Hydrology and Earth System Sciences Discussions

Interactive comment on "Simple estimation of fastest preferential contaminant travel times in the unsaturated zone: application to Rainier Mesa and Shoshone Mountain, Nevada" *by* B. A. Ebel and J. R. Nimmo

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Received and published: 22 October 2010

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Received and published: 27 September 2010

Author responses are **in Bold text**

This review from anonymous reviewer 3 (posted within the editor's comment) raises some important issues that need further explanation and have prompted desirable revisions in our manuscript. We respond to these and other comments below.

The authors utilize a very simple model termed the Source Responsive Preferential Flow (SRPF) model, originally proposed by Nimmo (2007), and apply this model for fastest travel time predictions for unsaturated zone transport of conservative radionuclides at Rainier and Shoshone Mountain, Nevada Test Site. The SRPF model is reliant on the presence of preferential flow and transport mechanisms, and assumes a constant maximum transport velocity over a defined infiltration duration, irrespective of medium type or transport distance. To apply the SRPF model to Shoshone Mountain and Rainier Mesa, underground tests were grouped according to infiltration source types: continuous or intermittent. Fastest transport times to the water table are then estimated from their simple model. The work contained in the manuscript does not provide further development nor validation for the SRPF model, and little if any information from the site – despite the length of the paper – are utilized in the fastest travel time predictions.

Remarks in the above paragraph are basically accurate as descriptions of the original manuscript. The main thrust of our paper, addressed in the greatest portion of its text and figures, is the evaluation of whether the extremely simple source-responsive travel-time model of Nimmo (2007) is suitable for estimating unsaturated zone travel times at the selected field site. Our revised manuscript has substantial added material in support of the SRPF model's applicability through tests with independent data. The revision has a considerably reduced amount of site-descriptive material, as appropriate to what is needed to support its conclusions.

The authors mention multiple times in the manuscript that the value of the SRPF model lies in its simplicity, and that only minimal site characterization is needed. While I personally feel that simple models (with simple inputs) that have the ability of capturing relevant features of hydrological systems is a worthwhile pursuit in hydrology, as noted by Sivapalan et al. (2003); the SRPF method falls far short of this goal by heavily relying on layers of assumptions that are inconsistent with the known hydrological conditions at Rainier Mesa, particularly the assumption of unsaturated flow conditions. Thus, it is my assessment that the transport predictions presented in the manuscript, especially for the continuously ponded sources at Rainer Mesa, are not scientifically defensible.

Neither the original nor revised manuscript relies on assumptions that are inconsistent with known hydrological conditions at Rainier Mesa, as elaborated in our comments below.

A further detraction from the manuscript is the SRPF model only provides the time for a single molecule (or particle) to reach a designated location. I strongly argue that this metric provides little or no information to a regulatory agency, and in reality may be counterproductive, as alarmingly fast and unjustifiable radionuclide transport rates to the water table will most likely lead agency personnel and their public constituents to overreact. I should mention here that transport distances from the test cavities to the water table at Rainier Mesa often exceed 400 vertical meters, and the authors predict this to occur in just a one month! It is well known that the transport of contaminants in geologic media will produce a broad distribution of arrival times, yet the SRPF model only addresses the arrival or breakthrough of a single molecule which in most cases, would not only be undetectable, but would not exceed the maximum contaminant level (MCL) for any contaminant that I am aware of. This leads me to ask the question: "Who is the intended audience of this manuscript?"

The source-responsive model is based on, and applicable to, physically detectable transport. The reviewer is wrong about what the model predicts; there is no mention of single-molecule detections or other physically unattainable con-

cepts in this paper or in any other publications concerning source-responsive models (Ebel and Nimmo, 2009; Nimmo, 2007; Nimmo, 2010; Nimmo, 2011).

