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Episodic Master Recession Evaluation of Groundwater and Streamflow Hydrographs for Water-Resource Estimation

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Core Ideas

- Analysis of streamflow and groundwater hydrographs were combined using a single set of tools.
- Calculation of hydrograph slope over time can quantify watershed storm response characteristics.
- A structured iterative approach facilitates development of expert judgments.
- Parameterization of hydrologic judgment criteria facilitates their transparent documentation.

Hydrograph analysis tools using a master recession curve (MRC) can produce many types of hydrologically important watershed-response quantifications, including aquifer recharge and stormflow characterization. An MRC is the relation between the value of a measured response *R* and its rate of change with time, d*R*/d*t*, occurring on the falling limb when there is no infiltration or other water input. We have developed MRC and episodic hydrograph-evaluation methods for multiple purposes, utilizing both water table and streamflow data. The determination of a parameterized MRC through a structured procedure provides a basis for quantification of hydrologic variables and characteristics that can be validly compared among different events, sites, and periods of time. Application of the MRC to needed hydrologic quantifications is done with our revised episodic master recession (EMR) method. Expert-guided iterative procedures are used to quantify parameters needed in applying the MRC and EMR methods to a given site. Hydrologic judgments such as the significance threshold for response magnitude, and the time window within which the precipitation is assumed to be the cause of an observed response, inherently involve some elements of subjectivity. Our structured iterative approach, however, affords much flexibility in formulating expert judgments and serves to confine them to statements and procedures that can be quantified and documented. Parallel application to streamflow and water table hydrographs can produce new hydrologic insights and understanding, not least in the role of unsaturated zone processes in controlling exchanges among components of the water cycle.

Abbreviations: EMR, episodic master recession; MRC, master recession curve; RPR, recharge/precipitation ratio; SPR, stormflow per watershed area/precipitation ratio.

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Important water-resource-related fluxes such as recharge, discharge, and stormflow can be estimated through evaluation of measured water-response data over time. The time-varying quantity can be a state of water such as pressure or wetness, a rate such as streamflow, or a water table level, whose record over time is broadly termed a *hydrograph*. Processes that influence the measured quantity usually involve the unsaturated zone directly (e.g., a fluctuating water table, varying soil moisture) or indirectly (e.g., streamflow as the combined result of different processes of the hydrologic cycle).

End products of hydrograph analysis include watershed-response evaluations (Elsenbeer and Vertessy, 2000), aquifer recharge (Bhaskar et al., 2018), stormflow characterization (Hornbeck, 1973), preferential flow occurrence and magnitude (Koch et al., 2013), and groundwater–surface water exchanges (Abo and Merkel, 2015). An important example is the estimation of episodic recharge by the water table fluctuation method, in which the temporary rise of the water table after a substantial infiltration event is ascribed to the fraction of event water that percolates down to the water table faster than saturated zone flow takes it elsewhere (Healy and Cook, 2002). Under many circumstances, especially with unsaturated zones at least moderately thick, episodic recharge occurs primarily as the result of preferential flow, so the quantification of individual recharge episodes can represent a measure of preferential flow through the unsaturated zone. Another widely used practice uses streamflow data and hydrograph-separation techniques to distinguish the amount of stormflow, considered as water contributed to the watershed by a particular storm, from baseflow, considered as water previously within the watershed's surface and subsurface storage (Blume et al., 2007). Important quantifications include hydrograph minima and maxima, times of occurrence of specific events such as commencement of rise or fall, rate of change, and the relation to other variables such as precipitation.

Non-computerized methods for hydrograph analysis were widely used in earlier decades, for example manual pencil-and-paper extrapolation of recessionary trends. These usually used fixed-interval data of coarse time resolution and often utilized a superimposition of hydrographs on base-10 logarithmic tracing paper. Such procedures can provide a starting point for expert-guided, computer-assisted evaluation of both groundwater (Heppner and Nimmo, 2005) and surface-water (Rutledge and Daniel, 1994) hydrographs. Today there is need for further adaptation of worthwhile features of methods developed in the pre-computer era, plus new techniques optimally utilizing today's tools to solve problems required for 21st-century applications.

Needs To Be Addressed

Time Resolution

The need for techniques that can handle greater-than-daily time resolution becomes ever more pressing with advanced instrumentation providing higher resolution data and also with the increasing diversity of applications. An obvious shortcoming of coarse resolution is an increased likelihood that significant events will be missed or poorly characterized, especially where fast-changing processes such as preferential flow are active. Another limitation concerns watershed size: with earlier generations of hydrograph tools, coarse time resolution prevented application to watersheds smaller than a certain minimum, for example 2.6 km^2 as noted by Rutledge (1998). Such a limit reduces the utility of hydrograph analysis, especially in certain areas of growing concern. Problems in urban hydrology, for example, require attention to individual small-area parcels, and to land surfaces dominated by anthropogenic modifications that are atypical of those in the historically examined watersheds.

Finer resolution also brings new challenges. The use of time intervals of 1 d or longer often eliminates all or nearly all short-term noise in the hydrograph trace and simplifies the analysis. For example, models using daily data may take any uptick in the data—representing a rise of at least 1-d duration—as indicating the end of a recessionary period. Noisier data of finer time resolution present the problem of discriminating between negligible and non-negligible fluctuations, requiring a separate judgment as to how long a reversal of trend must persist to be considered significant. The method of analysis must therefore provide a way to systematize the judgments necessary for this task.

Minimization and Confinement of Subjectivity

Judgment issues arise in any hydrograph analysis—what constitutes a trend, what constitutes a deviation from a trend, what fluctuations are insignificant, etc. A usual goal of automated hydrograph analysis is to mimic the judgment of an experienced hydrologist. Flexibility must be incorporated, however, to allow for the character of new applications, hydrographs, or landscapes that, because they are new, are not in the experience of any currently active hydrologist. Typical behaviors observed in many previously examined hydrographs (often composed of daily data), though forming the basis of many judgments concerning trends and time resolution, are unlikely to be appropriate in application to watersheds that diverge in character from those in the historical record. Past observations from hydrographs have been generalized into empirical rules-of-thumb—for example that the minimum persistence of a trend is proportional to the watershed area raised to the 0.2 power (Rutledge, 1998). Ideally, these should be discarded in favor of criteria based on the behavior of the watershed under investigation, independently from previously examined hydrographs. Criteria based more on the data at hand and less on historical treatments will permit recognition of new processes and relationships critical to a wider variety of contemporary needs.

Specifically, the main need is to reproducibly analyze a variety of commonly collected hydrologic datasets and to document any subjective judgment decisions made during the analysis. Tools to serve these purposes need to carry out efficient, consistent evaluation procedures while optimizing the value obtained from the data. The practical necessity then is to implement automated analysis alongside the necessary involvement of expert hydrologic judgment. A scheme for parametric quantification of specific judgment criteria can be an important asset in this task. The precise specification of parameter values requires iterative testing in which the hydrologist adjusts them while examining the results repeatedly across the whole term of the dataset. As for hydrologic modeling in general, the subjective element of such a procedure cannot be eliminated (Voss, 2011), but a well-constructed parameterization can add hydrologic value by transparently documenting the subjective judgments and confining their effects to precisely defined elements of the problem.

Parallel Evaluation of Groundwater and Streamflow

Although groundwater and surface water have long been considered to be inextricably connected components of the hydrologic system (Winter et al., 1998), most hydrograph analyses have been undertaken for just one or the other. Parallel analysis of streamflow and groundwater hydrographs, using the same algorithms (as closely as possible) for each, probably has great unexplored potential for providing insights and needed quantifications. Comparing, for example, the relative timing and magnitude of streamflow and water-table responses to the same series of input events can facilitate recognition of differences in different water-cycle components and understanding of the various processes (unsaturated-zone flow, rainfall–infiltration–runoff partitioning, pumping from wells, etc.) that affect both surface-water and groundwater dynamics.

Available Methods

Many automated streamflow hydrograph analysis techniques have been developed (e.g., Nathan and McMahon, 1990; Smith and Schwartz, 2017). Such methods commonly rely on digital filters and recession curve displacement techniques (Arnold and Allen, 1999). Lewis and Walker (2002) used a water-balance method to estimate episodic recharge. Various researchers have estimated episodic aquifer recharge using general-purpose numerical models, for example based on the soil–plant–atmosphere system (Zhang et al., 1999; Crosbie et al., 2012) and on unsaturated zone flow (Nasta et al., 2018). Episodic aquifer recharge has been widely estimated by various forms of the water table fluctuation method, for example by Rathay et al. (2018) and Cuthbert and Tindimugaya (2011). There are various published algorithms and procedures for these purposes (Heppner and Nimmo, 2005; Nimmo et al., 2015; Tang and Carey, 2017).

Many techniques for hydrologic evaluations, especially automated methods, utilize a master recession curve (MRC) (Tallaksen, 1995). Thomas et al. (2016), for example, used an MRC approach to produce a continuous time series of recharge estimates. An MRC is the relation between the value of a measured hydrograph response R (here, water level or flow rate) and its rate of change with time, $\mathrm{d}R/\mathrm{d}t$, within a period when there is no infiltration or other input of water. The MRC carries information representing the processes that cause the change in measured response. In hydrologically important episodes such as aquifer recharge or stormflow, the information inherent in a hydrograph deviation from master-recession behavior can quantitatively characterize that event.

The key MRC assumption is that a function depending only on R can specify the relation between the response and its rate of change:

$$f(R) \quad \text{—} \qquad [1]$$

The main point here is that, absent further system input, the response will decline at a rate that depends only on its magnitude. The form this function takes can vary with the properties of the hydrologic system and the processes that are causing the recession. In practice, it is frequently represented by a simple analytic function that approximates the actual system behavior, with some degree of support from empirical or theoretical considerations.

The use of a unique function in this way is analogous to the representation of soil water retention with a single function. The relation between soil water content and matric pressure varies hysteretically with the direction of wetness change, as well as with water chemistry, shrinking and swelling, temperature, and myriad other factors. Yet for practical purposes it is often approximated as a unique function of one variable, normally using one of the many functional forms that have been developed for this purpose. The recession of a hydrograph response varies with factors such as seasonality, storm duration or intensity, pre-storm conditions, and past history. One typical and traditional form for this function is based on the linear-reservoir assumption of a direct proportionality of measured response to its rate of change. Our approach is to start from this sort of simplicity, relying on the linear-reservoir assumption in much of the development, and, from the results of applying it to measured data, to judge the adequacy of this approach and possible needs for refinement.

Where complexities of watershed behavior render a single formulation of Eq. [1] inadequate for a given application, accommodation might be achieved by incorporating a seasonally dependent (or storm-duration dependent, etc.) parameter into the formulation of the MRC. Considering that parameter as a fundamental component of the MRC specification, Eq. [1] could be replaced by a single function of multiple variables, perhaps day-of-year in addition to R. The method used here does not incorporate this type of variation, although it could be implemented in further development. In any case, the MRC, or a parameterized family of MRCs, must be treated as a landscape property representing characteristic behavior, not a hydraulic condition that varies with time as soil moisture or water temperature does.

Utilizing MRCs determined for a specific site or well, the episodic master recession (EMR) method of Nimmo et al. (2015) primarily serves to evaluate recharge from water-table hydrographs. Based on the water table fluctuation method (Healy and Cook, 2002), this method identifies discrete recharge episodes from the hydrograph, then computes the amount of recharge attributable to each episode and the amount of precipitation that caused that response. A typical use of these results is to compute recharge/precipitation ratios, a measure of the efficiency of individual storms in generating recharge (Tashie et al., 2016). Here we describe several extensions and improvements of these methods, with new applications and additional types of hydrologic insights.

Objectives

Our overall objective is to create tools that use closely parallel methods for evaluating water-table and streamflow hydrographs to serve a variety of hydrologic purposes. There is need for a study combining the aims of coordinated groundwater–surface-water analysis, computerized iterative methodology, applicability to data of any time resolution, and documentation of expert judgments. Major specific objectives include the following:

- Expand options for enhanced utility and convenience in determining MRC parameters and EMR results, based fundamentally on the algorithm of Nimmo et al. (2015).
- Extend applicability of the methods developed for water-table hydrographs to streamflow hydrographs.
- Implement a multi-segment log-linear function to represent the MRC, as needed (i) for water-table hydrographs in media with pronounced stratification, and (ii) for streamflow hydrographs with different hydraulic processes occurring in different portions of the measured range (e.g., baseflow and stormflow processes).
- Apply the improved MRC and EMR methods to available hydrograph data from three different field sites, demonstrating the methods' soundness and capabilities.
- Evaluate the results of these hydrograph analyses with respect to hydrologic characteristics of the field settings

and to earlier published hydrograph analyses of the same data, with description of new insights and enhancements of hydrologic understanding.

Tools for Hydrograph Evaluation

Determination of a Master Recession Curve

The method starts with a hydrograph $R(t)$, the measured response (water level or streamflow) as a function of time. The steps described below are embodied in the code MRCfit, which determines an MRC from a dataset that includes both R and system input over time. The primary system input typically is precipitation, so we use that term here, although other, possibly more appropriate types of input, such as infiltration, may be used instead. If input data are lacking, the fit can still be obtained, although with slightly reduced accuracy in the recognition of recessionary periods. Data are read from a single input file with columns for t, R, and cumulative system input P.

The first step is to identify short intervals of the hydrograph that can be considered to represent pure recession. An interval of this type is similar to what Tallaksen (1995) termed a *recession segment*. Here we refer to it as a *slope element*. It is taken to be short enough that a straight line is an adequate approximation. This length is specified as a user-adjustable parameter, *tslength*. The slope elements are algorithmically identified, given the chosen parameter values, as representative of recessionary intervals in which hydraulic processes other than recession do not significantly affect the measurements. Initially, all data points are provisionally considered as starting points of slope elements. Of these provisional slope elements, the algorithm selects those that meet all of the essential criteria summarized in Table 1. Specifically, these are:

- The slope element's initial R value is within a user-specified range (*resplimits*).
- The slope element falls within a recessionary period. This may be determined by accepting only slope elements that are preceded by a user-defined period of insignificant system input (*mindrytime*), which may be set equal to zero to nullify this requirement.
- The total rise of all the slope element's upticks (minor rises in the otherwise declining limb) does not exceed a user-specified value (*maxtick*).
- Precipitation during the slope element is insignificant (*maxdelprec*).
- The slope element has no data gaps.
- The slope element does not overlap other selected slope elements. Included slope elements are preferentially taken as those representing the earliest portions of recessionary intervals.

