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An Unsaturated Zone Flux Study in a Highly-fractured Bedrock Area: Ground Water Recharge Processes at the Masser Recharge Site, East-central Pennsylvania

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AN UNSATURATED ZONE FLUX STUDY IN A HIGHLY-FRACTURED
BEDROCK AREA: GROUND WATER RECHARGE PROCESSES AT THE
MASSER RECHARGE SITE, EAST-CENTRAL PENNSYLVANIA

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Presented to

The Faculty of the Department of Geology

San José State University

In Partial Fulfillment

of the Requirements for the Degree

Masters of Science

by

Zhengzheng Qin

December 2014

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The Designated Thesis Committee Approves the Thesis Titled

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ABSTRACT

AN UNSATURATED ZONE FLUX STUDY IN A HIGHLY-FRACTURED BEDROCK AREA: GROUND WATER RECHARGE PROCESSES AT THE MASSER RECHARGE SITE, EAST-CENTRAL PENNSYLVANIA

By Zhengzheng Qin

This study tested the applicability of the Episodic Master Recession method and utilized the source-responsive flow theory to quantify ground water recharge and simulate preferential flow in the vadose zone at the Masser Recharge Site in east-central Pennsylvania. The ground water recharge shows strong seasonal variations. The shallow fractures form preferential flow paths and predominate in the vadose zone recharge processes, as reflected in the ground water-table elevation rise. They also influence the ground water-table recession rate, reflected in the rapid water-table recession in the deeper well with a high hydraulic conductivity fractured zone. Most importantly, the source-responsive flow model was able to predict closely the well water-level fluctuation over six months of wet-season recharge events with parameters assigned to this site. The calibrated parameters are reasonable for the fracture frequency and can serve as basis for predictions when applied to the following wet-season precipitation record.

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INTRODUCTION

Ground water recharge cannot be directly measured using field techniques; thus, methods for simulating the flux in the unsaturated zone have been used by researchers to estimate recharge processes. Two new methods, the source-responsive flow model and the Episodic Master Recession (EMR) method, can improve our understanding of certain types of hydrogeological relationships, the relation of preferential flow and recharge to seasonality and other climate-related conditions, and help to manage ground water basins.

The source-responsive flux model simulates how flow in the vadose zone responds sensitively to the dynamic conditions of the source of water input (Nimmo, 2010). In the source-responsive theory, the preferential flow transports infiltrated water films as laminar flow along the internal faces of macropore walls. Considering the relationship between the velocity and the thickness of laminar flows, the preferential flow should have a uniform rate when the water input is continuous and ample. Thus, we can use a formula to simulate how variations in water input and other hydrologic factors impact the amount and timing of recharge. Use of the source-responsive flow model can help in characterizing subsurface properties related to recharge. The EMR method (Nimmo et al., 2014) can be used to evaluate questions such as how the intensity or the seasonality of precipitation impacts

preferential flow and leads to rapid responses at the ground water table. It can estimate recharge from individual events throughout the year.

This study focused on the application of the source-responsive flow model for an entire water year of monitoring data selected from observation well measurements from the Masser site in east-central Pennsylvania. With evaluation of the hydraulic well-testing results and rock core data for the site, the relationships between the ground water recharge and the geologic characteristics of the Masser site can be evaluated. Previous studies of ground water recharge utilized the source-responsive model to make predictions for a single recharge episode (Nimmo, 2010). It is important to test the applicability of this model to see if it can simulate the unsaturated-zone fluxes and make reliable explanations for the observed water-table fluctuations during longer periods. The application of the EMR method for the Masser site permitted evaluation of the seasonal variations of ground water recharge and also evaluation of the specific yield for the site. Moreover, the ground water-table recession behavior at the Masser site can be characterized by using the master recession curve (MRC), which gives parameter values to use with both the source-responsive flow model and the EMR method.

BACKGROUND

Model

Diffuse flow is influenced mainly by capillarity and gravity. It can be formulated according to the Darcy-Buckingham Law,

$$q_D(z) = -K(\theta_D) \frac{\partial \phi}{\partial z} \quad [1]$$

where q_D is the flux density [LT^{-1}], K is the unsaturated hydraulic conductivity [LT^{-1}], θ_D is volumetric water content of the diffuse-flow domain [-], ϕ is the total potential relevant to flow in the diffuse domain [L], and z is upward distance [L].

In some cases, the ground water table shows a fast response to a water-infiltration event at the ground surface. This rapid response cannot be explained by slow, diffusive flow but rather involves preferential flow. Preferential flow is hydraulic transport via enhanced flow-paths that permits fast movement in the unsaturated zone.

The source-responsive theory is one way to investigate the preferential flow process. Changing conditions of rainfall, irrigation, or other water-infiltration events leads to sensitive responses of the water table. The input water from the land surface is thought to transfer to the underlying aquifer via free-surface films on macropore walls with varying velocity and thickness. Since preferential flow is another mode

of recharge in addition to the diffuse flow, the relation of wetness and flow patterns can be simply considered as

$$\theta = \theta_D + \theta_S \quad [2]$$

and

$$q = q_D + q_S \quad [3]$$

where θ_D and q_D are the water content and flux density of the diffuse flow domain and θ_S and q_S correspond to the source-responsive domain. The equation for situations with preferential flow would be a combination of Darcy-Buckingham law and laminar film flow concepts (Nimmo, 2010),

$$q(z, t) = -K(\theta_D) \frac{\partial \phi}{\partial z} + f(z, t) q_{S\text{MAX}}(z). \quad [4]$$

The dimensionless factor $f(z, t)$ is the active area fraction (fraction of the macropore surface area over which preferential flow is actively taking place), which ranges from 0 to 1, depending on the flow conditions in the preferential flow path. The parameter $q_{S\text{MAX}}(z)$ is the maximum possible source-responsive flow that could occur via macropores [LT^{-1}].

In a previous study (Nimmo, 2010), film-flow concepts were assumed to obey laminar flow principles and were represented by a mathematical framework:

$$q_S(z, t) = V_u L_u M(z) f(z, t) \quad [5]$$

and

$$V_u = \frac{1}{3} \frac{g}{v} L_u^2 \quad [6]$$

where ν [L^2T^{-1}] is the kinematic viscosity of water (assuming a temperature of 20 °C, equal to $10^{-6} \text{ m}^2\text{s}^{-1}$), and $M(z)$ [L^{-1}] is the macropore facial area density. The macropore facial area density is the surface area per unit volume of possible preferential flow paths. It describes the capacity for transmitting preferential flow and remains constant over time. The characteristic film velocity V_u [$L T^{-1}$] and film thickness L_u [L] are related by the laminar film-flow relation so that the source-responsive preferential flow is described as

$$q_S(z, t) = V_u^{1.5} \sqrt{3 \frac{\nu}{g}} M(z) f(z, t). \quad [7]$$

When simulating recharge and deep water-table fluctuations, the distribution and characteristics of fluxes in the vadose zone are unknown. We consider that the source-responsive flux $q_S(z, t)$ is integrated over the vertical profile, from the land surface (z_{ls}) to the depth of the water table (z_{wt}), so that variations in M and $f(z, t)$ with depth can be ignored for a given recharge event. The function $M(z)$ can be replaced by a constant value for the limiting macropore facial area density, M_{lim} , and only temporal variations in $f(z_{wt}, t)$ are considered (Mirus and Nimmo, 2013). Functional relations between the availability of the source of recharge $SR(z_{ls}, t)$ and activity of the preferential flow pathways to the water table $f(z_{wt}, t)$ reflect a lag time as

$$t_{lag} = \frac{z_{wt} - z_{ls}}{V_u} \quad \text{or} \quad V_u = \frac{z_{wt} - z_{ls}}{t_{lag}} \quad [8]$$

such that

$$f(z_{wt}, t + t_{lag}) \propto SR(z_{ls}, t). \quad [9]$$

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

$$\frac{\Delta H}{\Delta t} = \frac{q(z_{wt}, t)}{S_y} - \frac{H}{\tau} \quad [10]$$

where H is the hydraulic head [L] above the hydrologic base-level H_0 [L], or the zero recession elevation, which is the water-table elevation if no preferential flow recharge occurred for a long time (Fig. 1). 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). For most observations of rapid water-table response, diffuse recharge fluxes through the unsaturated matrix can be considered negligible and are set to zero. Combining equation [7], [8] with [10] and assigning the land surface (z_{ls}) as $z = 0$ produces an equation:

$$\frac{\Delta H}{\Delta t} = \frac{\left(\frac{z_{wt}}{t_{lag}}\right)^{1.5} \sqrt{3\frac{v}{g}} M_{limf}(z_{wt}, t)}{S_y} - \frac{H}{\tau}. \quad [11]$$

For the application of this model, the solution in recursion form is

$$H_{i+1} = H_i \exp\left(\frac{t_i - t_{i+1}}{\tau}\right) + \frac{\left(\frac{z_{wt}}{t_{lag}}\right)^{1.5} \sqrt{3\frac{v}{g}} M_{limf_{i+1}} \tau}{S_y} \left[1 - \exp\left(\frac{t_i - t_{i+1}}{\tau}\right)\right] \quad [12]$$

where H_i is the H at the time step of t_i . This formula can be used to predict H for a sequence of intervals. An exponential function, $\exp\left(\frac{t_i - t_{i+1}}{\tau}\right)$, is used to represent the recession processes. This version was developed based on Nimmo's (2010) source-responsive flow model.

