Groundwater

Discrete-Storm Water-Table Fluctuation Method to Estimate Episodic Recharge

by John R. Nimmo[1], Charles Horowitz[2], and Lara Mitchell[2]

Abstract

We have developed a method to identify and quantify recharge episodes, along with their associated infiltration-related inputs, by a consistent, systematic procedure. Our algorithm partitions a time series of water levels into discrete recharge episodes and intervals of no episodic recharge. It correlates each recharge episode with a specific interval of rainfall, so storm characteristics such as intensity and duration can be associated with the amount of recharge that results. To be useful in humid climates, the algorithm evaluates the separability of events, so that those whose recharge cannot be associated with a single storm can be appropriately lumped together. Elements of this method that are subject to subjectivity in the application of hydrologic judgment are values of lag time, fluctuation tolerance, and master recession parameters. Because these are determined once for a given site, they do not contribute subjective influences affecting episode-to-episode comparisons. By centralizing the elements requiring scientific judgment, our method facilitates such comparisons by keeping the most subjective elements openly apparent, making it easy to maintain consistency. If applied to a period of data long enough to include recharge episodes with broadly diverse characteristics, the method has value for predicting how climatic alterations in the distribution of storm intensities and seasonal duration may affect recharge.

Introduction

Water applied at the land surface as precipitation, irrigation, or ephemeral surface water varies with weather, seasonality, land management, and climate. These inputs to the hydrologic system travel through the unsaturated zone to produce recharge at a rate that in general has both constant-rate and episodic components (Lewis and Walker 2002). The constant component derives from downward flow that has a slow and diffusive character so as to damp out the temporal fluctuations imposed at the land surface (Nimmo et al. 1994). The episodic component comes through pathways that are fast or direct enough that some degree of rate fluctuation persists to the water table.

Recharge episodicity affects important hydrologic interactions, notably in determining what fraction of introduced water becomes recharge. This fraction, expressed for example as the recharge-to-precipitation ratio (RPR), has considerable utility for hydrologic estimations. Applied to average annual precipitation as a fixed proportion for a given site, assuming climatic stationarity, the RPR provides a simple way to estimate annual recharge. Applied to individual storms and their associated recharge episodes, as in this study, the RPR may vary systematically with storm magnitude (French et al. 1996; Wu et al. 1996; Kendy et al. 2004) and other factors. Alterations of episodicity patterns, as by climate change, can therefore have major impact on water supply (Crosbie et al. 2012). In particular, a climatic trend toward greater average storm intensity may greatly increase or reduce recharge, by producing more water in excess of that required to rewet dry soil or by generating more runoff that does not become recharge. Contaminant transport studies also need objective methods for episodicity analysis, as the spreading of contamination and degradation of water quality may vary systematically with factors similar to those that affect recharge. In general, any investigation of the effect of variable conditions (soil moisture, temperature, vegetation, etc.) on recharge can be improved by objective delineation of recharge episodes.

Water-table fluctuation (WTF) methods (Meinzer 1923; Healy and Cook 2002) can estimate episodic recharge using water-table hydrographs measured with adequate time resolution. Episodic analysis may be straightforward in arid regions where large infrequent events, which dominant recharge, are discernible by inspection. In humid locations, the interstorm intervals

[1]Corresponding author: U.S. Geological Survey, 345 Middlefield Road MS-420, Menlo Park, CA 94025; 1-650-329-4537; fax: 1-650-329-4538; jrnimmo@usgs.gov

[2]U.S. Geological Survey, 345 Middlefield Road MS-420, Menlo Park, CA 94025.

Received June 2013, accepted January 2014.

doi: 10.1111/gwat.12177

may not always exceed groundwater response times, so it may be difficult to separate the water-table rise caused by one storm from that of another.

To delineate particular recharge episodes, judgment can be applied case by case, or systematically, for example, based on the characteristics of peaks in the recharge rate over time (Wu et al. 1996). The analogous problem of storm delineation from precipitation records has received more attention, using various criteria such as a minimum interstorm duration and a minimum amount, duration, or intensity of precipitation (e.g., Huff 1967; Stocking and Elwell 1976; Cameron et al. 2000; Ireson and Butler 2011; Penna et al. 2011).

For evaluation of sensitivities to climate and other factors, the required hydrologic judgments must be consolidated and implemented through a strict framework that does not vary from one episode to the next. Thus the starting point is to quantitatively characterize response features of the subsurface system based on existing knowledge (Voss 2011), so that with these established an objective procedure may then be followed to analyze the data record as a whole. Typical issues include: what deviation from background noise signifies the start of an event? how much rise is attributable to recharge rather than ancillary effects? how much recession would have occurred if there had been no recharge? and when has an episode ceased? These can be parameterized using appropriate thresholds and rates of change that delineate separate events, and assigned values based on the site characteristics and the data set as a whole.

In this study, we develop a method that can identify and quantify recharge episodes, as well as their associated periods of water input, in a way that is useful for general understanding of the effect of storm variation and other variables on recharge. Our objective is to develop and apply the episodic master recession (EMR) method that maintains such uniformity of treatment and accomplishes the following:

1. Systematically partitions a water-table hydrograph into discrete time intervals that either do or do not have episodic recharge.
2. Computes the amount of recharge in each interval, with systematic error correction for effects of processes unrelated to recharge.
3. Uniquely associates each recharge episode with the period of water input that caused it, identifying storms separately when possible, and lumping episodes together when too close in time for the separate recharge contributions to be distinguished.

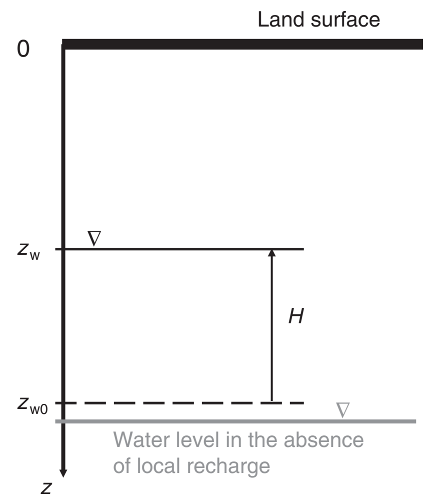

Figure 1. Definition of the z domain.

Current Methods

Basics of the WTF Method

The basis of a WTF method is that a recharging flux entering the saturated zone initially causes the water table to rise, before saturated zone dissipative processes can bring it back to its steady-state level. In this paper we express water-table data as a height, H, above the steady-state position (Figure 1). Recharge is estimated as the product of the specific yield (SY) and an effective change in H attributable to recharge:

$$R = SY \times \Delta H, \tag{1}$$

with ΔH computed as indicated by the vertical line segments in Figure 2. Error may result from influences other than recharge and dissipative saturated zone processes, for example, air trapping, groundwater withdrawal or injection, and barometric pressure changes. These have to be corrected for, or the affected portions of the data set excluded from analysis.

An important distinction among the various implementations of the WTF method is whether they consider the $H(t)$ record in terms of fixed increments or hydrologic episodes. Another is in the method of correcting for unrealized recession. Recessional processes (e.g., evaporation, discharge to springs, and lateral saturated-zone transport) continue while recharge is causing the water table to rise. Therefore the recharging water that compensates for ongoing recessional processes is not realized as water-table rise and needs to be corrected for. Some approaches are to (1) assume unrealized recession is negligible, (2) estimate and correct for it episode-by-episode, or (3) quantify system behavior with a functional relation between water-table level and decline rate, called a master recession curve (MRC). Figure 2 illustrates three such approaches.

RISE Method

Given a record of water level at equal time intervals, the rise for a given interval is the amount by which the water table at the end of that interval is higher than for the previous interval (Rutledge, unpublished manuscript). A decline is taken as a rise of zero. Though simple and objective, this method has deficiencies that include a pronounced sensitivity to measurement frequency, as well as the lack of correction for recession due to natural processes, which biases it toward underestimation.

