Two Digital Filters for Hydrograph Separation with the Hydrologic Toolbox

Version 1.1.0 Release
(Version 1.1.0 update: see yellow highlighted text on page 15)

Two digital-filtering techniques for hydrograph separation are provided in the Hydrologic Toolbox version 1.0 release. The techiques filter the high-frequency signals in the streamflow record associated with surface runoff from the low-frequency signals associated with groundwater discharge as base flow. The techiques are (1) a single-parameter digital filter originally described by Nathan and McMahon (1990) and implemented in the 'SWAT Bflow' computer program by Arnold and others (1995) and Arnold and Allen (1999) and (2) a two-parameter digital filter originally developed by Eckhardt (2005) and later implemented in a computer program described in Eckhardt (2008). The techniques are referred to in the Hydrologic Toolbox as the 'DF-One Param' and 'DF-Two Param' approaches. Each of the two computer programs was reprogrammed from its original Fortran language into the Visual Basic.Net language within Microsoft Visual Studio .NET.

Examples of the use of one or both of the two digital-filtering methods for the analysis of field data are provided in Nathan and McMahon (1990), Arnold and others (1995), Mau and Winter (1997), Arnold and Allen (1999), Arnold and others (2000), Eckhardt (2005, 2008), Lim and others (2005), Neff and others (2005), Gonzales and others (2009), Zhang and others (2011), Partington and others (2012), Collischonn and Fan (2013), Rimmer and Harmann (2014), and Miller and others (2016). Lim and others (2005) provide versions of the two filtering techniques as part of an online hydrograph analysis tool (https://engineering.purdue.edu/mapserve/WHAT/).

This document describes the two digital-filtering techniques, approaches for estimating the parameters for each method, and implementation and use of the techniques in the Hydrologic Toolbox.

The USGS thanks Dr. Jeffrey Arnold and Nancy Sammons, U.S. Department of Agriculture, Agricultural Research Service, and Dr. Klaus Eckhardt, Hochschule Weihenstephan-Triesdorf, Weidenbach, Germany, for use of their digital-filtering software in the Hydrologic Toolbox.

Digital Filters

The single-parameter digital filter can be written in terms of base flow as

$$b_k = \alpha b_{k-1} + \frac{1-\alpha}{2}(y_k + y_{k-1}) \,, \qquad (1)$$

subject to $b_k \leq y_k$. In equation 1, b_k and b_{k-1} are base flow (units of volume per time) at time steps k and $k-1$, respectively; α is the filter parameter (dimensionless); and y_k and y_{k-1} are total streamflow (units of volume per time) at time steps k and $k-1$, respectively. In the original Bflow software, the filter is passed over the streamflow record three times (forward in time, backward in time, and forward in time) and the results of all three passes are written to an output file. The number of passes over the streamflow data determines the degree of smoothing of the base-flow hydrograph and, in general, the calculated amount of base flow decreases with each pass (Arnold and others, 1995). Although the original Bflow program completes three passes, Arnold and others (1995) recommend that in the absence of site-specific data to the contrary, a default value of only one filter passs be used; the second and third passes tend to yield relatively low values of base flow. In Bflow, calculated values of daily base flow (b_k) cannot exceed daily streamflow (y_k); calculated base flow also cannot be less than zero. The value of base flow on the first day of analysis for the first filter pass is taken to be half the streamflow for that day. Typical values for the filter parameter α are in the range 0.90 to 0.95, with a value of 0.925 often found to be most appropriate (Nathan and McMahon, 1990; Chapman, 1991).

The two-parameter digital filter is written as

$$b_k = \frac{(1-BFI_{max})ab_{k-1}+(1-a)BFI_{max}y_k}{1-aBFI_{max}}, \qquad (2)$$

subject to $b_k \leq y_k$; where a is the base-flow recession constant (dimensionless), BFI_{max} is the maximum calculable long-term ratio of base flow to total streamflow for a given recession constant, and b_k, b_{k-1}, and $y_k$are defined for equation 1. The filter is passed over the streamflow record only once. Calculated values of b_k that are less than zero are set equal to $0.9 * BFI_{max} * y_k$; this equation also is used to calculate the initial value of base flow for the first day of analysis ($k = 1$). Eckhardt (2005) notes that the long-term ratio of base flow to total streamflow (that is, the base-flow index, or BFI) calculated by use of the two-parameter digital filter cannot exceed the value of BFI_{max} specified for a particular analysis; nevertheless, calculated values of BFI for relatively short periods of record or for particular months or seasons within a long-term record may exceed BFI_{max}.

The two filters are based on the assumptions that (1) total streamflow at each time step is equal to the sum of base flow and surface runoff and (2) groundwater discharge (outflow) from the aquifer as base flow is linearly proportional to storage within the aquifer. The linear-outflow assumption leads to the following relation between base flow at time steps k and $k-1$ during periods when surface runoff has ceased:

$$b_k = b_{k-1}e^{-\Delta t/\tau}, \qquad (3)$$

where Δt is the time-step length and τ is the characteristic time constant (Eckhardt, 2008). Because streamflow records that can be analyzed with the Hydrologic Toolbox have time-step lengths of 1 day, Δt is equal to 1 day; τ, therefore, has units of days (or days per log cycle, as described in the parameter-estimation section of this document). The characteristic time constant τ often is referred to in the literature by the symbol K; moreover, it is frequently referred to as the base-flow recesssion constant, as is parameter a. The relation between a and K can be shown by again considering periods of base-flow recession during which there are no surface-runoff contributions to streamflow. During these recession periods, the relation between base flow at time steps k and $k-1$ can be written in terms of a as

$$b_k = ab_{k-1} \, . \tag{4}$$

Combining equations 3 and 4 and redefining Δt and τ as 1 and K, respectively, the relation between parameters a and K can be written as either

$$a = e^{-1/K} \, . \tag{5}$$

or

$$K = \frac{-1}{\ln a} \, . \tag{6}$$

Whether expressed as a or K, the recession constant is a watershed-scale parameter that reflects the rate at which streamflow declines in the absence of groundwater recharge. As described in more detail below, typical values of K are on the order of 45 days; a, therefore, is typically on the order of 0.978.

Estimating Parameters for the Digital Filters

Single-parameter digital filter: The filter parameter α must be specified for use with the single-parameter digital-filtering technique. In practice, this parameter can be estimated from literature values or by a trial-and-error analysis in which the user varies the value of the filter parameter in repeated runs of the filtering program to obtain a satisfactory outcome of the base-flow separation process. Chapman (1991) showed that the filter defined by equation 1 incorrectly implies a constant rate of base flow after runoff has ceased, which is inconsistent with base-flow recession theory and observations. He derived an alternative single-parameter filter to address the limitations of equation 1 and noted that in his revised filter, parameter α was directly related to the base-flow recession constant a. In other words, the filter parameter α in equation 1 should not be taken as a direct estimate of the base-flow recession constant, and, in fact, the filter parameter will tend to have a value that is less than the base-flow recession constant. In a reply to Chapman's criticisms, Nathan and McMahon (1991) argued that although Chapman's proposed modification was preferred to equation 1, differences between base-flow rates estimated by use of equation 1 and those estimated by Chapman's alternative filter are in practice not appreciable, as long as the filter parameter in equation 1 is understood to have a value that is less than the base-flow recession parameter. Therefore, on the basis of the literature values reported for α cited above, a value equal to 0.925 is recommended for initial testing.