The water-table fluctuation method uses S_y to estimate recharge from observations of water-table fluctuations (ΔH) in wells with the formula,

$$Recharge = S_y \times \Delta H \quad [13]$$

Figure 1. Elevation elements of a water-table-fluctuation study.

This source-responsive model has been used in case studies at the Idaho Nuclear Technology and Engineering Center (INTEC), Rainier Mesa (RM), and the Masser Recharge Site to evaluate model utility and data needs (Mirus and Nimmo, 2013).

Field Site description

The Masser Recharge Site was established by the Agricultural Research Service (ARS), US Department of Agriculture, with installations including five ground water-monitoring wells (Fig. 2). It is located within the Valley and Ridge Physiographic Province and within the Susquehanna River Basin (Gburek and Folmar, 1999) in central Pennsylvania. This non-glaciated area has a temperate and humid climate. The site is about 266 m above mean sea level. It is situated near

the top of a knoll which is about 1,000 m long in the east-west direction and 400 m wide in the north-south direction.

Figure 2. Map of the study area showing the location, regional topography and instrumentation of the Masser Recharge Site (modified from Gburek and Folmar, 1999).

Soils over the site are classified as Calvin shaley silt loam and Hartleton channery silt loam that contain a high percentage of coarse fragments. They are shallow and well drained with moderately high permeability which results in little or no surface runoff. The surface elevation difference of the five wells is less than 1.6 m. Figure 2 shows where the wells are located. The slope of the study area is 0.024-0.04. It is relatively flat so that the infiltration produced by precipitation on this study area is uniform and not influenced by elevation differences.

The Masser Recharge Site is located on the northern flank of an east-plunging anticline; it is underlain by Mississippian-age, fractured, quartzitic sandstones with

The water table is 5-15 m below land surface in fractured sandstone with a small specific yield ($S_y \sim 0.01$) (Gburek and Folmar, 1999). The highly fractured nature of the bedrock results in its higher hydraulic conductivities (K) and lower specific yield (S_y) than typical unconsolidated porous material (Gburek and Folmar, 1999). These fractures are the likely sites of preferential flow in the vadose zone and the cause of rapid water-table response to water-infiltration events.

The reports of watershed WE-38, a 7.4 km² ARS research facility which is located about 1 km east of the Masser Recharge Site, show that the average annual precipitation of that area is approximately 1,090 mm (Gburek and Folmar, 1999). The frequent rainfall events provide continuous water recharge to the shallow water table, and 60%-80% of the total stream flow comes from subsurface return flow. The episodic recharge to the ground water is seasonal. It occurs during the late autumn, winter and spring months and sometimes, when there is a large precipitation event, during the summer growing season (Gburek et al., 1986).

Field data

In this study, I utilized the precipitation data, well water-level data, the drill core results, hydraulic testing results, fracture analysis, and seismic data interpretation from the Masser Recharge Site. Continuous rainfall data (from April 1994 to December 2001) were obtained in inches at the meteorological site (Fig. 2) at half-hour

intervals. Water-level data in wells were collected for about seven years (from 1994 to 2001) at the same study site. Instrumented in 1992, the Masser Recharge Site has both lysimeter measurements and ground water observation well data.

I did not use the lysimeter measurements but focused on the well data in this study. The four wells at the corners of the grid were 29-30 m deep, and the center well were 45 m deep (Table 1). The boreholes were cased to approximately five meters depth to prevent caving, and the space outside of the casing was filled and sealed with bentonite clay. The remainder of each borehole was left open. Water levels in these five wells were monitored at half-hour-intervals using floats, pulse generators and a dedicated data logger (Gburek and Folmar, 1999).

Table 1. Properties of ground water observation wells (measured on March 1, 2000).

Well	Depth (m) below land surface	Depth (m) to bottom of casing below land surface	Depth (m) to water below land surface	Depth (m) to major water-yielding fractures under non-pumping conditions
Center	45.1	5.5	11.5	12-14, 21, 35
SW	29.9	5.5	8.1	10.6-11, 22.8
NW	29.9	5.5	7.3	8,22.5,25,27
NE	29.0	5.5	6.7	7-10, 13,26
SE	29.6	5.5	9.1	9,12,23,25

Although the water-level data from observation wells were recorded from 1994 to 2001, there are many “gaps” in the data where no valid data were available. In addition, floats in two of the observation wells (SW and SE wells) malfunctioned.

I used data from two water years, October 1, 1997, to September 30, 1999, in the center well (CE), the northeast well (NE), and the northwest well (NW) in this study.

Interval packer tests (Gburek and Folmar, 1999) were also conducted within the five observation wells to determine hydraulic conductivity (K) values. Steady-state, one-hole, double-packer tests were conducted on 3 m open intervals within each well from below the casing to the bottom of the open borehole. K values of the open interval (Table 2) were calculated based on well geometry and on flow rate and pressure at steady state.

Table 2. Results of interval packer testing for hydraulic conductivity (K) (data from Gburek and Folmar, 1999).

Depth interval (m)		Fracture Layer	K (m/day)					
top	bottom		NW	NE	CE.	SW	SE	Ave.
4.6	7.6	Highly Fractured	0.62	0.75	1.8	high	2.16	1.3325
7.6	10.7	Moderately Fractured	0.32	0.23	0.16	0.36	2.9	0.794
10.7	13.7		0.18	0.03	0.07	1.5	0.28	0.412
13.7	16.8		0.52	0.03	0.33	0.11	0.14	0.226
16.8	19.8	Poorly Fractured (regional aquifer)	0.09	0.24	0.45	0.35	0.02	0.23
19.8	22.9		0.03	0.08	0.27	0.41	0.31	0.22
22.9	25.9		0.12	0.18	0.03	0.2	0.83	0.272
25.9	28.9		0.15	0.36	0.05	0.04	0.01	0.122
28.9	32		bottom	bottom	0.03	bottom	bottom	0.03
32	35				0.63			0.63
35	38.1				16.7			16.7
38.1	41.1				0.02			0.02
41.1	44.2				0.01			0.01

There is one NX-size rock core (Fig. 2) drilled to 30 m depth near the center well to observe the geology and extent of bedrock fracturing. The coring began at the 4 m depth, and recovery was excellent at all depths. The fracture frequency generally decreased with depth (Fig. 4), and the strike of the fractures was primarily in two dominant sets, one in the E-W direction, and one parallel to the bedding planes as in the regional pattern (Fig. 3).

Figure 4. Fracture frequency with depth for rock core taken at the site (modified from Gburek and Folmar, 1999).

Seismic investigations were conducted with eight 96-meter-long transects aligned with the grid of wells and sampled with a 24-channel seismograph. Results indicate a four-layer model at the study site: soil/overburden (0-1.5 m), highly fractured (1.5-5 m), moderately fractured (5-17 m) and poorly fractured (17 m-?) layers, which shows similar features with the layers of watershed WE-38. The four-layer model defined by the seismic investigation generally matches the rock core observations (Gburek and Folmar, 1999).

METHODS

There were three major steps in the analysis of the water-level data from the Masser Recharge Site. First, the recession periods were selected from the ground water elevation data and used to create the MRC, which specifies the relationship between the ground water-table decline rate (dH/dt) and the water-table elevation (H). It can predict the dH/dt for a given well water-level elevation. Using an exponential-decline model for the shape of the recession curve, this analysis also determines the ground water-table recession constant (τ) and the base level (H_0 , the level the ground water table would fall to without any episodic recharge). These two parameter values can be used in estimating the parameters of the source-responsive flow model, as well as in the application of the EMR method. Second is the calibration and application of the source-responsive flow model. In this step, different parameters that characterize the preferential flow and the ground water-table recession were assigned and put into the source-responsive flow equation [12] to calibrate the model to historic well water-level data. By conducting a global sensitivity analysis for parameters such as M_{lim} and q_{cap} using the available data from the NE, NW, and CE well, the optimal parameters could be selected to simulate the data from each specific well. Third, the EMR method was used to systematically partition well water-level records and precipitation data into discrete time intervals of recharge and non-recharge. The water-table fluctuation method was used to determine the beginning

and end of an individual recharge event (Nimmo et al., 2014). The advantage of the episodic recharge approach is that it provides a method to determine the relationship between water input and recharge for different precipitation events. The results help in understanding the hydrodynamic behavior of the Masser site over the course of the year. In this process, characteristics of each individual episode, such as the recharge duration (h), recharge magnitude (m), precipitation duration (h), precipitation magnitude (m), precipitation intensity (m/h), ground water-table rise (h), time lag (h), and recharge to precipitation ratio (RPR) [-], are determined, verified, and compared with other episodes.