Succeeding steps within the algorithm are to: (i) compute its rate of decline of R of each slope element by linear regression to the data within it; (ii) pair these $\mathrm{d}R/\mathrm{d}t$ values with R from the midpoint of each slope element; and (iii) by regression fit the chosen functional form to the paired values, thereby obtaining parameters of the optimized MRC.

Besides the user-specified values noted above, options that can be selected include forcing the fitted curve through the origin ($R = 0$ and $\mathrm{d}R/\mathrm{d}t = 0$), and lumping ($R$, $\mathrm{d}R/\mathrm{d}t$) points together before fitting by averaging within bins specified on intervals of R. Table 2 lists the main user-specified parameters, with the variable names that represent them in the MRCfit code.

Table 1. Criteria for master recession curve accepted slope elements in MRCfit.

Element	Criterion
Start time	response at that time must lie within the specified response limits *resplimits*
End time	later than start time by specified slope element length *tslength*
Reject slope element	gap criterion: if data are missing for any time step
Reject slope element	noise criterion: if the sum of all upticks (each computed on a single-interval basis) within a slope element exceeds the specified maximum
Reject slope element	slope criterion: if its computed slope exceeds the specified maximum *maxslope* (set to eliminate slopes too large to be indicative of recession)
Reject slope element (if precipitation data are available)	precipitation criteria: (i) if it starts earlier than the specified interval *mindrytime* after the last significant precipitation, where significance means that the precipitation event does not exceed the specified maximum *maxdelprec*; (ii) if significant precipitation occurs during the slope element

Table 2. Master recession curve parameters in MRCfit to be given values chosen by expert judgment, typically refined by repeated calculations with alternative values; R is the response variable (streamflow or water level).

Name	Type	Meaning
resplimits	2 numeric values	min. and max. of R values that are acceptable as starting points of slope elements (used in multi-segment fitting)
tslength	numeric	duration of slope elements for linearization
mindrytime	numeric	min. duration of interval between significant precipitation and recession start
maxdelprec	numeric	max. amount of precipitation considered negligible
maxtick	numeric	max. total uptick within a linearized slope element
throughorigin	true/false	force the fit through the origin?
binsize	numeric	bin size for lumping of $\mathrm{d}R/\mathrm{d}t$ for fitting (0 for no binning)
maxslope	numeric	max. allowable $\mathrm{d}R/\mathrm{d}t$ for fitting

The linear reservoir functional formula (Rutledge, 2006) represents the MRC as a straight line on a graph of R vs. dR/dt, therefore yielding an $R(t)$ curve in the form of exponential decline. In the original single-segment form, two parameters, slope and intercept, represent the MRC. The new versions of the code have an added capability to represent the MRC in the form of connected line segments of different slopes. This is achieved by running MRCfit multiple times, each time using different response limits (*resplimits*, Table 2) to get separate MRC parameters for different portions of the range of R. These fitted line segments, joined at their points of intersection, comprise a segmented MRC as an alternative parametric functional form. One application of such a form is for water-table hydrographs in stratified media where the water table level may fall within any of two or more hydraulically different layers. Another is for streamflow where different or additional recessionary processes are active for flows greater than a certain amount.

The MRCfit program outputs the results of slope element selection and MRC determination in tabular and graphical form. For perception of response magnitudes as vertical, intuitively appropriate for some types of hydrograph, the fitted MRC can be plotted with R on the y axis. The program MRCplot produces graphs of the individual computed decline-rate values and the segmented MRC obtained as a best fit to them. It also produces a text file of computed results. Importantly, this file includes the slope and intercept values defining the line that represents the fitted MRC, to be used in the EMR analysis.

Episodic Master Recession: Master Recession Curve to Extract Information from a Hydrograph

The main purpose of the episodic master recession method is to quantify the effects of individual water-input events, such as rainstorms, snowmelts, or floods, on a water resource such as aquifer storage or streamflow. With recognized discrete episodes, one can use an MRC to subtract out ongoing internal-system behavior from the hydrograph as a whole so that what remains is directly pertinent to short-term inputs and responses. For this purpose, we use a generalized EMR method and codes that handle water levels and streamflow in similar ways. In following this description, it may be helpful to examine the figures presented below with the first case study, the Shale Hills site.

Application of the EMR method uses the computed MRC parameter values (two for a single-segment MRC; more for multiple segments) and the same type of data required by MRCfit. From the data, EMR numerically calculates the rate of change (i.e., the slope of the hydrograph) during the period of record using a three-point differentiation formula. At each time step, the algorithm compares the measurement-based rate of change with that predicted by the MRC using the measured value of R (Eq. [1]). To discern hydrologically significant episodes, it applies user-specified parametric criteria, listed in Table 3, to the differences between measured and MRC-calculated rates of change. An important parameter called *fluc_tol* represents the minimum deviation of the hydrograph slope from the MRC slope for a rise in the hydrograph to be considered a significant departure from normal recessionary behavior. The fundamental recognition of an episode is the breakout of the hydrograph slope from the band defined by adding *fluc_tol* to the MRC slope. Then for each episode, EMR uses additional specified criteria to calculate important episode characteristics, several of which are shown in the output tables given below; one example is the amount of water added to a given element of the hydrologic system. Usually, iteration and repeated evaluation are needed to find the values of the judgment parameters that produce the most realistic picture of the complete hydrologic system.

Table 3. Criteria for episodic master recession (EMR) recognized episodes.

Episode feature†	Criterion
Episode start time WT, QS	crossing of master recession curve (MRC) before breakout above tolerance band, but no earlier than one lag time before breakout
Episode start time QC	the last crossing, before breakout above tolerance band, of the hydrograph slope with the specified constant-slope value
Episode end time WT, QS	crossing of MRC from below after having reentered the tolerance band, or one stabilization time (without exiting the band) after reentry, whichever is earlier
Episode end time QC	intersection of the constant-slope separation line with the hydrograph trace
Combine sequential episodes WT, QS, QC	if the start time of the later episode occurs on or before the end time of the earlier episode
Omit episode WT, QS, QC	if it starts before the start or ends before the end of the data record
Lengthen episode WT	if its duration is less than one lag time, increase by one-half of the lag time in each direction
Precipitation start time WT, QS, QC	one lag time before episode start time
Precipitation end time WT, QS, QC	episode end time, or the precipitation start time of the following episode, whichever is earlier

† Distinguishing features of three althernative criteria sets: WT, breakout of hydrograph slope from tolerance band for water levels; QS, breakout of hydrograph slope from tolerance band for streamflow; QC, constant slope hydrograph separation for streamflow.

Table 4 lists the hydrologic-judgment parameters of EMR, analogous to the MRC parameters in Table 2. Additionally, there is a parameter called *capacity*, which for water-table hydrographs is set equal to the specific yield of the aquifer material, used in computing episodic recharge; for streamflow the value has no consequence. The original recharge episode-discerning criteria set for groundwater, whose criteria and judgment parameters are in Tables 3 and 4, is given the designation "WT" in the EMR codes. It differs in only minor ways from the criteria set presented by Nimmo et al. (2015).

Episodic recharge is calculated using MRC extrapolations, as explained by Nimmo et al. (2015), to determine appropriate recession-corrected water level values for use in calculating the amount of recharge attributable to each episode. The vertical difference in these extrapolations at the time of the hydrograph peak indicates the episode's effective change in water level. Multiplication by the specific yield pertaining to the given well gives the estimated recharge.

The calculation of stormflow for each episode requires the episode's total streamflow, graphically the area under the hydrograph trace between the start and end times, to be partitioned into a baseflow component and a stormflow component. Many published techniques are available for computing this hydrograph separation (e.g., Blume et al., 2007). In adapting the EMR method, designed originally for water-table fluctuations and recharge, to calculate stormflow, we developed two alternative criteria sets. The first, designated "QS" in the EMR codes, is closely analogous to the WT method used for water-level hydrographs, the episode start being determined the same way. It also uses the same type of stability criterion for the episode end, selecting the time at which the declining hydrograph has stably returned to master-recession behavior. The separation of stormflow from baseflow is a line that simply connects the episode start and end points on the hydrograph. Trapezoidal integration of the area between this line and the hydrograph trace quantifies the stormflow. The second criteria set, designated "QC", is based on the widely used constant-slope method of hydrograph separation (Hewlett and Hibbert, 1967). The judgment parameter to be supplied (as *epend_par*) is the slope of the line to be used in separating stormflow from baseflow. The same slope is used for all episodes. As for WT and QS, an episode is recognized by breakout of the hydrograph slope from the tolerance band. The start time criterion uses the constant-slope value, identifying the incidents where the hydrograph slope starts to exceed this value. Of these incidents, the time of the last one before the breakout above the tolerance band is taken as the episode start time. The constant-slope line is extended from the episode starting point until it intersects the hydrograph trace, and the point of intersection is taken as the episode end. Again, a trapezoidal integration yields the episode stormflow. The QS and QC criteria sets each have advantages and disadvantages for different data sets and applications, as discussed below.

The causal precipitation or other water input of each episode is what occurs during an interval starting at a time preceding the episode start by the value of the *lag_time* parameter. The end of the precipitation interval is the same as the episode end, except when episodes are so closely spaced that the episode ends within the precipitation interval of the succeeding episode. In that case, the earlier episode's precipitation interval ends at the start time of the precipitation interval of the later episode. For use in hydrologic evaluation and interpretation, the ratio of recharge to water input for an episode is called the recharge/precipitation ratio (RPR). The analogous quantity for streamflow is the ratio of stormflow per watershed area to water input (SPR).

Procedure

Figure 1 diagrams the procedure for using the MRCfit and EMR programs. The programs are written in the R programming language (R Core Team, 2016).

The user starts by creating an input data file. This comma-delimited (.csv) file contains three columns, for time, hydrograph response, and cumulative precipitation. A water-level response can be given as height above sea level, depth below land surface (using negative numbers), or other suitable reference level. For a streamflow response, the data are given as volume per unit time (cfs, m^3/d, etc.). Precipitation in the third column is cumulative from a chosen reference time. The data can be in any consistent set of units. The use of numerical differentiation in the EMR algorithm imposes dataset requirements (not all of which are needed by MRCfit) that may require corrections and adjustments before running the code. Time steps need to be of uniform duration, and data gaps must be filled by interpolation or other estimates of missing data. Stair-step effects in data obtained with coarse measurement discretization may need smoothing of sharp edges. The EMR website (https://wwwrcamnl.wr.usgs.gov/uzf/EMR_Method/EMR.method.html)

Table 4. Episodic master recession parameters to be given values chosen by expert judgment, typically refined by repeated calculations with alternative values; R is the response variable (streamflow or water level).

Name	Type	Meaning
lag_time	numeric	lag time between start of input and response of hydrograph
epend_par	numeric	parameter used in determining episode end, implemented differently for the three sets of selection criteria: for WT and QS, the time allowed for stabilization of the return to master recession curve behavior after decline from the episode peak; for QC, the slope value used for the hydrograph separation line
fluc_tol	numeric	max. rate of change of response with time, dR/dt, allowable as system noise rather than response to incoming water flux
minprecip	numeric	min. amount of precipitation within precipitation window to allow inclusion as an episode
Nsmooth	numeric	used for smoothing of the computed hydrograph slope, the number of data points to left and to right of each point that will be averaged to give the dR/dt curve to be used in episode analysis

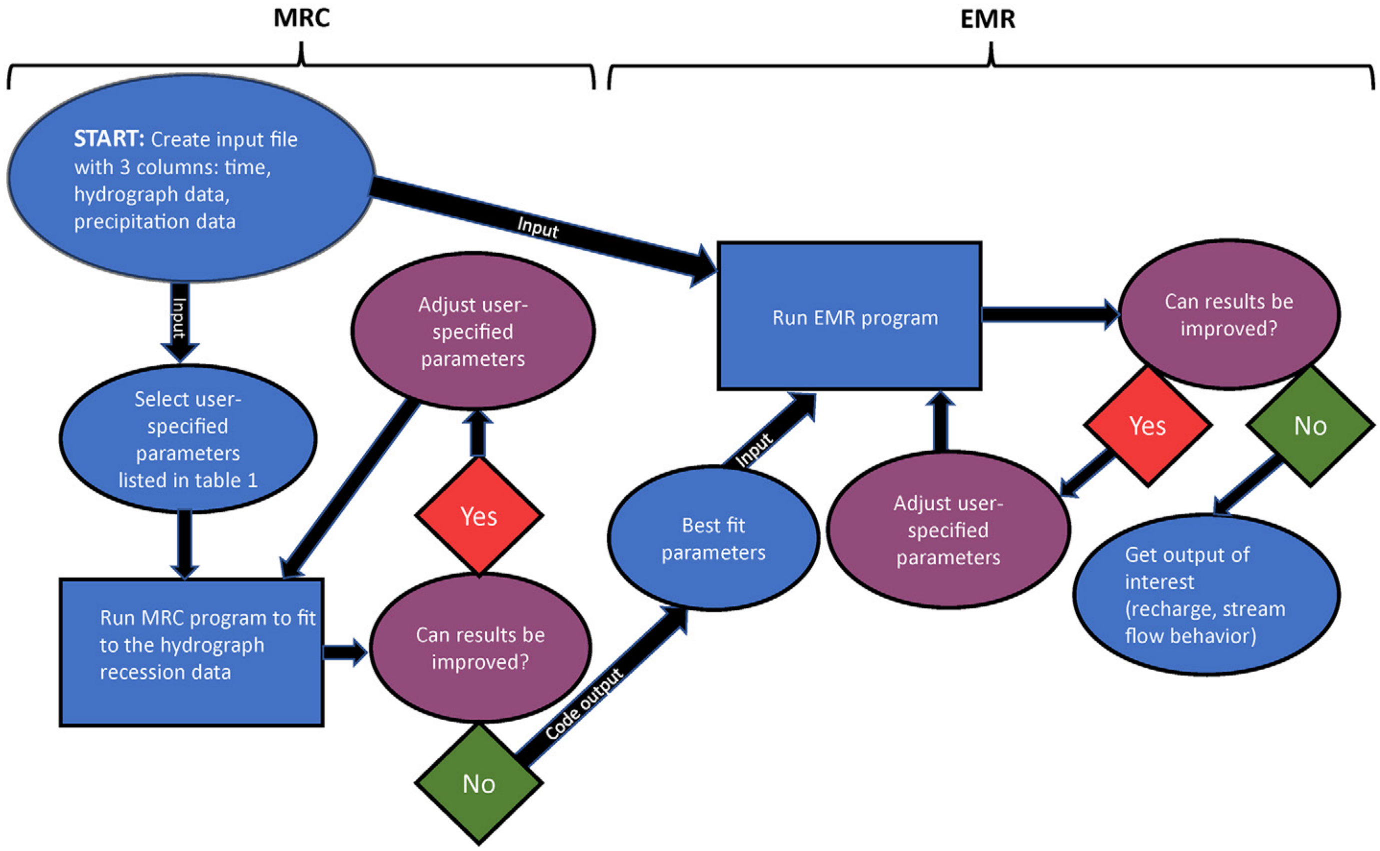


Fig. 1. Flow chart showing the procedure and interconnectedness of the episodic master recession (EMR) and master recession curve (MRC) programs. Steps involving hydrologic judgements are shaded in purple.

provides codes that can assist with the necessary modifications of the data file.

