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Balancing practicality and hydrologic realism: A parsimonious approach for simulating rapid groundwater recharge via unsaturated-zone preferential flow

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[1] The impact of preferential flow on recharge and contaminant transport poses a considerable challenge to water-resources management. Typical hydrologic models require extensive site characterization, but can underestimate fluxes when preferential flow is significant. A recently developed source-responsive model incorporates film-flow theory with conservation of mass to estimate unsaturated-zone preferential fluxes with readily available data. The term *source-responsive* describes the sensitivity of preferential flow in response to water availability at the source of input. We present the first rigorous tests of a parsimonious formulation for simulating water table fluctuations using two case studies, both in arid regions with thick unsaturated zones of fractured volcanic rock. Diffuse flow theory cannot adequately capture the observed water table responses at both sites; the source-responsive model is a viable alternative. We treat the active area fraction of preferential flow paths as a scaled function of water inputs at the land surface then calibrate the macropore density to fit observed water table rises. Unlike previous applications, we allow the characteristic film-flow velocity to vary, reflecting the lag time between source and deep water table responses. Analysis of model performance and parameter sensitivity for the two case studies underscores the importance of identifying thresholds for initiation of film flow in unsaturated rocks, and suggests that this parsimonious approach is potentially of great practical value.

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1. Introduction

[2] Field observations of rapid water table rises indicate that unsaturated-zone preferential flow can contribute substantially to groundwater recharge [*Lee et al.*, 2006; *Heppner et al.*, 2007; *Gleeson et al.*, 2009; *Cuthbert and Tindimugaya*, 2010]. This important process is rarely given physically realistic treatment in mathematical models of flow and transport. In unconfined aquifers, observed water table fluctuations can be used to quantify recharge [*Healy and Cook*, 2002; *Heppner and Nimmo*, 2005; *Cuthbert*, 2010]. These empirical water table fluctuation methods incorporate the impact of both preferential and diffuse flow processes into an area-averaged estimate of unsaturated fluxes. Although sensitive to preferential flow, water table fluctuation methods do not treat it explicitly and generally are not applicable for predicting recharge under a given set of environmental forcing conditions. Explicit treatment of preferential flow in a predictive model would be of great practical value for land and water resources management decisions, especially in the context of dealing with problems of contaminant transport and climate change impacts.

[3] Typical physically based hydrologic models employ numerical solutions for the Darcy-Buckingham formulation of the variably-saturated flow equation to simulate subsurface fluxes, which presents three major problems. First, adequate parameterization and evaluation of this type of model requires substantial data inputs that are essentially never available for operational applications [*Loague and VanderKwaak*, 2004]. Second, when sufficient data are available robust parameter estimation can be computationally expensive and the model user may still struggle with issues related to parameter identifiability, correlation, and heterogeneity [*Vrugt et al.*, 2002; *Hill and Tiedeman*, 2007; *Mirus et al.*, 2009]. Third, the flow equation relies on the assumption that capillarity dominates unsaturated fluxes, so it represents entirely diffusive flow behavior. The implication of this "diffuse flow" assumption is that even when treated explicitly, preferential flow networks do not activate until the air-entry values of these larger pores are exceeded. Thus, preferential flow is only simulated once the porous medium is nearly or completely saturated. However, numerous observations document preferential flow under far-from-saturated conditions [*Nimmo*, 2012]; as a

Additional supporting information may be found in the online version of this article.

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result, simulations often underestimate unsaturated fluxes of water and the solutes transported by advection. Without full knowledge of heterogeneity in the subsurface, highly parameterized deterministic models present the user with the often insurmountable challenge of being right for the right reasons [*Klemes*, 1986; *Loague and VanderKwaak*, 2004; *Kirchner*, 2006].

[4] The evidence for unsaturated-zone preferential flow is considerable and there is a need to improve quantitative understanding of this important process [*Nimmo*, 2012]. Several alternative mathematical formulations of unsaturated flow have been developed to address the prevalence of nondiffusive, nonequilibrium flow processes observed in natural and laboratory settings [*Rasmussen et al.*, 2000; *Ross and Smettem*, 2000; *Nimmo*, 2007, 2010a; *Peters and Durner*, 2008; *Vogel et al.*, 2010; *Or and Assouline*, 2011]. Although the need for such paradigm shifts and supplements to the Darcy-Buckingham formulation is becoming more widely accepted, these approaches have not been thoroughly tested for a range of practical applications.