Master Recession Curve

The MRC uses the water-table elevation data selected from the recession periods for a specified time period to relate the rate of water-table decline (dH/dt) with the water-table elevation (H). Given an MRC, one can predict the dH/dt as a function of the current water-table elevation (Nimmo et al., 2014). In my study, I utilized a Matlab code and an R code to pick out recession periods from times when water levels were declining and then made a linear best-fit to the recession data (dH/dt) as a function of water-table elevation (H). The scripts for this process are called `mrc_create`. The input parameters include the polynomial degree to be used in fitting the recession curve and the rain delay value. The output file gives the

coefficients of the formula that represent the MRC. Using a first-degree polynomial, that is, a linear fit, the formula of the MRC is

$$dH / dt = P[0] + P[1] \times H \quad [14]$$

where $P[0]$ and $P[1]$ are the coefficients (the y-intercept and the slope of the MRC, respectively), and H is the relative well water level expressed as the height above the base level (in meters). In the exponential form of the resulting $H(t)$ formula [12], the exponential decline constant τ and the zero recession elevation H_0 are

$$\tau = -1 / P[1] \quad [15]$$

and

$$H_0 = -P[0] / P[1]. \quad [16]$$

Both the R version and the Matlab version were created by Lara Mitchell, who worked with Dr. John R. Nimmo on preferential flow studies at the U.S. Geological Survey in 2014.

Source-Responsive Flow Model

To gain a better understanding and verify the source-responsive flow theory, precipitation data measured at the Masser Recharge Site were input into the source-responsive model to calculate the water-table-elevation variations based on the source-responsive flow equation [12]. Parameters that relate to the preferential flow behavior of the unsaturated zone in generating recharge, such as M_{lim} (m^{-1}), q_{cap}

(mm/h), and t_{lag} (h), and the parameters related to aquifer behavior, such as S_y [-] and τ (h), were used at the same time.

The data were separated into two major periods based on the ground water level and the season (Fig. 5). Beginning in October 1997, the ground water table was relatively low and kept declining, even when there were several precipitation events, up to the middle of November 1997. At that point, the well water levels suddenly rose more than five meters in the NW and the NE wells and about two meters in the CE well. The base levels of the three observation wells remained at relatively high elevations until May 1998. The well water levels slowly declined to a lower base level after May 1998. Since the base water levels and the well level behaviors varied greatly, the original data were analyzed separately and different input parameters were used for these two periods. To distinguish these two periods in this study, the one with relatively high ground water base levels and showing frequent water-table fluctuations was called the “wet season” (November 16, 1997 to May 15, 1998) while the rest of the year (October 1 to November 15, 1997 and May 16 to September 30, 1998) was called the “dry season”.

Figure 5. The ground water-table level in the NE, NW, and the CE wells and the cumulative precipitation record from October 1, 1997 to September 30, 1998.

Considering the different behavior of the ground water table for the wet season and for the dry season in all three observation wells, different parameters were assigned in running the model calibration separately for each sets of data. By setting up equations in an Excel worksheet and inputting the required parameters, predictions of the water-table rise or decline based on precipitation amount per half-hour interval were made beginning with an initial water-table elevation. The water level at the subsequent time step was determined based on the simulated ΔH for each time step. Before starting the calculation in Excel, it was necessary to determine the H_0 and the τ value for each well. Both parameters were determined by the MRC-fitted curve with the equations [14], [15], and [16].

The basic concept in applying the source-responsive flow model was to use one data set as a calibration sample. The calibrated parameters from that first data set were then used in a second set of data collected from the same site to do a verification simulation. As explained earlier, M_{lim} and $f(t)$ are two parameters that show porous medium characteristics and the preferential flow path availability, respectively. These are the major factors influencing the modeled ground water recharge processes. To evaluate the calibration, I calculated the root mean square error (RMSE) for the difference between the observed well water level and the simulated level. Sensitivity analyses for the M_{lim} and q_{cap} (which controls $f(t)$ value) values were performed by varying those values within a reasonable range to get the best estimations of both parameters (Fig. 6).

Figure 6. Example of a contour plot illustrating the sensitivity analysis of M_{lim} and q_{cap} for the source-responsive flow model.

Episodic Master Recession Method

A recharge episode is considered as a period during which the total recharge rate significantly exceeds its steady-state condition in response to a substantial water-input event. Delineating an episode begins with estimating the MRC, which represents the averaged recession behavior of an aquifer over a long period of time. The method distinguishes episodes that have significantly greater recharge rates by comparing the measured dH/dt curves with the MRC. With the output results from the MRC, I used another Matlab code to identify individual recharge episodes based on the water-table rise and the precipitation data. This EMR code is called `episodic_recharge.m` and was also created by Lara Mitchell in 2013.

Precipitation and well-response data at half-hour intervals from October 1997 to September 1998 were used for the analysis of responses at the CE well, the NW well, and the NE well at the Masser site. Data measured in the SE and SW wells were not used in this study since the floats in these two observation wells malfunctioned. The data file for running the Matlab script must contain time (days), the well water-level height above the zero recession elevation H_0 (m), and the cumulative precipitation with regular intervals (m). The polynomial order (zero to third) to fit the MRC and the storm recovery time t_p (days) should be included in the input file to run the script. The output files from this script includes several graphs such as a precipitation vs. time graph, a well water level vs. time graph, a dH/dt vs. time graph, a dH/dt vs. well water level graph, and also the polynomial order and coefficients of the fitted MRC curve (Fig. 7). Generally speaking, the higher the polynomial order, the larger the coefficient of determination (R^2). It is important to find a balance between maximizing the R^2 value and not letting the MRC fitted curve become too complex.

The polynomial order and the coefficients determined by the MRC curve were used as input parameters along with the fluctuation tolerance, lag time, and specific yield to identify recharge episodes from the water level data sets in the EMR code. The EMR output includes a well water level vs. time graph, a dH/dt vs. time graph, and a table with calculated precipitation and recharge features for each captured episode (Table 3).

Figure 7. Example of an MRC curve fitted to the dH/dt vs. H plot.

Table 3. Example of an output table from the EMR code.

Event	Start time since Jan. 1, 1997 (d)	End time (d)	Duration (d)	Recharge (m)	PPN (m)	RPR (-)	Avg. precip (m/d)	Max. precip rate (m/d)
	578.250	586.795	8.545	0.000	0.000	0.000	0.000	0.000
1	586.795	589.510	2.715	0.010	0.037	0.282	0.107	0.688
	589.510	595.448	5.939	0.000	0.015	0.000	0.003	0.383
2	595.448	597.783	2.334	0.007	0.012	0.601	0.047	0.447
	597.783	638.750	40.968	0.000	0.054	0.000	0.000	0.000

RPR is the abbreviation for the recharge-to-precipitation ratio. By summarizing the output information for both wet season and dry season from the three observation wells, it was possible to make comparisons and evaluations for the calculated recharge amount and RPR of each episode.

Parameter Identification

I used various hydrologic parameters to define the recharge characteristics and the geologic factors for the Masser site. Some parameters could be measured directly while some needed to be estimated with the analysis of water-table fluctuations and precipitation intensity.

Specific Yield

The specific yield S_y is a physical property that characterizes the storage capacity of the water-table aquifer. It is the ratio of the amount of water added or subtracted at the water table divided by the surface area of the aquifer (the volume per unit area [L]) over the change in water-table level [L] caused by the addition or subtraction of water. The water-table fluctuation method uses equation [13] to estimate recharge from observations of water-table fluctuations (ΔH) in wells. The method to calculate the recharge is simple. Previous studies for the Masser site showed that the value of S_y could vary from approximately 0.005 to 0.06. For instance, the specific yield value determined by Gburek and Folmar (1999) was between 0.0075 and 0.0097 according to the percolation data. The specific yield estimated by relating stream flow recession to the water-table decline for the WE-38 was 0.013 (Risser et al. 2005). The value used in this study was 0.006, based on

studies of previous recharge episodes and optimizing for a reasonable RPR value (Nimmo et al, 2014).