Once the data file is created, the MRCfit program is run to generate the MRC parameters as described above. The process is iterative with the following considerations: The values of judgment parameters (Table 2) are chosen so as to exclude portions of the hydrograph that might be influenced by significant hydraulic processes other than recession (e.g., storm-driven recharge flux) or that do not lend themselves to accurate slope determination because of system noise, gaps, calibration shifts, or other factors. The MRC fits should use only recession portions of the data. Parameter values can be adjusted to be more restrictive (e.g., decrease of *maxdelprec* or *maxtick*, increase of *mindrytime*) to accept fewer slope elements of higher quality. The parameter *maxtick* can accommodate noise in the data where minor upticks would otherwise cause rejection of suitable slope elements. The chosen values must not be so restrictive that there are too few slope elements for fitting the MRC or that some portions of the response range have too little representation. Output from MRCfit includes a graph of response vs. time, with highlighting of the slope elements used in fitting, a graph showing the MRC fit to the recession data, and a text file listing the selected slope elements and the fitted MRC parameter values to be used for EMR.

The input data used for the EMR program are the same as for MRCfit. The iterative process of running the code, like that of MRCfit, requires repeated evaluation of parameters together with the episodic output they generate. The generated output includes a graph of dR/dt computed from the data, with the tolerance band indicated, a graph of R vs. time with identified episodes highlighted, a tabular file (.csv format) with computed values of importance as described below, and a text file recording file names, parameter values, and documentation of certain data-handling operations (e.g., exclusion or combining of potential episodes) made in the course of execution.

Several questions and issues should be kept in mind in evaluating the results of a given run of the EMR program. Are all episodes captured? Are events captured that are probably not real episodes? Do MRC extrapolations appear to reasonably extend the hydrograph trend? Do hydrograph separation lines span the extent of substantially increased streamflow? Do they stay near the upper part of a range that can reasonably be considered baseflow? In addressing such issues, the tolerance parameter *fluc_tol* often requires particular attention. A greater value will result in the recognition of fewer episodes. Ideally, *fluc_tol* will be given a value small enough to include all episodes of significance to recharge or other issues being investigated, yet large enough to exclude potential episodes of negligible significance or attributable to noise in the data. Results should be examined to determine a *lag_time* value that serves as a site-specific characteristic approximating the time it takes for water input at the land surface to produce a response in the water table or streamflow. This parameter can have a significant effect on event designation. If the rain gauge is not colocated with response measurement, especially for groundwater hydrographs from a given well, it must be noted that the time difference between input and response may not follow the expected relationship. Also having a significant effect on event designation is the stability time (specified through the parameter *epend_par*), which should approximate the time it takes for the hydrograph to resume pre-event behavior (although not necessarily at the same level) after land-surface input ceases. Examination should also give insight on the minimum amount of precipitation (*minprecip*) that will cause a real response. Water level or streamflow increases are normally identified as episodes when there is a precipitation event that can be reasonably assumed to have caused the response. This parameter can be set to a negative number if a given application is better served by not imposing this requirement.

Application

Shale Hills

The Shale Hills Critical Zone Observatory is a small forested catchment in central Pennsylvania, described by Lin and Zhou (2008). The site has moderate slopes (up to 25–48%) with deep soils (>2 m) in swale regions that are underlain by fractured shale. The soils are silt loam textured with moderately developed soil structure and high permeability. The forest cover supplies the soils with an approximately 0.05-m-thick organic layer comprised of leaf litter and other organic material. We used a water-table hydrograph from Well W2 near Site 51 and the streamflow hydrograph from the stream gauge shown in Fig. 1 of Lin and Zhou (2008). The area contributing to the stream gauge measurements is 0.079 km^2. Water level and precipitation data are at 10-min intervals. From the data publicly available (http://criticalzone.org/shale-hills/data/datasets/), we chose a 7-mo interval with no apparent gaps or flaws from 20 Jan. to 18 Aug. 2009.

Water Table

The water table at the selected Shale Hills location varied between 0.5- and 1.3-m depth during the 7-mo evaluation period. The original data showed an apparent diurnal fluctuation, so we used a 24-h moving average to produce a revised data set whose variations represent storm-response processes apart from ongoing diurnal processes. MRCfit was run using these data to obtain a single-segment MRC. Figure 2a shows the water-table hydrograph with the selected slope elements, with cumulative precipitation in the background. Blue crosses in the figure identify the starting points of the slope elements. The remaining points in each slope element are shown as red symbols, which, given the 10-min resolution and the scale of this graph, overlap substantially to make a broad red line. Many of the peaks in the hydrograph tend to be nearly concurrent with near-vertical portions of the precipitation record, indicating a fairly rapid and direct response of the water table to storms. Table 5 gives the user-specified parameter values.

The regression-computed values of slope for each element, paired with the water level at the midpoint of the slope element, are plotted as blue diamonds in Fig. 2b. These points were bin-averaged to give the red points, which have somewhat less scatter. Linear regression to these points gives the fitted MRC, shown as a bold line. Scatter among the points in this plot is greater than desirable, but the trend represented by the MRC is clear. Bin averaging applied here does not significantly affect the parameterized MRC.

Figures 2c and 2d illustrate the application of EMR to the selected 7-mo period of data, using the computed MRC relation of Fig. 2b. Table 6 has a list of the discerned episodes and important output values for each. Figure 2c shows the computed derivative of water-table height with respect to time, as used to identify the episodes shown in both figures. The dashed black line indicates the tolerance band determined using *fluc_tol*, exceedance of which by dR/dt indicates an episode. Figure 2d shows the hydrograph and precipitation record, with recharge episodes indicated by a bold hydrograph trace. The red curves are MRC extrapolations from the episode start and end points. Multiplication of the vertical difference between these extrapolations by the specific yield gives the estimated recharge of the episode. In the absence of a known specific yield for this site, an estimated value of 0.05 was assigned. The precipitation inferred to have produced this recharge (seventh column of Table 6) is from the time intervals colored in dark blue in Fig. 2c and 2d. The last column of the table gives the recharge/precipitation ratio. Some of these RPR values are unreasonably large if interpreted as the fraction of the identified precipitation that recharges the water table aquifer. A lower value of specific yield could bring most of these down to realistic values. Episode 1 and 3 RPR values would be unrealistic with any plausible specific yield, suggesting that unknown complicating factors may be active. A likely possibility, because these episodes occur in midwinter, is that delayed snowmelt may cause the water table rise, the causal precipitation having occurred before the start of the designated precipitation interval.

Streamflow

Streamflow hydrographs and MRCs are shown in Fig. 3, and a list of episodes and output values in Table 7. This is a case where a two-part MRC is useful. Figure 3a shows the selected slope elements fitting the data in the lower portion of the range for streamflow values <100 m^3/d (Table 5). Figure 3b shows the selections made for the upper portion of the range, where recession slopes are much steeper. The change in recession rate quantifies the expected effect of additional processes becoming active at higher flow rates. An obvious possibility is that post-storm runoff is occurring in addition to the baseflow-related processes that are active even during low levels of streamflow. The MRC plot in Fig. 3c shows points obtained from the low-flow data in red and from the high-flow data in green. The bold line represents the composite MRC made of two linear segments, with the lower one constrained to indicate a zero rate of change when the streamflow is zero, as is physically realistic. With this constraint, the MRC is a three-parameter fit.

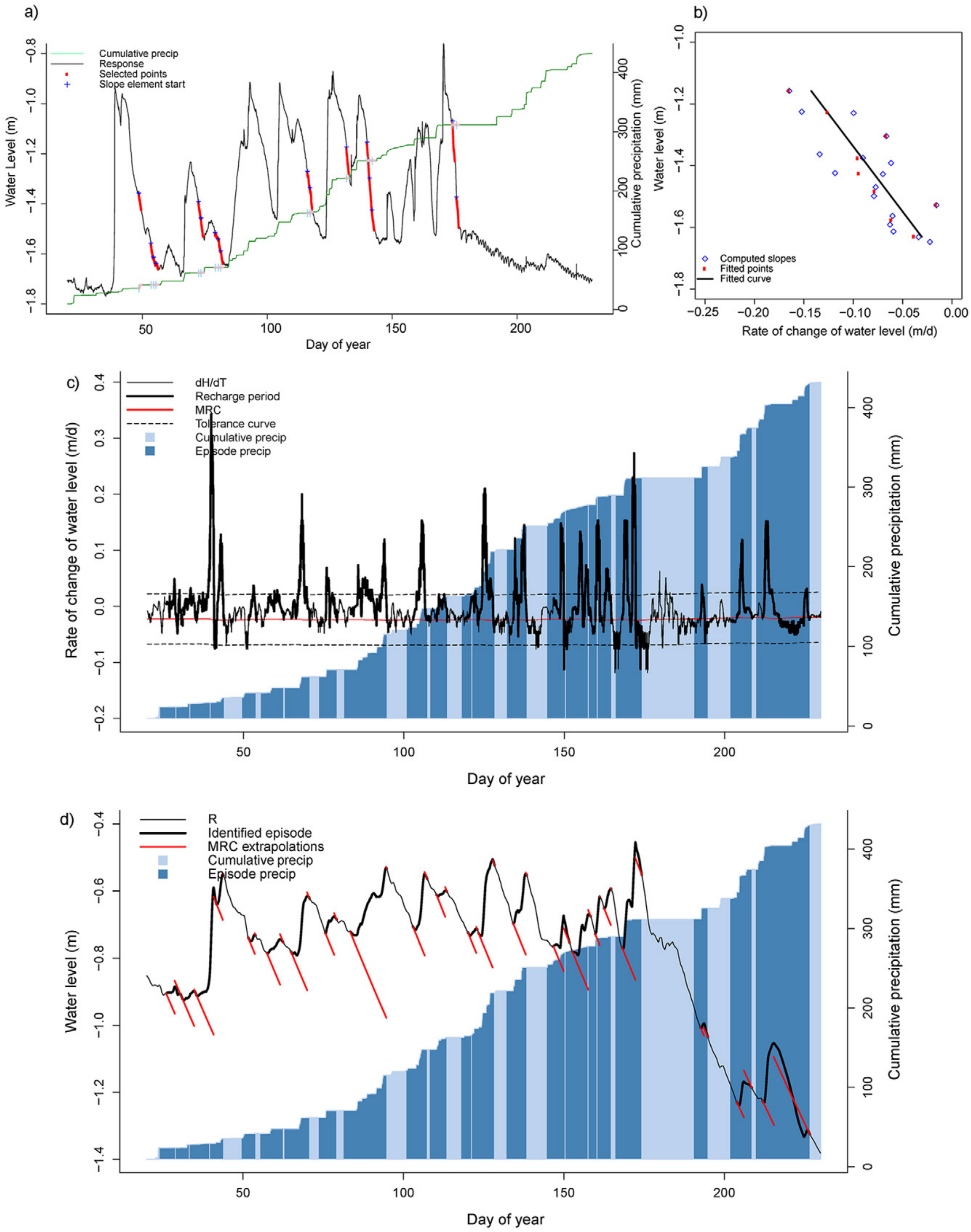


Fig. 2. Shale Hills water table: (a) the water table hydrograph with selected slope elements highlighted, and cumulative precipitation in the background; (b) points representing the slope elements determined by regression, with the fitted master recession curve (MRC) as a line; (c) the time derivative of the hydrograph, i.e., the instantaneous hydrograph slope, used in applying set criteria for discerning recharge episodes; and (d) the hydrograph with episodes distinguished: the red curves are MRC extrapolations from the points identified as the start and end times of the episode such that the vertical distance between the two extrapolated curves indicates the amount of recharge the episode has added to the water table aquifer.

Table 5. Shale Hills parameter values.

Parameter	Streamflow: Lower range	Streamflow: Upper range	Well levels
	Master recession curve parameters		
resplimits	0–100 m^3/d	100–1500 m^3/d	−10 to 0 m
throughorigin	TRUE	FALSE	FALSE
mindrytime	0.5 d	0.5 d	4 d
maxdelprec	0.1 mm	0.1 mm	0.4 mm
tslength	3 d	1 d	1 d
maxtick	0.01 m^3/d	0.01 m^3/d	0.03 m
	Episodic master recession parameters		
lag_time	0.7 d		2.2 d
epend_par	1.5 m^3/d^2 (QC)†		2 d (WT)†
fluc_tol	70 m^3/d		0.045 m/d
Nsmooth	8		0

† WT, breakout of hydrograph slope from tolerance band for water levels; QC, constant slope hydrograph separation for streamflow.

Using the computed MRC, the EMR method was applied to the streamflow as it was to the water-table hydrograph, using the QC selection criteria to produce the results in Fig. 3d and 3e. The red line segments are the constant-slope lines separating baseflow below from stormflow above. Integration above the line gives the episode stormflow in Table 7.

Use of the QC criteria works well here with an assigned constant slope of 1.5 m^3/d^2. The value assigned for this could be determined by the Hewlett and Hibbert (1967) rule of thumb that the slope should equal (0.0011 m/d^2)$\times A$, where A is the watershed area. For the small Shale Hills watershed, this gives a slope of 90 m^3/d^2, clearly too large, as it is comparable to some of the rising limbs in the hydrograph. Still, the method can be applied with the reasonable slope value chosen. The QC criteria have the advantage of a degree of consistency with general hydrologic practice. They also guarantee against an unrealistic negative slope. Drawbacks are that they work well only with data of high temporal resolution and are only partially consistent with the WT criteria for water-table hydrographs.