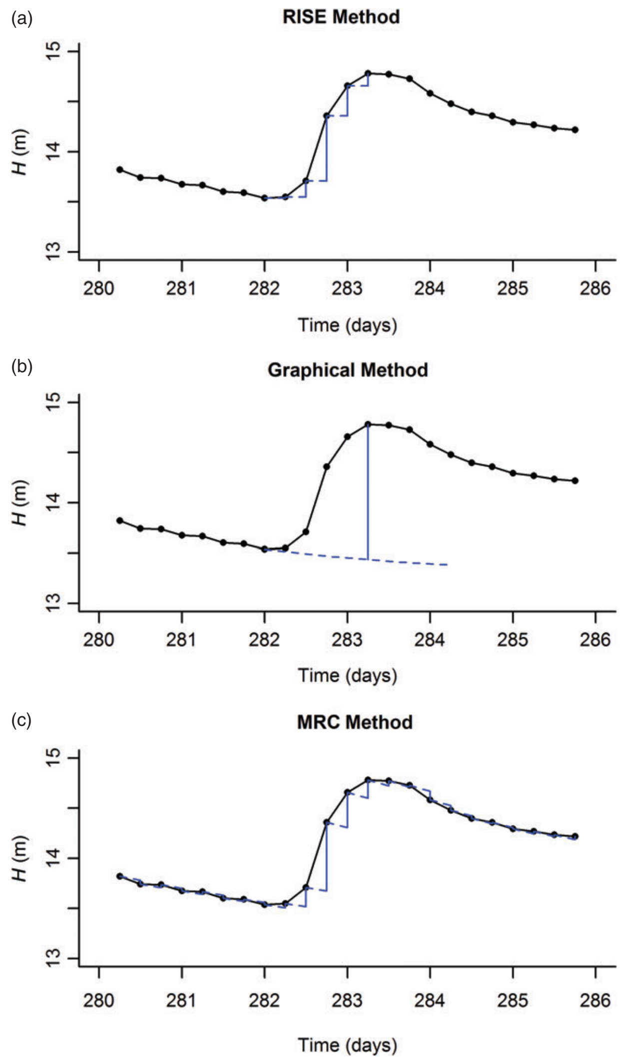

Figure 2. Three ways of implementing the WTF method to estimate the recharge-related response to storm input, illustrated using data from the Masser site over the time period 8 to 14 October 1999. (a) Fixed-interval (RISE) method without accounting for unrealized recession. (b) Episodic/individualized recession curve (graphical) method. (c) Fixed-interval MRC method.

Graphical Method

The graphical method works on the basis of hydrologic episodes rather than fixed time intervals and can estimate and correct for unrealized recession (Delin et al. 2007). The effective rise due to a recharge episode is taken to be the difference between the peak water-table position and the extrapolated recession at the time of the peak. Extrapolating the recession and judging start and end times require manual attention for each episode.

MRC Method

MRC is a characteristic of a particular well expressing the rate of water-table decline (dH/dt) as a function of H (Heppner and Nimmo 2005; Delin et al. 2007; Heppner et al. 2007). Crosbie et al. (2005) developed a similar method in which the rate of decline is a linear function of *H*. Cuthbert (2010) presented a refined version of the method that applies a constant drainage rate where circumstances make that appropriate. An MRC predicts the characteristic rate of change of water-table level as a function of the current level, typically with faster decline for greater H.

A shortcoming in common with other methods is that it does not identify the amount of input water responsible for the recharge in a given interval; in general the associated infiltration would have occurred over a time period different from the specific time interval evaluated for recharge. The method also requires more complex setup than the RISE and graphical methods. Like RISE, it does not account for nonrecharge influences on the water table such as air trapping, which leads to a calculation of negative recharge because of overshoot—H may rise too high at peaks and then decline faster than the MRC. This method is also likely to be sensitive to measurement frequency. The MRC method, like RISE, does not recognize or define individual hydrologic episodes. Because both of the methods quantify recharge over time without requiring further hydrologic judgments after the MRC has been established, however, they make possible the comparison of recharge on an episodic basis if the time interval of each episode can be established.

Summary and Need

Table 1 organizes the different variations of the WTF method according to the two attributes mentioned above, type of time increment and correction method for unrealized recession. The EMR method we present here was developed to fill the role of evaluating specific recharge episodes with a systematic extrapolation technique (bottom right in Table 1).

EMR Method

The EMR method (1) identifies discrete recharge episodes based on WTF rates, (2) estimates the recharge generated during individual episodes, and (3) uniquely associates each episode with a causal water-input period. Appendix S1 gives the detailed procedure and computer code documentation.

A recharge episode is defined as a period during which the total recharge rate significantly exceeds its steady-state condition in response to a substantial water-input event, such as a large rainstorm (Figure 3). The period between successive recharge episodes is labeled a constant-recharge interval, idealized as a period when the only recharge is the ongoing constant-rate component. As the constant component does not cause fluctuations, EMR, like other WTF methods, does not account for it. The constant component may be estimated by other means (Nimmo et al. 1994) and some applications may require supplementation of the WTF method with a complementary steady-state method to obtain total recharge.

The basic data requirement is a time series of water-table levels $H(t)$ over a period long enough to include multiple recharge episodes. The $H(t)$ record must have adequate time resolution and continuity to be

Table 1
Categorization of Selected Versions of the WTF Method

	No Extrapolation (Zero Recession Curve)	Case-by-Case Extrapolation (Individualized Recession Curve)	Systematic Extrapolation (Generalized Recession Relation)
Fixed increment	RISE (Rutledge, unpublished manuscript; Delin et al. 2007)	Special case of MRCR	MRCR (Heppner and Nimmo 2005; Delin et al. 2007); constant-drainage method (Crosbie et al. 2005)
Recognized episodes	Special case of graphical	Graphical (Delin et al. 2007)	EMR (this paper)

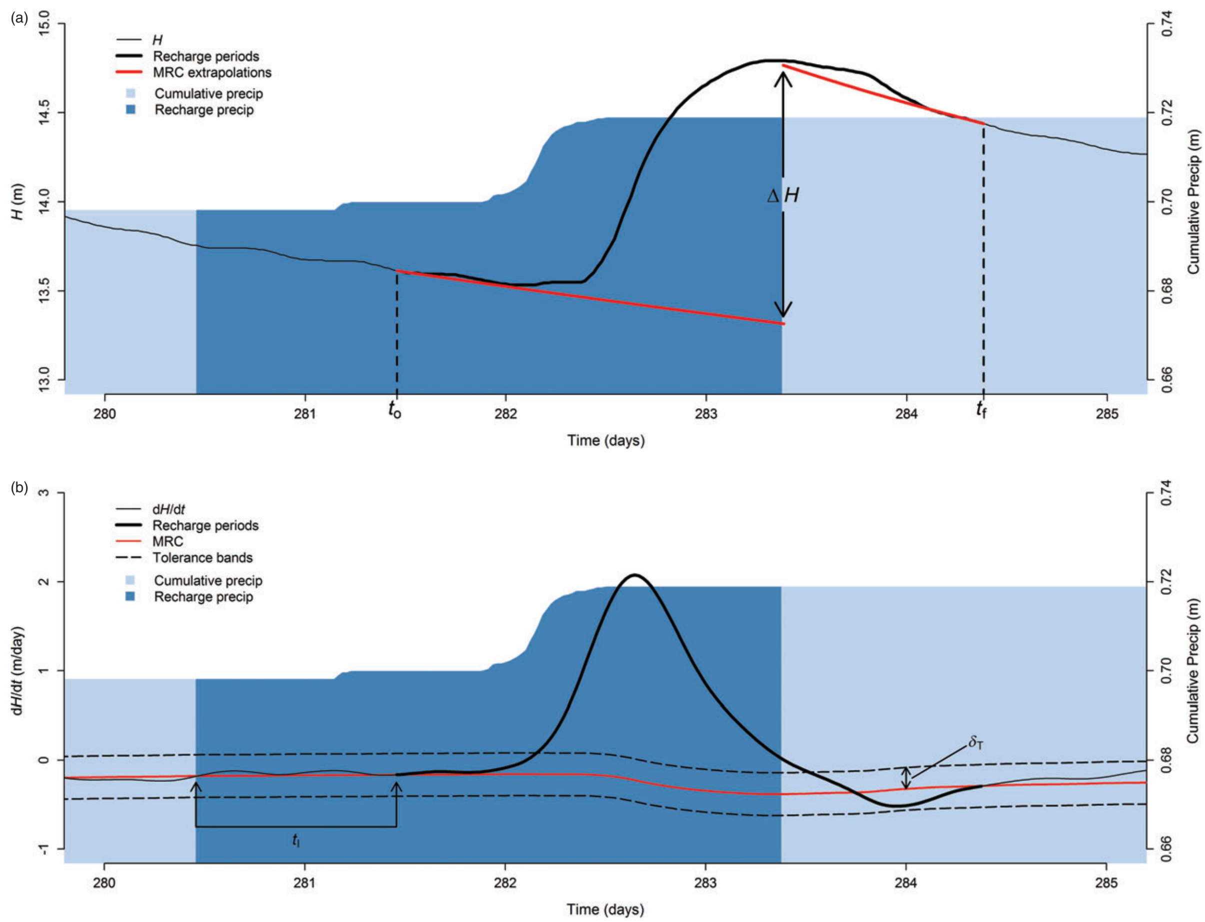

Figure 3. Recharge episode illustrating the EMR method. (a) Water-table level $H(t)$. The red curves are extrapolations based on the MRC, the vertical distance between which is taken to indicate the total recharge of the episode, corrected for both unrealized recession and overshoot. (b) Time rate of change of $H(t)$, shown with the MRC and tolerance band.

differentiable in time, so that the rate of change dH/dt can be used to discern hydrologically significant features of the data set. A concurrent time series of water-input at the land surface (e.g., cumulative precipitation) is also needed if the RPR or other correlations with inputs are to be considered. A value for SY is necessary as for any WTF method. Various options, noted in Appendix S1 and described in more detail by Heppner and Nimmo (2005), may be employed to establish an MRC for a site or a particular well.