Ground Water-Table Recession Constants

τ is a parameter representing the rate of water-table recession. It is the amount of time required for a water table to decline a specific fraction of the range between the initial water level and its base level (the fraction equals to $1-1/e$, or 63.2%). It is a linear constant related to the rate of water-table decline. It was assigned a value of 72 h for a case study at the Masser site (Nimmo, 2010). The water-table recession rate is determined by the site characteristics and may range from meters per day to meters per decade, which means the τ value may range from 24 hours to 87,600 hours (Mirus and Nimmo, 2013).

Macropore Facial Area Density

$M [L^{-1}]$ is a property of the porous medium, which represents the capacity for transmitting preferential flow. It cannot be calculated or measured directly. M_{lim} is the maximum surface area available for preferential flow per unit volume of porous medium $[L^{-1}]$. There should be a relationship between M_{lim} and the characteristics of the hydrogeologic medium (e.g., porosity, S_y , fracture frequency, or particle size). The range of M_{lim} values used in previous applications varied from $60 m^{-1}$ to $4000 m^{-1}$ (Nimmo, 2010). It is a constant parameter through time.

Active Area Fraction and Infiltration Capacity

The value of the active area fraction $f(t)$ determines the available preferential flow paths of the preferential-flow surface area (M_{lim}). It is assumed to be correlated with the source of recharge, $SR(z_{ls}, t)$, which represents records of precipitation, infiltration, and/or stream-flow characteristics (e.g., precipitation intensity, duration, and frequency). As described previously, the value of $f(t)$ ranges from 0 to 1, indicating what fraction of the macropore facial area is actively transmitting water. Its value is determined by the amount of water percolating below the zone of evapotranspiration. When calibrating the $f(t)$ for the source-responsive flow model, another coefficient, the infiltration rate needed to fully activate all preferential flow paths (q_{cap}), was used to relate the precipitation rate to the $f(t)$ as

$$f(t) = \frac{\text{Rain Intensity}}{q_{cap}}. \quad [17]$$

The q_{cap} is the maximum precipitation rate that can be absorbed at the land surface without runoff. It is an adjustable parameter which is considered as a transient value that is affected by the season and the soil moisture.

Lag Time

The lag time (t_{lag}) is how long it takes for the source of recharge to transfer from the land surface to the saturated zone and cause the ground water table to rise ($\Delta H > 0$), which is the time interval between the start of precipitation and the start of

the water-table rise (Fig. 8). The beginning of the recharge episode can be determined by the EMR method. The lag time for a single episode event can be determined by using a systematically applied criterion, which requires hydrologic judgment to establish.

Figure 8. A recharge episode graph illustrating the EMR method. The red lines are extrapolations of the recession curves based on the MRC, the vertical distance ΔH represents the total actual water-table rise caused by the relevant rainfall event which began t_{lag} days earlier.

From preliminary analysis between the precipitation data and the water-table level data, the value of t_{lag} could vary from a couple of hours to two to three days. I used the average lag time in this study.

Storm Recovery Time

The minimum time between precipitation and recession, allowing for storm generated accretion to become negligible, is called the storm recovery time (t_p). The MRC code can pick out recession data with a storm recovery time assigned to it.

Water-Table Fluctuation Tolerance

A water-table fluctuation tolerance (δ_T) was used to distinguish recharge periods from periods with non-significant water-table fluctuation rates, dH/dt (Figure 9). Since there are many small deviations that produce little recharge to the saturated zone, considered as noise in the dH/dt time series, I used the fluctuation tolerance to identify data within that noise range to be disregarded.

Figure 9. The fluctuation tolerance (δ_T) identified recharge periods (shown in darker blue) from insignificant variations in water level change rates. The blue area indicates cumulative precipitation.

When estimating the δ_T value, it should be large enough to eliminate the small water elevation fluctuations while allowing the significant recharge events to be clearly distinguished. My estimate of δ_T defined a band such that 90% of measured recessionary dH/dt values fell within the band; this value could be adjusted if the original δ_T designated unreasonable recharge episodes. For example, the δ_T value

needed to be increased if it designated some minor or frequent episodes as contributing positive recharge. On the other hand, it needed to be decreased if it eliminated any major recharge episode. As shown in Figure 9, the bands are determined by the fluctuation tolerance on either side of the recession curve. The bolded curve represents dH/dt that crossed the upper fluctuation tolerance band which means that a significant recharge event occurred.

RESULTS

Results for both the EMR method application and the source-responsive flow model calibration showed variability in response to seasonal changes. Considering the shifting vadose zone moisture state and the weather changes during the year, it is reasonable to analyze the responses for different seasons separately.

MRC Evaluation

Considering the rate of water-table decline, dH/dT , to be proportional to the head (H), with the result considered over time to be an exponential decline curve, the polynomial order I used to get the MRC fitted coefficients was first-order. Having determined the wet and dry periods in the observed records, I utilized the R script to create the MRC fitted curve (example provided in Figure 10) and obtained fitted coefficients for different periods in the water year 1997-98 as shown in Table 4. The plots for all three wells in both seasons are provided in Appendix A. Investigations using the MRC method showed that the ground water-level recession processes were faster (dH/dT was greater) if H was greater (Fig. 10).

Figure 10. The MRC fitted curve shows the relationship between the dH/dt and the H for the wet-season data collected from the CE well in the water year 1997-98.

Table 4. MRC fitted curve coefficients.

Period	Well	$P[0]$	$P[1]$
All water-year data (10/1/97-9/30/98)	CE	20.947	-0.083
	NE	4.207	-0.017
	NW	3.745	-0.015
Wet season data (11/16/97-5/15/98)	CE	26.239	-0.104
	NE	28.171	-0.109
	NW	49.505	-0.192
Dry season data (10/1/97-11/15/97, 5/16/98-9/30/98)	CE	13.108	-0.052
	NE	3.263	-0.013
	NW	1.197	-0.005

Utilizing the equations [15] and [16], respectively, the τ value and H_0 could be calculated by using the MRC fitted coefficients for each of the three wells for the different periods of the year (Table 5).

When comparing the various τ values in the different periods for the same well, the dry season data indicated a larger τ (more gradual recession) than the wet

season data. Among the three wells, the τ value changed much less in the CE well, while it changed much more in the other two wells between the different data periods.

Table 5. τ and H_0 values in different periods of the water year 1997-98.

Period	Well	τ (h)	H_0 (m)
All year data (10/1/97-9/30/98)	CE	287.76	251.15
	NE	1423.51	249.51
	NW	1591.31	248.30
Wet season data (11/16/97-5/15/98)	CE	230.61	252.13
	NE	219.93	258.15
	NW	124.83	257.49
Dry season data (10/1/97-11/15/97, 5/16/98-9/30/98)	CE	457.26	249.74
	NE	1820.40	247.47
	NW	4786.98	238.67

Calibration and Application of the Source-Responsive Flow Model

Assigning H_0 and τ values to each well according to values in Table 5 and 20 h (the reasonable assumption for lag time) as t_{lag} , a sensitivity analyses (Appendix B) was run with the source-responsive flow model for different M_{lim} and q_{cap} values (Fig. 11) to determine which combinations would produce the lowest RMSE value. M and $f(t)$ are strongly coupled with each other and determine the water-table responses together. The q_{cap} parameter inversely affects the magnitude of $f(t)$ as shown in equation [17]. It is likely that the M_{lim} and q_{cap} have a specific optimal ratio. The sensitivity analysis illustrates that the larger the M_{lim} assigned, the larger the q_{cap} value that needs to be utilized to minimize the RMSE.

Figure 11. Contours illustrating the results of a sensitivity analysis for the December 1997 - May 1998 period.

The result of sensitivity analyses showed that the potential M_{lim} value ranged from 50 to 100 m^{-1} , while the q_{cap} value ranged from 10 to 70 mm/h. Since M has a physical interpretation, representing the macropore facial area density of the medium, it should be set to a unique value. While the M_{lim} value should be held constant across the seasons, q_{cap} varies seasonally since it reflects the effectiveness of rainfall in producing recharge. The most reasonable M_{lim} and q_{cap} values for all the three wells during different time periods are shown in Table 6.

Table 6. The M_{lim} and q_{cap} values estimated by sensitivity analysis.

Parameter	10/1/97- 11/15/97	11/16/97- 5/15/98	5/16/98- 6/17/98	6/24/98- 9/30/98
M_{lim} (m^{-1})	50	50	50	50
q_{cap} (mm/h)	30	40	30	10

Having assigned the estimated parameters in the source-responsive flow model, well water level vs. time graphs were created by the model (Fig. 12, for the wet season) to show how the simulation matches the observed water level changes for the three wells. Simulations for all time periods are included in Appendix C.