Terminio

The second site is in the Acqua della Madonna test area, located in the south-central region of the Terminio Mount karst aquifer in the Campania region of southern Italy. At the land surface there are andesitic soils with thicknesses up to 0.50 to 0.60 m. The subsurface is a fractured and partially karstified Cretaceous limestone series overlain by ash-fall pyroclastic deposits derived mainly from the Somma–Vesuvius volcano (Allocca et al., 2008). The water table fluctuates between the layers of rock and pyroclastic deposits, which

Table 6. Shale Hills water table episodes.

Episode	Start time	Duration	Time of peak	Change in water level	Estimated recharge	Precipitation	RPR†
	d	d	d	m	mm	mm	
1	26.06	4.99	28.72	0.097	4.8	0.3	18.61
2	31.12	4.20	34.79	0.108	5.4	3.8	1.42
3	35.44	6.18	40.83	0.410	20.5	1.5	13.50
4	41.76	2.22	43.70	0.138	6.9	6.1	1.13
5	51.60	2.33	53.67	0.060	3.0	5.8	0.51
6	57.42	5.13	61.53	0.149	7.5	6.1	1.22
7	64.92	5.82	69.96	0.290	14.5	14.2	1.02
8	75.62	3.58	78.41	0.123	6.2	8.6	0.71
9	83.40	11.39	94.60	0.447	22.3	44.2	0.51
10	102.94	4.51	106.60	0.248	12.4	26.7	0.46
11	110.27	3.29	113.00	0.088	4.4	15.2	0.29
12	120.09	2.97	122.68	0.077	3.8	2.8	1.37
13	123.38	5.02	127.78	0.319	16.0	53.3	0.30
14	134.18	4.26	138.13	0.243	12.2	29.7	0.41
15	146.73	5.03	149.92	0.127	6.3	18.8	0.34
16	152.56	5.80	157.58	0.237	11.8	7.8	1.51
17	159.72	1.42	161.11	0.144	7.2	9.9	0.73
18	162.49	2.28	164.62	0.110	5.5	2.0	2.71
19	168.07	6.22	172.29	0.361	18.1	21.9	0.83
20	192.57	2.32	193.63	0.022	1.1	14.0	0.08
21	203.83	4.74	206.09	0.139	7.0	36.8	0.19
22	211.87	14.82	215.43	0.201	10.1	56.1	0.18

† Recharge/precipitation ratio.

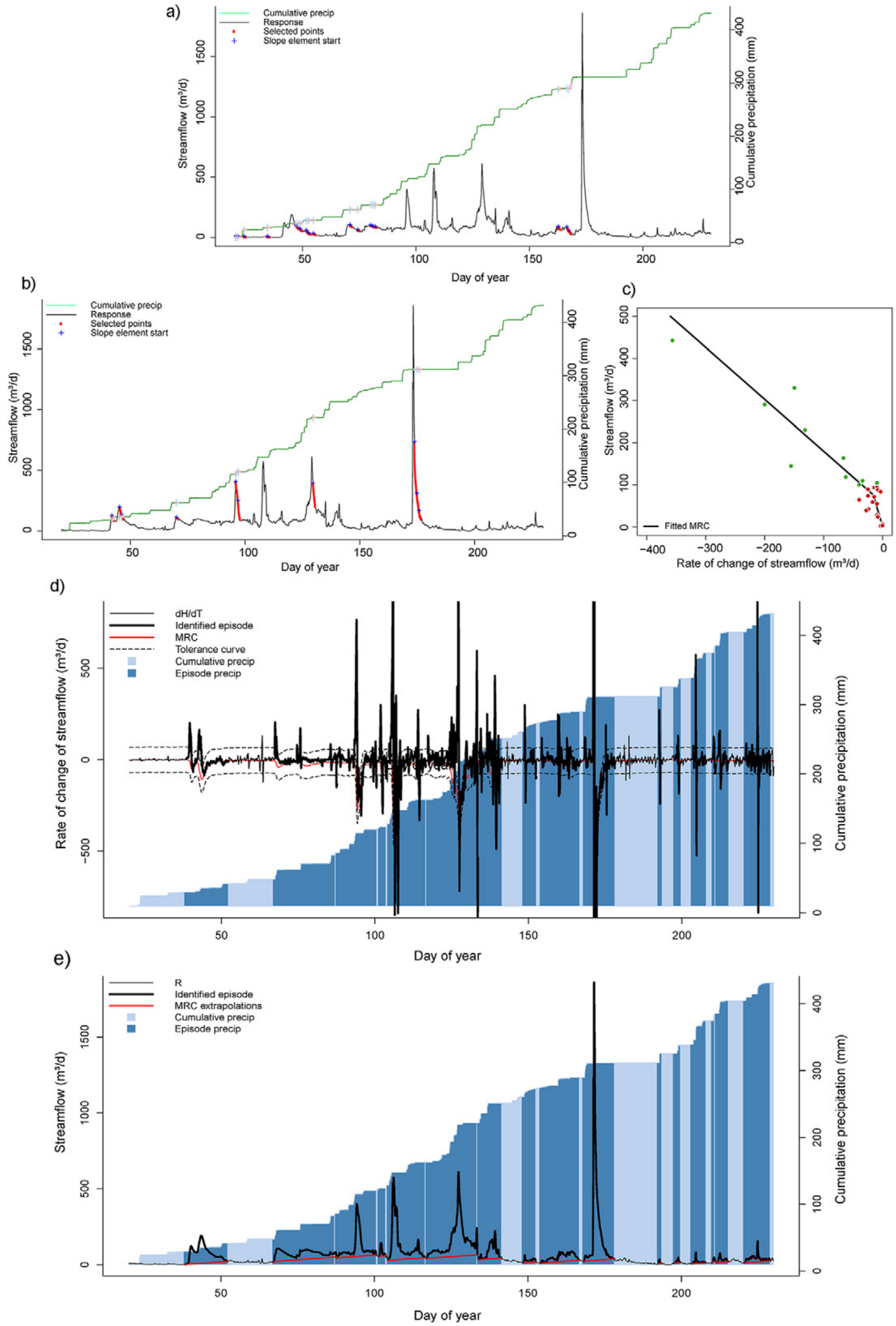


Fig. 3. Shale Hills streamflow: (a) the hydrograph with cumulative precipitation in the background and selected slope elements identified as representing characteristic recession at low flow rates, used for the lower, baseflow-related, segment of the master recession curve (MRC); (b) hydrograph and precipitation with slope elements selected for the higher, stormflow-related, segment of the MRC; (c) values of the hydrograph slope (red for low flow rates and green for high) and the two-segment MRC represented as two intersecting bold lines fitted separately to the two sets of points; (d) the time derivative of the hydrograph, used in discerning recharge episodes by the occurrence of upside breakout from the tolerance band shown as a dashed line; and (e) the hydrograph, distinguishing stormflow episodes that each correspond to a particular input event: the red lines connect the starting and ending points of each episode such that the area between the line and the hydrograph trace approximately represents stormflow, with the area below the line approximating baseflow.

Table 7. Shale Hills streamflow episodes.

Episode	Start time	Start response	End response	Duration	Time of peak	Peak response	Estimated storm flow	Precipitation
	d	———— m^3/d ————		d	d	m^3/d	m^3	mm
1	38.47	1.9	22.5	13.80	43.53	191.7	915.70	12.4
2	67.31	21.0	51.1	20.33	68.59	106.6	834.10	35.1
3	87.69	44.8	63.6	12.92	94.28	400.1	743.87	37.8
4	101.59	55.2	58.0	2.04	102.13	143.8	67.13	2.3
5	104.57	28.9	46.9	12.03	106.26	557.1	1178.65	39.1
6	117.22	42.0	64.7	16.37	127.40	610.4	1730.27	58.7
7	134.03	33.8	44.5	7.37	139.30	223.4	354.77	29.7
8	148.55	13.8	19.3	4.03	149.01	63.8	59.82	11.9
9	154.27	11.3	30.0	12.47	164.38	89.5	396.04	16.3
10	168.31	23.2	37.9	9.85	171.57	1860.7	1899.98	21.8
11	192.60	5.7	7.1	1.00	192.90	34.7	9.20	13.7
12	197.78	11.4	14.3	1.94	199.01	46.6	21.27	11.9
13	203.46	6.3	13.0	4.52	204.73	80.7	47.85	36.3
14	210.26	19.6	20.9	0.87	210.60	47.5	11.73	9.4
15	211.46	14.6	20.3	3.84	212.56	75.9	67.14	20.8
16	220.67	13.7	25.7	8.20	224.88	155.5	192.61	26.9

differ in hydraulic properties. The selected data, for the well designated P1 in calendar year 2008, were published by Allocca et al. (2015). Here we refer to this location as the Terminio well.

Because the Terminio water table fluctuates within two hydrogeologically distinct layers, it requires a more complex MRC than at sites where fluctuations do not take the water table outside a zone of relatively homogeneous hydraulic properties. Allocca et al. (2015) treated this complexity using an empirical cubic-polynomial fit to the water level vs. rate of change results computed with the 2015 version of MRCfit, as can be seen in Fig. 5 of their paper.

With our new code, it is possible to represent the MRC as line segments of two different slopes, one for each of the two media in the zone of fluctuation. Unlike the cubic polynomial fit, which was originally chosen as a simple form that appeared to fit the data reasonably, this two-part MRC has a physical interpretation as two hydraulically distinct linear reservoirs, corresponding to the two distinct layers of different hydraulic properties, as identified in the basic geologic assessment in Allocca et al. (2015). As for the Shale Hills streamflow results of Fig. 3a to 3c, Fig. 4a to 4c show the hydrographs with the two analyzed ranges and the two-segment MRC. Figure 4a identifies the slope elements for the range controlled by the hydraulic properties of the limestone (below 5.5 m), and Fig. 4b shows the corresponding information for the higher range water level within the pyroclastic deposits. The two-part MRC in Fig. 4c provides good fits to the two water level ranges, with the rate of change in the pyroclastic medium responding to water level variation with sensitivity greater by about a factor of 10.

The EMR results obtained using the two-part MRC are shown in Fig. 4d and 4e. Parameters and tabular results are in Tables 8 and 9. The recharge episodes and hydrologic quantities obtained do not substantially differ from the results obtained by Allocca et al. (2015) using the earlier version of the code. The number of recharge episodes distinguished here is 11, compared with 12 in the earlier study, but the difference is simply that Episode 4 here combines two narrowly separated episodes discerned earlier.

In this case study, with a groundwater but not a streamflow component, the main advantage of the newer version is that its four-parameter MRC, based on the two known hydrogeologically contrasting layers, has a stronger physical interpretation than the (also four-parameter) cubic polynomial. It also indicates quantitatively the relevant physical properties of the two media. At a site where three or more layers are important, the multi-segment form would have additional advantages.

Reedy Creek Watershed

The third site is in the watershed of Reedy Creek, a tributary to the Kissimmee River, located in central Florida within a basin of 192 km^2, draining and flowing through 30 km^2 of low-slope wetlands. The hydrograph data were taken from the study published by O'Reilly (1998). The surficial aquifer beneath the creek is within a 20-m-thick sequence of undifferentiated sand, silt, clay, and crushed shell. It is underlain by the deeper Upper Floridian Aquifer, which lies within a thick sequence of carbonate rocks. Along with streamflow records, data from three wells, all within the surficial aquifer, were analyzed. Specifically, these wells are those labeled EW11-4, SW16, and SW4 (O'Reilly, 1998, Fig. 3), whose initial water table depths below the land surface are 1.74, 7.05, and 25.75 m, respectively. Values used for the judgment parameters are given in Table 10, and tabular

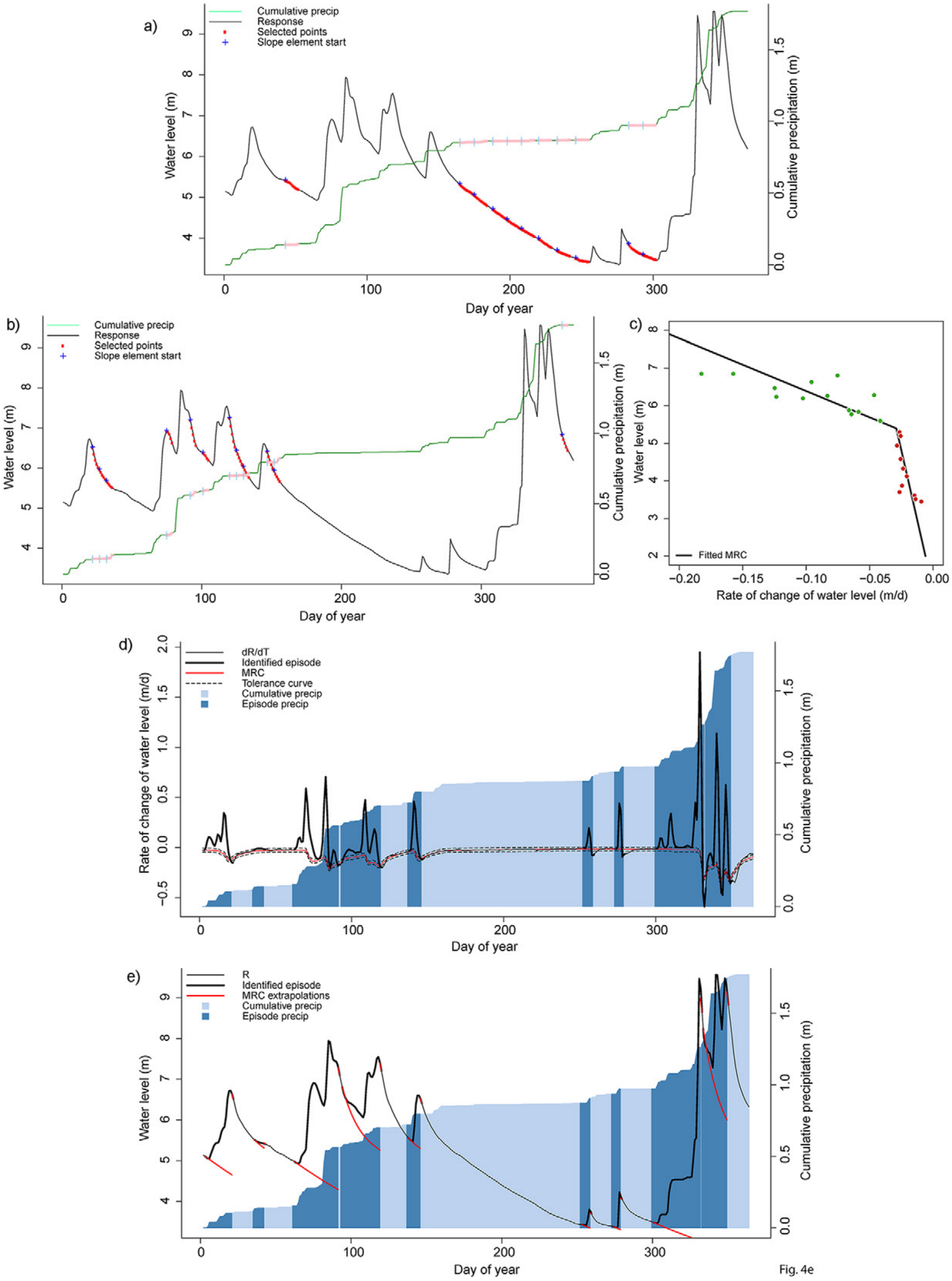


Fig. 4. Terminio water table: (a) the hydrograph with cumulative precipitation in the background and selected slope elements identified as representing characteristic recession for lower water levels, used for the lower segment of the master recession curve (MRC); (b) slope of the selected slope elements representing characteristic recession at higher water levels for the upper MRC segment; (c) values of the hydrograph slope (red for the lower range and green for the higher) and the two-part fitted MRC; (d) the time derivative of the hydrograph, used in discerning recharge episodes; and (e) the hydrograph with episodes distinguished: the red curves are MRC extrapolations from the points identified as the start and end times of the episode such that the vertical distance between them is an estimate of the episodic recharge.