[5] The primary objective of this work is to present the first rigorous testing of the source-responsive fluxes model, which was developed [*Nimmo*, 2007, 2010a] and modified here to provide a parsimonious, but physically realistic treatment of unsaturated preferential flow processes. We use two case studies not considered previously by *Nimmo* [2007, 2010a] to quantitatively evaluate practical applications of the model with limited data. Both case studies are in arid environments with deep vadose zones where simple, low-cost assessments of preferential flow are needed to inform land and water resources management decisions. Previous applications of source-responsive theory have highlighted several areas where the hydrologic realism of the model could be enhanced [*Nimmo*, 2010a, 2010b; *Mirus et al.*, 2011], which we now account for in the equations for source-responsive fluxes. A secondary objective of this study is to assess the value of these modifications to the model equations and identify additional data needed to further improve process representation.

2. Source-Responsive Model

[6] The term *source-responsive* is used to describe the observation that preferential flows respond sensitively to changing conditions at the source of water input [*Nimmo*, 2007]. The recently developed source-responsive fluxes model [*Nimmo*, 2010a] provides the framework for considering unsaturated porous media as a dual domain of slow matrix flow and rapid preferential flow. Within the matrix domain, capillary forces dominate; in the source-responsive domain, gravity-driven laminar films flow preferentially through a network of larger, more connected macropores or fractures. Film flow has been observed in discrete, unsaturated fractures under controlled laboratory conditions [*Tokunaga and Wan*, 1997; *Su et al.*, 2003] and film-flow theory can be used to explain other observed phenomena that are not consistent with traditional diffuse-flow theory [*Nimmo*, 2010a]. Although the source-responsive approach relies on several notable simplifying assumptions [*Germann*, 2010], the resulting parsimony of the model is advantageous in the common situation where characterization of the subsurface porous media is limited [*Nimmo*, 2010b]. In particular, the approach emphasizes the importance of variations in the supply of water for infiltration, for which measured data are often readily available.

[7] The characteristic film-flow velocity V_u [L T^{-1}] and film thickness L_u [L] have previously been assumed uniform and constant with values of 13 m d^{-1} and 10^{-6} m, respectively [*Nimmo*, 2007, 2010a; *Mirus et al.*, 2011]. This assumption was justifiable for these proof-of-concept simulations for individual recharge events because preferential flow velocities vary over a smaller range than diffuse flow. However, film thickness and velocity should vary, albeit over a relatively narrow range [*Germann*, 2010; *Nimmo*, 2010b]. Therefore, for the continuous simulations presented here we now allow V_u and L_u to vary with the laminar film-flow relation [*Bird et al.*, 2002], which we combine with equation (24) from *Nimmo* [2010a] to describe source-responsive preferential fluxes with variable velocity and film thickness as:

$$q(z,t) = V_u^{1.5}\sqrt{3\frac{\nu}{g}}M(z)f(z,t), \tag{1}$$

where q [L T^{-1}] is the flux density at depth z [L] and time t [T]; g [L T^{-2}] is the gravitational acceleration (9.81 m s^{-2}) and ν [L^2 T^{-1}] is the kinematic viscosity of water (assuming a temperature of 20°C, equal to 10^{-6} m^2 s^{-1}); M [L^{-1}] is the macropore facial area density; f [$-$] is the active area fraction. The macropore facial area density M is the surface area per unit volume of potential preferential flow paths, which is a property of the porous medium describing its capacity for transmitting preferential flow; it remains constant through time. The active area fraction f indicates the degree to which the available preferential flow paths are activated, and varies between values of f=0 when no preferential flow occurs, and f=1 when the preferential flow paths are completely activated. In using an activation concept related to the proportion of flow paths conducting at any particular time, this model has similarities to the active fracture model proposed by *Liu et al.* [1998].

[8] When simulating recharge and deep water table fluctuations, information regarding the distribution of fluxes and states in the overlying vadose zone are rarely available. Variations in preferential fluxes from the land surface z_{ls} [L] to the depth of the water table z_{wt} [L] are not considered explicitly, so the source-responsive flux $q(z,t)$ in (1) is integrated over the vertical profile, such that variations in M and f with depth can be ignored for a given recharge event. Assuming that the region of the profile with the lowest capacity for preferential flow presents the limit to the source-responsive flux from z_{ls} to z_{wt} (i.e., the bottleneck), we replace the function $M(z)$ with a constant value for the limiting macropore facial area density M_{lim}. Similarly, only temporal variations in $f(z_{wt},t)$ are considered, which are related to the temporal variations in the availability of water at the land surface (e.g., ponding, precipitation, streamflow transmission losses). Functional relations between the availability of the source of recharge $SR(z_{ls}, t)$ and the active area fraction of preferential flow pathways connecting to the water table $f(z_{wt},t)$ reflect a lag time t_{lag} [T] where:

$$t_{\text{lag}} = \frac{z_{wt} - z_{ls}}{V_u} \quad \text{or} \quad V_u = \frac{z_{wt} - z_{ls}}{t_{\text{lag}}}, \tag{2}$$

such that:

$$f(z_{wt}, t + t_{\text{lag}}) \propto SR(z_{ls}, t). \tag{3}$$

The basic formula relating recharge flux to water table fluctuations is:

$$\frac{\Delta H}{\Delta t} = \frac{q(z_{wt}, t)}{S_y} - \frac{H}{\tau}, \tag{4}$$

where H is the hydraulic head [L] above the hydrologic base level H_o [L], S_y is the specific yield [−], and τ is the linear master recession constant [T] derived from site-specific regression analysis [*Heppner and Nimmo*, 2005; *Heppner et al.*, 2007]. The datum H_o is selected for equation (4) so that in the absence of recharge (other than a small steady component) simulated water levels do not drop below the hydrologic base level.

[9] Over the time scales relevant to most observations of rapid water table responses, diffuse recharge fluxes through the unsaturated matrix can be considered negligible, and are set to zero. Thus, we assign the land surface as $z = 0$ and substitute equations (1) and (2) into equation (4) to produce a formula for water table fluctuations, where recharge occurs via source-responsive accretion and recession from diffuse saturated flow:

$$\frac{\Delta H}{\Delta t} = \frac{\left(\frac{z_{wt}}{t_{\text{lag}}}\right)^{1.5} \sqrt{3\frac{\nu}{g}} M_{lim} f(z_{wt}, t)}{S_y} - \frac{H}{\tau}. \tag{5}$$

Solution of equation (5) through time facilitates the direct comparison of simulated and observed water table fluctuations $H(t)$ required for the standard calibration and evaluation of any hydrologic model.

2.1. Model Implementation

[10] Estimation of M_{lim} and alternative functional relations between f and SR represent the degrees of freedom and greatest sources of epistemic uncertainty in applying the SR fluxes model. The parameter τ, representing the saturated zone recession [*Heppner and Nimmo*, 2005], is not directly tied to source-responsive theory, but is employed to approximate water table decline and allow continuous simulation of the water table fluctuations. The value of S_y can be taken from published pump tests in the hydrogeologic unit of interest. Recharge sources $SR(z_{ls}, t)$ can include records of precipitation intensity and duration [*Nimmo*, 2010a], streamflow [*Mirus et al.*, 2011], or an assessment of the soil-water balance [*Cuthbert et al.*, 2013], which are used to define $f(t)$ in equation (3). For the case studies reported here, we use the following generalized steps for model parameterization, with a commonly used split sample approach for calibration and performance evaluation:

[11] 1. Assign t_{lag} as the mean observed time between the source of recharge SR and the observed response $\Delta H > 0$.

[12] 2. Assign functional relation between f and SR in equation (3), based on known or inferred controls on recharge for the site of interest [see *Nimmo*, 2010a] and the observed t_{lag}.

[13] 3. Calibrate M_{lim} and τ to minimize root mean square error (RMSE) between simulated and observed water levels using the calibration subset of the data.

[14] 4. Calculate RMSE for the evaluation subset of the observed water level data to assess the performance and predictive capability of the calibrated model.

[15] 5. Conduct global sensitivity analysis using all available response data from both steps 3 and 4, compare optimal M_{lim} and τ values, and RMSE for all available data to those derived from calibration and evaluation steps.

[16] The range of observed velocities for source-responsive film flow varies modestly under continuous water input; for 64 test cases *Nimmo* [2007] reports a range of 1.3–130 m d^{-1}, which is confirmed by an additional 48 test cases identified by *Ebel and Nimmo* [2012]. For the source-responsive fluxes model, the V_u value can be evaluated on a case by case basis for different applications using the minimum and maximum observed t_{lag} in place of the average value. The corresponding influence of variable V_u is relatively small, which is consistent with observed variability in film thicknesses and flow velocities [*Nimmo*, 2010b]. The range of M values used in previous applications include 60 m^{-1} [*Mirus et al.*, 2011], 500 m^{-1} [*Cuthbert et al.*, 2013], and 4000 m^{-1} [*Nimmo*, 2010a]. Water table recession rates can range from meters per day to meters per decade, which correspond to τ values of 24–87,000 h. In step 5, the calibration and evaluation in steps 3 and 4 are further examined through the sensitivity of RMSE to individual perturbations in M_{lim} and τ for a range of reasonable values (10–10^6 for both parameters). We use this sensitivity analysis in step 5 to identify the global optimum parameter values with all data, which we compare to model performance for the calibration and evaluation periods, as proposed by *Flipo et al.* [2012]. Although step 1 relies on the model user's intuition and knowledge of the system, if the RMSE and optimal parameter values in steps 3 and 5 are similar, then the rules for equation (4) can be used with some confidence.