Two other parameters characterizing a site or well are unique to the EMR method. One is the WTF tolerance (δ_T), essentially a measurement-noise criterion used to ascertain whether or not a given fluctuation in $H(t)$ is hydrologically significant. The other, needed for assessing recharge/precipitation correlations, is the precipitation lag time (t_l), reflecting the response time for recharge caused by a given precipitation event.

After the MRC and parameter values have been determined, they can be applied to evaluate episodic recharge from data records of any duration. The first step is to determine the start and end times of recharge episodes. This is done using dH/dt and δ_T according to particular rules explained in Appendix S1. Subtracting t_l

from these gives the start and end times for precipitation contributing to the episode. Next is to compute the amount of recharge attributable to each episode. As illustrated in Figure 3, this is done using two extrapolations of $H(t)$ using the MRC. One of these extrapolations goes forward in time from the value of H at the episode start time, and indicates the estimated values of $H(t)$ that would have been observed if there were no episodic recharge. The other goes backward from the value of H at the episode end time, and indicates the estimated values that would have been observed if there were no overshoot. The estimated recharge of the episode is the difference in H between these extrapolated curves at a specified time within the episode. Recharge estimated in this way is thus corrected for both unrealized recession and overshoot.

Case Studies and Testing

Episodic Recharge at the Masser Site

Characteristics and Data

We applied our method to a data set from the Masser groundwater recharge site in the East Mahantango Creek Basin, Pennsylvania, where numerous hydrologic studies have been conducted (Gburek and Folmar 1999). The Masser site was instrumented by the USDA in the 1990s to investigate recharge processes in a humid region underlain by fractured bedrock. The mean annual precipitation of about 1 m is distributed fairly evenly through the year. Average temperatures range from -4°C in January to 22°C in July. The soil is a well-drained silty loam, 0- to 1.5-m thick, underlain by the fine grained sandstone with interbedded sandstone conglomerate, siltstone and shale of the Catskill formation. This formation is highly fractured, with three sets of orthogonal joint systems, which account for most of its permeability. The site lies near a topographic high which minimizes the lateral movement of subsurface water, enhancing the plausibility of approximations based on one dimensionality. These characteristics make it highly suitable for the WTF method.

The site is instrumented with five observation wells, four surrounding a central well, one each in an ordinal direction (NW, NE, SE, SW) with the outer wells 25 m apart. The center well was drilled to a depth of 46 m and the others to 30 m. Each is cased to 5.5 m and open below that. Floats and dataloggers collected water-table data from the wells with accuracy ± 3 mm. A meteorological station recorded precipitation, temperature, wind speed, and solar radiation.

Previous studies of recharge at Masser site include those of Gburek and Folmar (1999) and Risser et al. (2005, 2009). Heppner et al. (2007) analyzed individual recharge events at the Masser site using two methods: lysimeter data analysis and WTF analysis with the MRC method. Their criterion for storm selection was identifiable water-table response. Heppner et al. distinguished episodes as "Rainfall events . . . including all non-zero rainfall intervals during which any well was rising since the start of the event." This criterion yielded 28 reliably separable events during the 1994 through 1999 period. Correlation analysis showed a strong relationship between computed recharge and storm magnitude, and generally faster response times with greater rainfall intensity.

Recharge by EMR Method

We used 1994 through 2001 precipitation and well-response data at half-hour intervals for three wells that had sufficient data for analysis after excluding intervals having significant gaps or anomalous spikes or dips.

The MRC was determined from recessional data, those remaining after first excluding data within a storm recovery time t_{p} after a peak in $H(t)$. Doing this excluded data significantly affected by residual recharge from previous episodes. For the Masser site a t_{p} value of 1.75 days was determined by trial and error to minimize variability of $\mathrm{d}H/\mathrm{d}t$ while keeping the value small enough that a statistically significant number of data points remain for analysis. Additional details are in Appendix S1. We set the datum from which H is determined (z_{w0} in Figure 1) by trial and error, finding a value that gave good fits to a linear proportionality between H and recession rate. Using the bin-average method described by Heppner and Nimmo (2005), we chose a bin size of 0.5 m for intervals of H data and computed the average $\mathrm{d}H/\mathrm{d}t$ values of the each bin. The purpose of bin averaging is to equally weight all portions of the range, not overweighting those portions having greater density of data. These average values as a function of bin H were regressed to a third-order polynomial fit for use as the MRC.

Next, an iterative process determined the most realistic values of lag time and fluctuation tolerance. For a trial value of t_1 we began with the storm recovery time of 1.75 days, and varied it by integer multiples of the measurement interval. For δ_{T} we began with a trial value based on the absolute value of $[\mathrm{d}H/\mathrm{d}t]_{\mathrm{MRC}} - [\mathrm{d}H/\mathrm{d}t]_{\mathrm{obs}}$ during intervals suspected to have negligible components of episodic recharge. When the EMR algorithm was applied with this trial value some episodes produced negative recharge estimates—isolated events of rapid decline, faster than what was predicted by MRC. These were events during which $[\mathrm{d}H/\mathrm{d}t]_{\mathrm{obs}}$ deviated only slightly from $[\mathrm{d}H/\mathrm{d}t]_{\mathrm{MRC}}$. To avoid implying periods of negative recharge, we increased δ_{T} to a value large enough to eliminate these periods, but small enough not to affect the designation of other episodes.

Results

Our primary analysis was performed on the set of data from the center well during 1999, a period of few gaps and anomalies. Values of $\delta_{\mathrm{T}} = 0.195$ m/day and $t_1 = 0.875$ days gave results that we judged to show the most plausible hydrologic behavior. Using these values, the method identified 18 distinct recharge episodes for the year. We used the value 0.013 for SY, as determined by relating streamflow to recharge (Risser et al. 2005). Table 2 lists the

Table 2
Recharge Episodes (E) and Constant-Recharge Intervals (S) Identified by the EMR Method for the Masser Site During 1999

	Interval Start Date (in 1999)	Relative Date (Days Since Jan. 1, 1999)	Interval Length (Days)	Precipitation (mm)	H at Start of Interval (m)	Max. Rain Intensity (mm/h)	Recharge (mm)	Recharge to Precipitation Ratio (−)	Recharge Estimate of Heppner et al. (2007) (mm)
E-1	Feb 9	39.55	4.99	7.4	13.12	4.0	19.4	2.63	
S-1	Feb 14	44.54	12.79	13.3	13.00	2.5	0.0	—	
E-2	Feb 27	57.32	2.87	24.6	12.83	9.4	5.5	0.22	
S-2	Mar 2	60.19	0.75	1.3	13.90	14.5	0.0	—	
E-3	Mar 2	60.94	2.68	15.1	12.77	4.9	22.5	1.49	
S-3	Mar 5	63.62	10.66	37.4	12.89	4.7	0.0	—	
E-4	Mar 16	74.29	4.03	2.4	13.20	0.9	23.7	9.88	
S-4	Mar 20	78.32	0.46	0.0	14.07	0	0.0	—	
E-5	Mar 20	78.78	2.27	26.3	14.29	6.9	21.7	0.82	
S-5	Mar 23	81.05	16.57	18.2	14.35	8.8	0.0	—	
E-6	Apr 8	97.62	5.99	28.8	13.00	7.1	25.8	0.90	
S-6	Apr 14	103.62	22.76	22.1	15.11	3.3	0.0	—	
E-7	May 7	126.38	4.31	29.9	12.95	15.8	19.5	0.65	12.3
S-7	May 11	130.69	32.04	23.1	14.12	4.3	0.0	—	
E-8	Jun 12	162.73	2.98	9.1	12.42	7.6	5.2	0.57	
S-8	Jun 15	165.70	58.14	82.1	13.84	10.5	0.0	—	
E-9	Aug 12	223.84	2.31	59.1	11.40	23.8	4.0	0.07	
S-9	Aug 15	226.15	22.04	50.8	12.46	8.6	0.0	—	
E-10	Sep 6	248.19	3.16	44.0	11.30	15.0	11.0	0.25	
S-10	Sep 9	251.35	5.95	0.5	11.46	0.2	0.0	—	
E-11	Sep 15	257.30	2.61	70.0	11.36	9.1	45.9	0.66	77.7
S-11	Sep 17	259.91	3.42	12.9	11.83	0.6	0.0	—	
E-12	Sep 21	263.33	2.64	26.1	13.29	5.8	16.6	0.64	
S-12	Sep 23	265.96	4.89	0.8	14.44	0.3	0.0	—	
E-13	Sep 28	270.86	2.53	42.7	13.18	9.1	35.7	0.84	
S-13	Oct 1	273.39	2.46	0.0	14.11	0	0.0	—	
E-14	Oct 3	275.85	3.65	11.4	14.07	5.8	7.6	0.66	
S-14	Oct 7	279.51	1.95	1.8	15.17	0	0.0	—	
E-15	Oct 9	281.46	2.93	20.8	13.61	4.3	18.5	0.89	16.4
S-15	Oct 12	284.38	2.02	7.1	13.95	0	0.0	—	
E-16	Oct 14	286.40	2.30	7.1	14.13	6.1	4.3	0.60	
S-16	Oct 16	288.70	15.76	7.7	14.44	2.1	0.0	—	
E-17	Nov 1	304.46	3.07	28.9	12.84	14.9	26.2	0.91	23.8
S-17	Nov 4	307.53	20.78	13.5	13.97	1.0	0.0	—	
E-18	Nov 25	328.31	5.08	23.9	12.81	2.8	22.8	0.96	

