[d]	2.80×10^{-10} [a]	0.19	–
Zeolitic tuff[e]	9.44×10^{-9} [a]	0.38	~ 1.0
Zeolitic tuff[f]	1.40×10^{-9} [a]	0.35	~ 1.0
Zeolitic tuff[g]	–	0.32	~ 1.0
Zeolitic tuff[h]	–	0.25	~ 1.0
Carbonate rock	$3.30 - 9.43\times10^{-11}$ [a]	0.04	–
Welded tuff	3.66×10^{-5} [i]		
Carbonate rock[j]	2.31×10^{-6} [i]; 9.0×10^{-11} [k]		

[a] Saturated hydraulic conductivity based on permeameter measurements of core samples (Thordarson, 1965); [b] Rainier Mesa Tuff; [c] Paintbrush Group; [d] Grouse Canyon Tuff Member; [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 2007); [j] LCA3 in National Security Technologies, LLC (2007); [k] mean value from lab scale measurements (National Security Technologies, LLC 2007); – denotes unknown or unmeasured.

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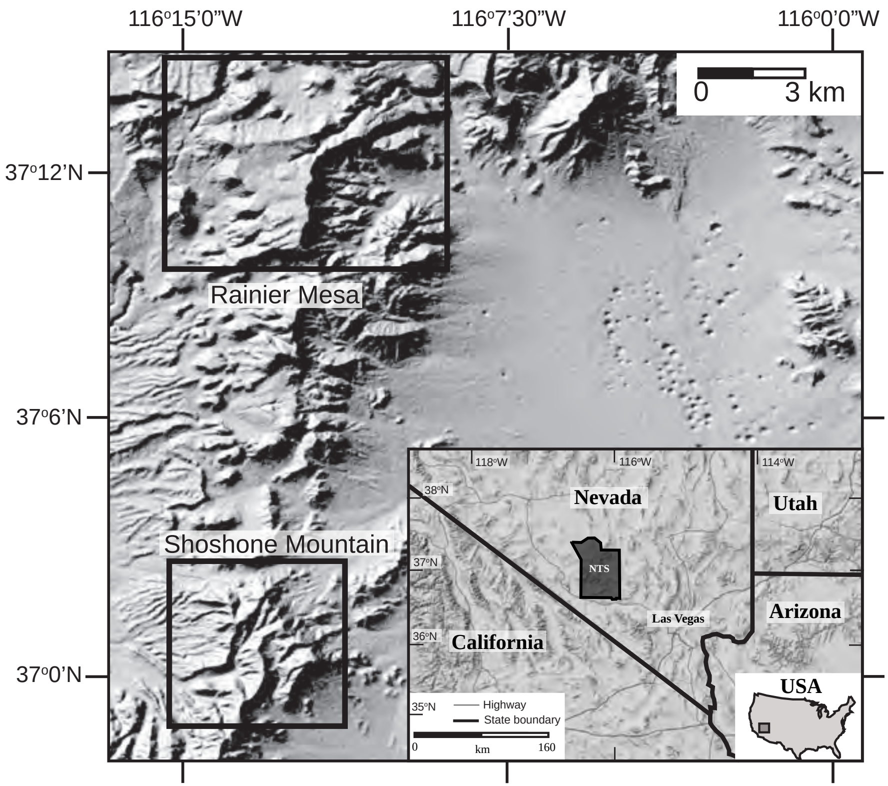

Fig. 1. Shaded relief map showing the location of the Nevada Test Site and the locations of Rainier Mesa and Shoshone Mountain.

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Estimation of contaminant travel times

B. A. Ebel and J. R. Nimmo

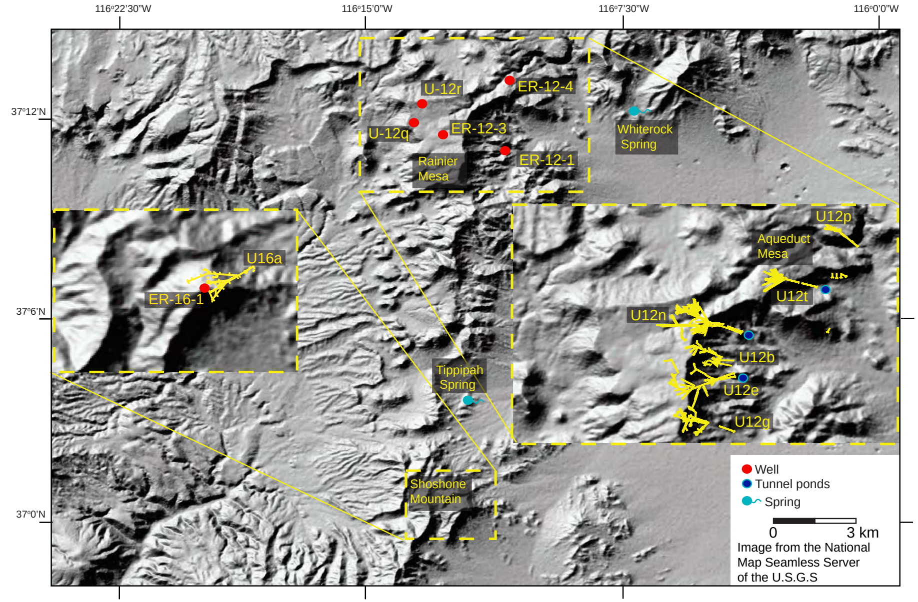

Fig. 2. Map of the major tunnels and selected boreholes at Rainier Mesa and Shoshone Mountain. See Fenelon et al. (2008) for a more complete map of Rainier Mesa boreholes.