3. Case Study Applications

[17] We selected two case studies, one at Idaho Nuclear Technology and Engineering Center (INTEC) and the other at Rainier Mesa (RM) in Nevada because they represent similar geologic conditions where assessment of preferential flow is needed to inform water-resources management. While there are substantial data from the vadose zone below INTEC [see *Mirus et al.*, 2011], minimal site-specific data at RM are available to assist decision makers [see *Ebel and Nimmo*, 2012]; contrasting the two sites is useful for evaluating model utility and data needs. Further information on the hydrogeologic setting and previous application of source-responsive theory at both INTEC and RM are provided in the supporting information.

3.1. Idaho Nuclear Technology and Engineering Center (INTEC)

[18] Building upon the preliminary event-based simulations and the conceptual model for the unsaturated zone beneath INTEC reported by *Mirus et al.* [2011], we used newly available data and equation (5) for continuous

simulations of water table dynamics. There were eight discharge events in the Big Lost River (BLR), which contributed to rapid rise in the neighboring piezometer at BLR-CH (see Supplementary material) during the period of record from 2005 through 2012. Given that mean observed t_{lag} between these discharge events and water table response of 5 days and that z_{wt} is 40 m, then $V_u = 8$ m d^{-1} and $L_u = 5$ μm, which is well within the realistic range discussed by *Nimmo* [2010b]. We used the same functional relation between *SR* and *f* from *Mirus et al.* [2011], which applies a step function of the daily BLR discharge Q_{BLR} [L^{-3} T^{-1}] measured at Lincoln Blvd. By including the time lag in equations (2) and (3), the time series assigned for *f(t)* becomes:

$$\begin{array}{lll} \text{If } Q_{\mathrm{BLR}}(t) = 0 & \text{then} & f\left(t + t_{\mathrm{lag}}\right) = 0 \\ \text{If } 0 < Q_{\mathrm{BLR}}(t) > 50\,\text{cfs} & \text{then} & f\left(t + t_{\mathrm{lag}}\right) = 0.5 \\ \text{If } Q_{\mathrm{BLR}}(t) > 50\,\text{cfs} & \text{then} & f\left(t + t_{\mathrm{lag}}\right) = 1.0 \end{array} \quad (6)$$

We set the initial water level equal to the base of the screened interval in well BLR-CH, which is coincident with the base of the well and the top of the shallow perching unit.

[19] We calibrate the M_{lim} and τ values to minimize root mean square error (RMSE) using all water level measurements from the period between January 2005 and December 2008, then evaluate the simulations using the RMSE calculated for the previously unavailable period of record from January 2009 to September 2012. Finally, we conduct the sensitivity analysis of RMSE to perturbations in M_{lim} and τ values with data from 2005 to 2012. The continuous simulation results in Figure 1 shows that the model captures the important observed recharge events. The results of the sensitivity analysis are shown in Figure 2, which shows that a clear global minimum RMSE was reached for unique values of M_{lim} and τ with no strong indication of parameter correlation. The model performance statistics are given in Table 1, which shows that the optimal M_{lim} and τ values

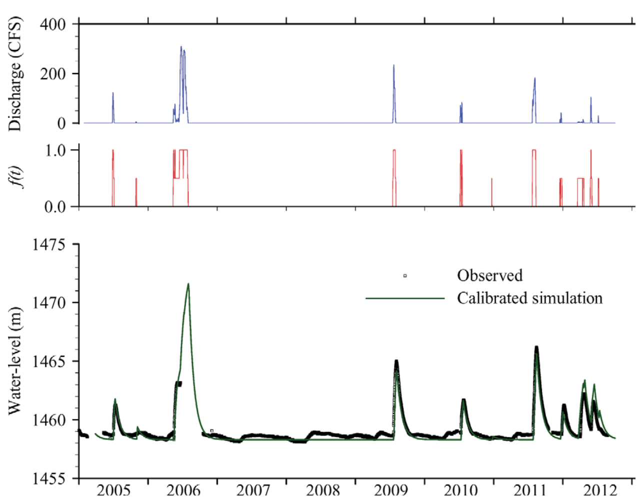

Figure 1. Continuous time series of discharge in the Big Lost River at Lincoln Blvd., the corresponding active area fraction parameter calculated with equation (6), and observed versus simulated water table fluctuations in monitoring well BLR-CH.