results of this analysis for both recharge and nonrecharge intervals. Figure 4 shows the series of episodes.

Four of these episodes, E7, E11, E15, and E17, are among the 28 recharge events that Heppner et al. (2007) identified directly from precipitation and $H(t)$ data. The rightmost column of Table 2 gives the previously estimated recharge values, using the same SY, 0.013. Deviations from our values range from −37% to +41%, with two of the values differing by about 10%. Differences may result from particular features of the $H(t)$ data, for example in the treatment of overshoot. Two of the EMR values are greater and two are smaller, suggesting minimal relative bias of the two methods. An undercorrection for overshoot may be the reason the Heppner et al. estimate for episode E-11 is so large. In terms of the recharge-to-precipitation ratio (RPR) there is greater discrepancy between either of these methods and the various estimates of Risser et al. (2009). For calendar year 1999, their estimates from several methods give an average RPR of 0.20, whereas our estimated RPR values exceed 0.5 for most episodes and indicate an overall value of 0.43 for the year. A likely cause of this discrepancy is the high uncertainty in specific yield. The extremely low SY at this site, while making for large, easily-investigated WTFs, unfortunately also makes the results sensitive to very small errors in SY. Risser et al. (2009) found SY for nearby wells to range from 0.0035 to 0.035. Thus the regionally determined 0.013 value we used may be too large for the wells of our study. A different value within this range would bring our RPR values into general agreement with others; using 0.0060 for example, our estimated overall RPR would equal 0.20 as for the Risser et al. (2009) study.

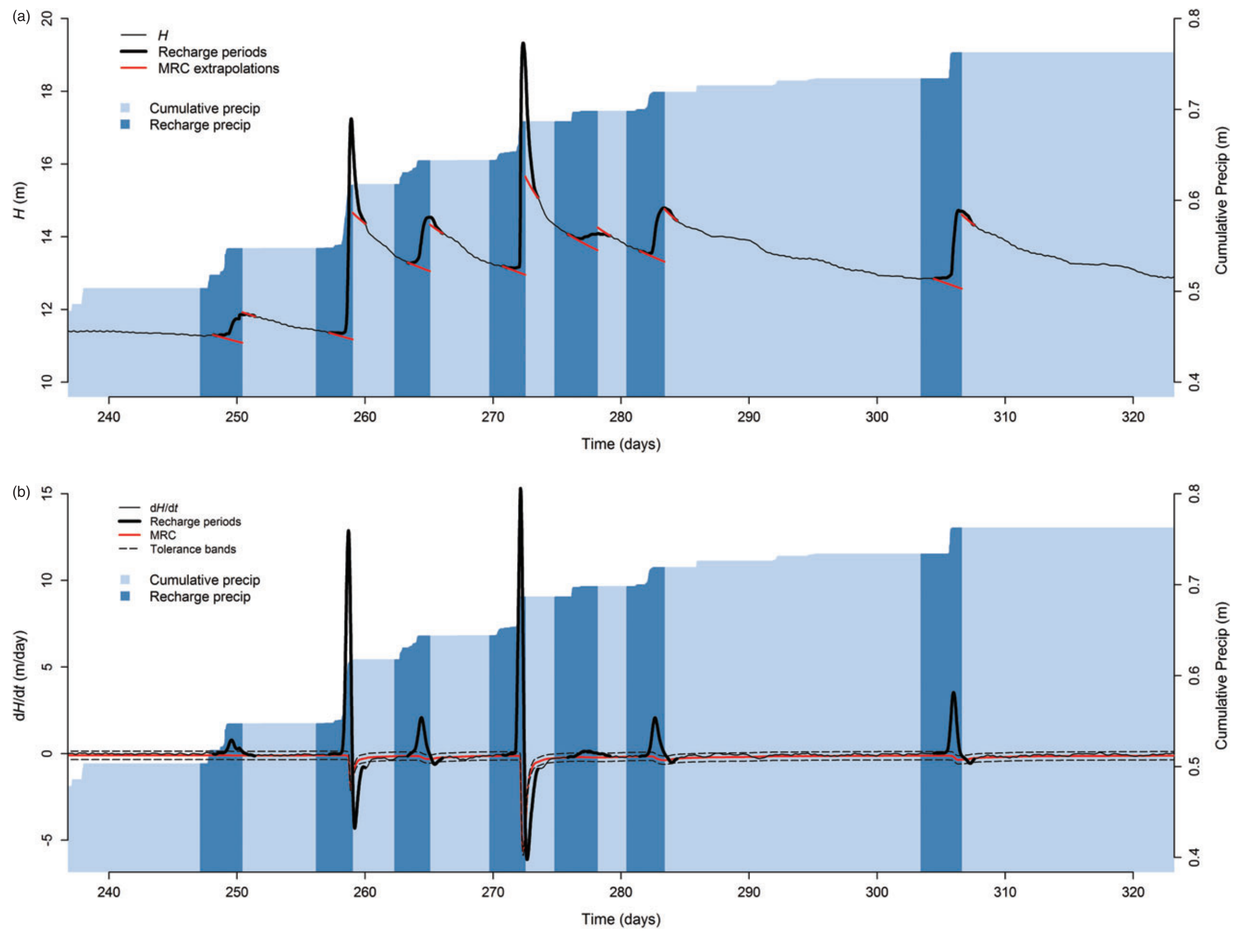

Figure 4. EMR analysis, for the Masser site over the year 1999, of (a) $H(t)$ data and (b) calculated $\mathrm{d}H/\mathrm{d}t$ vs. t.

Episodic Recharge at the Silstrup Site

We applied our model to data from Silstrup in Denmark to test it at a site of distinct contrast from the Masser site that provided data for the model's development. Silstrup is a tile-drained field research site situated on a glacial moraine of Weichselian Age. Tile drains are located at 1.1-m depth and lateral spacings of 17 to 18 m. The research site covers approximately 1.7 ha and slopes about 1 to 2°. The soil is predominantly glacial till that has been exposed to pedologic and geomorphologic processes for approximately 16,000 years (Lindhardt et al. 2001). The topsoil is about 0.5 m thick. Below the topsoil to 13-m depth are three clay till units. The top meter of the soil is heavily fractured and contains 100 to 1000 biopores/m^2. The till has various fracture networks, with both horizontal and vertical fractures to 3.5-m depth, and horizontal with only very sparse vertical fractures from 3.5- to 13-m depth. The water table is generally between 0.5 and 5 m below ground level and recedes rapidly after infiltration ceases.

Various quantities have been measured continuously since September 1999, including hourly precipitation, water-table level, and volumetric water content at various depths using TDR probes (Rosenbom et al. 2010). Water levels were measured in piezometers with 0.5-m long screens distributed over the 2- to 12-m depth interval. For our analysis, we chose the period in 2006 between July 1 and October 15, during which the water table stayed low enough that water removal through tile drains would not limit water-table rise. Cultural practices during 2006 that may have affected soil water response during our study period were as follows: (1) ploughed to a depth of 18 cm on April 7; (2) spring barley sown on April 12; (3) rolled with a cam roller on May 1; and (4) barley harvested on August 17.

To estimate SY, we first considered the average measured water content at 1.9 to 2.1-m depth in late July, with the water table at 2.3 to 2.4-m depth. This value was 0.33. The average water content in the same 1.9 to 2.1 m interval during a period in April, when the water table was at 0.6-m depth, was 0.366. Taking the difference to be the amount of soil water content increase during a typical water-table rise in summer, SY = 0.036.