Two-parameter digital filter: Two parameters need to be estimated for the Eckhardt digital filter, the recession constant a and the maximum calculable long-term ratio of base flow to total streamflow for a given recession constant, BFI_{max}. The recession constant can be estimated by one of several methods described in the literature (see, for example, Hall, 1968; Brutsaert and Nieber, 1977; Nathan and McMahon, 1990; Tallaksen, 1995; Mau and Winter, 1997; Rutledge, 1998; and Brutsaert, 2008). The Hydrologic Toolbox provides two methods to estimate the recession constant, the RECESS method (Rutledge, 1998; Barlow and others, 2014) and a correlation method described in Eckhardt (2008). Because the recession constant calculated by the RECESS method is reported in days per log cycle (that is, as K), the user must convert the calculated values of K to the dimensionless form a by use of equation 5 before applying the digital filter to a streamflow record.

Eckhardt's correlation method follows the general approach initially described by Langbein (1938). In Eckhardt's implementation of the approach, daily mean values of streamflow (y_k) during periods of recession are plotted against daily mean values of streamflow for each day $k+1$ (y_{k+1}). The slope of the resulting line that passes through the origin of y_k versus y_{k+1} is taken to be the recession constant; that is, $y_{k+1} = ay_k$, or $a = y_{k+1}/y_k$. In Eckhardt's approach, only those streamflow values that meet a minimum criterion of 5 days of recession are included in the correlation. Further details of the method are described in Eckhardt (2008); implementation of the approach in the Hydrologic Toolbox is described below.

Methods for estimating parameter BFI_{max} are not as well established in the literature as those for estimating the recession constant. As a result, the process for selecting a particular value for BFI_{max} introduces subjectivity into the digital-filtering approach. Eckhardt suggests that values of BFI_{max} should reflect characteristic hydrologic and hydrogeologic conditions for classes of watershed types. On the basis of analyses of base flow for several streams in the United States and Germany, Eckhardt (2005) suggests as a first approximation values of BFI_{max} equal to 0.8 for perennial streams draining porous aquifers, 0.5 for ephemeral streams draining porous aquifers, and 0.25 for perennial streams draining hard-rock aquifers. Eckhardt (2005, 2008) also suggested that BFI_{max} might be estimated by calibration of results of the two-parameter digital filter to chemical or isotopic tracer data collected at a streamflow gage and adjoining aquifer. Such an approach has been taken by Gonzales and others (2009) using dissolved silica as the tracer and by Rimmer and Harmann (2014) using sulfate and total dissolved solids as tracers.

Collischonn and Fan (2013) have developed a backwards-filtering approach to estimate BFI_{max} that has been implemented in the Hydrologic Toolbox. The approach uses a streamflow record and an estimate of the recession constant for the watershed of interest. The approach is based on the assumption that during long periods of recession, groundwater discharge from the aquifer is linearly proportional to storage, such that the relation between b_k and b_{k-1} can be expressed by equation 4. Rearrangement of equation 4 provides an expression for base flow on day $k-1$ in terms of base flow for the current day k:

$$b_{k-1} = \frac{b_k}{a}, \qquad (7)$$

subject to $b_{k-1} < y_{k-1}$.

Equation 7 is the basis for the backwards filter, in which the base flow on each day of a period of record is calculated backwards in time. The approach requires that the streamflow record to be analyzed ends with a period of recession. As implemented in the Hydrologic Toolbox, the user selects a period of recession from which the backwards filter will begin. Streamflow on the last day of the recession is taken to be the initial value of baseflow. The filter then continues backward for a total of N days (the value of which is specified by the user); the first calculated value of base flow occurs on the day before the last day of recession. Each value of base flow is calculated from equation 7 as

$$b'_{k-1} = \frac{b'_k}{a}, \quad (8)$$

subject to $b'_{k-1} < y_{k-1}$. Primes are used for b'_{k-1} and b'_k to emphasize that the calculated base flows are made with the backwards filter. If the calculated value of base flow on a particular day is greater than or equal to streamflow on that day, the base flow is set equal to streamflow for that day.

The value of BFI_{max} is then found by dividing the sum of the calculated daily base-flow values by the sum of the daily streamflow values:

$$BFI_{max} = \frac{\sum_{k=1}^{N} b'_k}{\sum_{k=1}^{N} y_k} \ . \quad (9)$$

Collinshonn and Fan (2013) note that the value of BFI_{max} calculated by the backwards filter is the maximum value of the BFI that can be found with the specified recession constant.

Collinshonn and Fan (2013) applied their approach to 15 perennial streams that drain a wide range of porous and hard-rock aquifer types in south and central Brazil. The values of BFI_{max} calculated using their approach ranged from 0.25 to 0.51 for the hard-rock aquifers and 0.52 to 0.95 for the porous aquifers, a much wider range of values than those suggested by Eckhardt (2005; 0.25 for hard-rock aquifers and 0.80 for porous aquifers). Miller and others (2016) applied the approach to three streams in the Chesapeake Bay watershed. Recession constants (a) for each stream were estimated using the RECESS program and varied between 0.973 to 0.980 (K = 36.5 to 49.5 days); calculated values of BFI_{max} for the three streams ranged from 0.406 to 0.655. The method also was applied in a more recent study done in the Chesapeake Bay watershed by the USGS (Jeff Raffensperger, USGS, written commun. March 2017). In that study, recession constants were estimated using a simple algorithm based on rearrangement of equation 4 for periods of at least three days of base-flow recession. The resulting values of a ranged from 0.63 to 0.99 (K = 2.1 to 100 days), with a mean of 0.95 (K = 19.5 days), and with most values larger than 0.9, especially in watersheds larger than 100 mi^2. Calculated values of BFI_{max} ranged from 0.26 to 0.92, with a mean of 0.61; the range in BFI_{max} generally decreased with increasing watershed area.

Eckhardt (2012) derived sensitivity indices for a and BFI_{max} to evaluate the sensitivity of the calculated BFI to changes in each parameter. He found for 65 streamflow records within the Great Lakes region that on average the calculated BFI was nearly three times more sensitive to the specified value of a than that specified for BFI_{max}. Nevertheless, the sensitivity of BFI for a particular watershed may differ from these findings. Eckhardt's sensitivity indices are reported in an output file generated when using the filtering method in "Interactive" mode in the Hydrologic Toolbox; these indices can assist the user to better understand the relative importance of the two parameters to the calculated base-flow hydrograph.