Table 8. Terminio parameter values.

Parameter	Well levels	
	Lower range	Upper range
	Master recession curve parameters	
resplimits	0–5.5 m	5.5–10 m
throughorigin	FALSE	FALSE
mindrytime	5 d	5 d
maxdelprec	0.001 m	0.01 m
tslength	10 d	5 d
maxtick	0.001 m	0.1 m
	Episodic master recession parameters	
lag_time	1.1 d	
epend_par	2 d (WT)†	
fluc_tol	0.02 m/d	
Nsmooth	0	

† WT, breakout of hydrograph slope from tolerance band for water levels.

outputs are in Table 11 for the water table analysis and Table 12 for streamflow.

Water Table

The hydrograph of the shallowest of the three investigated Reedy Creek wells (EW11-4, Fig. 5a) shows distinct recessionary periods lasting from a few days to several months. The seasonal pattern is strong: a long recession from late fall through most of spring, with a few broad recharge periods in summer. The slope elements identified by MRCfit provide an MRC (Fig. 5b) whose slope, intercept, and other characteristics pose no problems for interpretation or use. Strong damping of short-term events is clear from there being only five defined episodes for the year (Fig. 5c and 5d), typically 20 or more days long.

The intermediate well has a hydrograph (SW16, Fig. 5e) similar to the shallow one. Again, the selected slope elements clearly define the MRC (Fig. 5f). Comparing the slopes of the computed MRCs, the intermediate well shows that the water level has a weaker influence on the rate of change than for the shallow well (Fig. 5b). The EMR output (Fig. 5g and 5h) indicates somewhat greater sensitivity, relative to the shallow well, to small events during the fall and winter. Broad peaks indicate few but fairly long recharge episodes in summer.

The hydrograph of the deepest well (SW4, Fig. 5i) shows important differences from the other two. Again, there are some long recessions, although the especially long winter recession is less smooth. The winter period shows the signature of small recharge events superimposed on the seasonal recession, making slope assessment more difficult. Consequently, the slope-element values are more scattered (Fig. 5j), consistent with greater noise causing more uncertainty. The fitted MRC curve shows less sensitivity of the rate of change to the water level than for either of the other two wells. The set of discerned episodes (Fig. 5k and 5l) is strikingly different. The summer is almost one long episode. Winter has many episodes, corresponding to modest individual storms. This correspondence with the storms argues for including them as real episodes, not dismissal as noise. This inclusion is easily accomplished by setting an appropriate value of the tolerance parameter *fluc_tol* (Fig. 5k).

Streamflow

Reedy Creek streamflow recessions are reasonably well-defined for both the lower range fit (Fig. 6a), prevalent in winter and spring, and the upper range fit (Fig. 6b), prevalent during the wet summer. The two-part MRC (Fig. 6c) is a good representation of the trends of the calculated values and fits easily into the stormflow–baseflow framework. The EMR-determined streamflow episodes (Fig. 6d and 6e) are of large magnitude and duration in the summer, more closely resembling the results from the deep SW4 well than from the two shallower ones. There are several small episodes in winter, corresponding to some of the small groundwater episodes noted for the deep well.

Because of the coarse temporal resolution (daily) of the streamflow, the constant-slope QC criteria proved impractical, and the QS

Table 9. Terminio water table episodes.

Episode	Start time	Duration	Time of peak	Change in water level	Estimated recharge	Precipitation	RPR†
	d	d	d	m	m	m	
1	3.15	18.56	20	1.989	0.099	0.104	0.96
2	35.50	8.46	36	0.154	0.008	0.023	0.33
3	62.26	16.28	75	2.184	0.109	0.129	0.85
4	79.20	12.83	85	1.624	0.081	0.276	0.29
5	94.52	25.34	118	2.151	0.108	0.136	0.79
6	137.92	8.80	144	1.248	0.062	0.076	0.82
7	253.03	6.52	258	0.368	0.018	0.033	0.56
8	273.89	5.91	278	0.768	0.038	0.036	1.05
9	300.46	32.39	331	5.887	0.294	0.291	1.01
10	333.80	10.44	342	2.592	0.130	0.371	0.35
11	344.43	5.56	348	1.249	0.062	0.088	0.71

† Recharge/precipitation ratio.

Table 10. Reedy Creek parameter values.

Parameter	Streamflow Lower range	Streamflow Upper range	Well levels EW11-4	Well levels SW16	Well levels SW4
		Master recession curve parameters			
resplimits	0–8.56 × 10^4 m^3/d	1.47 × 10^5–9.79 × 10^6 m^3/d	−4 to 4 m	−4 to 4 m	−4 to 4 m
throughorigin	TRUE	FALSE	FALSE	FALSE	FALSE
mindrytime	0.07 d	0.07 d	4 d	4 d	1 d
maxdelprec	0.254 mm	2.54 mm	0.025 mm	0.025 mm	2.54 mm
tslength	4 d	3 d	10 d	10 d	6 d
maxtick	245 m^3/d	245 m^3/d	3.05 mm	3.05 mm	3.05 mm
		Episodic master recession parameters			
lag_time	0.5 d		1 d	1.5 d	2.2 d
epend_par	8 d (QS)		8 d (WT)	1 d (WT)	8 d (WT)
fluc_tol	2.2 × 10^4 m^3/d^2		9.1 mm/d	6.0 mm/d	6.0 mm/d
Nsmooth	1		1	1	1

criteria were used instead. This optimizes the drawing of parallels with the water-level hydrographs, but with the drawback that the hydrograph separation lines sometimes have unrealistic, sometimes negative, slopes. For strongly evident episodes, however, errors in stormflow calculation resulting from these slope values are likely to be small.

Discussion

Interpretation of Judgment Parameters

Optimization of the judgment parameters, especially the EMR parameters in Table 4, results in values that quantify systematic features of the hydrograph, potentially having hydrologic interpretive value.

The *lag_time* parameter, as mentioned above, has clear significance as an indication of the amount of time necessary for precipitation to reach the water table through the unsaturated zone, or for precipitation to travel by runoff and streamflow to the stream gauge. It could be determined from or compared with similar quantifications obtained by means such as correlation analysis. For Shale Hills, the optimized *lag_time* values of 2.2 d for groundwater and 0.7 d for surface water (Table 5) indicate an unsurprising threefold slower response for water that travels through soil. For Reedy Creek, the values from 1 to 2.2 d for groundwater and 0.5 d for surface water (Table 10) have a similar ratio for the two hydrograph types. That these values are small, given the relatively large area and deep wells, indicates that the watershed as a whole has a fast-responding character, perhaps related to the coarse texture and normally high water content of the subsurface materials. Of particular interest is the short 1-d *lag_time* of the 26-m-deep well SW4, strongly suggesting a major role of preferential flow in percolation to the water table.

Other parameters also have significance. The stabilization time (*epend_par* in the WT and QS selection criteria) is the characteristic duration of the interval from the time at which the recessing hydrograph comes to a slope within measurement error of the MRC slope to the time when it can be confidently associated with a full return of the hydrograph to master-recession behavior. It is largely empirical in the context of the EMR algorithm, although it may have a relation to measurement precision or streamflow responsiveness. The value of *fluc_tol* can be directly indicative of measurement noise. In cases where a wide range of values gives the same recognized episodes for the period of record, it may be suggestive of a threshold effect such that significant episodes occur only for events that exceed a certain minimum magnitude. In many cases *minprecip* is best given as a small positive number so that no episodes will be recognized as significant in cases where the inferred causal precipitation is negligible. For some applications, it can usefully be given a negative value to recognize all episodes whether they result from recognizable precipitation or not. Doing so can prevent exclusion of episodes such as those resulting from delayed snowmelt or causes other than precipitation, although the calculated RPR or SPR values of such episodes will be useless. *Nsmooth*, the degree of smoothing applied to the computed hydrograph slope before evaluation of episodes, is a parameter chiefly of practical value in obtaining the most instructive episode recognition. A value of zero results in no smoothing. Larger values tend to be useful for data sets that are noisy, flashy, or coarsely discretized.

Evaluation of Combined Results

At the Shale Hills location, during the winter-to-summer interval of Days 35 to 180, streamflow peaks are mostly small but tend to increase in magnitude with time (Fig. 3e). The rest of the time (Days 0–35 and 180–230), even with substantial storms the streamflow is close to zero. Water level fluctuations, in contrast, occur with significant magnitude throughout the whole record. Except for late spring and summer, the water table seems to more sensitively indicate storage change than streamflow. Given the complexity of infiltration and runoff mechanisms in times of snowfall, snowmelt, frozen soil, and thawing conditions (Shanley and Chalmers, 1999; Appels et al., 2018), the processes causing these trends cannot be

Table 11. Reedy Creek water table episodes.

Episode	Start time	Duration	Time of peak	Change in water level	Estimated recharge	Precipitation	RPR†
	——————— d ———————			m	——— mm ———		
Well EW11-4							
1	78.89	10.19	82	0.036	1.8	1.3	1.45
2	96.07	14.03	103	0.097	4.9	50.8	0.10
3	170.50	21.08	186	0.524	26.2	177.0	0.15
4	202.10	38.84	238	1.333	66.8	483.4	0.14
5	264.03	21.76	284	0.554	26.5	212.6	0.12
Well SW16							
1	73.89	65.32	119	0.283	14.0	138.9	0.10
2	162.47	9.25	169	0.032	1.5	26.9	0.06
3	172.66	23.19	188	0.354	17.7	176.8	0.10
4	204.26	45.60	244	1.133	56.7	500.4	0.11
5	269.09	27.39	291	1.817	27.7	188.7	0.15
Well SW4							
1	7.71	6.14	13	0.066	3.4	8.4	0.39
2	15.84	2.94	16	0.021	0.9	21.3	0.05
3	20.07	2.37	21	0.012	0.6	1.0	0.57
4	23.60	4.52	28	0.038	1.8	0.3	7.54
5	30.03	4.81	32	0.043	2.1	11.2	0.19
6	38.37	3.54	41	0.036	1.8		
7	45.60	13.74	51	0.069	3.4	15.5	0.22
8	61.65	4.82	64	0.039	1.8	3.8	0.52
9	68.56	8.90	74	0.055	2.7	16.5	0.17
10	83.57	2.50	84	0.005	0.3		
11	91.52	3.87	95	0.027	1.2	17.3	0.08
12	99.90	2.27	100	0.003	0.3	20.6	0.01
13	136.39	2.68	137	0.009	0.3		
14	151.80	3.40	152	0.010	0.6	7.6	0.07
15	192.95	5.52	198	0.041	2.1	11.9	0.17
16	200.02	13.72	213	0.213	10.7	227.1	0.05
17	214.50	72.89	287	1.526	76.2	535.7	0.14
18	288.30	44.75	333	1.065	53.3	18.0	2.96
19	345.50	7.49	346	0.072	3.7		

† Recharge/precipitation ratio.

uniquely identified from a single study. A plausible hypothesis is for this behavior to result from a winter-active runoff-limiting effect that reduces streamflow but without a corresponding limitation of preferential flow through the unsaturated zone. Air temperature data from the site (http://www.czo.psu.edu/data_hpat51.html) indicate a period of thaw from Days 41 to 45 (10–14 February). If occurring slowly, snowmelt could have generated more infiltration than runoff, as the hydrographs suggest.

Beyond the initial observations that arise from basic comparison of the two hydrographs and the precipitation record, MRC–EMR analysis affords additional important observations, most of them more precisely quantitative. Quantification of the MRCs based on the whole data set gives a parametric representation of characteristic recession behavior. The EMR gives a precise and consistent delineation of episode start and end times according to documented quantitative criteria. An example of the benefits is a recognition of episodes that are only subtly apparent or hard to distinguish from noise, as at Day 194 (Fig. 3e). Failure to confidently recognize such events, as may be likely without the precision and consistency afforded by EMR, would give a distorted view of the range of possible water level responses to storms.

Comparing EMR outputs for the Shale Hills water level and streamflow (Fig. 2d and 3e), there is more lumping together of

Table 12. Reedy Creek streamflow episodes.