Our analysis of this 3.5-month period used values of $\delta_{\mathrm{T}} = 0.02$ m/days and $t_{\mathrm{l}} = 1.00$ days and yielded seven distinct episodes of recharge (Table 3 and Figure 5). RPR over the 3.5 months was determined to be 0.305, compared to 0.302 for the average among episodes. Of the precipitation that fell in this period, our method assigned 94.1% to recharge intervals, a high percentage as would be expected for a site where most of the recharge is from precipitation-driven episodes. Because the method

Table 3
Recharge Episodes (E) and Constant-Recharge Intervals (S) Identified by the EMR Method for the Silstrup Site Between 1 July and 15 October 2006

	Interval Start Date (in 2006)	Relative Date (Days Since July 1, 2006)	Interval Length (Days)	Precipitation (mm)	H at Start of Interval (m)	Max. Rain Intensity (mm/h)	Recharge (mm)	Recharge to Precipitation Ratio (−)
E-1	Jul 7	6.71	2.85	8.9	3.98	7.1	1.6	0.18
S-1	Jul 10	9.56	18.53	2.4	3.97	7.1	0.0	—
E-2	Jul 29	28.08	5.82	47.5	3.56	19.9	9.9	0.21
S-2	Aug 3	33.90	6.19	0.1	3.73	6.2	0.0	—
E-3	Aug 10	40.09	7.20	23.9	3.53	7.7	9.4	0.39
S-3	Aug 17	47.30	0.31	0.0	3.67	1.5	0.0	—
E-4	Aug 17	47.61	3.79	13.9	3.65	6.1	4.6	0.33
S-4	Aug 21	51.40	4.09	0.0	3.71	1.3	0.0	—
E-5	Aug 25	55.49	4.23	22.9	3.58	11.3	6.5	0.29
S-5	Aug 29	59.72	1.21	0.9	3.69	3.1	0.0	—
E-6	Aug 30	60.92	4.92	37.4	3.64	14.7	10.6	0.28
S-6	Sep 4	65.84	19.67	7.0	3.85	2.5	0.0	—
E-7	Sep 24	85.51	15.01	75.2	3.56	14.9	31.7	0.42

determines precipitation intervals solely through analysis of the well-level record, a high percentage of associated precipitation for such a site shows consistency with expected performance. The ability of the EMR method to account for virtually all precipitation in recharge intervals, exclusively from analysis of the record of well-level fluctuations, supports its adequacy for identifying recharge episodes and constant-recharge intervals.

For the Silstrup site there are annual total recharge estimates by Rosenbom et al. (2010), though no episodic estimates. From 1 July 2006 to 30 June 2007, they estimated 249 mm of recharge, calculated as precipitation minus actual evapotranspiration minus measured drainage. Precipitation of 1150 mm over that period indicates RPR of 0.217. This value is lower than our estimate of 0.305, though during most of the period they studied, the water table was above the drains, so their RPR estimate reflects a reduction of recharge by the drainage that occurred at these times. The lack of tile drainage over our test period (with water table below the drains) can reasonably account for the greater RPR.

Discussion

Focusing of Hydrologic Judgment

A key feature of the EMR method is that it confines the necessary use of subjective hydrologic judgment to the initial site-specific stage of investigation. Avoidance of episode-specific judgments maintains a sound basis for episode-to-episode comparisons. Besides specific yield as needed for any WTF recharge application, the main assessments needed are lag time, fluctuation tolerance, and master recession parameters. Ideally these can be determined once for a given site using a representative portion of available data.

The two parameters t_1 and δ_T supplement the usual recession curve evaluation to centralize the elements requiring judgment and keep them openly apparent. The lag time t_1 represents a characteristic unsaturated-zone transport time applicable under conditions which permit episodic recharge. A parameter like this, or at least the general transport-speed concept behind it, is unavoidable in efforts to link a specific amount of precipitation with the amount of recharge it eventually causes. In general t_1 would be greater for deeper water tables, for less permeable unsaturated-zone materials, and for a lesser role of preferential flow. The fluctuation tolerance δ_T may depend on the instrumentation and measurement frequency, in addition to subsurface characteristics. Like lag time, this tolerance concept is essential to the use of measured data to distinguish between intervals with and without episodic recharge. The success of our model tests suggests these two parameters effectively embody the hydrologic judgments needed to use the WTF method to delineate and quantify episodic recharge.

Overshoot Correction

Another significant advantage is that the EMR method provides a systematic correction for overshoot, the component of water-table rise that results from changes in temperature or atmospheric pressure (Healy and Cook 2002), air trapping in the medium (Faybishenko 1995; Fayer and Hillel 1986; Stonestrom and Rubin 1989), or other causes unrelated to recharge accretion. The EMR method recognizes overshoot by its signature of faster-than-MRC decline, which implies that a mechanism such as air trapping is active that did not affect the data used to establish the MRC. Our double-use of MRC extrapolation (both before and after peak H) implicitly corrects for overshoot errors without applying different subjective judgments to separate instances.

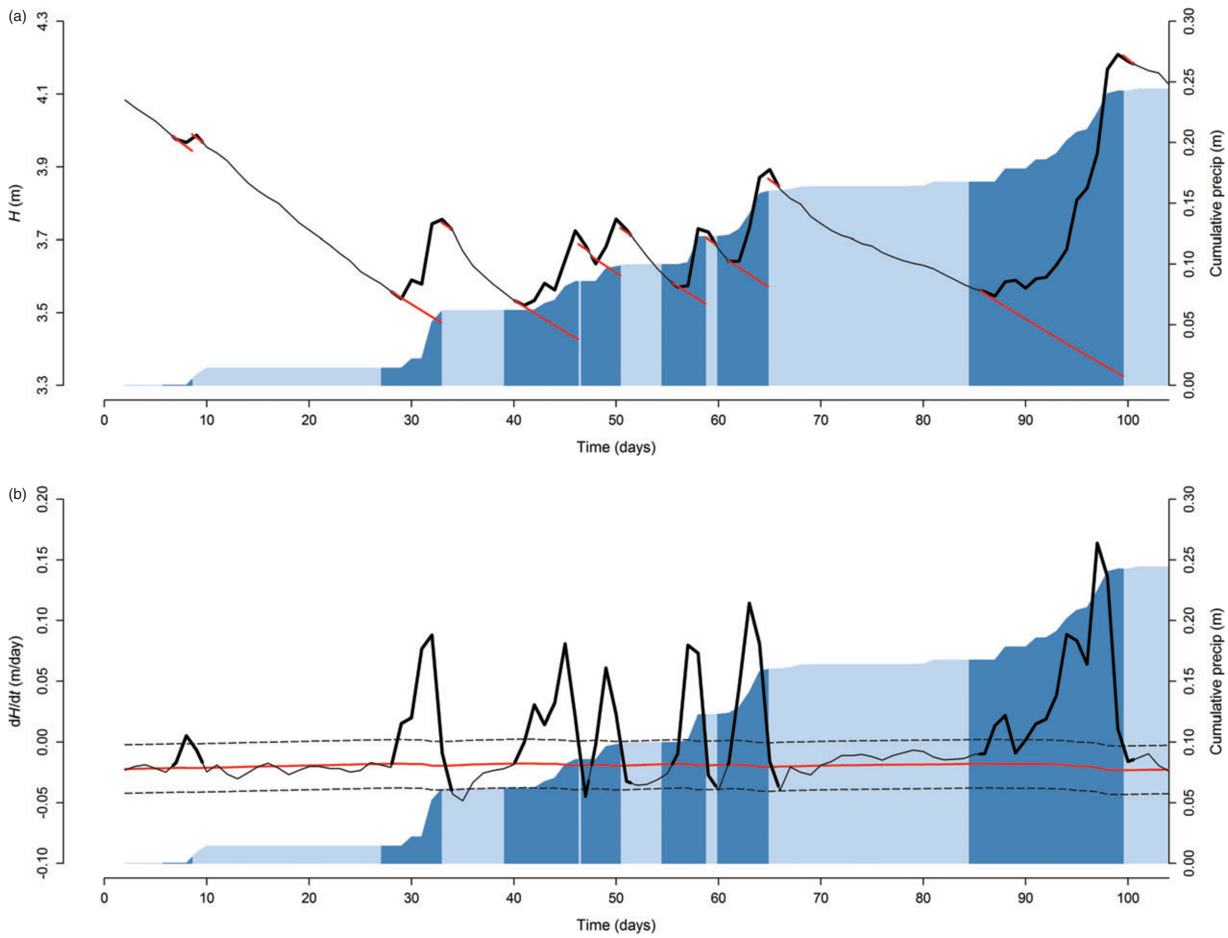

Figure 5. EMR analysis, for the Silstrup site from 1 July to 15 October 2006, of (a) $H(t)$ data and (b) calculated dH/dt vs. t.

