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Base Flow Discharge to Streams and Rivers: Terminology, Concepts, and Base-flow Estimation using Optimal Hydrograph Separation

In Cooperation With:

The USGS National Water-Quality Assessment (NAWQA) Program

U.S. Department of the Interior
U.S. Geological Survey

Base Flow

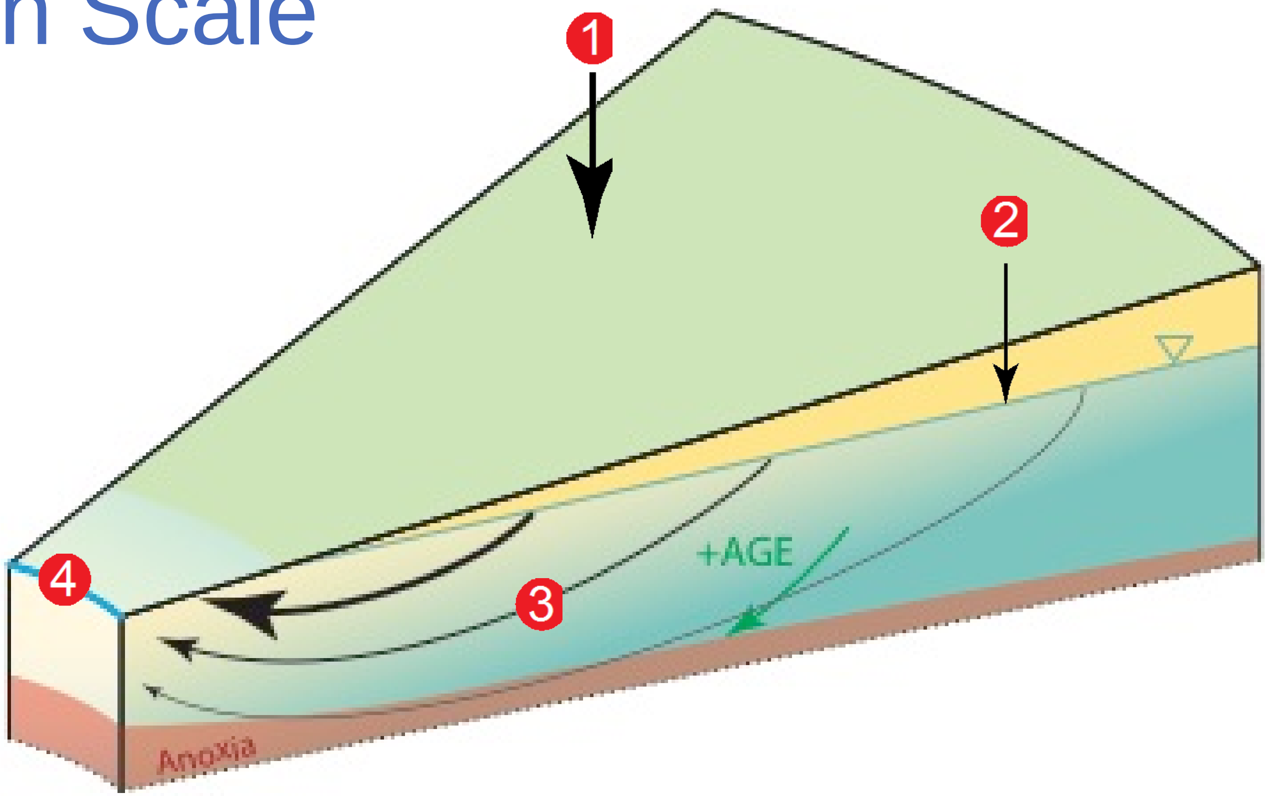
“Baseflow is the portion of streamflow that is sustained between precipitation events, fed to stream channels by delayed (usually subsurface) pathways.”

Price, K., 2011, Effects of watershed topography, soils, land use, and climate on baseflow hydrology in humid regions: A review: Progress in Physical Geography, v. 35, no. 4, p. 465-492.