There is a valid scientific issue in what distinguishes a detection from a nondetection, in terms of criteria for level above background, instrument noise, etc., but this is not a topic we are attempting to break new ground on. The measured data that the source-responsive model is based on, and the hypothetical detections whose probability the model is used to estimate, are in accord with acceptable standards of detectability. Thus first-arrival must be taken as the arrival of a finite quantity of material sufficient to measurably establish that transit through the medium in question has actually occurred. First-arrival time by this definition is valuable scientifically. For example by itself it is instructive about what transport paths and processes might be active. It is also valuable where the distribution of arrival times is important. Transport analyses commonly have information on computed moments of tracer arrival, but these on their own are an incomplete story. First arrival time is a valuable supplement, as in combination with average arrival times it provides important detail about the nature of the distribution of arrival times.

First-arrival time is also valuable for management purposes, especially in the context of worst-case scenarios. In this role it may have reassuring as well as alarming consequences. For example if the source-responsive model's estimated worst-case first-arrival time was 5000 years rather than one month, the results would likely be taken as reassuring rather than alarming. The potential for alarm or reassurance comes from the specific value that the model calculation produces, not on the model itself. It is absolutely essential that choice of a model not be made on the basis of what results the model gives. Selection based on the desirability of results obtained is a flagrant violation of scientific principles. A scientist must be sensitive to the practical and psychological implications of a scientific result, but it would do great harm to suppress a result,

whether alarming, reassuring, or neither, for any reason other than scientific soundness.

As to the soundness of the source-responsive model results, we believe there is sufficient explanation in our response to this and other reviewers, and the text in our revised manuscript and other publications. As to the particular worst-case scenario of a one-month travel time is consistent with directly observed travel time documented in references cited by Nimmo (2007) as well as new ones added to the revised manuscript. It should also be noted that a possible one-month worst-case travel time is presented in both the original and the revised manuscript in a probabilistic context and with appropriate qualification. Besides the order-of-magnitude agreement attendant with source-responsive model predictions (as shown in Figure 7), it is an end member of a range of possible travel times that includes values up to about 100 years. In other words, a one-month travel time is physically possible but of low probability.

The measured data that form the basis for the source-responsive model The most major violations of the SRPF conceptual model as applied to Rainier Mesa are discussed in detail below. I focus on radionuclide transport under ponded source conditions as these conditions produced the shortest maximum travel times in the manuscript.

[[Reviewer's numbered point 1] The volcanic tuffs below the test cavities for E-, N- and T-tunnel complexes are saturated. Rainier Mesa has two distinct flow systems: a laterally extensive upper zone of saturation in the Tertiary volcanics at an elevation of approximately 1800 m amsl (ER-12-3 and ER-12-4 piezometers; wells: U-12M1 UG, U-12e.03- 1, Hagestad 1, and many others) and a second zone of saturation mostly in the Paleozoic carbonates at an elevation of 1300 m amsl (ER-12-3 and ER-12-4 main completions) (Thordarson, 1965; Fenelon et al., 2006). The test cavities at E-, N-, and T-tunnel are all located well below the upper zone of saturation at 1800 m. There have not been any dry wells drilled in the Tertiary volcanics below the upper zone of saturation. This is despite the fact that the average fracture spacing in these units is quite

large, which is strong evidence that the water levels are independent on intercepting water-bearing fractures. Moreover, water level measurements collected from U-12M1 UG, U-12e.03-1, and Hagestad 1 during drilling indicate that the entire thickness of the volcanic sequence (over 300 meters), starting at Tn4 down to Tl is saturated. The only known evidence of unsaturated flow conditions below the E-, N- and T-tunnel complexes is a narrow unsaturated zone located at the contact of the base of the Tertiary volcanics and top of the Paleozoic carbonates detected during well drilling and hydrologic testing at ER-12-3 and ER-12-4 (SNJV, 2006a,b). The tunnel ponds associated with the E-, N- and T-tunnel complexes are unsaturated directly below, but this zone of unsaturation is expected to be of limited extent given the evidence above. These observations violate the number one assumption of the SRPF model - unsaturated flow.