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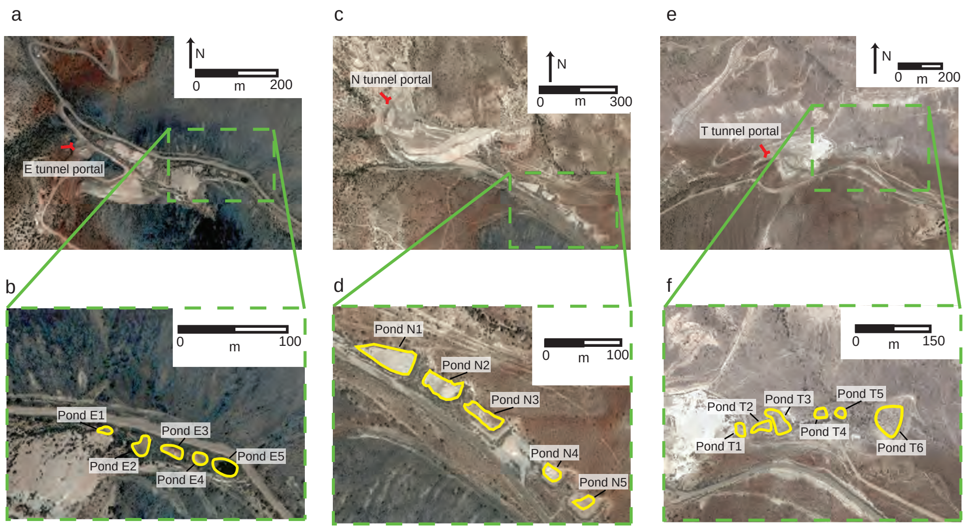

Fig. 3. Satellite images of the Rainier Mesa tunnel effluent ponds **(a)** U12e tunnel portal, **(b)** U12e tunnel ponds, **(c)** U12n tunnel portal, **(d)** U12n tunnel ponds, **(e)** U12t tunnel portal, **(f)** U12t tunnel ponds.

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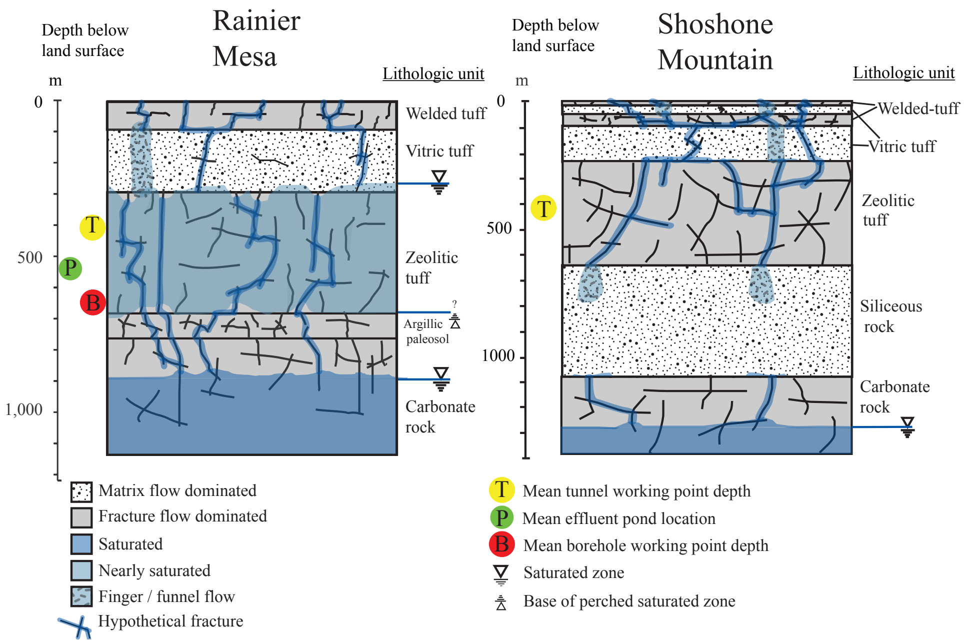

Fig. 4. Conceptual models of unsaturated flow, showing fracture, finger, and funnel preferential flow, for Rainier Mesa and Shoshone Mountain at the Nevada Test Site, USA. Tunnel and borehole working point depths are to detonation cavity bottoms; the mean depths of working points and effluent ponds are approximate. The fracture geometries, lithologic configurations and water table locations shown are for schematic purposes.