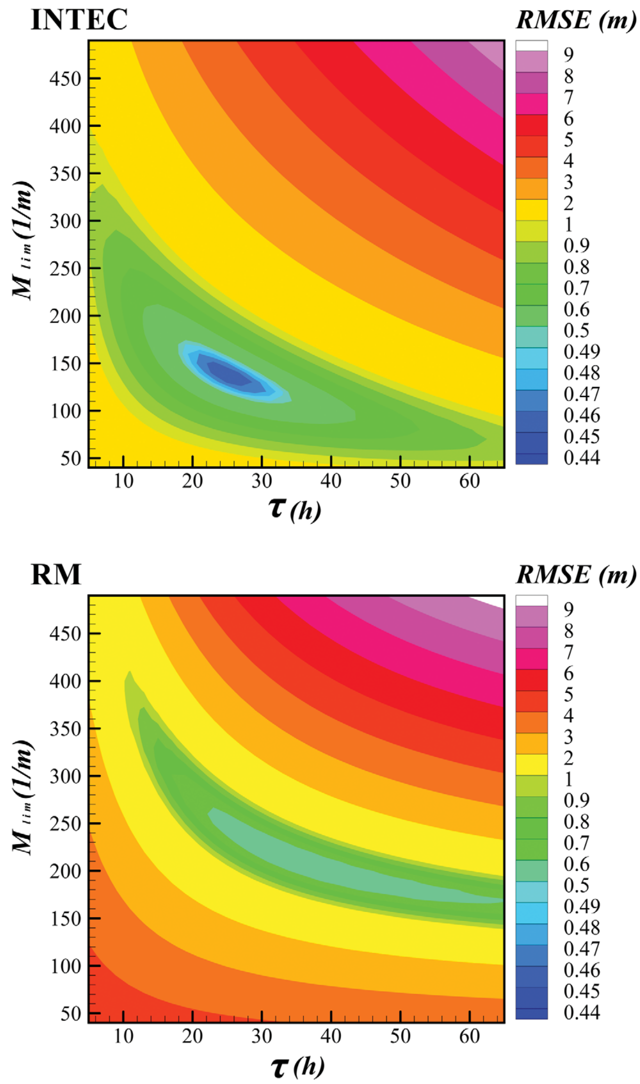

Figure 2. Contour plots showing a detail of the objective functions (around the minimum RMSE values) from the sensitivity analysis with parameters M_{lim} and τ for the Idaho Nuclear Technology and Engineering Center (INTEC) and Rainier Mesa (RM).

for the entire period of record are similar to the calibrated model values and produce similar RMSE for the entire continuous simulation. The calibration produced good model performance for the evaluation period, illustrating the potential predictive capability of the model. Although the small diffuse flow component of recharge associated with annual spring snowmelt occurring in March [see *Mirus et al.*, 2011] is clearly not captured by the continuous simulations, this component of the recharge is less significant at the BLR-CH location. Therefore, the simplifying assumption that water table rise is due chiefly to source-responsive flow applied in equation (5) is reasonable for this application at INTEC.

3.2. Rainier Mesa (RM)

[20] Building upon the conceptual model of the vadose zone below RM reported by *Ebel and Nimmo* [2009], we used the USGS records reported by *Elliot and Fenelon*

Table 1. Model Parameter Values and Performance Statistics for Simulations at Both Idaho Nuclear Technology and Engineering Center (INTEC) and Rainier Mesa (RM)

Location	Simulation	M_{lim} (m^{-1})	τ (d)	Years	Calibration	Evaluation	Sensitivity	RMSE (m)[a]
INTEC								
	Calibrated model	132	27	2005–2009	x			0.31
				2009–2012		x		0.54
				2005–2012	x	x		0.45
	Global optimum	143	24	2005–2012			x	0.44
RM								
	Calibration							
	ER-12-1	164	1706	1993–2002	x			0.39
				2003–2012		x		1.73
				1993–2012	x	x		1.25
	ER-12-3			2005–2012		x		0.61
	ER-12-4			2005–2012		x		0.53
	Global optimum							
	ER-12-1	118	3971	1993–2012			x	0.52
	ER-12-3	118	1555	2005–2012			x	0.16
	ER-12-4	92	2752	2005–2012			x	0.16

[a]Root mean square error, RMSE $= \sqrt{\sum_{i=1}^{n} (O_i - P_i)^2 / n}$.