To our knowledge, all previous investigators, agencies that conducted the nuclear tests, and the site manager (US Department of Energy) have taken test cavities of the tunnel complexes of Rainier Mesa to be in the unsaturated zone, albeit near-saturation. For example, with reference to the overall flow system at Rainier Mesa on Page 1-8 of Stoller-Navarro Joint Venture(2008b): "The RMSM CAU is hydrologically different from all the other CAUs. In this CAU, all sources are in the unsaturated zone; well above the regional water table. These sources are a result of detonations in tunnel complexes. As a result of unsaturated and/or perched conditions, two vadose zone sub-CAU models are being constructed to determine near-field uncertainty for Rainier Mesa (RM) and provide radionuclide, and water flux required, as input to the saturated zone CAU model. The different hydrologic system at RMSM required an integrated approach to capture the conceptual components in meaningful numerical models."

Note :RMSM is Rainier Mesa and Shoshone Mountain and CAU is a Corrective Action Unit, which is an administrative grouping of test locations and contamination regime.

There is perched water, with local saturation, in the vicinity of the test cavities and likely at some locations between those cavities and the regional water table in the carbonate rock, but the presence of isolated volumes of saturated rock does not render the source responsive model to be inapplicable. For it to be inapplicable on this basis would require the absence of unsaturated rock between the test cavities and the regional water table, which has not been demonstrated.

With regards to the reviewers assertion that water levels in the perched zone are "independent on intercepting water-bearing fractures", Thordarson (1965) noted that breaching a fracture in a drift in the U12e tunnel flooded the drift and caused the nearby Hagestad 1 well (see fig. 2), which is 30 m from the drift, to drop 37 m in 1962. The nature of the perched zone, described as "hummocky" by many scientific studies at the site, does not suggest a smooth potentiometric surface (as described by the reviewer), but instead points to an irregular potentiometric surface controlled by fractures.

[Reviewer's numbered point 2] Application of a non-site specific universal maximum velocity. A single value for maximum velocity of 13 m/d, obtained using the geometric mean of the continuous source cases in presented Nimmo (2007), was deemed in the manuscript to provide a "universal" maximum velocity for all media types and transport scales. I strongly reject this premise as this maximum velocity was deterministically obtained from a limited number of tracer tests at other field sites in different media, and the order of magnitude of error about this mean value precludes any reasonable level of predictive certainty. The application of a constant maximum velocity is also dependent on the presence of continuous preferential flow pathways over very large transport distances (discussed below).

Frequently, where properties or dynamics are unknown at the site of interest, to quantitatively generalize from one or more other sites with pertinent data is the best available course to follow. This practice is very common in unsaturated-zone hydrology, e.g. with property-transfer functions that incorporate data from

various sites into a database and then apply an algorithm to ascertain suitable values of characterizing properties for the site not represented in the database. Among methods and models that do this, what is unusual about the Nimmo (2007) source-responsive model is that the algorithm is just to take a single value and adjust it by a factor based on the prevailing hydrologic conditions at the site of interest. That the source-responsive model takes a single average value from the database is appropriate because the available data are few, the quantity taken has been shown to have little site-sensitivity (see our response to reviewer 1), and the level of uncertainty presently achievable in unsaturated zone travel-time predictions is too great to warrant additional complication. The paucity of hard data on unsaturated-zone travel times, especially over distances of more than a few m, does not provide a basis for a much more detailed assessment. Of course we need more data, but in the absence of that data, we should not apply schematizations more complex than our limited data can justify.

[Reviewer's numbered point 3] Lack of a proven, direct route for unsaturated preferential flow to water table. The authors explain the SRPF model in a perspective that unsaturated preferential flow is expected to occur, perhaps through different mechanisms (persistent finger flow over large distances does seem very unlikely, so unsaturated fracture flow would be the dominant choice), but key details on the actual pathways from the test cavities down to the water table are neglected in the manuscript. For example, the zeolitized tuffs below E-, N- and T-tunnel complexes are sparsely fractured (nearly all fractures are small normal faults with relatively small or nonexistent damage zones) and poorly connected (Thordarson, 1965). So, unlike other large-scale tracer tests in Nimmo (2007) in fractured media consisting of intermediate or well connected fracture networks, Rainier Mesa is a very different site. The authors ignore this and maintain that there are interred pathways through the Mesa that yield a sustainable, maximum velocity of 13 m/d.