Why Base Flow is Important

- A scientific understanding of watershed processes and base flow is critical to effective water policy and management.
- Population growth is associated with increasing demands on freshwater resources for industry, agriculture, and human consumption, and water shortages are not uncommon, even in humid regions.
- Ensuring safe concentrations of contaminants associated with wastewater effluent requires accurate estimation of base flow discharge, and contaminants that enter stream systems via soil or groundwater storage are most highly concentrated during base flow.

Reach Scale



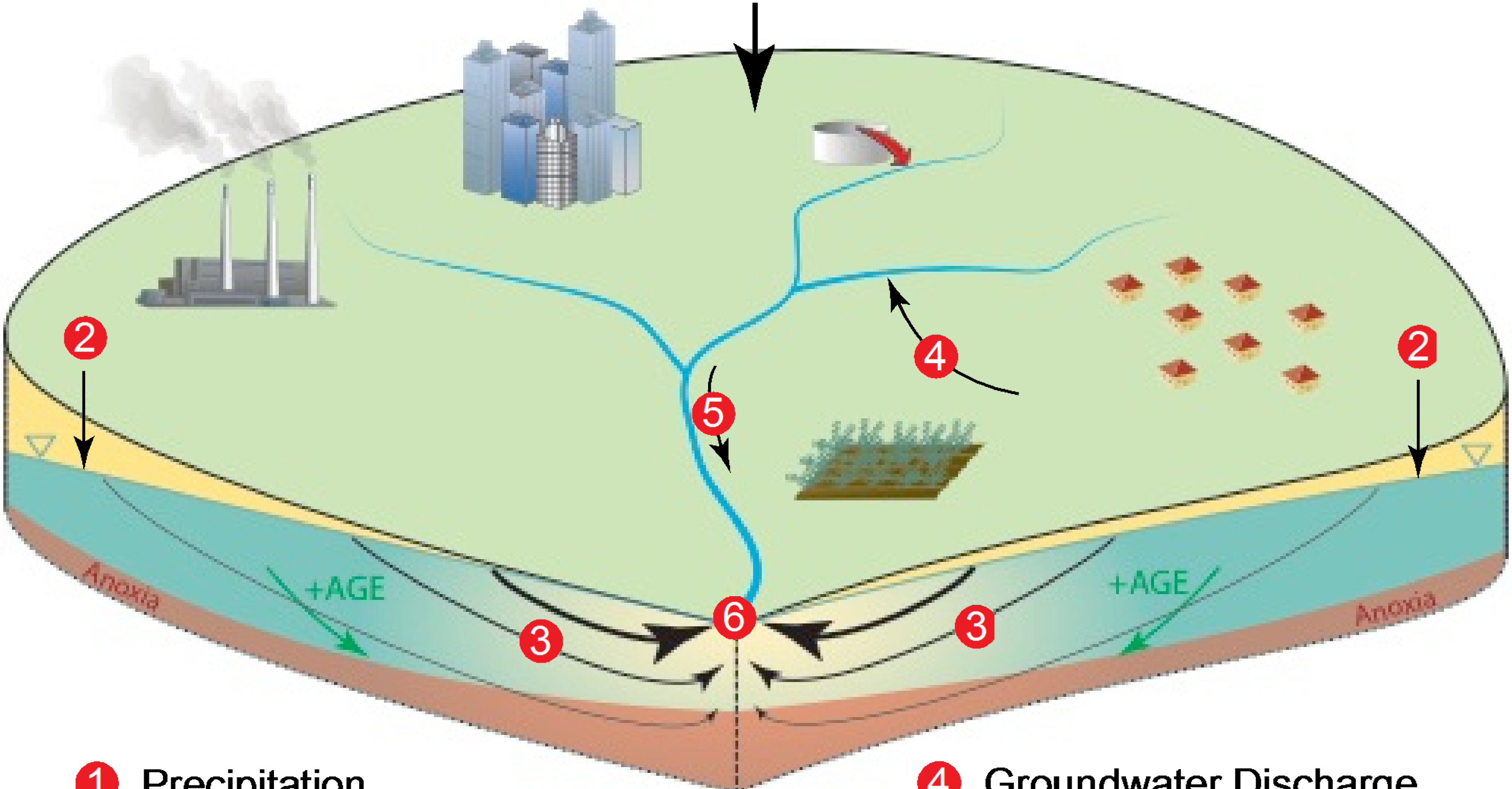
1 Precipitation
Atmospheric N

2 Recharge
N to Groundwater

3 Groundwater Transport
Denitrification

4 Groundwater Discharge
Groundwater N

Watershed Scale



1. Precipitation
   Atmospheric N
2. Recharge
   N to Groundwater
3. Groundwater Transport
   Denitrification
4. Groundwater Discharge
   Groundwater N
5. In-stream Routing
   In-stream N Processing
6. Base Flow
   Base-flow N

Hydrograph Separation Approaches

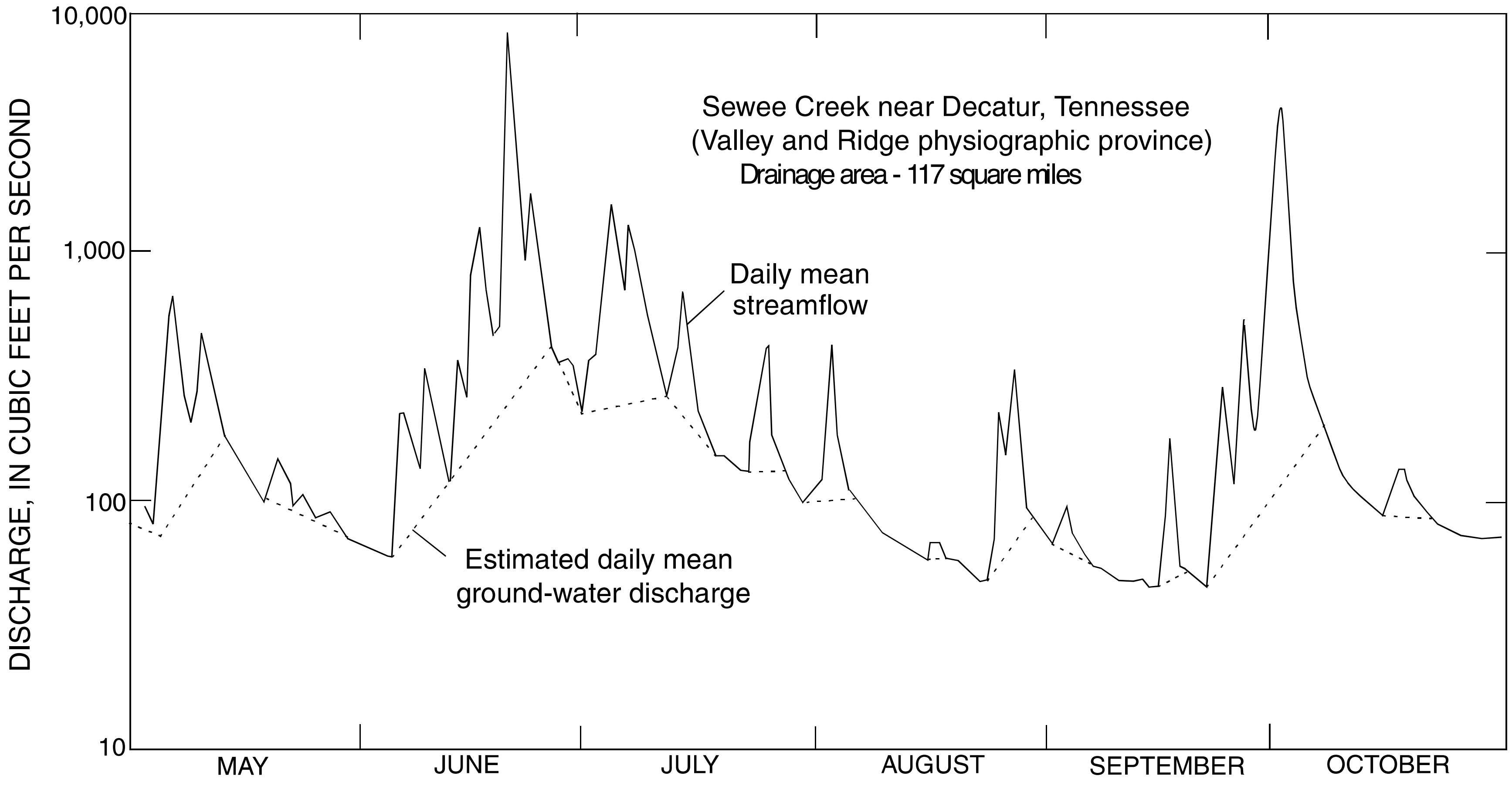
- Graphical
  - PART
  - HySEP
- Digital Filters
  - BFI
  - Eckhardt (2005)
- Chemical Hydrograph Separation
- Deterministic Modeling