The source-responsive model can reproduce the water-table elevation changes accurately by using the seasonal τ and H_0 values, representing the ground water-table recession characteristics, and the calibrated M_{lim} and q_{cap} values, which reflect the site geologic features and the seasonal infiltration capacity. The root mean square error (RMSE) for the NE well calibration during the wet season was 0.58 m, for the NW well calibration was 0.46 m, and for the CE well was 0.97 m.

When these parameters were utilized with another precipitation data set measured for the Masser site in 1999, the model also provided relatively reasonable simulations that matched most of the observed well water level changes over a long period (Fig. 13). The RMSE between the simulated well level and the observed well level was 0.58 in the NE well, 0.28 in the NW well, and 0.54 in the CE well.

Figure 12. Comparison between the observed well water-table elevation and the predicted well water-table elevation simulated by the source-responsive flow model using data from December 1997 to May 1998 in (a) NE well, (b) NW well, and (c) CE well.

Figure 13. Application of the source-responsive model to measured precipitation and water-table elevations at the Masser site from February 1999 to May 1999 for (a) NE well, (b) NW well, and (c) CE well.

EMR Method

The primary analysis was performed on the set of data from the NE well during February 1998 to May 1998; this data set had few gaps or anomalies. Having used first order polynomial for the MRC-fitted curves, 20 h as the lag time, 0.006 as the specific yield, and 0.45 m as the water-table-fluctuation tolerance, the method identified 12 distinct recharge episodes for the set of data. These values gave results that showed the most reasonable hydrologic behavior with this data set. Table 7 lists the results of this analysis for both recharge and non-recharge intervals. Figure 14 shows the series of episodes.

The RPR values shown in Table 7 were calculated using a S_y of 0.006. The average value was 0.30, slightly higher than the average recharge-to-precipitation ratio estimated by Risser et al. (2009) for the same site in calendar year 1999. The $\delta=0.45$ m worked for most of the year, except for one instance that occurred on Jan. 7, 1998 (Fig. D2, Fig. D6, and Fig. D10 of Appendix D), which was caused by a series of intense storms. In this event, the recharge produced by the first storm was still taking place when the next storm started, which violates the assumption of the EMR method. By using the same δ value, the estimated ΔH value for the first portion of the event was unreasonably large and for the second portion was negative. In order to prevent abnormally large RPR values and negative RPR values in the EMR analysis results, I artificially combined those storms by adjusting the δ value to 2 m

for the time period from 1/6/1998 to 1/10/1998 to make the program recognize the series of storms as a single event. Since the δ value was different from what I used for other events, I am less confident about the results estimated by using $\delta=2$ m (Appendix E).

Table 7. Results of the EMR analysis for the NE well.

Interval Start Date (in 1998)	Relative Date (days since Jan. 1, 1997)	Duration (day)	Recharge (m)	Precip. (m)	RPR (-)	Avg. precip (m)	Max. precip rate (m/day)
1-Feb	397.25	2.51	-	0.003	-	-	-
3-Feb	399.76	3.39	0.009	0.037	0.252	0.011	0.175
7-Feb	403.15	4.34	-	0.001	-	0.001	0.019
11-Feb	407.48	2.75	0.006	0.013	0.471	0.004	0.097
14-Feb	410.23	2.70	-	0.001	-	0.000	0.007
16-Feb	412.93	3.91	0.010	0.038	0.263	0.010	0.128
21-Feb	416.85	2.48	-	0.001	-	0.000	0.005
23-Feb	419.33	3.07	0.011	0.059	0.179	0.019	0.246
26-Feb	422.40	9.91	-	0.008	-	0.001	0.020
8-Mar	432.30	3.13	0.011	0.024	0.447	0.008	0.169
11-Mar	435.43	8.57	-	0.010	-	0.001	0.036
20-Mar	444.00	2.90	0.012	0.028	0.441	0.010	0.155
22-Mar	446.90	9.04	-	0.004	-	0.001	0.012
31-Mar	455.94	2.74	0.006	0.019	0.297	0.007	0.274
3-Apr	458.68	4.91	-	0.000	-	0.000	0.005
8-Apr	463.59	3.04	0.012	0.057	0.220	0.018	0.236
11-Apr	466.63	6.83	-	0.006	-	0.001	0.043
18-Apr	473.46	3.11	0.013	0.050	0.258	0.016	0.181
21-Apr	476.58	4.49	-	0.000	-	0.000	0.000
26-Apr	481.07	2.66	0.005	0.023	0.229	0.008	0.079
28-Apr	483.73	5.95	-	0.014	-	0.002	0.048
4-May	489.69	2.92	0.013	0.038	0.343	0.013	0.298
7-May	492.60	0.06	-	0.000	-	0.020	0.065

The EMR Matlab scripts were utilized with well water-level data and precipitation data for the entire 1997-to-1998 water year in the three adjacent observation-wells, with some revision for overlapping events. The plots, which show distinct behaviors between wells for the same recharge event, are presented in Appendix D. The tabulated output results of the EMR analysis are given in Appendix E.

Figure 14. EMR analysis for the Masser site for the NE well data from February 1998 to May 1998, of (a) $H(t)$ data and (b) calculated dH/dt vs. time.

The ground water level in the NE well was 1.38 m higher than in the NW well, on average, and was 5.48 m higher than in the CE well. The average ground water level in the NW well was 4.10 m higher than in the CE well. The recharge events lasted longer in the NE well than in the CE and NW wells. Events lasted 0.30 days

longer in the NE well than in the CE well on average, and lasted 0.27 days longer than in the NW well on average. The average recharge-event durations of the CE and NW wells were about the same, approximately 2.60 days. Comparing the recharge start times for the same event, the CE well responded approximately 0.1 days later than the NE and NW wells on average, and the NE well responded a little earlier than the NW well with only 0.04 days difference on average. The average recharge amount for each event was found to be slightly greater in the CE well than in the NE by a factor of 1.31, and 1.79 times greater in the CE well than in the NW well. The recharge was greater in the NE well than in the NW well by a factor of 1.26.

The average precipitation amount detected by the EMR script in different wells for the same event was about the same. Slight differences may have been caused by the varying durations and start times of events determined for each well by the EMR method. The maximum rainfall intensities of the three wells estimated by the EMR method were about the same, about 0.15 m/day on average (6.3 mm/h). The maximum rainfall intensity detected by the method was 17.46 mm/h for the event occurred on June 26, 1998. This value is reliable since the maximum half-hour precipitation amount on the same day was 9.7 mm in the original precipitation record, which is slightly greater than the EMR calculated value.

When comparing the RPR values between wells, the results for the whole year results were separated into three parts based on the local temperature variations (Fig. 15). Figure 15 used data collected from the observation station in Fort Indiantown

Gap, which is about 25 km north of the Masser Site. The average daily temperatures in November 1997, December 1997, and January 1998 were as low as the dew point. This period was named the “cold period”. The average RPR for the cold period was 0.62. The RPR values in the spring (February to April) period were relatively small, with an average value of 0.34 for all the three months. The RPR values were even smaller during summer (defined as when the average daily temperatures were above 22 Celsius) with an average value of 0.27. The average RPR values for all the wells seem reasonable when compared with previous estimations by Risser et al. (2009) and show significant seasonal variations (Table 8). While comparing the seasonal variations between wells, the CE well was found to have larger RPR values during the entire year.

Figure 15. The average temperature curve for the water year from 1997-98 at Fort Indiantown Gap (temperature records were searched from <http://i.wund.com>).

Table 8. Comparison of RPRs for different periods between the three observation wells.

Period	NE Well	NW Well	CE Well
Winter (Nov.-Jan.)	0.671	0.491	0.696
Spring (Feb.-Apr.)	0.306	0.251	0.460
Summer (May-Sep.)	0.254	0.179	0.390
Whole year (97-98)	0.442	0.344	0.535

DISCUSSION

Effects of Geological Factors

The sensitivity analysis for the source-responsive flow model showed that a M_{lim} value of approximately 50 m^{-1} would work best at the Masser site in combination with a reasonable q_{cap} value. This means that the value of the total internal facial area of macropores (the preferential flow paths) within the unsaturated-medium divided by the volume of the medium should be approximately 50 m^{-1} . This value is much smaller than the previous value hypothesized for this site, $M_{lim} = 4000 \text{ m}^{-1}$ (Nimmo, 2010). Considering the fractured sandstone bedrock under the thin overburden soil of the site (Fig. 3), we can suppose that the fractures form the macropores and paths for the flux. If we assume that the fractures are more or less planar, then the surface area for both sides of the fracture would vary from 2 m^{-1} to 2.82 m^{-1} in a characteristic volume. According to the elevations and depths of the observation wells (Fig. 16) and the fracture analysis for the study area (Fig. 3), we can find that the ground water-table elevation changes took place at approximately eight to fifteen meters depth below the land surface, where the average fracture frequency is 22.875 m^{-1} (moderately fractured zone). If we use the fracture frequency multiplied by the surface area of the fracture, the M value for this moderately fractured zone should be approximately 45.75 m^{-1} to 64.5 m^{-1} . This calculated range of M matches

the sensitivity analysis results of the source-responsive flow model very well. The $M = 50 \text{ m}^{-1}$ is assumed to represent an average value that is relatively constant over the lateral distance of the well installations.