Rainier Mesa is a minimally extended terrain, and as such, many of the faults are

not only closed to flow, but most likely do not persist from the tunnel cavities down to the water table and terminate at the argillic paleocolluvium at the base of the Tertiary sequence (Thordarson, 1965; NSTec Geologists, unpublished white paper on fault persistence). Only the largest faults are thought to extend down to the water table (NSTec Geologists, unpublished white paper on fault persistence), and the "conductiveness" of any fault planes passing through the argillic paleocolluvium remains an open question, rather than a known fact. Thordarson (1965) hypothesized that water-filled faults are closed at depth in the argillic paleocolluvium unit, and this is what enables these faults to remain saturated and not drain. Thordarson (1965) further states that the closure of faults at depths leads to an impedance (or retardation) of flow at depth, not a fast transport pathway as the authors suggest when try to justify their SRPF model. There have not been any fractures detected in cores collected from the argillic paleocolluvium unit. And, given the high clay content, any other forms of preferential flow through this unit appear unlikely. My concern here is that only the largest faults may be open at depth but this is not known with any degree of certainty, and further questions the 1 month fastest travel time predictions based on the 13 m/d constant maximum velocity.

Yes, connectedness of preferential flow paths is of major importance. Of course within the complex and heterogeneous material of Rainier Mesa is it is likely that many fractures, perhaps the vast majority, terminate without connection to other potential fast pathways, but this does not justify a statement that all preferential flow paths terminate in this way. Preferential flow by definition occurs in a very small portion of the medium, and it may occur through a very few paths that are widely-spaced but hydraulically effective. Based on what is known from sites with better information on transport paths than presently exists for Rainier Mesa, it is highly likely that within the approximately 1 km3 of rock between the level of the test cavities and the carbonate aquifer there exist at least a small number of preferential flow paths that traverse the vertical distance.

Where there are few paths, at many sites it is clear that lateral preferential flow

may develop to conduct water eventually to a vertical preferential flow path that goes further downward. If there is no preferential flow path connecting tunnels with carbonate aquifer, that would mean that somewhere below tunnel level there is an encapsulating layer in which all fractures are isolated from each other, that would extend essentially unbroken throughout a horizontal plane. This is unlikely, for example based on the evidence from Thordarson, that some fractures were filled with water and some were not. It is possible, perhaps likely, that unfilled fractures are major preferential flow paths. Source-responsive preferential flow may occur primarily along the walls of fractures that are not completely water-filled (Nimmo, 2010).

There is mixed evidence regarding the presence and interconnectedness of faults and fractures in the zeolitized tuffs. As noted by Russell et al. (2001): "The only unit not appreciably fractured is the friable tuff of the Paintbrush Formation" Note: The friable tuff is the vitric tuff.

With reference to U12t tunnel water inflow from fractures, from page 2-12 in National Security Technologies, LLC (2007) states: "Significant volumes of water (more than a few gallons per minute) were encountered during mining of the T-Tunnel complex at only two locations, one in the main access drift, approximately 610 m (2,000 ft) from the portal, and the other near the terminus of the bypass drift in the U12t.03 complex. However, large volumes of water (more than 1,514 lpm [400 gpm]) were encountered during the drilling of several horizontal exploratory holes located northwest of the drifts. The water was determined to be flowing from fault and fracture systems located entirely beyond the open drifts, which were interconnected over distances of greater than 30 m (100 ft)."

With reference to the overall hydrologic system at Rainier Mesa and Shoshone Mountain, from Page 2-29 of Stoller-Navarro Joint Venture(2008b): "The construction of underground nuclear tests and associated tunnels significantly disturbed the natural hydrologic system. Once isolated fracture zones, are now

connected by the tunnel workings, and connectivity of the perched zones is increased beyond the tunnels due to testing induced fracturing. The result is the potential for significant lateral movement of groundwater from one high conductivity vertical conduit to another; challenging the concept of strict vertical infiltration beneath the test cavities."