Default Parameter Values Implemented in the Groundwater Toolbox

Default parameter values are provided in the Hydrologic Toolbox for the two digital-filtering techniques. These default values can be changed by the user.

For the single-parameter filter, a default value of 0.925 is provided, based on the literature values for α cited previously.

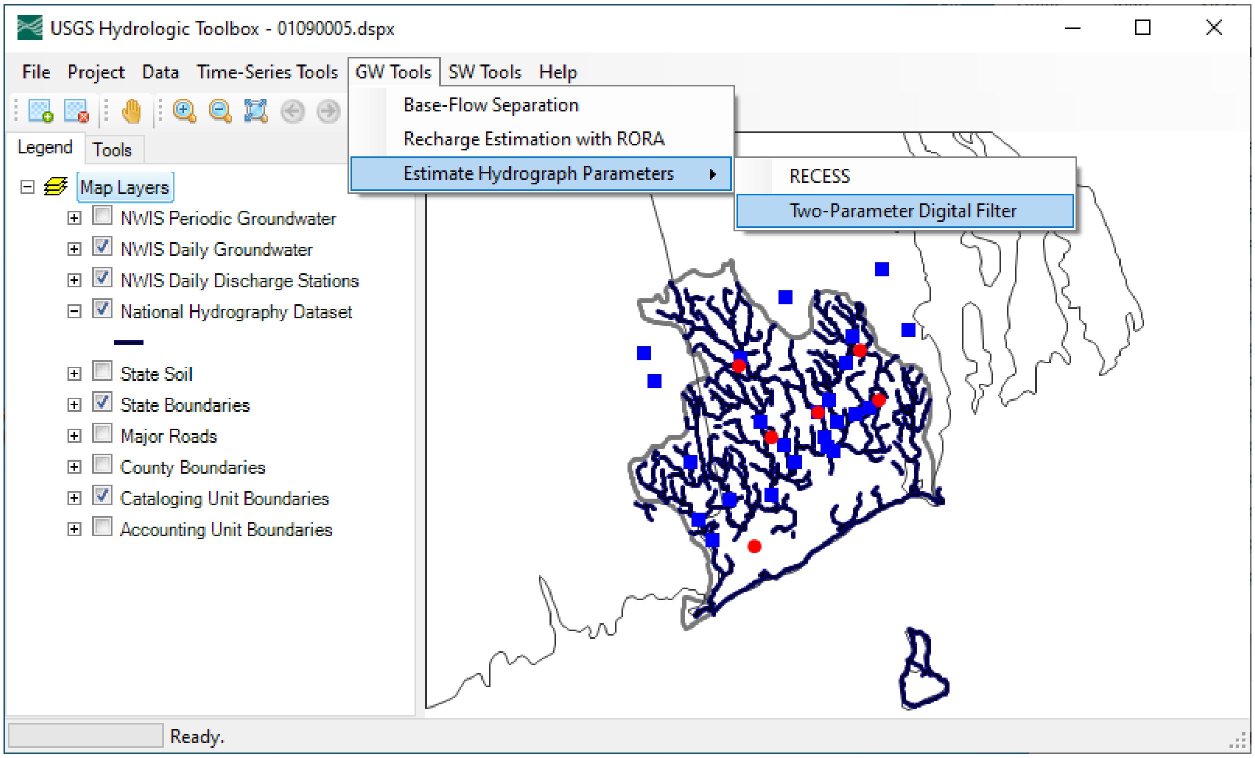
For the two-parameter filter, default values of 0.978 for the recession constant a and of 0.8 for BFI_{max} are provided. The value of a = 0.978 is equivalent to a K of 45 days. This value is based on the work of Brutsaert (2008, 2010, and 2012), who presents evidence that indicates that the recession constant tends to be relatively invariant for large river basins, and typically lies in the range 45 ± 15 days. The results of more recent studies by Sánchez-Murillo and others (2015) and Miller and others (2016) lend support to Brutsaert's findings. Although many authors report recession-constant values outside this typical range, the value of 45 days is used as a starting point for initial tests of the filter. The reader is encouraged to review the papers by Brutsaert, Sánchez-Murillo and others, and Miller and others, as well as the citations provided in those papers, for examples of recession constants estimated for a wide range of Hydrologic and hydrogeologic conditions. The default value provided for BFI_{max} (0.8) is based on Eckhardt's suggested value for perennial streams draining porous aquifers.

Implementation and Use of the Digital Filters in the Groundwater Toolbox

There are two components to the digital-filtering methods implemented in the Hydrologic Toolbox—estimating parameters for the two-parameter digital filter (the first part of this section) and using the digital filters within the base-flow separation functionality (the second part of this section). It is not necessary to do both components. If a user already has estimates for the parameters, then they can go directly to the base-flow separation functionality.

<u>Estimating Parameters for the Two-Parameter Digital Filter:</u>

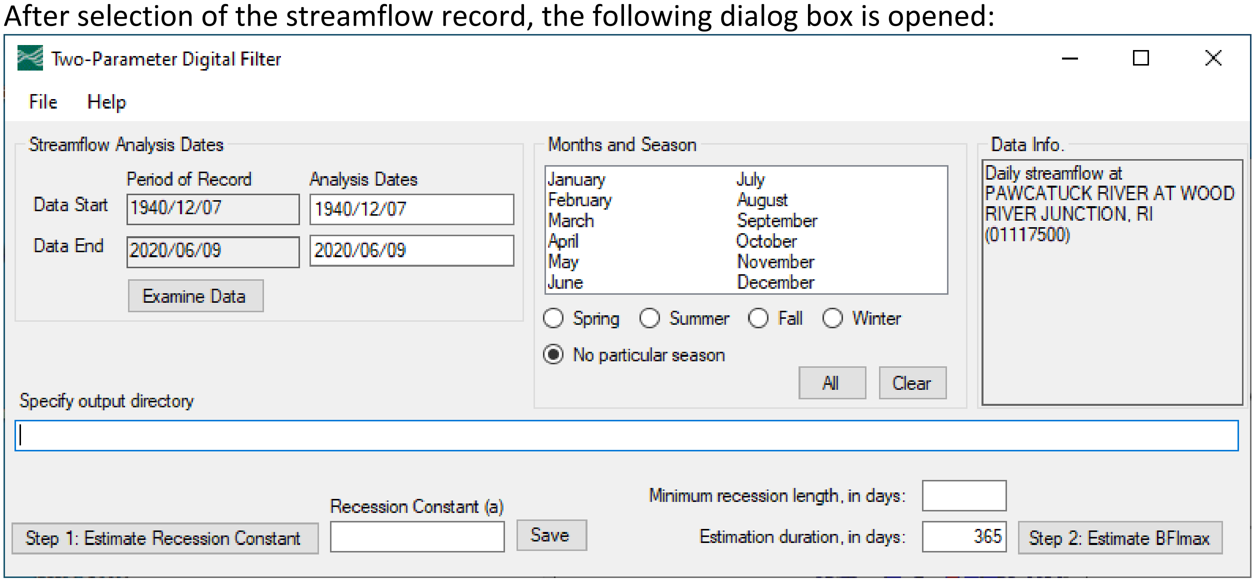
Two parameters must be estimated for the two-parameter digital filter: the recession constant, a, and the long-term maximum calculable ratio of base flow to total streamflow, BFI_{max}. The parameters can be estimated by use of the "**Two-Parameter Digital Filter**" functionality under the "**GW Tools>Estimate Hydrograph Parameters**" menu option:



Note that the recession constant also can be estimated separately by use of the "**RECESS**" functionality (see Barlow and others, 2014, as well as a separte tutorial titled "RECESS").