Figure 16. Cross-section of the observation wells and core for the Masser site.

Geological factors may also account for the different behaviors between the CE well and the NE and the NW wells indicated by the well water-table elevation vs. time graph (Fig. 5). The CE well responded earlier than the other two wells with a smaller initial water-table rise when the season shifted from the dry-period to the wet-period (on November 4, 1997). The CE well also had a consistently lower water elevation. The explanation can most likely be found in the interval-packer-testing results (Table 2). The hydraulic conductivity for the CE well was 16.7 m/day at 35

to 38 meters depth, which is much higher compared with the hydraulic conductivity values measured from all wells in other depth intervals. The abnormally high hydraulic conductivity may indicate that a regional fracture zone intersects the CE well within that depth interval, below the termination depths of the other wells. The EMR results also shows that the CE well tends to get more recharge and have larger RPR values for each episode than the other two wells, on average, while the water-table elevation of the CE well was lower than the other two well. My hypothesis is that the fracture zone located at the 35 to 38 meter interval of the CE well allows the ground water to drain faster, which means the τ value for the CE well would be smaller (consistent with the optimized results in Table 5) and the slope of the recession curve would be steeper. With a steeper recession curve, the ΔH for each recharge episode in the CE well would be larger than in the other two shallower wells (Fig. 17), which means that a greater recharge amount would be calculated.

Figure 17. A sample hydrograph illustrates how MRC curve slope affects the ΔH value. The dashed curve has smaller τ value.

Seasonal and Episodic Variations

Both the EMR method and the source-responsive flow model are sensitive to the precipitation events and the seasonal weather patterns according to the above results. The annual average temperature plot for the region (Fig. 15) shows significant seasonal changes. Cold weather that reached the freezing point started from November 1997 and continued to January 1998. There were several periods that had an average daily temperature below the freezing point in December 1997 and January 1998. Since precipitation in the form of snow or ice cannot transport through the preferential flow paths until the snow melts, the well water-level response may take a longer time during cold weather. The recharge-to-precipitation ratio also shows significant seasonal variations (Table 8). The RPR values during summer were much smaller than those during winter, which may be related to the variable air or soil temperature, the rainfall intensity, the evapotranspiration, and the vegetation. For instance, a plot of RPR vs. maximum rainfall intensity shows that the greater the maximum rainfall intensity, the smaller the RPR value (Fig. 18). The RPR vs. average rainfall intensity plot shows the same trend (Fig. 19). One hypothesis for this phenomenon is that a large portion of the precipitation during a heavy rainfall may go to runoff instead of producing recharge, which makes the RPR value smaller.

Figure 18. Plots of RPR vs. maximum rainfall intensity.

Figure 19. Plots of RPR vs. average rainfall intensity.

The seasonal changes also affect the parameters of the source-responsive flow model. Figure 5 indicated there were two different base levels for the wet season and the dry season over one water-year. While comparing the τ and H_0 values calculated with the MRC fitted curve for different periods, the wet season has a higher

base level and water levels decline faster than during the dry season (Table 5). The base-level-differences between the two periods can range from three meters in the CE well to about ten meters in the NE and the NW wells. One possible explanation for these phenomena is that the $f(t)$ value is greater during the wet season, which makes it easier for the infiltrated water to move through the vadose zone and contributes to the ground water-table elevation rise. On the other hand, the strong evapotranspiration during the summer and the little precipitation during the fall let the subsurface layers dry out, which may result in minimal recharge and a lower base level.

The sensitivity analysis for M_{lim} and q_{cap} indicated that the maximum precipitation rate that could be absorbed from the land surface by preferential flow was greatest during December to the following May (Table 6). The q_{cap} value ranges from 10 mm/h to 40 mm/h according to the sensitivity analysis results for the entire water year 1997-98. From the definition of q_{cap} (equation [17]), all the preferential flow paths would be available when the precipitation rate is greater than the q_{cap} value for a specific period. For instance, the q_{cap} value of the wet season (11/16/97-5/15/98) was determined to be 40 mm/h while the greatest observed precipitation intensity was 15.75 mm/h in the same period. This indicates that approximately 40% of the preferential flow paths are effectively open for input flux during that period. The greatest observed precipitation intensity in the water year 1997-98 was 41.15 mm/h which occurred on June 23, 1998, which indicates that all the preferential flow paths were available compared with the q_{cap} value of 30 mm/h determined for

that time. A lower q_{cap} value implies that a given storm is more likely to reach its maximum, which means that additional rainfall intensity does not go into preferential flow because the preferential flow paths are already flowing at their maximum capacity. For example, a bigger proportion of the rain goes to surface runoff and therefore less goes into recharge during summer. The source-responsive flow model is very sensitive to the precipitation, and it worked better for the period with frequent or regular precipitation and recharge events (wet season) than during the period with few precipitation and recharge episodes (dry season).

Sources of Uncertainty

As a relatively new ground water recharge research approach, the EMR method performs well for the Masser site. Errors may come from shortcomings of the original data, subjective judgment on parameters, and the scripts. Errors may occur when there is a gap in the data or when recharge events overlap. To avoid these errors, I deleted the data periods where there were no water-elevation measurements available and adjusted the width of the tolerance band to combine overlapping events (Appendix E). This artificial revision can avoid abnormal large RPR values or negative RPR values in the EMR analysis results. However, it may cause underestimation of the recharge amount and there is less confidence in the results since the criteria have been artificially changed. Several parameters were

initially assigned values using subjective judgment based on evaluation of the data set, including the lag time, the specific yield, and the storm recovery time. These parameters were adjusted several times when they were utilized in the EMR and source-responsive model to produce the most reasonable results for the site.

One important step in both the EMR study and the source-responsive flow model was to determine the value of the specific yield. According to a previous study conducted by Risser et al. (2009), the average RPR for the Masser site in 1999 was 0.20, which indicated a small specific yield for the site. The value used in this study may have still been larger than the actual value.

The lag time links the recharge episodes to the precipitation events. Generally speaking, the lag time should vary as it is influenced by the depth of the ground water table, the rainfall intensity, and the unsaturated-zone material. The use of a single value of lag time may result in the inclusion of less precipitation for a recharge episode. For instance, the start time of a recharge period that is determined by a constant lag time is sometimes located at a time without any observed precipitation.

The storm recovery time determines which part of the data will be used to calculate the MRC-fitted curve. A larger storm recovery time will result in less data being selected for the MRC estimation while a smaller storm recovery time will leave too much data being selected for the MRC estimation; even the recharge period may be included.

Overshoot in the well water-level measurements happened in the wet season when frequent, large precipitation events occurred. The peaks of the water-level hydrograph measured in the observation wells were sharp, and the well water level dropped rapidly in these overshoot situations. This phenomenon is likely caused by air entrapment as recharging water approaches the saturated zone. The source-responsive flow model does not reflect the entrapped air that would cause overshoot. The predicted water-table fluctuation curves underestimated many of the sharpest hydrograph peaks (Fig. 12), which made the RMSE large, but probably resulted in more accurate reflection of actual recharge.

When comparing the RMSE of the simulated curves for the wet seasons in the water years 1997-98 and 1998-99, the RMSE values were somewhat smaller in 1998-99 wet season. This is surprising since the simulated curves for the 1998-99 wet season do not match the observed curves as well as for the water year 1997-98. One possible reason to explain this abnormal result is that the cumulative precipitation in the water year 1998-99 was less (Fig. 20), the infiltration rate was smaller than in the water year 1997-98 on average, and there were fewer overshoot events in the 1998-99 wet season (Fig. 20). Taking the overshoot phenomenon (which made the measured well water level higher than the predicted ground water level) into account, the source-responsive flow model can provide reliable predictions and can reflect the real water-table recharge characteristics.

Figure 20. The cumulative precipitation for the water year 1997-98 and 1998-99 (data provided by Dr. Gordon J. Folmar, USDA-ARS).