PART

- **The method designates base flow to be equal to streamflow on days that fit a requirement of antecedent recession, linearly interpolates base flow for other days, and is applied to a long period of record to obtain an estimate of the mean rate of groundwater discharge.**
  - **daily values of streamflow are used and**
  - **linear interpolation is used to estimate groundwater discharge during periods of surface runoff.**
- **Based on antecedent streamflow recession.**

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.

PART

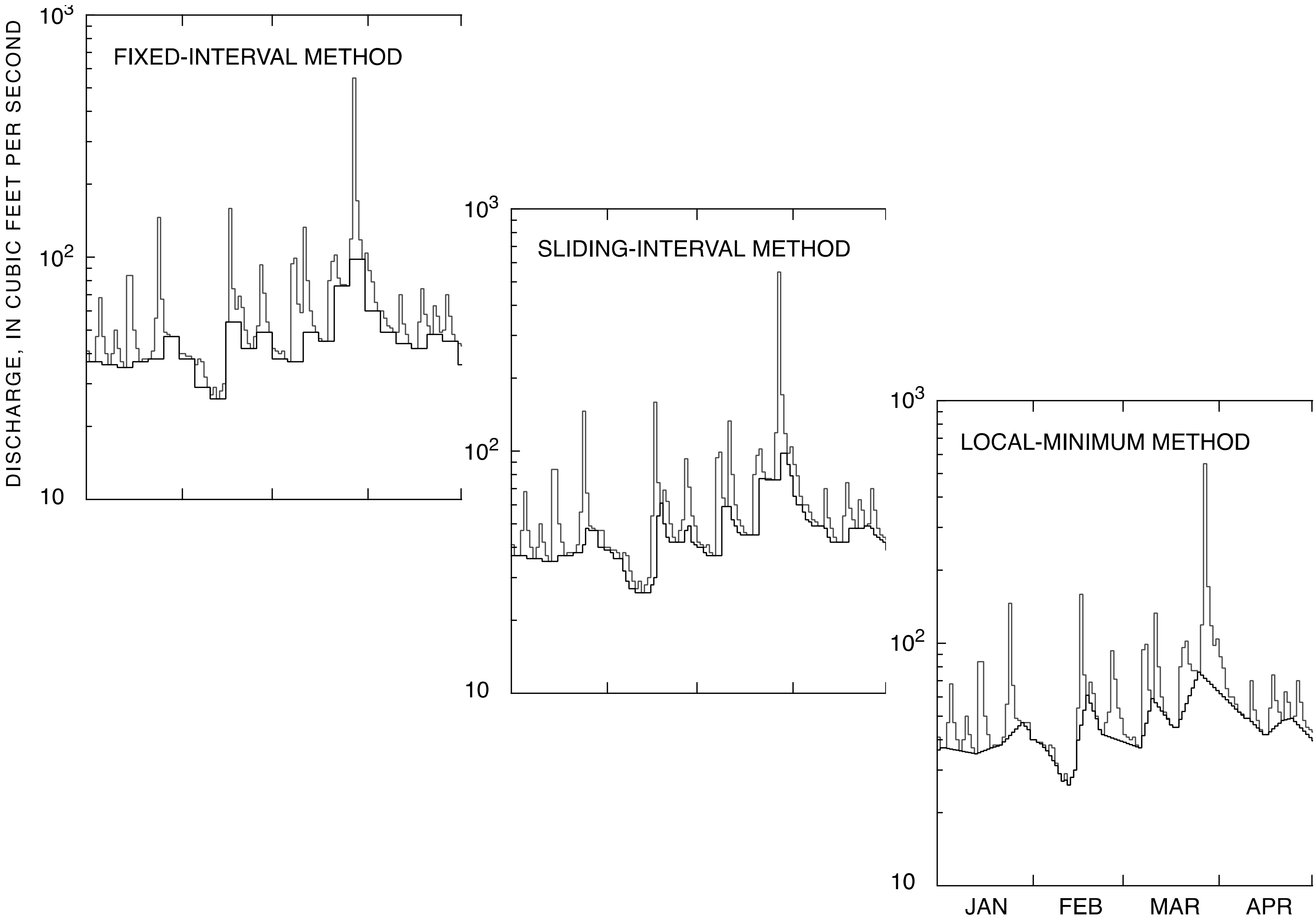


Sewee Creek near Decatur, Tennessee
(Valley and Ridge physiographic province)
Drainage area - 117 square miles
Daily mean streamflow
Estimated daily mean ground-water discharge
DISCHARGE, IN CUBIC FEET PER SECOND
10,000
1,000
100
10
MAY
JUNE
JULY
AUGUST
SEPTEMBER
OCTOBER

HySEP

- HYSEP is a computer program that can be used to separate a streamflow hydrograph into base-flow and surface-runoff components.
- The base-flow component has traditionally been associated with groundwater discharge and the surface-runoff component with precipitation that enters the stream as overland runoff.
- HYSEP includes three methods of hydrograph separation that are referred to in the literature as the fixed-interval, sliding-interval, and local-minimum methods.

Sloto, R.A., and Crouse, M.Y., 1996, HYSEP: a computer program for streamflow hydrograph separation and analysis: U.S. Geological Survey Water-Resources Investigations Report 96-4040, 45 p.



DISCHARGE, IN CUBIC FEET PER SECOND
FIXED-INTERVAL METHOD
SLIDING-INTERVAL METHOD