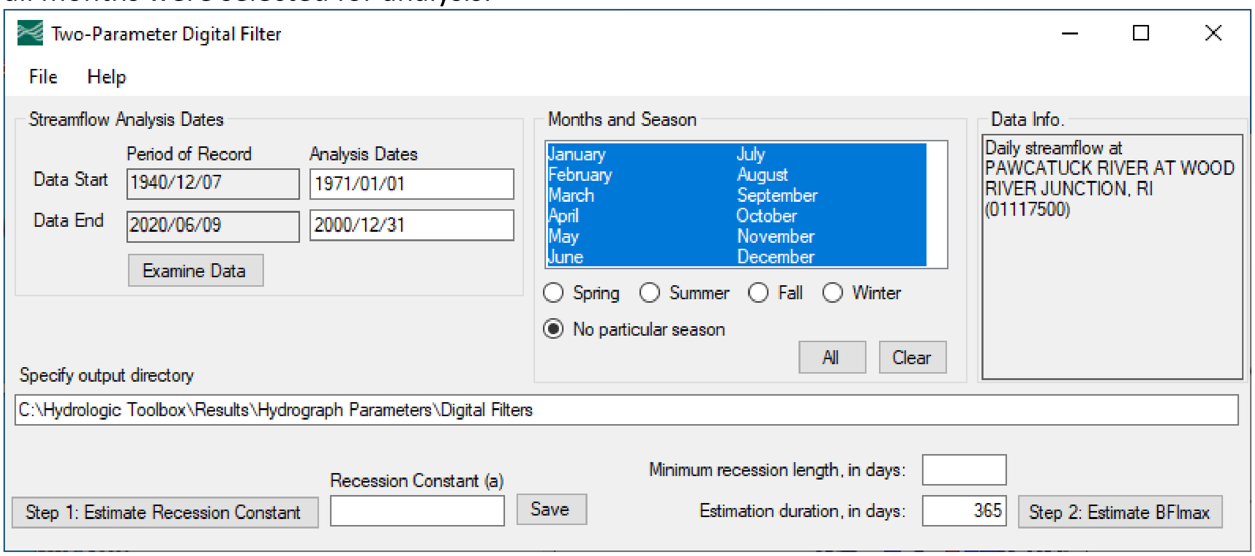
Selection of the "**Two-Parameter Digital Filter**" option takes the user to the "Select Daily Streamflow for Analysis" dialog box, where the user selects a streamflow record for analysis. For this analysis, the record for the Pawcatuck River at Wood River Junction, Rhode Island (USGS streamgage 01117500), was selected.

After selection of the streamflow record, the following dialog box is opened:

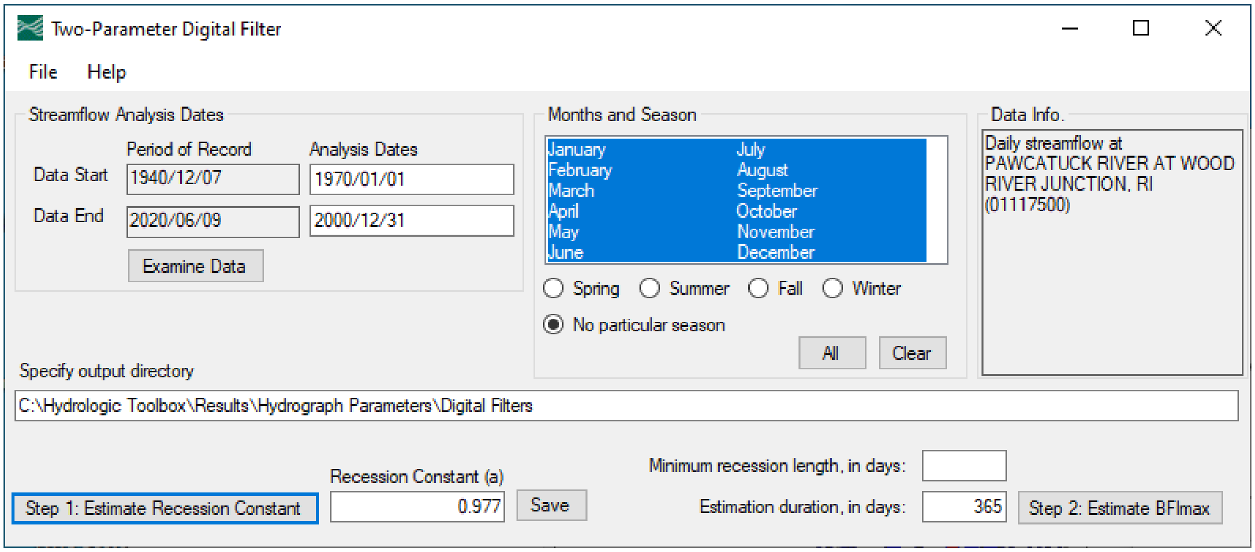


This is the first dialog box in the two-step process for estimating a and BFI_{max}. In the first step, the recession constant is either specified or estimated using the Eckhardt (2008) correlation method. In the second step, BFI_{max} is estimated.

The user must specify the following information in this first dialog box: The analysis dates, the months and season for analysis, and an output directory in which to save the results of the analysis. The "Examine Data" button can be used to identify continuous periods of analysis. For this analysis, the period January 1, 1971, through December 31, 2000, will be selected. The user can select specific months to analyze, such as the winter months December-March when evapotranspiration rates tend to be low in the basin, or all 12 months. The radio buttons below the "Months and Season" cell are simply used as an identifier in the output file. In this example, all months were selected for analysis:



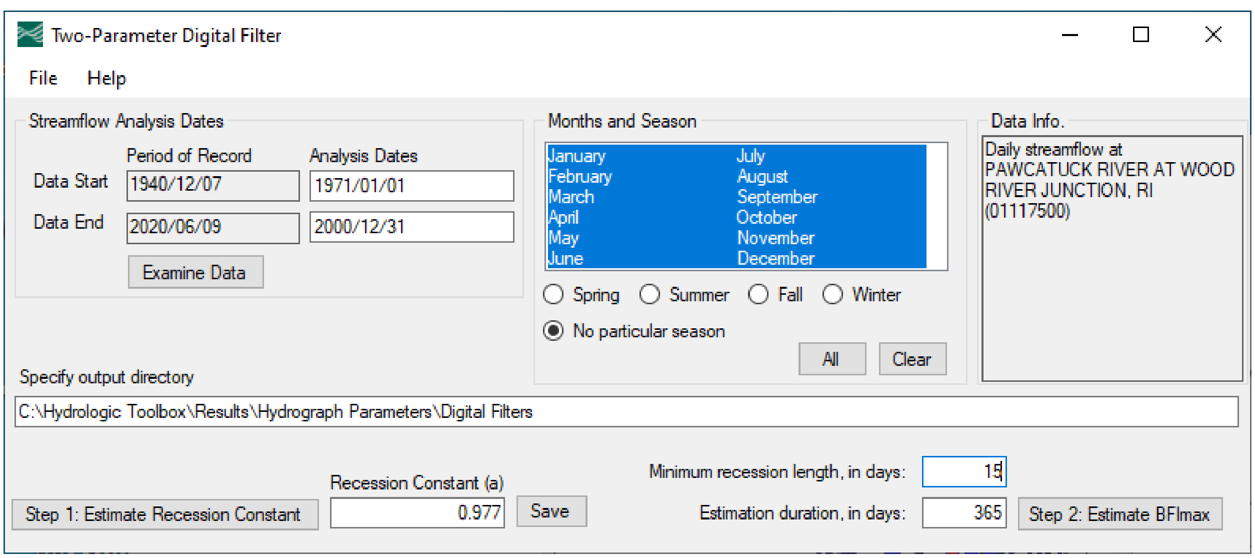
The user now has the option of either specifying the recession constant in the "Recession Constant (a)" cell or letting the program estimate the recession constant based on the period and months of streamflow record specified in the input information. In this first example, the option "Step 1: Estimate Recession Constant" was clicked, which resulted in a calculated value of 0.977 for the recession constant:



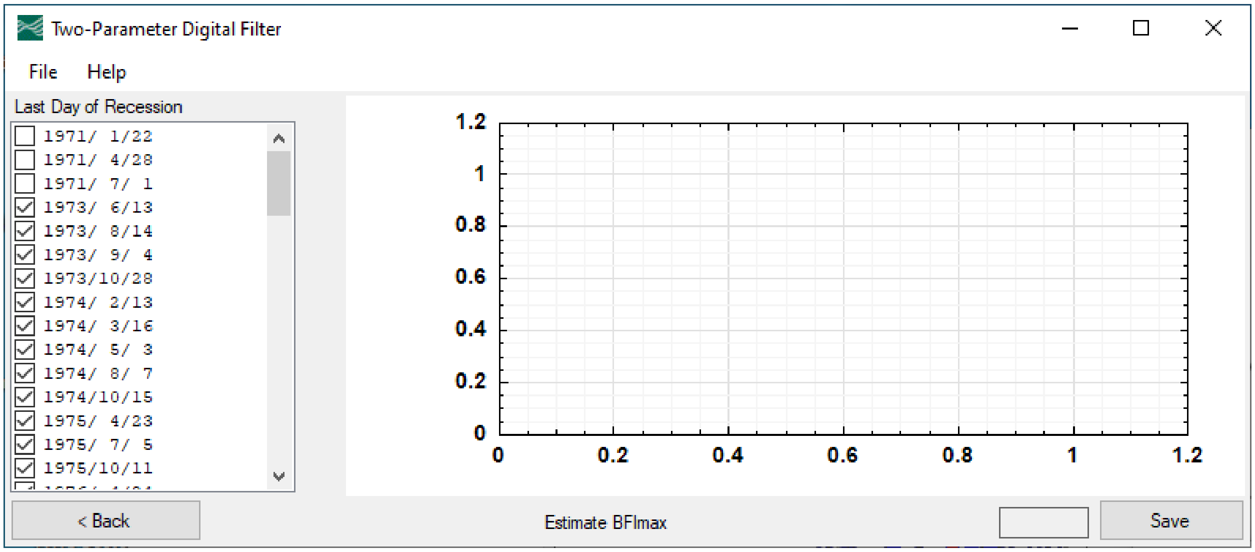
The user now has the option to save the results of the analysis to an output file by clicking the "Save" button. The result is written to the file "DF2P_RC_BFImax.txt" file in the output directory specified by the user. The contents of the file for this initial estimation of the recession constant are as follows:

```
                                                         BFImax
Gage              Recession Constant (a)      Start        End          Duration     Calc.
number      Season Dates          Spec.  Calc.   Date         Date          (days)       BFImax
----------- -------------------------------- ------------------------------------------
01117500    n       1971-2001           0.977
```

The user now specifies a "Minimum flow recession length, in days" and "Estimation duration, in days," which will be used in the second step to estimate BFI_{max}. For this initial example, a minimum recession length of 15 days and estimation duration of 365 days will be used:

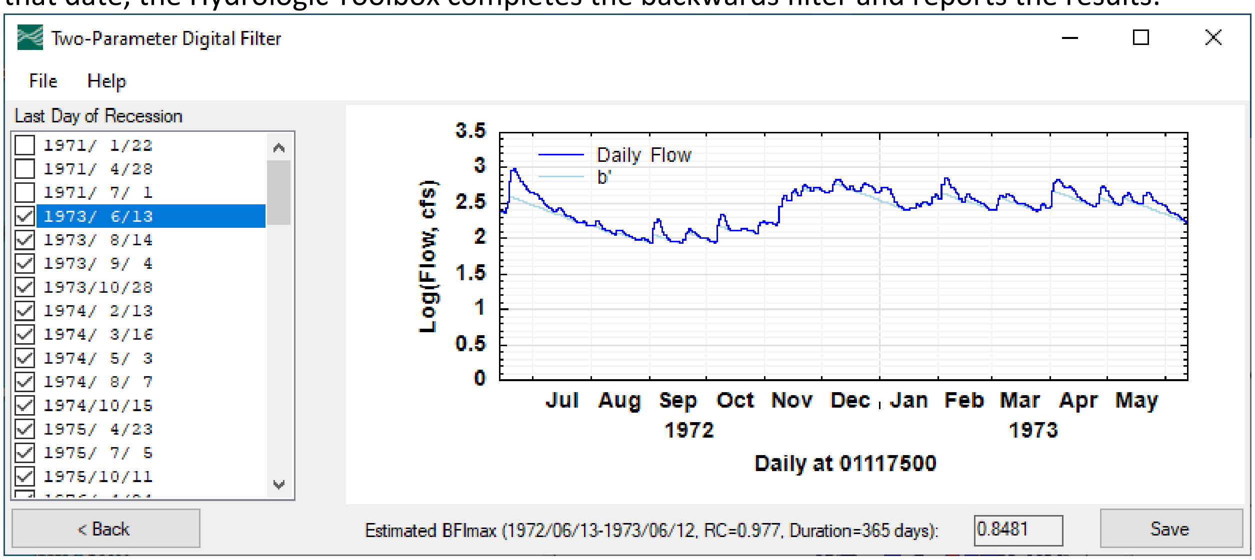


The user now clicks "Step 2: Estimate BFImax >" which results in the following dialog box:



The left-hand side of the dialog box shows the last day of each of the recession periods that meet the 15-day minimum recession-length criterion. For example, the first recession shown ended on January 22, 1971 (and began on January 7, 1971, although that date is not shown on the dialog box). The recessions listed with a check-mark are those for which there are 365 days of streamflow record available for analysis; in other words, those recessions that have a record length prior to the end of the recession period that is at least as long as the number of days specified for the "estimation duration" period. For the first recession-period shown, there are 21 days of record available for analysis from the beginning of the record specified in step 1 (January 1, 1971) through the end of the recession period (January 22, 1971), minus one day because base flow is not etimated for January 22, 1971, by the backwards filter.