In reference to the effects of nuclear tests on fracture preferential flow paths, see Figure 2-4 in National Security Technologies, LLC (2007), which is a map of the surface expressions of fractures from underground tests, showing that test-induced fractures extend distances of hundreds of meters in the subsurface.

Clearly there is substantial fracturing from tectonics and nuclear testing at Rainier Mesa and the spatial extent of these fractures makes some connectivity likely.

With respect to the reviewers statement: "Rainier Mesa is a minimally extended terrain, and as such, many of the faults are not only closed to flow, but most likely do not persist from the tunnel cavities down to the water table and terminate at the argillic paleocolluvium at the base of the Tertiary sequence"

Page 1-7 from National Security Technologies, LLC (2007) states: "The more recent large-scale extensional faulting in the NTS area is significant because the faults have profoundly affected the hydrogeology of the Tertiary volcanic units by controlling to a large extent their alteration potential and final geometry. In addition, the faults themselves may facilitate flow of potentially contaminated groundwater from sources in the younger rocks into the underlying regional aquifers.."

With respect to the argillic paleocolluvium, reliance on this unit as a complete barrier to flow is questionable. For example, Page 4-1 of Bechtel Nevada (2006) states that:

"The volcanic rocks at Rainier Mesa are draped unconformably over an irregular substrate of Paleozoic and late Precambrian sedimentary and Mesozoic intrusive rocks (SNJV, 2004)."

Page 4-12 of Bechtel Nevada (2006) states:

"The base of the volcanic section at Well ER-12-3 consists of 9.4 m (31 ft) of mostly argillic bedded tuff that lies directly on Paleozoic dolomite."

Page 4-19 of Stoller-Navarro Joint Venture (2006a) states:

"Well ER-12-4 penetrated interbedded tuffaceous siltstone and bedded tuff with intercalated coal beds from 674.2 to 688.8 m (2,212 to 2,260 ft). The siltstone is argillic and laminated, and the bedded tuffs are zeolitic and argillic. Beneath this, a 69.5-m (228-ft) thick interval of tuffaceous paleocolluvium was encountered to 758.3 m (2,488 ft). Stratigraphically, this entire section from 674.2 to 758.3 m (2,212 to 2,488 ft) is designated as paleocolluvium."

This makes the minimum variability of the argillic section thickness between 9.4 to 84.1 m thick, illustrating the large variability in the thickness of this unit, given that it is "draped unconformably over an irregular substrate of Paleozoic" rocks, there may even be gaps where the argillic unit is completely absent or very thin, and thus is not a complete barrier to flow everywhere at Rainier Mesa.

Geochemical evidence reported by Stoller-Navarro Joint Venture (2006d), quoted below:

"The chlorine-36/Cl (36Cl/Cl) ratio reported by LLNL, 5.39 x 10-13, is in the range of the modern atmospheric ratio for southern Nevada (Fabryka-Martin et al., 1993) but greater than that observed for groundwaters of the LCA3 in Yucca Flat (SNJV, 2006a). The strontium-87/86 (87Sr/86Sr) ratios of 0.71055 and 0.71034 are in general lower than observed in Yucca Flat LCA3/LCA groundwater (SNJV, 2006a). The elevated 36Cl/Cl and lower 87Sr/86Sr suggest mixing of groundwater

of the LCA3 with that of the overlying volcanic aquifer (LLNL, 2006)."

This data suggests that some water is making it through the volcanics (i.e. through the argillized unit at the base of the zeolitized tuffs) to the carbonate aquifer, possibly via fracture flow.

It is the authors opinion that the conclusion that ALL faults or fractures are closed at the argillic paleocolluvium is not supported by available evidence.

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Interactive comment on Hydrol. Earth Syst. Sci. Discuss., 7, 3879, 2010.

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