LOCAL-MINIMUM METHOD
10
10^2
10^3
JAN
FEB
MAR
APR

BFI

- Divides the water year into *N*-day increments and the minimum flow for each *N*-day period is identified, where *N* is a user-specified duration in days.
- Minimum flows are then compared to adjacent minimum flows to determine turning points on the base-flow hydrograph.
- Minimum flows that are less than a fixed proportion (*f*) of adjacent minimum flows are designated as turning points, and a straight line is established between turning points. The area below this line is an estimate of the volume of base flow.

Goals of New Work

- Develop or recommend an approach that:
  - has some physical basis related to the dynamics of the groundwater system;
  - is consistent with chemical mass balance methods;
  - is as objective as possible;
  - is reproducible;
  - can be automated and run in batch mode for multiple sites; and
  - includes some estimate of uncertainty.

Recursive Digital Filter

Eckhardt (2005) proposed the following Recursive Digital Filter (RDF) to estimate base flow:

$$Q_{B_j} = \frac{\left[(1-\beta)\alpha Q_{B_{j-1}} + (1-\alpha)\beta Q_j\right]}{(1-\alpha\beta)}$$

where α and β (BFI_{max}) are adjustable parameters, Q is streamflow, Q_B is base flow, and j is an index representing the time step (typically a daily time step).

Alpha

When β = 0 or $Q_j = Q_{B_j}$

$$Q_{B_j} = \alpha Q_{B_{j-1}}$$

which demonstrates that α is a recession constant, assuming that during dry periods without groundwater recharge base flow recesses exponentially, or that the groundwater system acts as a linear reservoir.