[2011] and equation (5) to simulate continuous water table dynamics. Water levels are measured manually at roughly 2–3 month intervals in three different wells, all screened within intervals of the primary aquifer of concern below RM: ER-12-1, ER-12-3, and ER-12-4 (see supporting information). The continuous period of record for ER-12-1 is from 1993—present, with a large gap in 1993–1994. The records for ER-12-3 and ER-12-4 are more limited, beginning in 2005. The recharge sources to the aquifers beneath RM are precipitation and snowmelt, which percolate into the subsurface diffusely through the soil, or in focused areas along topographically convergent areas. Upon reaching the bedrock interface, recharge has the potential to travel rapidly through connected fractures networks in the bedrock. There were only two periods of rapid water table rise in the observed records, both of which occur approximately 1 year after wet winters in 1995 and 2005–2006. Thus, we employed a t_{lag} of 365 days. Given that z_{wt} is 470 m for well ER-12-1, equations (2) and (3) result in $V_u = 1.3$ m d^{-1} and $L_u = 2$ µm, which is at the lower end of the expected range for film thickness and velocity discussed by *Nimmo* [2010b].

[21] Given the absence of ET data and the uncertainty in timing of snowmelt, runoff, and infiltration at RM, the best available information to estimate the time series for $f(t)$ are the precipitation records measured at RM for two locations [National Oceanic and Atmospheric Administration, 2010]. We linearly scaled the monthly precipitation totals $P(t)$ [L] by the maximum monthly precipitation $P_{\max}$ in the observed records and add the shift introduced by the characteristic lag time t_r to yield the simple function:

$$f(t) = P(t{-}t_r)/P_{\max} \tag{7}$$

[22] Given the depth to the water table (hundreds of meters below the surface) and the difficulty in constraining the physical controls on infiltration, this parsimonious representation of the active area fraction is preferable to using higher temporal resolution precipitation data or another more complex relation. Equation (7) reflects a simplification of the general observation that during wetter periods, precipitation is more likely to exceed evaporative demands and promote percolation below the root zone [*DeMeo et al.*, 2006]. This allows a monthly calculation of water table fluctuations, which is of greater temporal resolution than the available records of $H(t)$. For the preliminary simulations reported here, the initial head was set equal to the most recent reliable observation. The values for M_{lim}, and τ are calibrated to minimize RMSE using the observed water level dynamics for ER-12-1 between 1993 and 2002. We then evaluate the calibrated model using the remaining measurements from 2003 to 2012 for ER-12-1, as well as for all measurements from ER-12-3 and ER-12-4. Finally, we conduct a sensitivity analysis to evaluate RMSE for a broad parameter space using all available data for ER-12-1.

[23] The continuous simulated and observed water levels for wells ER-12-1, ER-12-3, and ER-12-4 between 1993 and 2012 are shown in Figure 3 for both the calibrated model and for the global optimum values identified in the sensitivity analysis for all three wells. The sensitivity

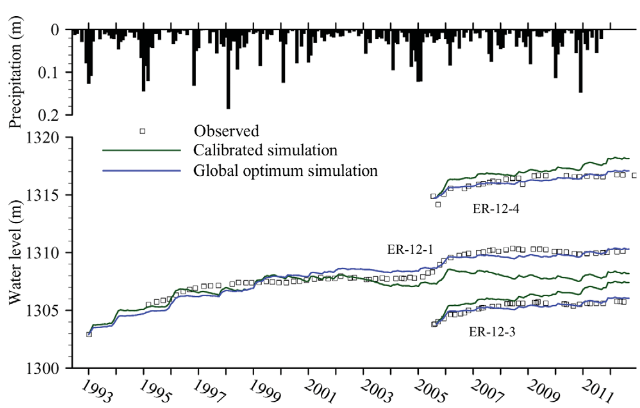

Figure 3. Continuous time series of the precipitation hyetograph at Rainier Mesa, and observed versus simulated water table fluctuations in monitoring wells ER-12-1, ER-12-3, and ER-12-4. Green line indicates the calibrated simulation and blue line indicates the simulations optimized with all available data for each well.

analysis (Figure 2) identified a broad minimum in the objective function, indicating that some parameter correlation may be possible. The model performance statistics are given in Table 1, which indicate that the calibrated model produces a substantially higher RMSE for the entire simulation period than for the global optimum. Additionally, global optimum M_{lim} and τ values for each well vary considerably from the calibrated model values (Table 1). The model consistently captures the rapid water table rises following wet years, but performs poorly for the evaluation period of the observed record (Table 1 and Figure 3). It is unclear why the observed water levels in ER-12-1 appear to be gradually increasing over the entire 19 year period, since climate records do not indicate that average annual precipitation has increased over the past two decades.