Because the first three recession periods listed have less than 365 days of record, for the first analysis we will will select the recession period that ends on June 13, 1973. By clicking on the that date, the Hydrologic Toolbox completes the backwards filter and reports the results:



The graph shows the streamflow record in the dark-blue curve and the daily base flow (b') record estimated by the backwards filter in the light-blue curve. The information at the bottom of the screen shows the dates used for the analysis, the specified value of the recession constant (RC), the total duration of the analysis, and the calculated value of BFI_{max}. Note again that the last day for which a value of base flow is calculated is June 12, 1973, which is the day before the end of the recession period selected for analysis.

By clicking "Save," a second line of output is written to the output file:

Gage number	Season	Recession Constant (a) Dates	Spec.	Calc.	BFImax Start Date	End Date	Duration (days)	Calc. BFImax
01117500	n	1971-2001		0.977				
01117500	n	1971-2001		0.977	1972/06/13	1973/06/12	365	0.8481

The user can then do additional analyses of BFI_{max} with the currently specified value of the recession constant or go back to the previous dialog box to specify or determine a new value of the recession constant and repeat the estimation of BFI_{max}. This process was done for this sample problem and the results are summarized in the following output file:

Gage number	Season	Recession Constant (a) Dates	Spec.	Calc.	BFImax Start Date	End Date	Duration (days)	Calc. BFImax
01117500	n	1971-2001		0.977				
01117500	n	1971-2001		0.977	1972/06/13	1973/06/12	365	0.8481
01117500	n	1971-2001		0.977	1973/10/15	1974/10/14	365	0.8924
01117500	n	1971-2001		0.977	1989/06/29	1990/06/28	365	0.8606
01117500	n	1971-2001		0.977	1999/10/19	2000/10/17	365	0.8145
01117500	n	1971-2001	0.9849					
01117500	n	1971-2001	0.9849		1972/06/13	1973/06/12	365	0.7739
01117500	n	1971-2001	0.9849		1973/10/15	1974/10/14	365	0.8305
01117500	n	1971-2001	0.9849		1989/06/29	1990/06/28	365	0.7882
01117500	n	1971-2001	0.9849		1999/10/19	2000/10/17	365	0.7289

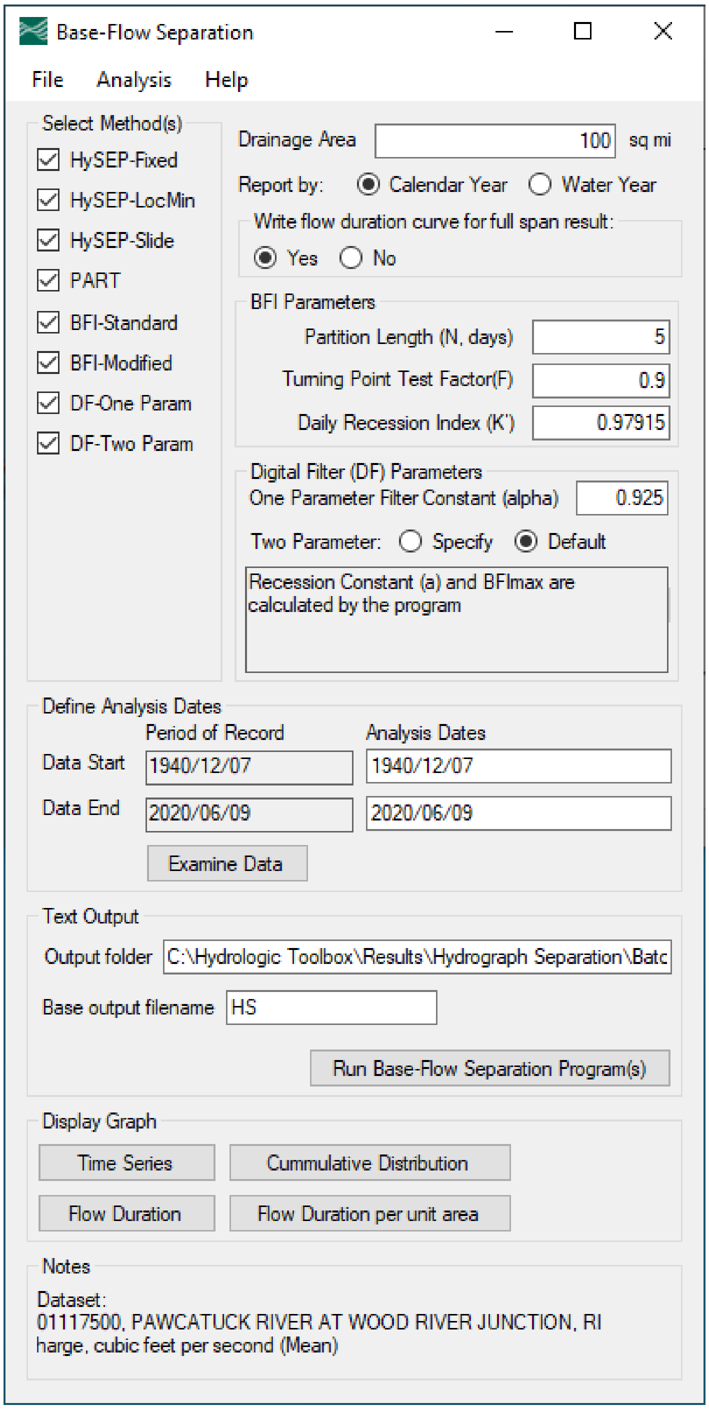
Note the dependence of the estimated value of BFI_{max} on the value of the recession constant used in the BFImax analysis.

The final values of the recession constant and BFI_{max} are held in memory and appear in the base-flow separation dialog box if it is used in the current Hydrologic Toolbox session.

<u>Using the Digital Filters within the Base-Flow Separation Functionality:</u>

The user accesses the digital-filtering techniques through the "**GW Tools>Base-Flow Separation**" menu option. The user is then given the option to do the hydrograph-separation analysis in either "Interactive," "Batch File," or "Batch Map" modes. Each of these modes is described in the tutorial "Hydrograph Separation" distributed with the Hydrologic Toolbox software. For this discussion, we'll assume that the "Interactive" mode has been selected; the topics described here also are relevant to the other two modes of analysis. Selection of the "Interactive" mode takes the user to the "Select Daily Streamflow for Analysis" dialog box, where the user selects a streamflow record for analysis. For this analysis, the record for the Pawcatuck River at Wood River Junction, Rhode Island (USGS streamgage 01117500), was selected for analysis.