Episodic and Total Recharge

Like all WTF implementations, the EMR method is insensitive to any steady and continuous component of recharge. This attribute can be an advantage in applications needing separate discernment of constant-rate and episodic recharge components, or in which the episodic component is the main objective. Where estimated total (episodic plus constant) recharge over a time interval is needed, estimates from a supplemental method sensitive to the constant-rate component of recharge, for example the steady-state Darcian method (Nimmo et al. 1994), can be added to the total cumulative episodic recharge. For applications requiring estimation of total episodic recharge over annual or other specified time intervals, the entire record over time must be partitioned into intervals of either episodic recharge or constant-rate recharge.

A constant-recharge interval may include precipitation that does not contribute to any episodic recharge. Possible causes include runoff, evapotranspiration, lateral subsurface flow, freezing temperatures that prevent percolation to substantial depths, or input rates so slow that the recharge becomes averaged into the constant-rate component. This effect can be related to a minimum threshold for generation of recharge, dependent on such factors as soil moisture and storm magnitude.

Comprehensive Hydrologic Processes and Climate Change

Beyond recharge and its episodicity, with the EMR method one can also estimate the water input associated with each episode and calculate the ratio of recharge to a measure of water input. Possible expressions of input include precipitation, infiltration, net infiltration, and similar hydrologic quantities; in this paper we use gross precipitation and thus compute the episodic RPR. The RPR has advantages in that precipitation data are generally much more available than other forms of input, and that its use accounts empirically and implicitly for evapotranspiration. With a set of RPR values computed for diverse episodes, it is straightforward to correlate these with individual factors that recharge depends on, such as storm magnitude, antecedent soil water, air or soil temperature, vegetation, and surface conditions. Comparisons on the basis of episodic RPR can elucidate the dependence of recharge on the factors considered.

An important intended use of this method is as a modular component of studies predicting effects of climate change on water resources. A widespread expectation is that greater average storm intensity, commonly predicted in climate-change scenarios, leads to increased recharge (Owor et al. 2009). This could easily result if recharge processes during a storm become more efficient after a prestorm soil water deficit has been filled. On the other hand, a larger portion of the precipitation from intense storms may go to runoff, causing a reduction in recharge. The testing of such hypotheses is obviously a critical research need, and the EMR method provides a means of doing so through analysis of existing long-term data, regardless of whether climate has undergone change over the period of measurement. Another advantage is that this approach is independent of any particular climate model or scenario, so it can be applied in connection with any present or predicted changed climate, including predictions using future models more advanced than those available now.

Conclusions

Our EMR implementation of the WTF method for recharge estimation affords new capabilities such as quantitative association of water from an individual storm with the recharge it causes, and comparison of total recharge and recharge-to-precipitation ratios on various time scales. Data required for episodic recharge estimation are recorded water-table levels at good time resolution and minimal interruptions. Besides the MRC values, two parameters represent the site-specific features essential to episodic analysis. By systematizing the application of hydrologic judgment required in WTF analyses, it enables valid comparison of total predicted recharge and RPR over different episodes or arbitrary time intervals. We developed the method using data from the Masser site in Pennsylvania and tested it further with data from the Silstrup site in Denmark.

Further development can improve the accuracy and adaptability of this method. Its basic structure can be modified, for example, with variable specific yield, infiltration- or net infiltration-based water input, variable storm-recovery time, or more finely detailed recession behavior.

The EMR method has additional advantages in application. It essentially eliminates the time-increment dependence (Delin et al. 2007), and moderates some of the overestimation typically associated with WTF methods. It incorporates built-in compensation for overshoot without applying different subjective judgments to different storms. For climate-change predictions, its stand-alone recharge and RPR estimates afford much advantage and adaptability for modular-component evaluations, a critical need because of the complexity of climate/resource interactions and the rapid evolution of climate forecasting.

Acknowledgments

Jon Moen made early stage calculations with the Masser data and observed key features that prompted much of the development in this paper. Heather Scott assisted with later calculations and evaluation of previous studies. We are grateful to Annette Rosenbom and the Danish Pesticide Leaching Assessment Programme for supplying the Silstrup data in tabular form. Brandon Fleming and Brian Thomas provided helpful manuscript reviews. Funding was provided by these USGS programs: Hydrologic Research and Development, Ground Water Resources, National Water Quality Assessment, Youth Initiative Funding, and the NAGT/USGS Cooperative Program.

Supporting Information

Additional Supporting Information may be found in the online version of this article:

Appendix S1. Details of the episodic master recession method.

References

Cameron, D., K. Beven, and J. Tawn. 2000. An evaluation of three stochastic rainfall models. *Journal of Hydrology* 228, no. 1–2: 130–149.

Crosbie, R.S., P. Binning, and J.D. Kalma. 2005. A time series approach to inferring groundwater recharge using the water table fluctuation method. *Water Resources Research* 41, 1. DOI: 10.1029/2004WR003077.

Crosbie, R., J. McCallum, G. Walker, and F. Chiew. 2012. Episodic recharge and climate change in the Murray-Darling Basin, Australia. *Hydrogeology Journal* 20, no. 2: 1–17.

Cuthbert, M.O. 2010. An improved time series approach for estimating groundwater recharge from groundwater level fluctuations. *Water Resources Research* 46, no. 9.

Delin, G.N., R.W. Healy, D.L. Lorenz, and J.R. Nimmo. 2007. Comparison of local- to regional-scale estimates of groundwater recharge in Minnesota, USA. *Journal of Hydrology* 334, no. 1–2: 231–249.

Faybishenko, B.A. 1995. Hydraulic behavior of quasi-saturated soils in the presence of entrapped air–Laboratory experiments. *Water Resources Research* 31, no. 10: 2421–2435.

Fayer, M.J., and D. Hillel. 1986. Air encapsulation–II. Profile water storage and shallow water table fluctuations. *Soil Science Society of America Journal* 50: 572–577.

French, R.H., R.L. Jacobson, and B.F. Lyles. 1996. Threshold Precipitation Events and Potential Ground-Water Recharge. *Journal of Hydraulic Engineering* 122, no. 10: 573–578.

Gburek, W.J., and G.J. Folmar. 1999. A ground water recharge field study—Site characterization and initial results. *Hydrological Processes* 13: 2813–2831.

Healy, R.W., and P.G. Cook. 2002. Using groundwater levels to estimate recharge. *Hydrogeology Journal* 10, no. 1: 91–109.

Heppner, C.S., and J.R. Nimmo. 2005. A computer program for predicting recharge with a master recession curve. U.S. Geological Survey Scientific Investigations Report 2005-5172.

Heppner, C.S., J.R. Nimmo, G.J. Folmar, W.J. Gburek, and D.W. Risser. 2007. Multiple-methods investigation of recharge at a humid-region fractured Rock Site, Pennsylvania, USA. *Hydrogeology Journal* 15, no. 5: 915–927.

Huff, F.A. 1967. Time distribution of rainfall in heavy storms. *Water Resources Research* 3, no. 4: 1007–1019.

Ireson, A.M., and A.P. Butler. 2011. Controls on preferential recharge to Chalk aquifers. *Journal of Hydrology* 398, no. 1–2: 109–123.

Kendy, E., Y. Zhang, C. Liu, J. Wang, and T. Steenhuis. 2004. Groundwater recharge from irrigated cropland in the North China Plain—Case study of Luancheng County, Hebei Province, 1949–2000. *Hydrological Processes* 18, no. 12: 2289–2302.

Lewis, M.F., and G.R. Walker. 2002. Assessing the potential for significant and episodic recharge in southwestern Australia using rainfall data. *Hydrogeology Journal* 10, no. 1: 229–237.

Lindhardt, B., C. Abildtrup, H. Vosgerau, P. Olsen, S. Torp, B.V. Iversen, J.O. Jørgensen, F. Plauborg, P. Rasmussen, and P. Gravesen. 2001. *The Danish Pesticide Leaching Assessment Programme*. Copenhagen, Denmark: Geological Survey of Denmark and Greenland.

Meinzer, O.E. 1923. The occurrence of ground water in the United States, with a discussion of principles. U.S. Geological Survey Water-Supply Paper 489.

Nimmo, J.R., D.A. Stonestrom, and K.C. Akstin. 1994. The feasibility of recharge rate determinations using the steady-state centrifuge method. *Soil Science Society of America Journal* 58, no. 1: 49–56.

Owor, M., R.G. Taylor, C. Tindimugaya, and D. Mwesigwa. 2009. Rainfall intensity and groundwater recharge—Empirical evidence from the Upper Nile Basin. *Environmental Research Letters* 4: 035009.

Penna, D., H.J. Tromp-van Meerveld, A. Gobbi, M. Borga, and G. Dalla Fontana. 2011. The influence of soil moisture on threshold runoff generation processes in an alpine headwater catchment. *Hydrology and Earth System Sciences* 15, no. 3: 689–702.