CONCLUSIONS

The Episodic Master Recession method used in this study delineated recharge episodes by using the well water-level measurements over an entire water year and provided an automated method to analyze the relationships between the precipitation and the ground water recharge. The source-responsive flow model was a convenient method to study the ground water recharge processes and was able to provide a reliable approach to predict water-table response and recharge over many months and multiple recharge/precipitation events based on the precipitation data. It was capable of predicting the water-table fluctuations, both for the case where parameters were optimized for a particular data set and when those optimized parameters were applied to a new data set (with precipitation and well water level measured for a different time period at the same site). In other words, the source-responsive flow model appeared to be robust, particularly for periods with significant recharge during the wet season. Moreover, it gave reasonable estimations of hydraulic characteristics that showed strong relationships with the site geology. The EMR method and the source-responsive flow model also provided results that showed the different ground water recharge and recession characteristics between the CE well and the NE and the NW wells, reflecting the actual fracture frequency data and the hydraulic conductivity measurements for the different well depths. Based on the results from both methods, the ground water recharge showed strong seasonal variations.

An additional advantage of both methods is that they provided a systematic correction for overshoot and overestimation in well water-level rise. More accurate determination of the specific yield value for the Masser site would have helped to make the ground water recharge estimate more accurate. Also, the physical basis for the abrupt transition in the ground water-table elevation between the dry season and the wet season needs to be determined.

REFERENCES CITED

- Wyrick, G. G. and Borchers, J. W., 1981, Hydrologic effects of stressed relief fracturing in an Appalachian Valley: U.S. Geological Survey, *Water Supply Paper*, 2117, U.S. Government Printing Office, Washington DC, p. 55.
- Gburek, W.J., Urban, B.J., and Schnabel, R.R., 1986, 'Nitrate contamination of ground water in an upland Pennsylvania watershed', in *Proceedings of Agricultural Impacts on Ground Water*: National Water Well Association, Dublin, Ohio, p. 352-380.
- Gburek, W.J. and Folmar, G.J., 1999, A ground water recharge field study: site characterization and initial results: *Hydrological Processes*: v. 13, p. 2813-2831.
- Burton, W.C., Plummer, L.N., Busenberg, E., Lindsey, B.D., and Gburek, W. J., 2002, Influence of fracture anisotropy on ground water ages and chemistry, Valley and Ridge Province, Pennsylvania: *Ground Water*, v. 40, no. 3, May to June 2002, p.242-257.
- Healy, C.S. and Cook, P.G., 2002, Using ground water levels to estimate recharge: *Hydrogeology Journal*, v. 10, no. 1, p. 91-109.
- Heppner, C. S. and Nimmo, J. R., 2005, A computer program for predicting recharge with a master recession curve: U.S. Geological Survey, *Scientific Investigations Report 2005-5172*.
- Niu, Jianzhi and Yu, Xinxiao, 2005, Preferential flow and its scientific significance: *Science of Soil and Water Conservation*. v. 3, no. 3, p.110-116.
- Heppner, C. S., Nimmo, J. R., Folmar G. J., Gburek, W. J., Risser, D. W., 2007, Multiple-methods investigation of recharge at a humid-region fractured rock site, Pennsylvania, USA: *Hydrogeology Journal*, 2007, v. 15, p. 915-927.
- Nimmo, J.R., 2010, Theory for source-responsive and free-surface film modeling of unsaturated flow: *Vadose Zone Journal*. v. 9, p. 295-306.
- Reese, S. O. and Risser, D. W., 2010, Summary of groundwater-recharge estimates for Pennsylvania: *Pennsylvania Geological Survey, 4th ser., Water Resource Report 70*, p. 18.

Mirus, B.B. and Nimmo, J.R., 2013, Balancing practicality and hydrologic realism: A parsimonious approach for simulating rapid ground water recharge via unsaturated-zone preferential flow: *Water Resources Research*, v. 49, no. 3, p. 1458-1465.

Nimmo, J.R., Horowitz, C., and Mitchell, L., 2014, Discrete-storm water table fluctuation method to estimate episodic recharge and climatic sensitivities: *Ground Water*, v. 52.

Weather Underground, 2014, Monthly History Weather in Fort Indiantow Gap, PA.
<http://i.wund.com/auto/iphone/history/airport/KMUI/1997/9/30/MonthlyHistory.html>

APPENDIX A: MRC Fitted Curves

Figure A1. The MRC fitted curves for the wet season (11/16/1997-5/15/1998) in the NE well.

Figure A2. The MRC fitted curves for the wet season (11/16/1997-5/15/1998) in the NW well.

Figure A3. The MRC fitted curves for the wet season (11/16/1997-5/15/1998) in the CE well.

Figure A4. The MRC fitted curves for the dry season (10/1/1997-11/15/1997 and 5/16/1998-9/30/1998) in the NE well.

Figure A5. The MRC fitted curves for the dry season (10/1/1997-11/15/1997 and 5/16/1998-9/30/1998) in the NW well.

Figure A6. The MRC fitted curves for the dry season (10/1/1997-11/15/1997 and 5/16/1998-9/30/1998) in the CE well.

Figure A7. The MRC fitted curves for the whole water year (10/1/1997-9/30/1998) in the NE well.

Figure A8. The MRC fitted curves for the whole water year (10/1/1997-9/30/1998) in the NW well.

Figure A9. The MRC Fitted Curve for the Whole Water Year (10/1/1997-9/30/1998) in the CE well.

APPENDIX B: Source-Responsive Model Sensitivity Analysis

Figure B1. The sensitivity analysis for the NE well in the period 10/31/1997-11/15/1997.

Figure B2. The sensitivity analysis for the NE well in the period 11/16/1997-5/15/1998.

Figure B3. The sensitivity analysis for the NE well in the period 5/16/1998-6/17/1998.

Figure B4. The sensitivity analysis for the NE well in the period 6/24/1998-9/30/1998.

Figure B5. The sensitivity analysis for the NW well in the period 10/1/1997-11/15/1997.

Figure B6. The sensitivity analysis for the NW well in the period 11/16/1997-5/15/1998.

Figure B7. The sensitivity analysis for the NW well in the period 5/16/1998-6/17/1998.

Figure B8. The sensitivity analysis for the NW well in the period 6/24/1998-9/30/1998.

Figure B9. The sensitivity analysis for the CE well in the period 10/1/1997-11/15/1997.

Figure B10. The sensitivity analysis for the CE well in the period 11/16/1997-5/15/1998.

Figure B11. The sensitivity analysis for the CE well in the period 5/16/1998-6/25/1998.

Figure B12. The sensitivity analysis for the CE well in the period 6/26/1998-7/2/1998.

Figure B13. The sensitivity analysis for the CE well in the period 8/1/1998-9/30/1998.

APPENDIX C: Source-Responsive Model Calibration Plots

Figure C1. The source-responsive model calibration for the NE well in the period 10/31/1997-11/15/1997.

Figure C2. The source-responsive model calibration for the NE well in the period 11/16/1997-5/15/1998.

Figure C3. The source-responsive model calibration for the NE well in the period 5/16/1998-6/17/1998.

Figure C4. The source-responsive model calibration for the NE well in the period 6/24/1998-9/30/1998.

Figure C5. The source-responsive model calibration for the NW well in the period 10/1/1997-11/15/1997.

Figure C6. The source-responsive model calibration for the NW well in the period 11/16/1997-5/15/1998.

Figure C7. The source-responsive model calibration for the NW well in the period 5/16/1998-6/17/1998.

Figure C8. The source-responsive model calibration for the NW well in the period 6/24/1998-9/30/1998.

Figure C9. The source-responsive model calibration for the CE well in the period 10/1/1997-11/15/1997.

Figure C10. The source-responsive model calibration for the CE well in the period 11/16/1997-5/15/1998.

Figure C11. The source-responsive model calibration for the CE well in the period 5/16/1998-6/25/1998.

Figure C12. The source-responsive model calibration for the CE well in the period 6/26/1998-7/2/1998.

Figure C13. The source-responsive model calibration for the CE well in the period 8/1/1998-9/30/1998.

APPENDIX D: EMR Output Plots

Figure D1. The EMR output figures for the NE well from 10/1/1997 to 11/6/1997, of (a) $H(t)$ data and (b) calculated dH/dt vs. time.

Figure D2. The EMR output figures for the NE well from 11/7/1997 to 2/4/1998, of (a) $H(t)$ data and (b) calculated dH/dt vs. time.

Figure D3. The EMR output figures for the NE well from 2/5/1998 to 5/15/1998, of (a) $H(t)$ data and (b) calculated dH/dt vs. time.

Figure D4. The EMR output figures for the NE well from 5/16/1998 to 9/30/1998, of (a) $H(t)$ data and (b) calculated dH/dt vs. time.

Figure D5. The EMR output figures for the NW well from 10/3/1997 to 11/4/1997, of (a) $H(t)$ data and (b) calculated dH/dt vs. time.

Figure D6. The EMR output figures for the NW well from 11/6/1997 to 2/4/1998, of (a) $H(t)$ data and (b) calculated dH/dt vs. time.

Figure D7. The EMR output figures for the NW well from 2/4/1998 to 5/15/1998, of (a) $H(t)$ data and (b) calculated dH/dt vs. time.