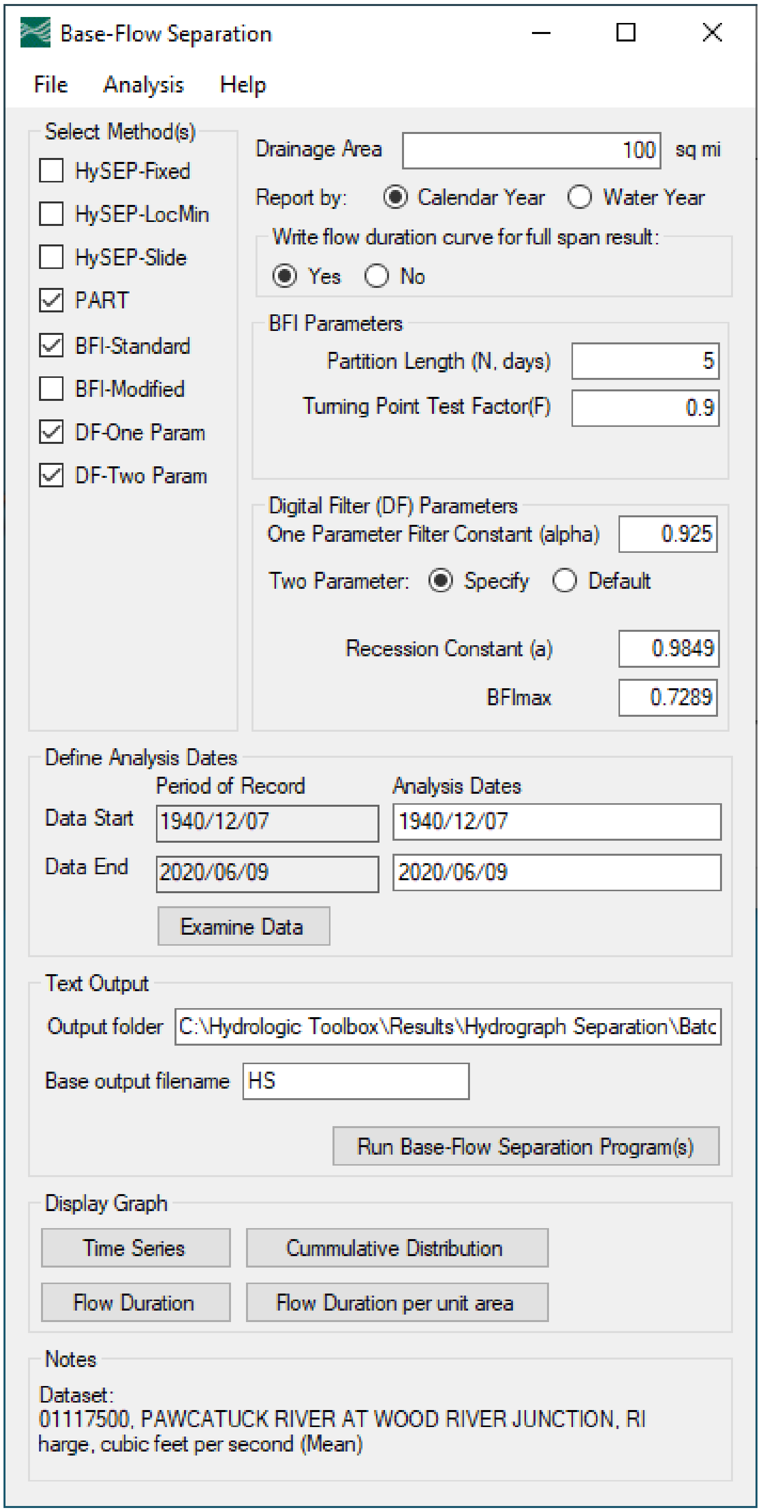
After selection of the streamflow record, the following “Base-Flow Separation” dialog box is opened:



If the user selects one or both of the two digital filters, they need to specify parameters for the filters. As described previously in the section "Default Parameter Values Implemented in the Groundwater Toolbox," default values for the filter constant for the single-parameter filter and for the recession constant and BFI_{max} for the two-parameter filter are provided. However, if the user has used the "**Two-Parameter Digital Filter**" functionality described above to estimate values for the recession constant and BFImax in the Hydrologic Toolbox session, as was done for this tutorial, those values will be loaded automatically into the "Recession Constant (a)" and "BFImax" cells when the "Specify" radio button is selected.

The user also has the option to use the approaches of Eckhardt (2008) to estimate the recession constant and BFI_{max}. This is the "Default" option shown for the "Two Parameter" filter. If this option is selected, a message will be written to the dialog box that indicates that the two parameters will be estimated by the program. The recession constant will be estimated using the correlation method described in Eckhardt (2008), which is also implemented in the "**Two-Parameter Digital Filter**" functionality described previously. The streamflow record can include gaps; a single value of the recession constant will be determined for the entire period of record, even if gaps are present. The value of BFI_{max} will be set to 0.8 (Eckhardt's value for a perennial stream draining a porous aquifer) unless the program detects that the streamflow record to be analyzed consists of no-flow conditions (that is, streamflow less than 0.001 cubic foot per second) more than 10 percent of the time, in which case BFI_{max} is set to 0.5 (Eckhardt's value for an ephemeral stream draining a porous aquifer).

In the example used here, the default value of 0.925 was used for the filter constant and the values of the recession constant and BFI_{max} from the "Two-Parameter Digital Filter" analysis were used. The "PART" and "BFI-Standard" hydrograph-separation techniques also were specified:



The user then clicks the “Run Base-Flow Separation Program(s)” to run the four hydrograph-seperation methods that have been specified.

For the conditions specified in the dialog box above, the program ran successfully and output was written to the folder specified in the “Output folder” directory. The several files that are generated by the Hydrologic Toolbox and written to this directory include those generated by the original programs, which are identified by 'BFLOW' and 'TwoPRDF' in their names. The file that includes 'BFLOW_stationnumber_out' in its name contains the daily base-flow estimates for each of three filter passes of the single-parameter filter; as described in the "Digital Filters" section of this tutorial, only the results of the first filter pass are reported in the CSV files. The file that includes 'BFLOW_stationnumber' in its name contains a summary of the long-term fraction of streamflow that is base flow for each of the three filter passes for the period of analysis. The file also contains an estimate of the recession constant for the basin ('Baseflow_Days') that is made by the Bflow program using a master-recession curve approach described in Allen and others (1995). The file that includes 'TwoPRDF_baseflow' in its name contains the daily base-flow estimates for the two-parameter filter, as well as the recession constant ('a') used for the analysis and the calculated fraction of streamflow that is base flow for the period of analysis ('BFI'). The file that includes 'TwoPRDF_bfi' in its name also contains values for 'a' and 'BFI,' as well as the sensitivity coefficients for BFI as a function of the recession constant and BFI_{max}, as described in Eckhardt (2012).