[24] Simulations for all three wells show stronger rises in water level in 2010–2011 and 2011–2012 than were observed in the actual wells, which along with the predicted rise in 1998–1999 that was not observed in ER-12-1, suggests that the simple function for $f(t)$ in equation (7) could be improved considerably. The calibrated model performance for ER-12-3 and ER-12-4 is fair, but examination of Table 1 and Figure 3 reveals that much better model performance is possible for these two wells. Given that the relatively short period of record has only one major water table rise, it is difficult to establish parameter values with much certainty for any numerical model, though the simplicity of the source-responsive model is consistent with the availability of data at RM. Disparities between model performance and the optimal parameter values for the three wells (Table 1) are not surprising given the simplified formulation of $f(t)$ and the uniform M_{lim} value, which was calibrated with data from ER-12-1 only. The three wells are several kilometers apart (see supporting information) and the subsurface below RM exhibits considerable heterogeneity, so the variability between these three wells likely reflects local variations in subsurface properties and flow paths controlling M_{lim}, τ, and even S_y values.

4. Discussion

[25] The parsimonious formulation of the source-responsive model presented here was developed to simulate water table fluctuations and recharge fluxes in situations where preferential flow is important and available data are limited. The simplifying assumptions employed in the model are tied together in equations for water table fluctuations [*Heppner and Nimmo*, 2005], source-responsive fluxes [*Nimmo*, 2010a], and our incorporation of a variable film-flow velocity and thickness in equations (1) through (5). The implementation of active area fraction described in equations (6) and (7) is arguably somewhat subjective, but the split sample calibration and evaluation routine in combination with the sensitivity analysis provide some quantitative basis for evaluating confidence in $f(t)$.

4.1. Application and Testing with Data-Rich and Data-Poor Cases

[26] Both INTEC and RM are characterized by deep vadose zones comprised of volcanic rocks with low-permeability matrix and an extensive fracture network, so relatively slow interaction between the diffuse flow and source-responsive flow domains is expected. In contrast to the high-frequency measurements at INTEC, the manual water table measurements at RM are too infrequent to consider simulations with greater temporal resolution than the monthly time step we employ here. The case study at INTEC thus provides considerably stronger support for the assumption that preferential flow is the dominant recharge process. For RM the deeper, more complex unsaturated zone, and the longer response time suggest that greater interaction between the matrix and preferential flow domains is likely. Moreover, the lack of a discrete recharge events distinguished at RM increases the difficulty in applying any model for this site. Compared to the eight discrete flow events in the BLR and the corresponding water table rise and declines observed at INTEC, there were no major water table declines observed at RM. The differences between these two datasets are also reflected by the different levels of confidence in parameter values for the two sites (Figure 2).

[27] Techniques for direct measurement of $f(t)$ or M_{lim} are not available, though constraints on reasonable M_{lim} values could be approximated with simple geometry and field measured fracture densities. As shown with the INTEC case study, with adequate information to assign $f(t)$, parameter correlation and identifiability of M_{lim} and τ are not a problem. The upper bound on M_{lim} for a given setting must be a function of the available pore space for source responsive flow, and some quantitative relations may exist between M_{lim} and S_y for different types of porous media.

[28] Both case studies illustrate that the delay between water table response and activity of the recharge source is adequately accounted for with a variable lag time t_{lag}. The simplifying assumptions works particularly well in the case of INTEC, perhaps in part because the timing and magnitude of the recharge source (i.e., streamflow in the BLR) is well constrained. Regardless, the contrasting values of M_{lim} and t_r for INTEC and RM (Table 1) are physically consistent with the conceptual understanding of the different flow systems. The higher optimum M_{lim} value at INTEC compared to RM (Table 1) suggests the fracture network through the basalt is more continuous and connected, whereas the complex hydrogeologic layering and the presence of possible impeding layers at RM [see *Ebel and Nimmo*, 2009] are likely to limit the connectivity of unsaturated preferential flow paths to the underlying water table. The lower V_u value at RM compared to INTEC (1.3 versus 8 m d^{-1}, respectively) demonstrates that inclusion of a variable film-flow velocity is a necessary development of the source-responsive model, particularly for deep vadose zones.