Risser, D.W., W.J. Gburek, and G.J. Folmar. 2005. Comparison of methods for estimating ground-water recharge and base flow at a small watershed underlain by fractured bedrock in the eastern United States. US Geological Survey Scientific Investigations Report 2005-5038.

Risser, D.W., W.J. Gburek, and G.J. Folmar. 2009. Comparison of recharge estimates at a small watershed in east-central Pennsylvania, USA. *Hydrogeology Journal* 17, no. 2: 287–298.

Rosenbom, A.E., W. Brüsch, R.K. Juhler, V. Ernstsen, L. Gudmundsson, J. Kjær, F. Plauborg, R. Grant, P. Nyegaard, and P. Olsen. 2010. *The Danish Pesticide Leaching Assessment Programme Monitoring Results May 1999–June 2009*. Copenhagen, Denmark: Geological Survey of Denmark and Greenland.

Stocking, M.A., and H.A. Elwell. 1976. Rainfall Erosivity over Rhodesia. *Transactions of the Institute of British Geographers* 1, no. 2: 231–245.

Stonestrom, D.A., and J. Rubin. 1989. Water content dependence of trapped air in two soils. *Water Resources Research* 25, no. 9: 1947–1958.

Voss, C. 2011. Editor's message: Groundwater modeling fantasies—Part 2, down to earth. *Hydrogeology Journal* 19: 1455–1458.

Wu, J., R. Zhang, and J. Yang. 1996. Analysis of rainfall-recharge relationships. *Journal of Hydrology* 177, no. 1–2: 143–160.

Supplementary Material for *Discrete-storm water-table fluctuation method to estimate episodic recharge*

Appendix: Details of the Episodic Master Recession Method

For a given data set, the MRC can be estimated by fitting dH/dt vs. H using a subset of the original data corresponding to periods of pure water-table recession. Recession during a given time step is then estimated based on the MRC and initial value of H. The MRC-extrapolated value of H subtracted from the measured H at the end of the time increment indicates the estimated H rise, which is multiplied by SY to give recharge. Summation over multiple time steps indicates total recharge over an extended period.

Hydrologic characterization for a given site and well

Master recession curve

The first step in the EMR method involves using the water level time series, H(t), and the calculated rate of change, dH/dt, to fit a master recession curve. The derivative dH/dt can be computed in various ways; we have used a standard three-point numerical differentiation formula. The MRC should be fit to a subset of the original data that best reflects the behavior of the water table when it is declining without episodic recharge. An appropriate subset includes periods (1) during which the observed water level is decreasing, and (2) occurring well after the last non-zero precipitation, irrigation, or other input. The minimum time between precipitation and recession, allowing for storm-generated accretion to become negligible, is called the storm recovery time, t_p. An acceptable value or functional relationship for t_p must be established using hydrologic judgment applied to the paired precipitation and H(t) records. The continuous representation of dH/dt vs. H can be determined using a regression algorithm for a reasonable functional form such as a power law, or by bin averaging on designated intervals of H (Heppner and Nimmo 2005). In the examples of this paper, we approximate t_p as a constant value.

It is possible for a substantial precipitation event to have little discernible effect on the dynamics of the water table. Possible causes include runoff, evapotranspiration, lateral subsurface flow, freezing temperatures that prevent percolation to substantial depths, or input rates so slow that the recharge becomes averaged into the constant-rate component. In this case, the period following the event may be identified as a constant-recharge interval despite the substantial precipitation.

Fluctuation tolerance

After a time t_p since the last significant precipitation, the observed rate, $(dH/dt)_{obs}$, is expected to equal the predicted rate, $(dH/dt)_{mrc}$. Minor deviations are considered noise in the $(dH/dt)_{obs}$ time series. The fluctuation tolerance parameter, δ_T, reflects the maximum amplitude of noise that can be expected under conditions that produce negligible recharge. Periods of significant recharge are therefore identifiable by observed rates of water level rise that significantly exceed the predicted rates, where δ_T is the criterion for significance. Graphically, this means that recharge occurs when the curve $(dH/dt)_{obs}$ crosses the upper fluctuation tolerance curve defined by $(dH/dt)_{mrc} + \delta_T$ (Figure 3b).

An initial estimate of δ_T may be obtained from 95% confidence bounds on dH/dt from the MRC fitting process, in effect defining a band that 95% of measured recessionary dH/dt values fall within. This value can be adjusted as recharge episodes are delineated (see below). For example, the value can be increased if the original δ_T would designate unreasonably minor episodes as contributing positive recharge.

Lag time

The precipitation lag time t_ℓ is the time interval between the occurrence of a precipitation event and its resultant water table response. As t_ℓ relates to leading-edge rather than trailing-edge phenomena, it is not expected to equal the storm recovery time used in fitting an MRC. Various factors affect t_ℓ, including preferential pathways, antecedent soil moisture, unsaturated hydraulic conductivity, crop harvesting cycles, regional climate patterns, and depth to the water table. Functional dependences on such variables could be incorporated to investigate or correct for these influences, though we have not done this in the examples of this paper.

Specific yield

Specific yield, SY, is the ratio of the amount of water (as a volume per unit area [L]) added or subtracted (neglecting hysteresis), at the position of the water table, to the change in water-table level [L] caused by that addition or subtraction. The value of SY is determined by hydrogeologic factors that are independent of the chosen WTF implementation. It is possible to use a variable SY, as discussed by Heppner et al. (2007), though our examples take SY as constant. Without data on hydraulic properties or conditions of the unsaturated zone, there is little information to set parameter values for a variable specific yield so its likely effect would be to improve fits without adding insights about the method. Healy and Cook (2002) give a helpful discussion of SY and ways of estimating it.

Interval partitioning

Episodic recharge intervals

The *detection time* of an episode is defined as the time at which $(dH/dt)_{obs}$ intersects the tolerance curve $(dH/dt)_{mrc} + \delta_T$ before surpassing it. By the time an episode is detected in this manner, it is expected that a fraction of the recharge has already reached the water table—implying that the recharge episode has already started. We adjust for this in a systematic though approximate way, by taking the episode start time t_o as the time at which the curve $(dH/dt)_{obs}$ last intersects $(dH/dt)_{mrc}$ before intersecting the tolerance curve Depending on data quality and a possibly large noise tolerance reflected in δ_T, this criterion may lead to a start time that precedes the detection time by more than natural processes could cause. To mitigate this problem, the start time is set at one t_ℓ before the detection time if it would otherwise fall before this.

An episode ends at time t_f when $(dH/dt)_{obs}$ intersects $(dH/dt)_{mrc}$ after having reentered the tolerance band. We additionally require that the curve $(dH/dt)_{obs}$ be monotonically increasing at the time of intersection with $(dH/dt)_{mrc}$ (in other words after it has dipped below the MRC and has started increasing again). This criterion generally extends the episode duration by a small amount to allow for resettling of the system into a non-recharge period. To avoid episodes that are unrealistically long, we require that the episode end no later than one precipitation lag time after the time when $(dH/dt)_{obs}$ drops below $(dH/dt)_{mrc}$.

Overlapping episodes

These criteria may result in episodes that overlap. Especially in humid climates, storms are sometimes close enough in time that recharge from the later one adds to the water-table rise that is still occurring from the previous storm. Without a means to ascertain what portion of the rise is caused by each storm, an appropriate way to treat this situation is to lump the storms and their combined recharge together into one episode. In this case, the earliest start time and latest end time of the overlapping potential episodes are taken to define the newly-designated episode.

It may be possible to reduce the number of overlapping episodes by adjusting δ_T or t_ι downward. This should be considered as part of the procedure for optimizing these parameters to best apply to the whole data set, not as an ad hoc device to eliminate specific cases of overlap. Where overlap results from physical blending of recharge contributions from multiple storms, it is most appropriate to consider those storms as a unit.

Recharge of an episode

The graphical method as shown in Figure 2 corrects for the unrealized recession by taking the starting point for ΔH on an extrapolation of the pre-rise H(t) curve. In the EMR method two separate extrapolations of this sort are performed, both based on the MRC, one starting from the level at t_o and moving forward in time, the other starting at the level at t_f and moving backward in time (Figure 3a). An estimate for ΔH is given by the difference between the upper and lower extrapolations at the time $t_f - t_\iota$. Actually, because ΔH is computed between two extrapolated curves, any time in the period of recharge-elevated H could be chosen as the time at which it is computed. Because the upper extrapolated curve has a steeper downward slope, the computed ΔH will be somewhat greater for an earlier chosen time. We have used $t_f - t_\iota$ to have a systematic way of locating this time in the middle portion of the possible range. Episodes must be at least one lag time in duration so as not to push beyond the time resolution limits that can be justified by the dissipative character of the unsaturated-zone hydraulics. If an episode does not meet this length criterion, the alternative start and end criteria are applied; that is, the start is taken to be one lag time before the first tolerance curve crossing and the end is taken to be one lag time after the second crossing.