Episode	Start time	Start response	End response	Duration	Time of peak	Peak response	Estimated storm flow	Precipitation
	d	m^3/d		d		m^3/d	m^3	mm
1	9.75	1.35×10^5	1.17×10^5	27.67	27	2.18×10^5	6.74	38.35
2	45.79	1.00×10^5	8.81×10^4	9.66	49	1.64×10^5	0.96	13.97
3	64.24	6.61×10^4	7.10×10^4	20.07	72	8.56×10^4	6.09	51.31
4	93.63	4.65×10^4	7.10×10^4	10.34	97	1.42×10^5	2.44	52.58
5	138.36	2.23×10^4	2.94×10^4	8.77	141	6.61×10^4	1.73	41.91
6	161.14	2.08×10^4	2.15×10^4	9.47	164	7.34×10^4	1.90	26.92
7	170.79	2.10×10^4	6.61×10^4	13.85	177	5.68×10^5	16.15	171.70
8	186.09	4.89×10^4	1.37×10^5	133.63	284	1.84×10^6	392.01	795.02
9	331.39	1.08×10^5	1.08×10^5	8.73	334	1.35×10^5	1.08	6.10

streamflow than of water-level episodes up until about Day 180. This is an effect of sensitivity to brief fluctuations being greater for streamflow than for water level, generating potential episodes so close together that the algorithm combines them. The effect is not surprising because passage through the unsaturated zone has a buffering effect that damps out the brief fluctuations that more directly influence streamflow. The time derivatives in Fig. 2c and 3d make this effect clear. Strong peaks in water level within this time range are clearly distinguishable from noise, whereas some of the significant streamflow peaks rise only a little above the noise. In the EMR analysis for water level it is easy to set the tolerance parameter *fluc_tol*, but for streamflow it is harder to find a value of this parameter that cleanly separates real events from noise. A compromise value of *fluc_tol* that results in lumping together of streamflow episodes, as shown here, probably produces the most useful results.

A potentially valuable EMR application is for the comparison of water-level and streamflow episodes deriving from the same precipitation event. One obstacle to doing so is the greater lumping together observed for streamflow episodes, but a way around this is to compare consecutive clusters of episodes chosen so that the water-level cluster derives from essentially the same precipitation as the streamflow cluster. Eight such cluster pairs can be identified in the data record, with quantitative characteristics given in Table 13. Each cluster pair is characterized here by the amount of causal water input, the total output (defined as recharge plus stormflow per unit area for the watershed), and the ratio of the RPR and the SPR. This ratio of ratios indicates the efficacy of a given precipitation event to generate recharge relative to its efficacy for stormflow generation. Figure 7 illustrates the utility of this comparison in graphs of the ratio of ratios with respect to the episode precipitation (Fig. 7a) and to the total output (Fig. 7b). Although confidence in the interpretation is limited by the small number of clusters, there is a distinct trend with total output but not with episode precipitation. These results suggest that for episodes that generate little recharge and stormflow, regardless of the amount of precipitation, the generation of streamflow is much smaller than that of recharge (e.g., Clusters 7–9, Table 13).

Comparing hydrographs for streamflow (Fig. 6e) and three wells (Fig. 5d, 5h, and 5l) in the Reedy Creek catchment, seasonal effects are strong, corresponding to a summer that is much wetter than the rest of the year. Water tables reach their highest levels in the summer, and streamflow peaks strongly in response to the large summer storms. The rest of the year the water levels are declining, with some interruption by small storm responses. Streamflow continues to respond to storms in the drier seasons but with much smaller rises. Hydrologic features of these same data have been discussed, sometimes contentiously, in several earlier studies (O'Reilly, 1998; Halford and Mayer, 2000; Rutledge, 2000, 2007, 2008; Halford, 2007).

With EMR, many more hydrological processes become apparent. There is a gradual decline of water table sensitivity as the winter progresses and the water table reaches lower depths. This is graphically apparent for the deep well (SW4) in Fig. 5k, where oscillations of the rate of change diminish in magnitude during the period from Days 1 to 180 ending when the water level is near its annual minimum. It is fascinating that the water level in the deepest well shows rapid responses to modest winter storms while the levels in the two shallower wells appear not to. Remarkably, given the nature of the granular material above the water table, this rapid response suggests that a significant preferential flow process can be active through 25 m of unsaturated zone at the location of this well. Yet this well follows the longer term seasonal trends more smoothly than the shallower wells. O'Reilly (1998) suggested a possible alternative explanation from Winter (1983): that storm-augmented groundwater mounds near the land surface in lowland areas near the edge of a hill may supply water laterally to increase water levels beneath the hill. This explanation, however, would necessitate unusually fast lateral transport from the lowland areas and would have to be reconciled with the lack of rapid rises in the shallow well (EW11-4), which is in a lowland area. Further analysis of these combined observations could give insight into catchment hysteresis. In any case, there is clear evidence of unusual unsaturated zone processes,

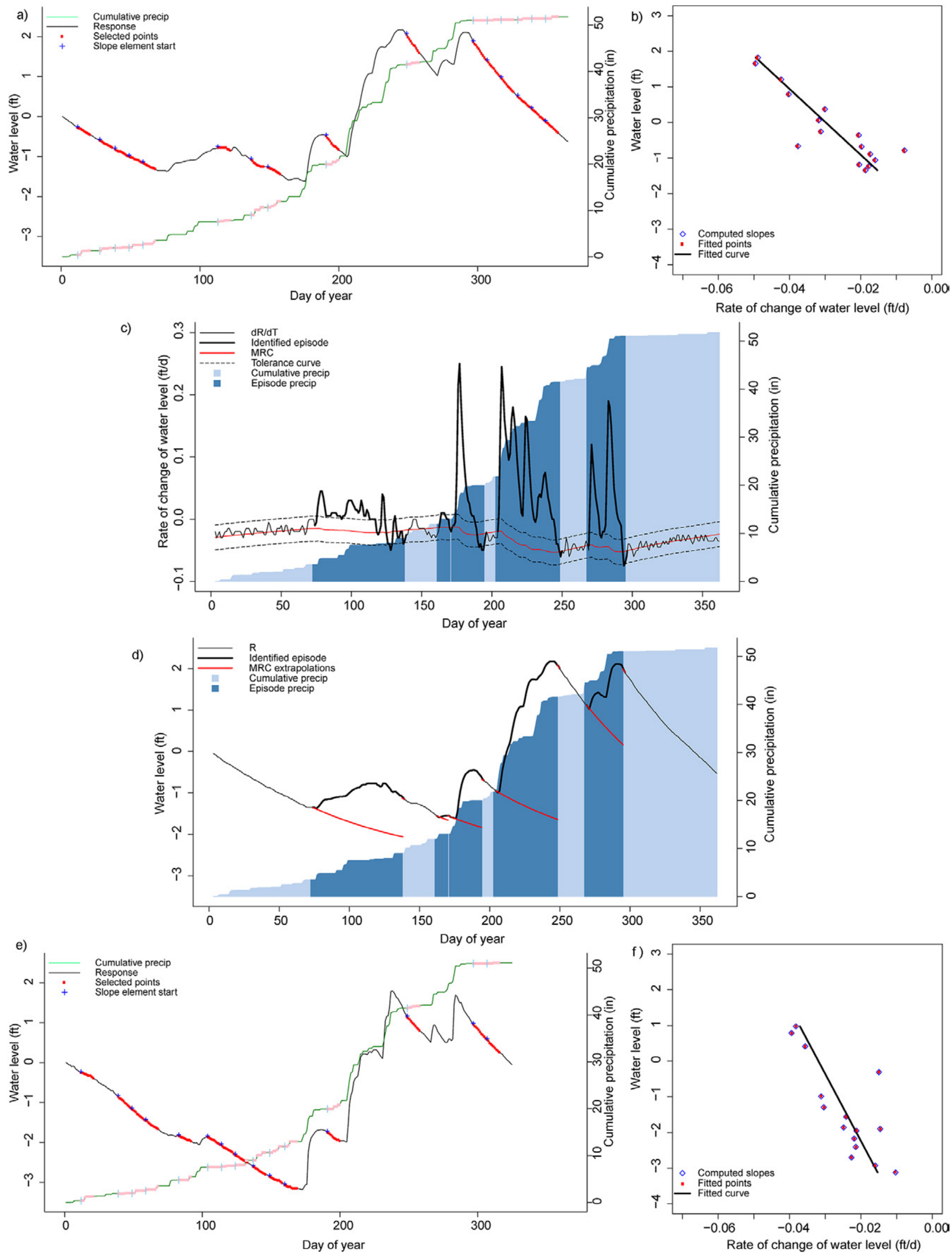


Fig. 5. Reedy Creek water levels in three wells, shown by a threefold repetition of the pattern used for Fig. 2 and 4: the designated slope elements, the master recession curve (MRC), the time derivative of the hydrograph, and the hydrograph with designated episodes for (a–d) the intermediate well SW16, (e–h) the shallow well EW11-4, and (i–l) the deep well SW4 (1 ft = 0.3048 m; 1 in = 25.4 mm).