4.2. Comparison to Diffuse Flow

[29] The speed of water table responses to temporal variations in the source of water inputs suggest that at both INTEC and RM unsaturated-zone preferential flow is a more important process in controlling recharge than diffuse flow. In both case studies, the bedrock above the water table remains in an unsaturated state during and between episodes of recharge. For example, tensiometer measurements at INTEC show that just above the shallow perched zone matric potentials are on the order of -1 m before and after recharge events [see *Mirus et al*., 2011], equivalent to the

air-entry value for a pore of roughly 15 μm radius and considerably smaller than the large pores within the fractured basalt. Second, the water table fluctuations in Figures 1 and 2 represent recharge traveling at fast velocities of 8.0 m d^{-1} and 1.3 m d^{-1}, respectively, yet the specific fluxes are of relatively small magnitude. For example, given a specific yield of 0.01 measured at INTEC [*Johnson et al.*, 2002] and equation (4), the 3 m water table rise over 9 days associated with the BLR flow event in 2005 corresponds to a vertical unsaturated-zone flux density on the order of 3×10^{-3} m d^{-1}.

[30] Given these observations, the application of diffuse flow theory to vertical fluxes at INTEC can be evaluated analytically. Assuming the recharge flux is equivalent to the velocity multiplied by the effective mobile water content [*Scanlon et al.*, 2002], the observed velocity and flux requires an effective mobile water content of less than 0.0004. Albeit possible, diffuse flow traveling with such low-mobile water content is very unlikely to propagate so quickly as a uniform wetting front. It is more reasonable to consider this small volume of mobile water to be traveling preferentially in sparse films along the connected pores, as proposed by source-responsive theory. Similarly, we also used these same observations from INTEC in combination with a numerical model and an inverse algorithm to demonstrate that Richards' equation cannot adequately capture the rapid water table response (see supporting information).

[31] The simple calibration of the two primary parameters of the source responsive model is considerably less computationally demanding than estimating the handful of parameters necessary for even a homogeneous single-layer Richards' equation model. While the source-responsive model has yet to be evaluated with solute transport data, it allows more physically realistic representation of unsaturated preferential flow and can be combined with traditional theory for diffuse flow [*Nimmo*, 2010a]. Such a coupled model could limit the problematic aspects of simulating contaminant transport with the incomplete flow physics embodied by Richards' equation alone.

4.3. Perspectives and Future Directions

[32] Until now, the source-responsive model has not been rigorously tested with a quantitative calibration, evaluation, and sensitivity analysis. Relative to previous applications of source-responsive theory [*Nimmo*, 2010a; *Mirus et al.*, 2011; *Cuthbert et al.*, 2013], our use of variable film-flow velocity and thickness is more physically realistic and allows approximation of the lag time between recharge source and water table response that are particularly important to capture in deep vadose zones. Where it can be established that diffuse flow alone is unlikely to govern all recharge processes and that preferential flow could dominate, the parsimonious model can be employed in a continuous mode over decadal time scales. The contrasting model performance for the case studies at INTEC and RM illustrate that confidence in the model ultimately relies on the detail with which the timing and relative magnitude of the recharge source can be constrained to parameterize $f(t)$. Additionally, water-level sampling frequency must adequately capture rapid water table rises and gradual declines. Despite relatively poor quantitative characterization of recharge and water table dynamics at RM, the simple treatment of $f(t)$ using only precipitation could allow the parsimonious formulation of the model to be of widespread practical value, since some form of precipitation data are virtually always available.

[33] Preferential flow presents a major challenge to parameterization and evaluation of commonly used hydrologic models of unsaturated flow. The parsimonious source-responsive model provides a practical tool for estimating a physically reasonable upper bound on possible recharge and advective contaminant transport fluxes for a given site. At INTEC the detection of radionuclides in the perched zones and underlying aquifer, including increasing levels of Iodine-129 [*Bartholomay*, 2009], highlight the importance of improving capability for quantifying preferential flow and incorporating transport into future formulations of the model. In the case of RM, it is uncertain whether preferential flow paths connect the underground nuclear test locations to the aquifer, and reported monitoring has not revealed a definitive detection of radionuclide contaminants. In the absence of available data, quantifying a "worst case" scenario for the contaminant center of mass can be of great value to water resources managers. The calibration, evaluation, and sensitivity analysis for a source-responsive model for solute transport can build upon the work presented here, but will require more extensive distributed measurements of state variables with depth. Further case studies and perhaps laboratory experiments [e.g., *Su et al.*, 2003] are also needed to explore possible relations between M_{lim}, V_u, and fracture properties, as well as controls on $f(t)$.

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