Note that the two-parameter digital filter approach only calculates baseflow if the daily streamflow value is greater than zero; for other values of streamflow, such as zero, the Hydrologic Toolbox reports 'NA' for calculated Baseflow in the daily output csv file. The user can search the output file for values of 'NA' and, depending on the value of streamflow, decide whether or not the 'NA' values should be changed to zero.

References

Arnold, J.G., and Allen, P.M., 1999, Automated methods for estimating baseflow and ground water recharge from streamflow records: Journal of the American Water Resources Association, v. 35, no. 2, p. 411-424.

Arnold, J.G., Allen, P.M., Muttiah, R., and Bernhardt, G., 1995, Automated base flow separation and recession analysis techniques: Ground Water, v. 33, no. 6, p. 1010-1018.

Arnold, J.G., Muttiah, R.S., Srinivasan, R., and Allen, P.M., 2000, Regional estimation of base flow and groundwater recharge in the Upper Mississippi river basin: Journal of Hydrology, v. 227, p. 21-40.

Barlow, P.M., Cunningham, W.L., Zhai, Tong, and Gray, Mark, 2014, U.S. Geological Survey Groundwater Toolbox, a graphical and mapping interface for analysis of Hydrologic data (version 1.0)—User guide for estimation of base flow, runoff, and groundwater recharge from streamflow data: U.S. Geological Survey Techniques and Methods, book 3, chap. B10, 27 p., *http://dx.doi.org/10.3133/tm3B10*.

Brutsaert, Wilfried, 2008, Long-term groundwater storage trends estimated from streamflow records—climatic perspective: Water Resources Research, v. 44, W02409, doi:10.1029/2007WR006518.

Brutsaert, Wilfried, 2010, Annual drought flow and groundwater storage trends in the eastern half of the United States during the past two-third century: Theoretical and Applied Climatology, v. 100, p. 93-103, doi:10.1007/s00704-009-0180-3.

Brutsaert, Wilfried, 2012, Are the North American deserts expanding? Some climate signals from groundwater storage conditions: Ecohydrology, v. 5, p. 541-549, doi:10.1002eco.263.

Brutsaert, Wilfried, and Nieber, J.L., 1977, Regionalized drought flow hydrographs from a mature glaciated plateau: Water Resources Research, v. 13, no. 3, p. 637-643.

Chapman, T.G., 1991, Comment on “Evaluation of automated techniques for base flow and recession analyses” by R.J. Nathan and T.A. McMahon: Water Resources Research, v. 27, no. 7, p. 1783-1784.

Collischonn, Walter, and Fan, F. M., 2013, Defining parameters for Eckhardt’s digital baseflow filter: Hydrological Processes, v. 27, p. 2614-2622.

Eckhardt, K., 2005, How to construct recurvsive digital filters for baseflow separation: Hydrological Processes, v. 19, p. 507-515.

Eckhardt, K., 2008, A comparison of baseflow indices, which were calculated with seven different baseflow separation methods: Journal of Hydrology, v. 352, p. 168-173.

Eckhardt, K., 2012, Technical note: Analytical sensitivity analysis of a two parameter recursive digital baseflow separation filter: Hydrology and Earth System Sciences, v. 16, p. 451-455.

Gonzales, A.L., Nonner, J., Heijkers, J., and Uhlenbrook, S., 2009, Comparison of different base flow separation methods in a lowland catchment: Hydrology and Earth System Sciences, v. 13, p. 2055-2068.

Hall, F.R., 1968, Base-Flow Recessions—A review: Water Resources Research, v. 4, no. 5, p. 973-983.

Langbein, W.B., 1938, Some channel-storage studies and their application to the determination of infiltration: Transactions of the American Geophysical Union, v. 19, p. 435-445.

Lim, K.J., Engel, B.A., Tang, Zhenxu, Choi, Joongdae, Kim, K-S, Muthukrishnana, Suresh, and Tripathy, Dibyajyoti, 2005, Automated web GIS based hydrograph analysis tool, WHAT: Journal of the American Water Resources Association, v. 41, no. 6, p. 1407-1416.

Mau, D.P., and Winter, T.C., 1997, Estimating ground-water recharge from streamflow hydrographs for a small mountain watershed in a temperate humid climate, New Hampshire, USA: Ground Water, v. 35, no. 2, p. 291-304.

Miller, M.P., Tesoriero, A.J., Capel, P.D., Pellerin, B.A., Hyer, K.E., and Burns, D.A., 2016, Quantifying watershed-scale groundwater loading and in-stream fate of nitrate using high-frequency water quality data: Water Resources Research, v. 52, p. 330-347, doi:10.1002/2015WR017753.

Nathan, R.J., and McMahon, T.A., 1990, Evaluation of automated techniques for base flow and recession analyses: Water Resources Research, v. 26, no. 7, p. 1465-1473.

Nathan, R.J., and McMahon, T.A., 1991, Reply: Water Resources Research, v. 27, no. 7, p. 1785-1786.

Neff, B.P., Day, S.M., Piggott, A.R., and Fuller, L.M., 2005, Base flow in the Great Lakes Basin: U.S. Geological Survey Scientific Investigations Report 2005-5217, 23 p.

Partington, D., Brunner, P., Simmons, C.T., Werner, A.D., Therrien, R., Maier, H.R., and Dandy, G.C., 2012, Evaluation of outputs from automated baseflow separation methods against simulated baseflow from a physically based, surface water-groundwater flow model: Journal of Hydrology, v. 458-459, p 28-39.

Rimmer, Alon, and Hartmann, Andreas, 2014, Optimal hydrograph separation filter to evaluate transport routines of Hydrologic models: Journal of Hydrology, v. 514, p. 249-257.

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: U.S. Geological Survey Water-Resources Investigations Report 98–4148, 43 p., http://pubs.usgs.gov/wri/wri984148/.

Sánchez-Murillo, R., Brooks, E.S., Elliot, W.J., Gazel, E., and Boll, J., 2015, Baseflow recession analysis in the inland Pacific Northwest of the United States: Hydrogeology Journal, v. 23, p. 287-303, doi:10.1007/s10040-014-1191-4.

Tallaksen, L.M., 1995: A review of baseflow recession analysis: Journal of Hydrology, v. 165, p. 349-370.

Zhang, Xuesong, Srinivasan, Raghavan, Arnold, Jeff, Izaurrald, R.C., and Bosch, David, 2011, Simultaneous calibration of surface flow and baseflow simulations: a revisit of the SWAT model calibration framework: Hydrological Processes, v. 25, p. 2313-2320, doi:10.1002/hyp.8058.