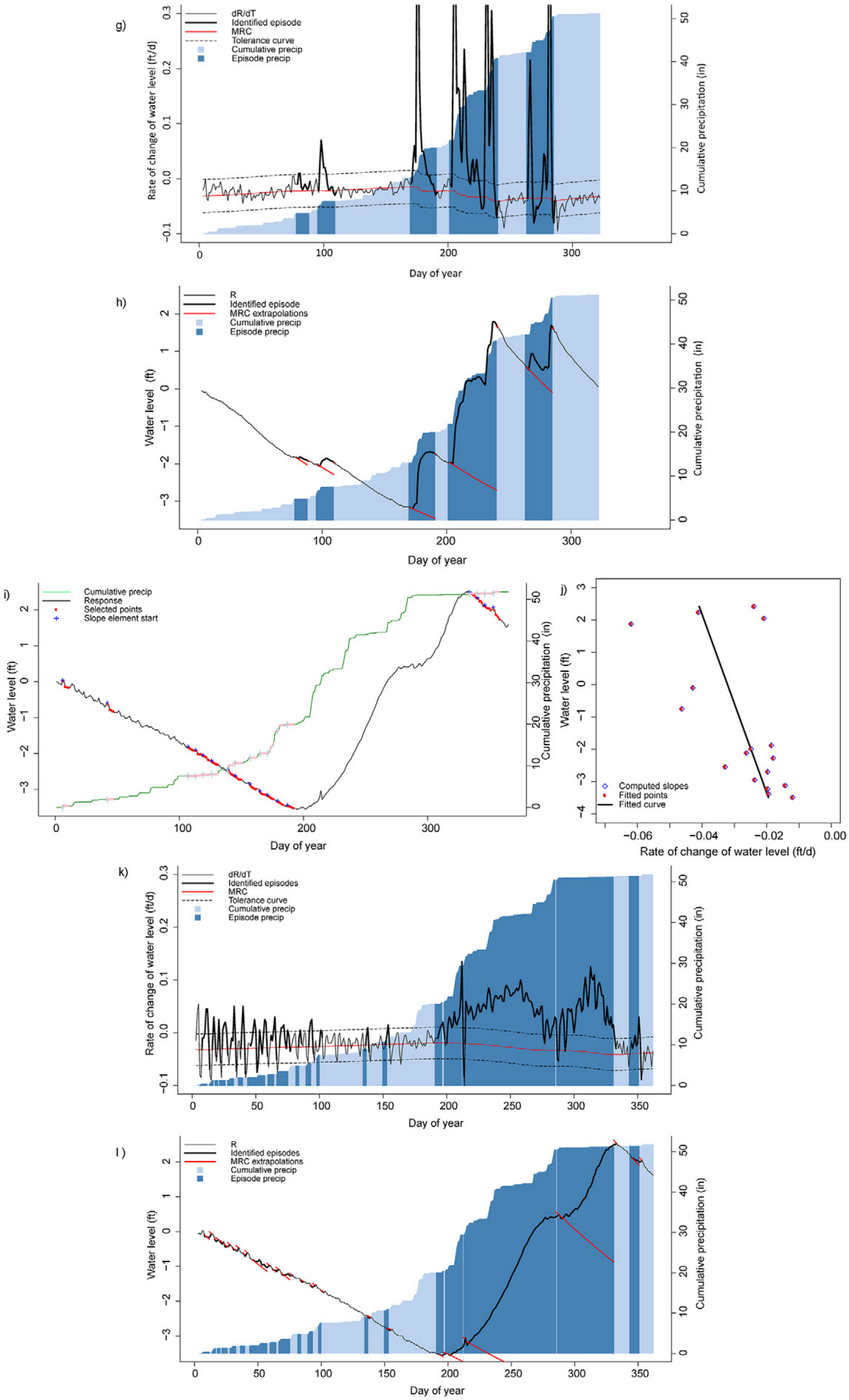


Fig. 5. Continued

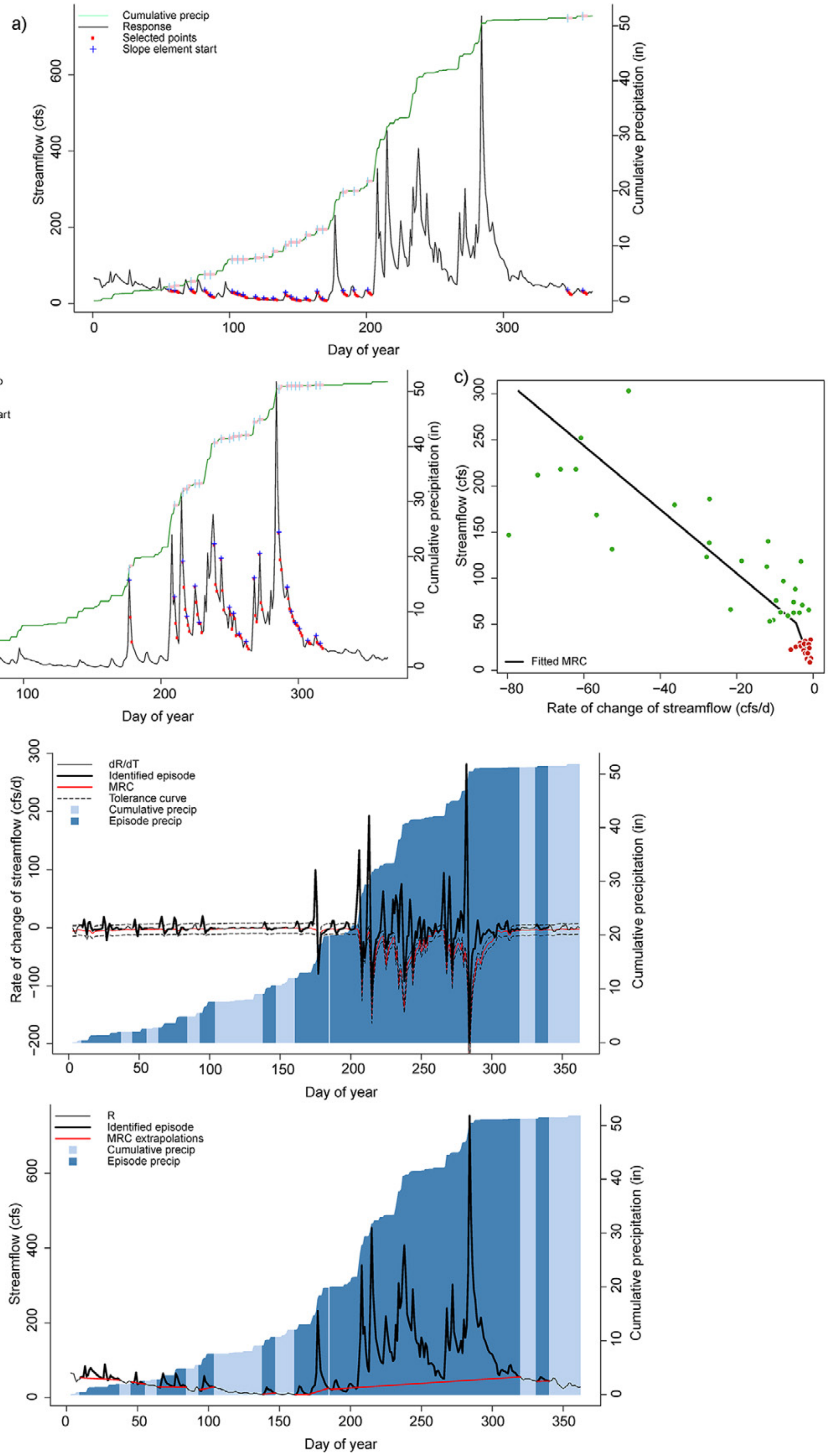


Fig. 6. Reedy Creek streamflow: (a) the hydrograph with cumulative precipitation and slope elements selected for the baseflow-related segment of the master recession curve (MRC); (b) the hydrograph and precipitation with slope elements selected for the stormflow-related segment of the MRC; (c) values of the hydrograph slope (red for low flow and green for high flow) and the two-part fitted MRC; (d) the time derivative of the hydrograph for discerning recharge episodes; and (e) the hydrograph with episodes distinguished: the red lines connect the starting and ending points of each episode to approximately separate baseflow from stormflow (1 cfs = 2446.6 m^3/d; 1 in = 25.4 mm).

Table 13. Comparable episode clusters for Shale Hills. Episodes (W for water table and Q for streamflow) were selected for clustering based on nearly equivalent precipitation contributing to both recharge and stormflow. Values in Columns 3 to 7 are based on summations of each cluster's episodes. Total episode output is the sum of recharge and stormflow per unit area for each cluster pair. Ratio of ratios is the RPR divided by the SPR; greater values imply a greater effectiveness for recharge generation than for stormflow generation for the given precipitation.

Cluster	Episodes	Precipitation	Change in water level	Change in stormflow	Recharge or stormflow per area	RPR or SPR†	Avg. precipitation	Episode output	RPR/SPR ratio
		mm	m	m^3/d	mm		mm	mm	mm
1	W4–5	12.0	0.20		9.9	0.827	12.2	21.5	0.89
	Q1	12.4		916	11.6	0.934			
2	W10–11	41.9	0.34		16.8	0.401	41.7	32.6	1.05
	Q4–5	41.4		1246	15.8	0.381			
3	W12–13	56.1	0.40		19.8	0.353	57.4	41.7	0.95
	Q6	58.7		1730	21.9	0.373			
4	W14	29.7	0.24		12.2	0.409	29.7	16.7	2.71
	Q7	29.7		355	4.5	0.151			
5	W19	21.9	0.36		18.1	0.827	21.8	42.1	0.75
	Q10	21.8		1900	24.1	1.101			
6	W20	14.0	0.02		1.1	0.078	13.8	1.2	9.23
	Q11	13.7		9	0.1	0.008			
7	W21	36.8	0.14		7.0	0.189	36.6	7.6	11.32
	Q13	36.3		48	0.6	0.017			
8	W22	56.1	0.20		10.1	0.179	56.6	13.5	2.98
	Q14–16	57.2		271	3.4	0.060			

† RPR, recharge/precipitation ratio; SPR, stormflow per watershed area/precipitation ratio.

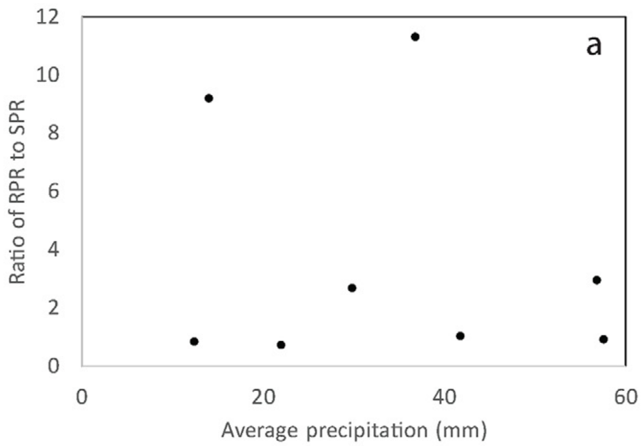
also worth further investigation, that might be hard to recognize without the sort of analysis the EMR method supplies.

Another apparent behavior of the deep well is that its small-magnitude rapid responses do not occur during the rising limb (Fig. 5l). Regardless of where the water comes from to cause the rise, a probable cause is the hysteresis effects associated with a falling (from near-complete saturation) rather than rising (into a zone of unsaturation) water table. The moisture state of the unsaturated material above the declining water table is on the main drainage branch of the hysteretic water retention relation. On this branch, it can remain very near saturation even as the water table has fallen some distance below, so that a very small contribution of additional water can quickly cause significant re-saturation through a significant vertical distance and an attendant water table rise. During a long-term rise of the water table, the wetting branch of the retention relation applies, which means that material above the water table remains distinctly unsaturated until the water table has come very near. Thus, there is nothing resembling a capillary fringe, and it would be necessary to overcome the unsaturated conditions before registering a rapid short-term increase in the rate of rise. Development of a new form of the master recession function that explicitly incorporates soil-water hysteresis could more directly explain and account for these effects. This phenomenon also suggests that a gradually declining water table in a granular medium could be a sensitive detector of preferential flow by registering abrupt rises when preferentially transported water arrives at the water table.

Further analysis of quantitative results such as episode timing, recharge evaluation, MRC slopes and intercepts, optimized values of the judgment parameters, and others has potential to provide more value to hydrologic understanding and water-resource management.

Episodicity Quantified by a Parameterized Master Recession Curve

Parametric forms of the MRC are ultimately of empirical character because hydrologic processes are complex and involve multiple mechanisms. When a known mechanism or group of similar mechanisms dominates the recession of the hydrograph, however, a particular functional form can be applied with some theoretical justification. The exponential hydrograph decline deriving from a linear fit to the rate of change is appealing because it says that the loss rate of a stored quantity is proportional to the amount in storage, as is reasonable in many physical processes. Besides this degree of theoretical support, this linear reservoir model has considerable versatility. A special case is a constant recession rate, for situations as described by Cuthbert (2014); the MRC is then a one-parameter fit, a vertical line positioned at the average of slope values computed by MRCfit. Another special case is the fit forced to go through the origin or other designated point, a one-parameter fit in which only the slope parameter is nonzero. Such forcing is particularly useful for streamflow, in order that a zero flow rate corresponds to a zero recession rate, as apparent in Fig. 3c and 6c. Multipart segmented linear fits have obvious relevance when recessionary



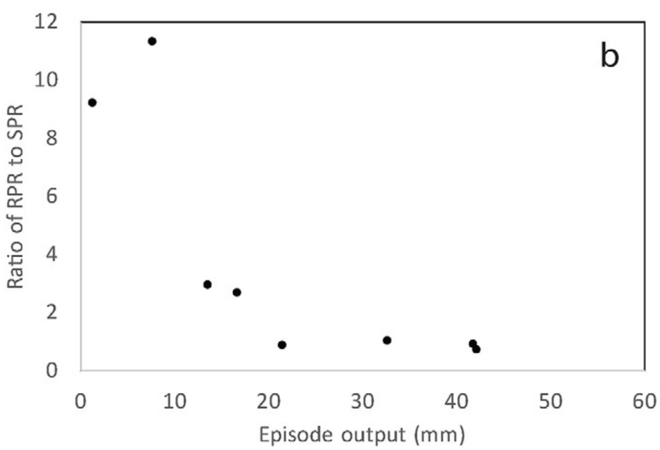


Fig. 7. Comparisons of calculated recharge and stormflow for comparable clusters of episodes in the episodic master recession results for the Shale Hills site, determined as the ratio of RPR (recharge) to SPR (stormflow) vs. average precipitation for each cluster pair (Table 13): (a) no significant trend with episode precipitation; (b) a tendency for stormflow to be reduced much more than recharge in cases where the precipitation events generate little of either.

processes are dominated by different media properties or different sets of mechanisms in different parts of the measured range, as has been demonstrated here for the contrasting layer properties at the Terminio well and the flow-rate-dependent recessionary mechanisms of the Shale Hills and Reedy Creek streamflow.

Strong reliance on the use of a MRC, basing hydrologic quantifications on changes in the hydrograph, is central to the EMR method, allowing it to provide information about episodic or time-varying processes. Attention to and determination of episodicity resulting from natural processes, as opposed to being limited to fixed-interval periodicities such as annual, seasonal, weekly, or hourly, can help to evaluate what is generated by individual inputs taken in their entirety. It opens new possibilities for hydrologic analyses on timescales appropriate to the actual events rather than fixed intervals determined independently.

Because it covers a continuous time record with alternating periods of significant and negligible episodic recharge, EMR estimates summed over a season, year, or other period of interest can indicate the total recharge or stormflow resulting from episodic processes during the chosen period. Especially for groundwater applications, however, exclusive reliance on such methods neglects steady components of the processes involved. Any water table fluctuation-based estimation of recharge, for example, is well known to exclude any steady component of recharging flux. Thus, if steady components are significant, they need to be estimated separately by a different method, such as steady-state Darcian analysis (Nimmo et al., 1994). In the case of streamflow, baseflow has a role analogous to the steady component of recharge. Baseflow, however, can be quantified by integration under the hydrograph separation lines and the hydrograph trace between episodes, so there is no need for an additional method.

Extension to Streamflow

The rate of change relative to an MRC is a useful concept not only for estimating recharge from a water-table hydrograph but also for estimating the total stormflow of individual input events, and other important quantifiers, from a streamflow hydrograph. Closely related MRC and EMR algorithms are applicable to different but analogous elements of the hydrologic system. The streamflow adaptation of these methods designed for groundwater hydrographs has some points of difference from the original methodology but retains the same fundamental principles and function.

Streamflow, unlike water-table level, is already a rate. The water transmitted downstream by streamflow during a specified time interval is given as a volume. It can alternatively be expressed in dimensions of length, as for water level, by dividing by a relevant measured area, such as the area of the catchment that supplies water to the stream, or the area of a surface water reservoir to indicate a change in water depth.

In traditional applications of streamflow hydrographs, additional quantitative empirical assumptions (e.g., Eq. [1], [2], and [8] of Rutledge, 1998) are often applied for use in the calculation of recharge and discharge between surface- and groundwater. Although we do not attempt here to estimate aquifer recharge from streamflow, such estimations could be done with these methods, with EMR determinations serving in place of some of the more traditional empiricisms. For example, in place of a specific quantity empirically determined from analyses of historical hydrographs (typically for large watersheds with large time increments) to determine the minimum persistence of a trend, EMR applies fixed rules (Table 3) and data-derived parameter values. This replacement of presumptively universal quantities with quantified features of the hydrographs under investigation may strengthen the physical basis of the analysis and improve accuracy by tailoring the results to the investigated site.

A feature deriving from the original application to water-table hydrographs is the treatment of streamflow primarily on a linear rather than logarithmic scale. For water tables there is little reason to do otherwise, as the water table moves up and down within a limited range of response. Because it is the relative change in water level that is important, measurement from an arbitrary reference level is legitimate, as are negative values of the response variable. For streamflow there are several reasons logarithmic portrayals are often used, including the facilitation of certain hydrologic interpretations (Kirchner, 2009), the practical accommodation of streamflow across many orders of magnitude, and the ability to immediately visualize the degree of conformance to linear-reservoir behavior. Because streamflow does not become less than zero, the log-of-a-negative problem does not occur. The EMR and MRC programs can be applied to logarithmic data simply by replacement of response data with the logarithms of the response data in the input file. Linear treatment has advantages, however, especially because hydrologic processes related to the transfer of water from one category to another (e.g., groundwater to or from surface water) are fundamentally additive, not multiplicative. For these, the linear scale is more directly representative of physical processes. Hydrograph examination on a linear scale, alone or supplementary to a logarithmic scale, can facilitate the development of quantitative understanding; for example, the visual assessment of areas under a curve can be directly connected to flow volumes of different stormflow episodes.

Value and Future Development

With hydrograph slope evaluation as their underlying basis, the MRC and EMR methods serve to automate and systematize the determination of major end-use hydrologic values such as recharge and discharge, while quantifying and documenting the judgments needed to do so. The hydrograph slope and other characteristics can be difficult to ascertain from measured data, and our methods facilitate and reduce the effort of doing so. Hydrograph analysis is made easier and more efficient even with long data sets of high temporal resolution. Besides the efficiency afforded by the degree of automation in these methods, a major benefit is that they can provide interpretational consistency throughout the evaluation of a large dataset, such that events at two different times can be meaningfully compared. Another advantage of EMR over earlier methods is that it works with data sets of any degree of time resolution, including the very fine time resolutions needed for applicability to small watersheds.

Issues of judgment and subjectivity always arise in going from a large set of raw data to valid interpretations; the need for judgments provided by a knowledgeable hydrologist can be minimized but not eliminated. Automation, with the influence of hydrologic judgment introduced in only a few ways that are specific, quantifiable, and applicable across the entire input dataset, is an important tool for limiting the role of subjectivity. Another important element is to parameterize judgments to the extent possible. This does not make them objective but reduces the effect of subjectivity in several ways. Notably, it confines judgments to particular specified realms and improves transparency by creating a record of the judgments made.