Precipitation causing an episode

The time interval associated with the precipitation causing a recharge episode has the same duration as the recharge episode itself, but starts one precipitation lag time before the beginning of the recharge episode. The precipitation that occurs during this interval is assumed to directly contribute to recharge during the associated episode only.

Constant-recharge intervals

Constant-recharge intervals are identified as periods during which the observed rate of change does not exceed the tolerance curve. Additionally, intervals of nominally positive recharge are reclassified as constant-recharge intervals if no precipitation occurs in the associated precipitation time interval. In this case, the interval should be investigated to determine whether the observed rise in water table is due to measurement error, for example, or non-optimal choices of δ_T and t_ι values. If the site is subject to delayed responses, for example from snowmelt, a seasonal or temperature-dependent valuation of t_ι may be desirable.

Documentation of computer code EMR

The program EMR consists of three text files designed to be run in the R statistical software environment. R is supported by Windows, Mac, and Unix platforms and is available for free at http://www.r-project.org/. The three code files are named rch_interface, rch_main, and plot_rch.

EMR is run using the file rch_interface, which serves as an interface for the entire program. The first three executable lines of the file are used to specify the name and directory of the parameter file as well as the directory of the EMR code files (all the code files are assumed to be in the same folder). The next four lines read in the parameter file, the data file, and the two remaining code files.

The script rch_main performs routine calculations and data formatting procedures before calling the function “find_episodes”, which finds the recharge episodes and the function “find_recharge”, which calculates the episodic recharge. The script plot_rch creates a series of figures indicating where within the water table time series the recharge episodes occur.

Data File

The data text file contains the well and precipitation data. Its contents should be formatted in three tab-separated columns: time, water table level, and cumulative precipitation. Time values should be in numerical format, e.g. number of hours since well monitoring began, as opposed to date format. As indicated in the section “Episodic Master Recession Method”, it is assumed that the water table level, H, is given as the height of the water table above its steady state level. The first line of the file should be a header giving the units of each column. Any desired data transformations, e.g. unit conversions, should be done before creating the data file and running EMR.

Sample data file:

Hours	Meters	Meters
32.50	13.182	0.0107
32.52	13.209	0.0108
32.54	13.233	0.0110
32.56	13.255	0.0110
32.58	13.279	0.0111
32.60	13.297	0.0112
32.62	13.310	0.0112

Parameter File

The parameter file is a text file containing a list of the parameter values needed to run EMR. The following table gives the parameter name in the left column and a verbal description of the parameter in the right column. Below that is an example of how to define each parameter within the file. Parameter names are to the left of the assignment operator, **`<-`**, and should remain unchanged; the user only needs to update the values to the right of this operator.

Basic parameters for running EMR.

`data_file`	Name of the data file, with extension.
`data_folder`	Directory of the data file (with / in place of \).
`mrc_type`	Format of the MRC to be used. Four options: ‘polynomial’, ‘power’, ‘tabulated’, or ‘bin-averaged’.
`flctn_tol`	Water table fluctuation tolerance, δ_T.
`lag_time`	Water table response lag time, t_L.
`SY`	Specific yield; see Equation (1).
`output_file`	Name of output file summarizing EMR results, with .csv extension. (Optional – use if desired, otherwise NULL.)

Further parameters for defining the MRC.

Only the parameters relating to the chosen MRC type need to be defined. The others can be set to NULL or omitted from the parameter file entirely.

`p`	Coefficient vector if the MRC has a polynomial form. Coefficients should be in the order of decreasing power, i.e. if $\mathrm{MRC} = \mathrm{A}x^{n} + \mathrm{B}x^{n-1} + \mathrm{C}x^{n-2} + \cdots$, then `p <- c(A,B,C,...)`. Note that the structure `c()` is used to define a vector in R.
`p`	Coefficient vector if the MRC has the form of a power function: $\mathrm{MRC} = \mathrm{A} + \mathrm{B}(x - \mathrm{C})^{\mathrm{D}}$. Same vector notation as above and coefficients must be in this order: `p <- c(A,B,C,D)`.
`MRC_fit_file`	Name of the file containing tabulated MRC data, with extension. See below for further details.
`bin_size` `min_rate` `max_rate`	Bin size and water table rates used for bin-averaged MRC. See below for further details.

Additional, optional parameters that may help in unusual circumstances.

`N`	Moving average smoothing parameter.
`min_precip_diff`	Minimum amount of precipitation required during an episode in order for it to be considered an episode; the default is any amount greater than 0, regardless of the precipitation units.
`WT_diff_max`	Maximum allowable difference in water table, ΔH.

Sample parameter file:

```
data_file <- 'well_data.txt'
data_folder <- 'C:/Users/ ... /'
flctn_tol <- .25
lag_time <-0.88
SY <- .013
output_file <- 'EMR_output.csv'

mrc_type <- 'polynomial'       # MRC = .2x^2 - .3x + .7
p <- c(.2, -.3, .7)

N <- 17
min_precip_diff <- NULL
WT_diff_max <- NULL
```

The MRC options used here are similar to those of Heppner and Nimmo (2005). Note that a polynomial or power MRC must be fit before the EMR program can be run. A tabulated MRC is defined by two vectors, one containing unique water table levels (H_{tab}) and one containing the corresponding MRC-predicted water table rates ($dHdt_{tab}$). Note that H_{tab} does not need to be identical to H, i.e. the water table vector used in the EMR analysis. However, the range of H should be a subset of the range of H_{tab}. A linear interpolation algorithm is used to define the MRC at water table levels in between the elements of H_{tab}. If the tabulated MRC option is chosen, the vectors H_{tab} and $dHdt_{tab}$ should be the first and second columns, respectively, of a text file with no header. The parameter MRC_fit_file contains the name of this file.

In the case of a bin-averaged MRC, the program extracts the water table levels, H_{dec}, and water table rates, $dHdt_{dec}$, corresponding to times when the water table is declining. For the data vector H_{dec}, a set of equally-sized intervals (or bins) spanning the range of the data is generated, where the number of bins is determined by the parameter bin_size. Each element of the vector is assigned to the appropriate bin and the mean (arithmetic average) of each bin is calculated, giving a new vector H_{bin}. A similar procedure is used to bin and average the elements of $dHdt_{dec}$, resulting in the vector $dHdt_{bin}$. The program linearly interpolates over H_{bin} and $dHdt_{bin}$ to produce a numerical MRC. For any values in the original vector H that are less than the minimum of H_{bin}, the program assumes the user-specified minimum water table rate, min_rate. Likewise, for any values of H that are greater than the maximum of H_{bin}, the program assumes the user-specified maximum water table rate, max_rate.

Output File

The EMR program outputs an optional CSV file summarizing the results of the analysis. The first line indicates the name of the parameter file used in generating the results. The next three lines give the measurement units for the time, water table, and precipitation data, as specified in the data file. After that is the total calculated recharge for the data set. Finally, a table is produced showing the recharge episodes detected by the EMR algorithm. The following information is provided for each episode: start and end times, duration, recharge, total and average precipitation during the episode, and maximum precipitation rate during the episode. Constant-recharge intervals are also shown in the table and are indicated by a value of NA in the left-most column.

Sample output file:

Data file: Masser_cw_1999_rch_input_final.txt

Time units: d
Well level units: m
Precipitation units: m

Total recharge: 0.335735869375472

Episode Number	Start time	End time	Duration	Recharge	Total precip	Avg. precip rate	Max. precip rate
NA	31.39583	39.54646	8.150625	0	0.0187	0.002557	0.0792
1	39.54646	44.53587	4.989418	0.019431	0.0074	0.001477	0.096
NA	44.53587	57.32269	12.78682	0	0.0133	0.001043	0.06
2	57.32269	60.19487	2.872174	0.00553	0.024684	0.00911	0.2257
NA	60.19487	60.9438	0.748935	0	0.0013	0.022162	0.3481
3	60.9438	63.62471	2.68091	0.02246	0.0151	0.005491	0.1176

References

Healy, R.W., and P.G. Cook. 2002. Using groundwater levels to estimate recharge. *Hydrogeology Journal* 10, no. 1: 91-109.

Heppner, C.S., and J.R. Nimmo. 2005. A computer program for predicting recharge with a master recession curve. U.S. Geological Survey Scientific Investigations Report 2005-5172.

Heppner, C.S., J.R. Nimmo, G.J. Folmar, W.J. Gburek, and D.W. Risser. 2007. Multiple-Methods Investigation of Recharge at a Humid-Region Fractured Rock Site, Pennsylvania, USA. *Hydrogeology Journal* 15, no. 5: 915-927.