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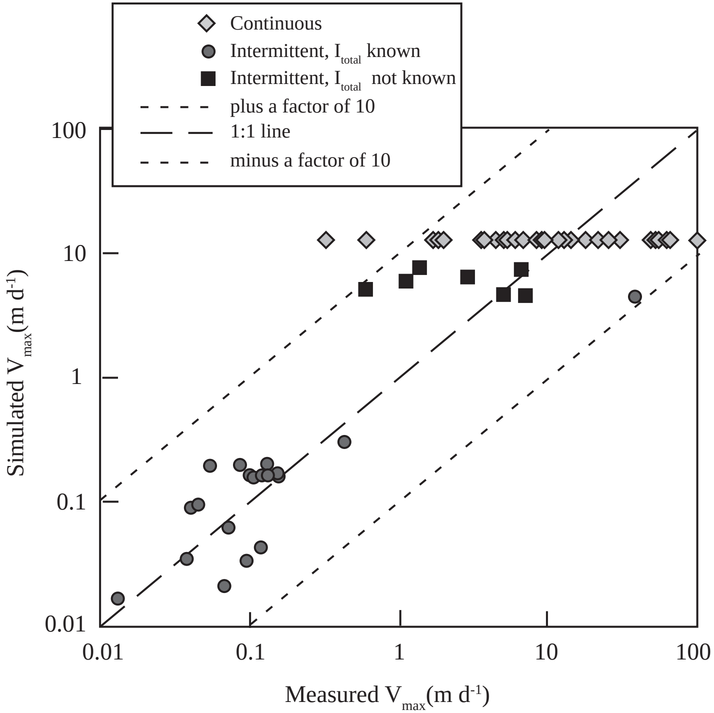

Fig. 5. Simulated versus measured maximum transport speed of unsaturated zone preferential flow for the 64 selected tracer tests analyzed by Nimmo (2007) demonstrating the factor-of-ten bounds of uncertainty for fastest travel time estimates and the distinction between continuous and intermittent water-supply made by the Source Responsive Preferential Flow (SRPF) model. 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.

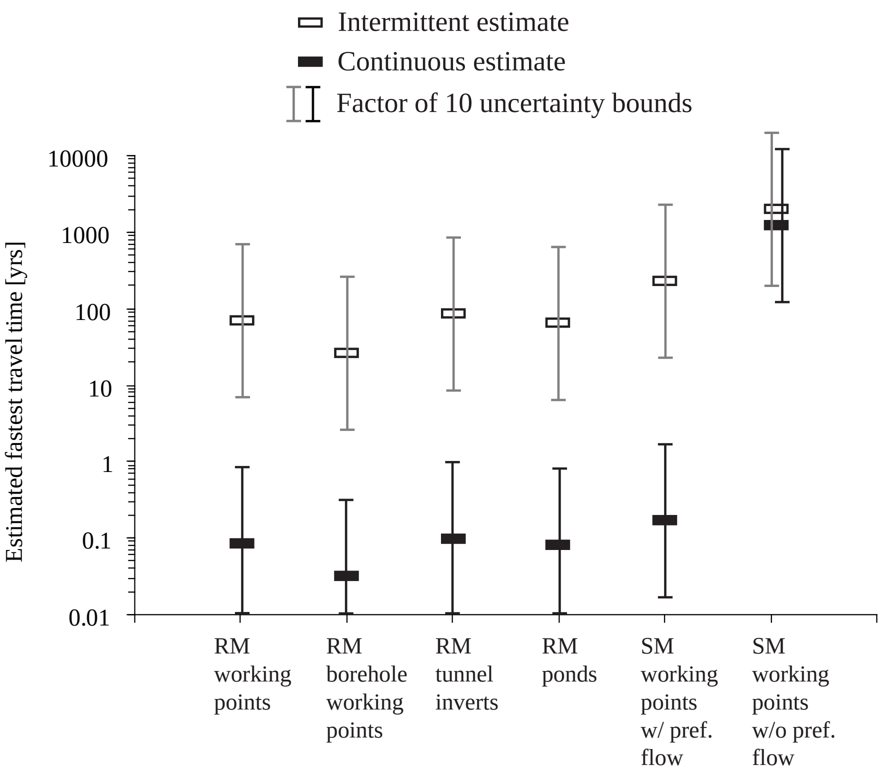

Fig. 6. Range of unsaturated travel time estimates for Rainier Mesa and Shoshone Mountain using a Source-Responsive Preferential Flow (SRPF) model (Nimmo, 2007) for continuous and intermittent water supply. The Shoshone Mountain travel time estimates are given for the cases with and without preferential flow in the siliceous rock. The bracketed lines provide uncertainty estimates based on the approximate factor-of ten accuracy of the SRPF model.