Figure D8. The EMR output figures for the NW well from 5/16/1998 to 9/30/1998, of (a) $H(t)$ data and (b) calculated dH/dt vs. time.

Figure D9. The EMR output figures for the CE well from 10/3/1997 to 11/1/1997, of (a) $H(t)$ data and (b) calculated dH/dt vs. time.

Figure D10. The EMR output figures for the CE well from 9/28/1997 to 2/4/1998, of (a) $H(t)$ data and (b) calculated dH/dt vs. time.

Figure D11. The EMR output figures for the CE well from 2/4/1998 to 5/15/1998, of (a) $H(t)$ data and (b) calculated dH/dt vs. time.

Figure D12. The EMR output figures for the CE well from 5/16/1998 to 6/24/1998, of (a) $H(t)$ data and (b) calculated dH/dt vs. time.

Figure D13. The EMR output figures for the CE well from 6/25/1998 to 6/30/1998, of (a) $H(t)$ data and (b) calculated dH/dt vs. time.

Figure D14. The EMR output figures for the CE well from 8/3/1998 to 9/30/1998, of (a) $H(t)$ data and (b) calculated dH/dt vs. time.

APPENDIX E: EMR Output Tables

Table E1. Results of the EMR analysis for the NE well.

Time in 1997 (day)	Water level (m)	Duration (day)	Recharge (m)	Precip. (m)	RPR (-)	Avg. precip. (m/day)	Max. precip. rate (m/day)
11/7/1997	254.09	3.965	0.034	0.026	1.303	0.007	0.091
11/14/1997	259.263	2.418	0.008	0.008	0.934	0.004	0.079
11/21/1997	259.409	2.865	0.006	0.016	0.406	0.005	0.08
11/29/1997	259.278	2.671	0.009	0.021	0.4	0.008	0.08
12/12/1997	258.827	2.965	0.007	0.01	0.704	0.003	0.076
12/24/1997	258.769	2.251	0.011	0.019	0.585	0.009	0.091
*1/7/1998	260.229	1.971	0.016	0.039	0.413	0.022	0.236
1/15/1998	259.495	2.914	0.009	0.025	0.362	0.008	0.079
1/22/1998	259.653	3.212	0.007	0.02	0.367	0.006	0.122
1/28/1998	259.674	3.275	0.006	0.005	1.245	0.001	0.014
2/3/1998	259.58	3.386	0.009	0.037	0.252	0.011	0.175
2/11/1998	259.458	2.75	0.006	0.013	0.471	0.004	0.097
2/16/1998	259.562	3.914	0.01	0.038	0.263	0.01	0.128
2/23/1998	259.656	3.068	0.011	0.059	0.179	0.019	0.246
3/8/1998	259.299	3.126	0.011	0.024	0.447	0.008	0.169
3/20/1998	259.254	2.896	0.012	0.028	0.441	0.01	0.155
3/31/1998	259.296	2.745	0.006	0.019	0.297	0.007	0.274
4/8/1998	259.345	3.042	0.012	0.057	0.22	0.018	0.236
4/18/1998	259.266	3.112	0.013	0.05	0.258	0.016	0.181
4/26/1998	259.458	2.662	0.005	0.023	0.229	0.008	0.079
5/4/1998	259.309	2.919	0.013	0.038	0.343	0.013	0.298
5/7/1998	260.305	5.963	0.01	0.055	0.191	0.009	0.098
6/13/1998	257.041	3.443	0.014	0.032	0.441	0.009	0.145
6/26/1998	259.9	1.508	0.002	0.018	0.133	0.011	0.419
7/7/1998	259.168	2.718	0.005	0.03	0.162	0.011	0.162
Average	259.143	3.030	0.010	0.028	0.442	0.009	0.152

*EMR criteria have been artificially adjusted to combine intense storms. Lack of confidence in the results.

Table E2. Results of the EMR analysis for the NW well.

Time in 1997 (day)	Water level (m)	Duration (day)	Recharge (m)	Precip. (m)	RPR (-)	Avg. precip. (m/day)	Max. precip. rate (m/day)
11/8/1997	252.975	2.93	0.024	0.026	0.928	0.009	0.091
11/13/1997	257.964	3.402	0.005	0.01	0.549	0.003	0.079
11/21/1997	258.01	3.635	0.004	0.016	0.285	0.004	0.08
11/29/1997	257.958	3.302	0.006	0.022	0.276	0.007	0.08
12/24/1997	257.852	2.475	0.006	0.022	0.284	0.009	0.091
*1/7/1998	258.821	2.082	0.008	0.043	0.18	0.02	0.236
1/14/1998	258.062	3.117	0.007	0.025	0.274	0.008	0.079
1/22/1998	258.199	3.369	0.006	0.02	0.319	0.006	0.122
1/28/1998	258.22	3.827	0.005	0.005	1.092	0.001	0.014
2/4/1998	258.08	2.617	0.008	0.037	0.221	0.014	0.175
2/11/1998	258.025	2.242	0.004	0.013	0.334	0.005	0.097
2/17/1998	258.065	1.985	0.009	0.029	0.314	0.014	0.128
2/23/1998	258.193	2.62	0.01	0.058	0.168	0.022	0.246
3/8/1998	257.958	2.254	0.008	0.023	0.337	0.01	0.169
3/20/1998	257.94	1.797	0.009	0.025	0.37	0.014	0.155
4/8/1998	257.977	2.245	0.01	0.055	0.173	0.024	0.236
4/18/1998	257.943	2.264	0.009	0.047	0.194	0.02	0.181
4/26/1998	258.016	2.059	0.003	0.023	0.148	0.011	0.079
5/4/1998	257.971	2.161	0.009	0.034	0.256	0.016	0.298
5/7/1998	258.733	5.352	0.009	0.055	0.167	0.01	0.098
6/26/1998	258.367	1.249	0.002	0.018	0.114	0.019	0.419
Average	257.873	2.714	0.008	0.029	0.333	0.012	0.150

*EMR criteria have been artificially adjusted to combine intense storms. Lack of confidence in the results.

Table E3. Results of the EMR analysis for the CE well.

Time in 1997 (day)	Water level (m)	Duration (day)	Recharge (m)	Precip. (m)	RPR (-)	Avg. precip. (m/day)	Max. precip. rate (m/day)
11/1/1997	251.622	2.891	0.009	0.016	0.586	0.006	0.138
11/6/1997	252.393	4.302	0.015	0.026	0.569	0.006	0.091
11/13/1997	253.359	2.558	0.008	0.007	1.155	0.003	0.079
11/21/1997	253.545	2.907	0.008	0.016	0.49	0.005	0.08
11/29/1997	253.414	2.849	0.01	0.021	0.485	0.007	0.08
12/12/1997	253.167	3.194	0.007	0.01	0.639	0.003	0.076
*1/7/1998	258.483	1.91	0.033	0.046	0.721	0.024	0.236
1/15/1998	254.072	2.463	0.013	0.025	0.546	0.01	0.079
1/22/1998	254.383	3.14	0.011	0.02	0.543	0.006	0.124
1/29/1998	254.121	2.786	0.005	0.004	1.211	0.002	0.012
2/4/1998	253.892	2.649	0.014	0.037	0.37	0.014	0.175
2/11/1998	253.673	2.628	0.006	0.013	0.507	0.005	0.097
2/17/1998	253.801	1.935	0.018	0.029	0.624	0.015	0.128
2/22/1998	254.215	3.022	0.021	0.059	0.364	0.019	0.246
3/8/1998	253.42	2.919	0.014	0.023	0.626	0.008	0.168
3/20/1998	253.368	1.941	0.017	0.025	0.661	0.013	0.155
3/31/1998	253.469	2.512	0.007	0.019	0.383	0.007	0.273
4/8/1998	253.542	2.457	0.022	0.056	0.393	0.022	0.235
4/18/1998	253.523	2.457	0.021	0.047	0.445	0.019	0.181
4/26/1998	253.798	2.16	0.005	0.023	0.231	0.011	0.079
5/4/1998	253.563	2.203	0.019	0.034	0.564	0.015	0.296
5/10/1998	254.804	2.666	0.023	0.041	0.573	0.015	0.098
6/17/1998	253.036	2.362	0.005	0.01	0.458	0.004	0.121
6/26/1998	253.807	1.17	0.006	0.018	0.337	0.018	0.417
8/9/1998	252.649	2.715	0.005	0.037	0.13	0.015	0.321
8/18/1998	252.932	2.334	0.003	0.012	0.277	0.002	0.103
Average	253.694	2.582	0.013	0.026	0.534	0.011	0.157

*EMR criteria have been artificially adjusted to combine intense storms. Lack of confidence in the results.