The MRCfit code serves as a convenience, although it also provides greater rigor and consistency than less systematic methods of determining the values of a parametric function to represent an MRC. Its product is a parameterized MRC, a very useful, though essentially artificial, hydrologic characteristic. Because of this utilitarian character, the algorithms in MRCfit do not need as high a standard of rigor as those in the EMR programs with their more end-use-directed products. Accordingly, as can be seen in Tables 2 and 4, MRCfit provides a wide array of adjustable options to produce better-fitting results, whereas EMR has fewer, but they are more physically meaningful.

The multisegment MRC used in several presented case studies in effect represents a series of linear reservoir behaviors that differ for different ranges of hydrograph response. It is useful for assessing streamflow subject to ongoing baseflow in addition to stormflow and other processes that become activated under certain conditions. For water-table hydrographs, it can represent changes in hydraulic properties when the water table moves past a layer transition.

These tools have application for various purposes beyond the original objective of aquifer recharge. In surface-water evaluations and trends, for example, they can facilitate and regularize consistent determinations of times and magnitudes of streamflow responses and start and end times of particular events. Another application, now in development, is in using soil water content hydrographs to evaluate preferential flow and its effect on infiltration–runoff and subsurface stormflow. To address large-scale issues, they could be formulated into specific-process modules connectable to regional- or continental-scale water models. As users of these tools gain more experience with diverse datasets, the knowledge obtained in doing so can help in developing a next-generation set of tools that incorporate codified guidelines that put the iterative procedures onto a more fully automated basis.

Further information, including R-language codes, user instructions, guidelines for parameter adjustments, and auxiliary programs to facilitate construction of input data files, are available at https://wwwrcamnl.wr.usgs.gov/uzf/EMR_Method/EMR.method.html, to be updated with future developments.

Conclusions

Rate-of-change based analysis tools using a master recession curve can be beneficially applied to different types of hydrographs, as shown here for water tables and streamflow. These tools have important potential applications for diverse hydrologic quantities, including aquifer recharge, preferential flow, and stormflow characterization. The determination of a parameterized MRC through a structured procedure provides a basis for quantification of hydrologic variables and characteristics that can be validly compared among different events, sites, and periods of time. Episodic master recession and associated methods provide means to evaluate long-term hydrographs to discern and illuminate trends with storm characteristics, seasons, soil conditions, and other factors.

Through their self-consistency and their conformance to interpretable, largely expected, hydrologic behaviors, the results as seen in Fig. 2 through 7 and Tables 5 to 13 support the underlying assumptions of the revised MRC and EMR methods, as well as demonstrating their utility and practical advantages. The combined analysis of streamflow and groundwater hydrographs using essentially the same algorithms can provide new insights into the active hydrologic processes. Examples include:

1. At the Shale Hills Critical Zone Observatory, the relative magnitudes of recharge and stormflow based on water inputs from individual storms can be determined. The analyses presented here illustrate a proof-of-concept for combined recharge–stormflow analysis. A result from the examined 7-mo data record is that in episodes subject to effects that limit both recharge and stormflow, stormflow is relatively much more curtailed than recharge. If applied to a multiyear dataset with many episodes, the EMR method could potentially support generalizations about the recharge and stormflow effects of variation in season and in storm characteristics such as magnitude, intensity, and duration.
2. At the Acqua della Madonna test area (Terminio), the analysis demonstrated the applicability of a multistage linear-reservoir model of the recession characteristic to account for layer contrasts in hydraulic properties. With additional hydrogeologic information, it might be possible to derive a relationship between MRC parameters and more standard measurable hydraulic properties.
3. In the Reedy Creek watershed, the EMR method clearly discerned quantifiable recharge and stormflow episodes during wintertime even though previous published analyses had concluded there were no such responses during the same interval. The numerical derivative-based algorithm of EMR gives it heightened sensitivity to these small-magnitude episodes. The water-table analyses revealed the additional surprising fact that, of three wells analyzed, only the deepest (26 m below the land surface) registered the small-recharge episodes.

In implementation, these are expert-guided iterative evaluation methods, to serve as an alternative or supplement to methods of more fully manual or fully automatic evaluation. Various approaches can get important answers out of large datasets, although always with some element of subjectivity, whether it enters into the evaluation through event-by-event decisions, through the choices made in the coding of computerized algorithms, or through a structured iterative process as we present here. The MRC and EMR approaches afford much flexibility in formulating expert judgments and serve to confine the judgments to statements and procedures that can be quantified and documented.

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References

Abo, R.K., and B.J. Merkel. 2015. Investigation of the potential surface–groundwater relationship using automated base-flow separation techniques and recession curve analysis in Al Zerba region of Aleppo, Syria. Arab. J. Geosci. 8:10543–10563. doi:10.1007/s12517-015-1965-6

Allocca, V., F. Celico, E. Petrella, G. Marzullo, and G. Naclerio. 2008. The role of land use and environmental factors on microbial pollution of mountainous limestone aquifers. Environ. Geol. 55:277–283. doi:10.1007/s00254-007-1002-5

Allocca, V., P. De Vita, F. Manna, and J.R. Nimmo. 2015. Groundwater recharge assessment at local and episodic scale in a soil mantled perched karst aquifer in southern Italy. J. Hydrol. 529:843–853. doi:10.1016/j.jhydrol.2015.08.032

Appels, W.M., A.E. Coles, and J.J. McDonnell. 2018. Infiltration into frozen soil: From core-scale dynamics to hillslope-scale connectivity. Hydrol. Processes 32:66–79. doi:10.1002/hyp.11399

Arnold, J.G., and P.M. Allen. 1999. Automated methods for estimating baseflow and ground water recharge from streamflow records. J. Am. Water Resour. Assoc. 35:411–424. doi:10.1111/j.1752-1688.1999.tb03599.x

Bhaskar, A.S., D.M. Hogan, J.R. Nimmo, and K.S. Perkins. 2018. Groundwater recharge amidst focused stormwater infiltration. Hydrol. Processes 32:2058–2068. doi:10.1002/hyp.13137

Blume, T., E. Zehe, and A. Bronstert. 2007. Rainfall–runoff response, event-based runoff coefficients and hydrograph separation. Hydrol. Sci. J. 52:843–862. doi:10.1623/hysj.52.5.843

Crosbie, R., J. McCallum, G. Walker, and F. Chiew. 2012. Episodic recharge and climate change in the Murray-Darling Basin, Australia. Hydrogeol. J. 20:245–261. doi:10.1007/s10040-011-0804-4

Cuthbert, M.O. 2014. Straight thinking about groundwater recession. Water Resour. Res. 50:2407–2424. doi:10.1002/2013WR014060

Cuthbert, M.O., and C. Tindimugaya. 2011. The importance of preferential flow in controlling groundwater recharge in tropical Africa and implications for modelling the impact of climate change on groundwater resources. J. Water Clim. Change 1:234–245. doi:10.2166/wcc.2010.040

Elsenbeer, H., and R.A. Vertessy. 2000. Stormflow generation and flowpath characteristics in an Amazonian rainforest catchment. Hydrol. Processes 14:2367–2381. doi:10.1002/1099-1085(20001015)14:14<2367::AID-HYP107>3.0.CO;2-H

Halford, K.J. 2007. [Comment on] Update on the use of the RORA program for recharge estimation. Groundwater 46:10–11. doi:10.1111/j.1745-6584.2007.00392_1.x

Halford, K.J., and G.C. Mayer. 2000. Problems associated with estimating ground water discharge and recharge from stream-discharge records. Groundwater 38:331–342. doi:10.1111/j.1745-6584.2000.tb00218.x

Healy, R.W., and P.G. Cook. 2002. Using groundwater levels to estimate recharge. Hydrogeol. J. 10:91–109. doi:10.1007/s10040-001-0178-0

Heppner, C.S., and J.R. Nimmo. 2005. A computer program for predicting recharge with a master recession curve. Sci. Invest. Rep. 2005-5172. USGS, Reston, VA. doi:10.3133/sir20055172

Hewlett, J.D., and A.R. Hibbert. 1967. Factors affecting the response of small watersheds to precipitation in humid areas. In: W.E. Sopper and H.W. Lull, editors, Forest hydrology. Pergamon Press, New York. p. 275–290.

Hornbeck, J.W. 1973. Storm flow from hardwood-forested and cleared watersheds in New Hampshire. Water Resour. Res. 9:346–354. doi:10.1029/WR009i002p00346

Kirchner, J.W. 2009. Catchments as simple dynamical systems: Catchment characterization, rainfall–runoff modeling, and doing hydrology backward. Water Resour. Res. 45:W02429. doi:10.1029/2008WR006912

Koch, J.C., S.A. Ewing, R. Striegl, and D.M. McKnight. 2013. Rapid runoff via shallow throughflow and deeper preferential flow in a boreal catchment underlain by frozen silt (Alaska, USA). Hydrogeol. J. 21:93–106. doi:10.1007/s10040-012-0934-3

Lewis, M.F., and G.R. Walker. 2002. Assessing the potential for significant and episodic recharge in southwestern Australia using rainfall data. Hydrogeol. J. 10:229–237. doi:10.1007/s10040-001-0172-6

Lin, H., and X. Zhou. 2008. Evidence of subsurface preferential flow using soil hydrologic monitoring in the Shale Hills catchment. Eur. J. Soil Sci. 59:34–49. doi:10.1111/j.1365-2389.2007.00988.x

Nasta, P., Z. Adane, N. Lock, A. Houston, and J.B. Gates. 2018. Links between episodic groundwater recharge rates and rainfall events classified according to stratiform-convective storm scoring: A plot-scale study in eastern Nebraska. Agric. For. Meteorol. 259:154–161. doi:10.1016/j.agrformet.2018.05.003

Nathan, R.J., and T.A. McMahon. 1990. Evaluation of automated techniques for base flow and recession analyses. Water Resour. Res. 26:1465–1473. doi:10.1029/WR026i007p01465

Nimmo, J.R., C. Horowitz, and L. Mitchell. 2015. Discrete-storm water-table fluctuation method to estimate episodic recharge. Groundwater 53:282–292. doi:10.1111/gwat.12177

Nimmo, J.R., D.A. Stonestrom, and K.C. Akstin. 1994. The feasibility of recharge rate determinations using the steady-state centrifuge method. Soil Sci. Soc. Am. J. 58:49–56. doi:10.2136/sssaj1994.03615995005800010007x

O'Reilly, A.M. 1998. Hydrogeology and simulation of the effects of reclaimed-water application in west Orange and southeast Lake counties, Florida. Rep. 97-4199. USGS, Reston, VA. http://pubs.er.usgs.gov/publication/wri974199.

R Core Team. 2016. R: A language and environment for statistical computing. R Found. Stat. Comput., Vienna. https://www.R-project.org/

Rathay, S.Y., D.M. Allen, and D. Kirste. 2018. Response of a fractured bedrock aquifer to recharge from heavy rainfall events. J. Hydrol. 561:1048–1062. doi:10.1016/j.jhydrol.2017.07.042

Rutledge, A.T. 1998. Computer programs for describing the recession of ground-water discharge and for estimating mean ground-water recharge and discharge from streamflow records: Update. Water-Resour. Invest. Rep. 98-4148. USGS, Reston, VA. http://pubs.er.usgs.gov/publication/wri984148.

Rutledge, A.T. 2000. Considerations for use of the RORA program to estimate ground-water recharge from streamflow records. Rep. 2000-156. USGS, Reston, VA. doi:10.3133/ofr00156

Rutledge, A.T. 2006. Basic concepts for the linear model of ground water level recession. Groundwater 44:483–487. doi:10.1111/j.1745-6584.2005.00157.x

Rutledge, A.T. 2007. Update on the use of the RORA program for recharge estimation. Groundwater 45:374–382. doi:10.1111/j.1745-6584.2006.00294.x

Rutledge, A. 2008. Author's reply. Groundwater 46:11–12. doi:10.1111/j.1745-6584.2007.00392_2.x

Rutledge, A.T., and C.C. Daniel III. 1994. Testing an automated method to estimate ground-water recharge from streamflow records. Groundwater 32:180–189. doi:10.1111/j.1745-6584.1994.tb00632.x

Shanley, J.B., and A. Chalmers. 1999. The effect of frozen soil on snowmelt runoff at Sleepers River, Vermont. Hydrol. Processes 13:1843–1857. doi:10.1002/(SICI)1099-1085(199909)13:12/13

Smith, B., and S. Schwartz. 2017. Automating recession curve displacement recharge estimation. Groundwater 55:81–87. doi:10.1111/gwat.12439

Tallaksen, L.M. 1995. A review of baseflow recession analysis. J. Hydrol. 165:349–370. doi:10.1016/0022-1694(94)02540-R

Tang, W., and S.K. Carey. 2017. HydRun: A MATLAB toolbox for rainfall–runoff analysis. Hydrol. Processes 31:2670–2682. doi:10.1002/hyp.11185

Tashie, A.M., B.B. Mirus, and T.M. Pavelsky. 2016. Identifying long-term empirical relationships between storm characteristics and episodic groundwater recharge. Water Resour. Res. 52:21–35. doi:10.1002/2015WR017876

Thomas, B., A. Behrangi, and J. Famiglietti. 2016. Precipitation intensity effects on groundwater recharge in the southwestern United States. Water 8(3):90. doi:10.3390/w8030090

Voss, C. 2011. Editor's message: Groundwater modeling fantasies—Part 2, Down to earth. Hydrogeol. J. 19:1455–1458. doi:10.1007/s10040-011-0790-6

Winter, T.C. 1983. The interaction of lakes with variably saturated porous media. Water Resour. Res. 19:1203–1218. doi:10.1029/WR019i005p01203

Winter, T.C., J.W. Harvey, L.O. Franke, and W.M. Alley. 1998. Ground water and surface water: A single resource. Circ. 1139. USGS, Reston, VA.

Zhang, L., W.R. Dawes, T.J. Hatton, I.H. Hume, M.G. O'Connell, D.C. Mitchell, et al. 1999. Estimating episodic recharge under different crop/pasture rotations in the Mallee region: 2. Recharge control by agronomic practices. Agric. Water Manage. 42:237–249. doi:10.1016/S0378-3774(99)00034-7