Alpha

The relation between the exponential recession constant [1/t] in:

$$Q_B = Q_{B_0} e^{-ct}$$

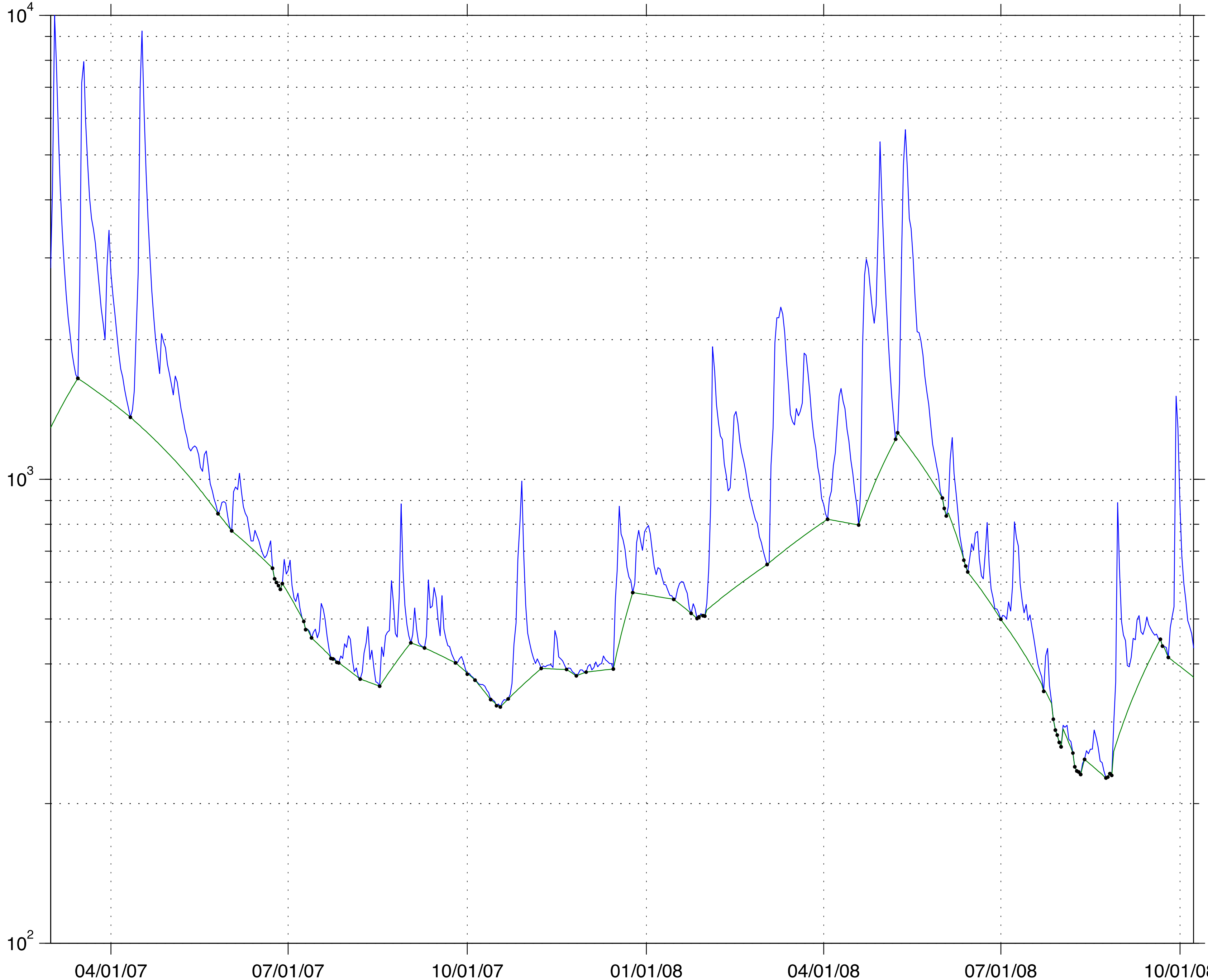
and α is as follows:

$$\alpha = e^{-c\Delta t}$$

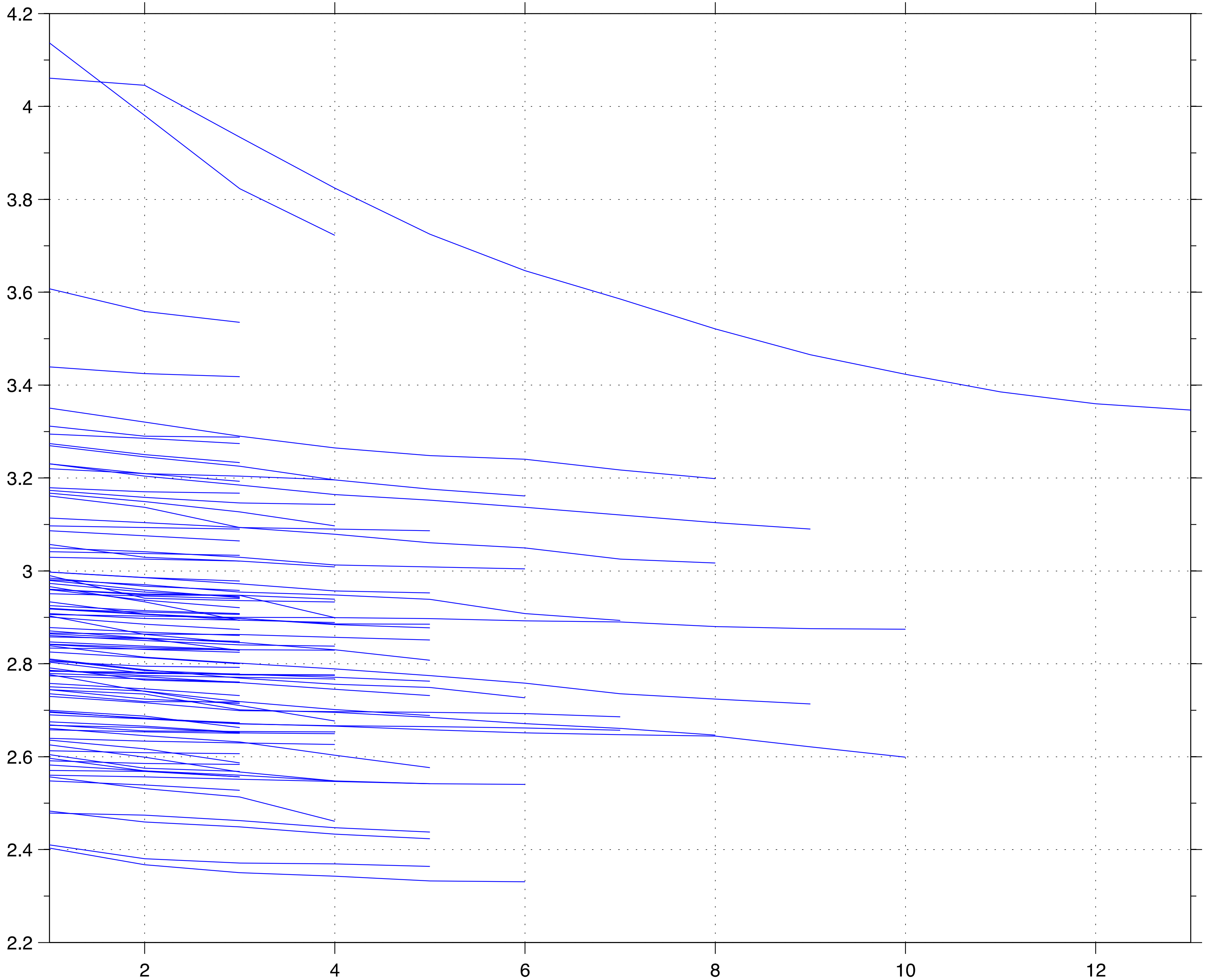
$$c = \ln\left(-\alpha / \Delta t\right)$$

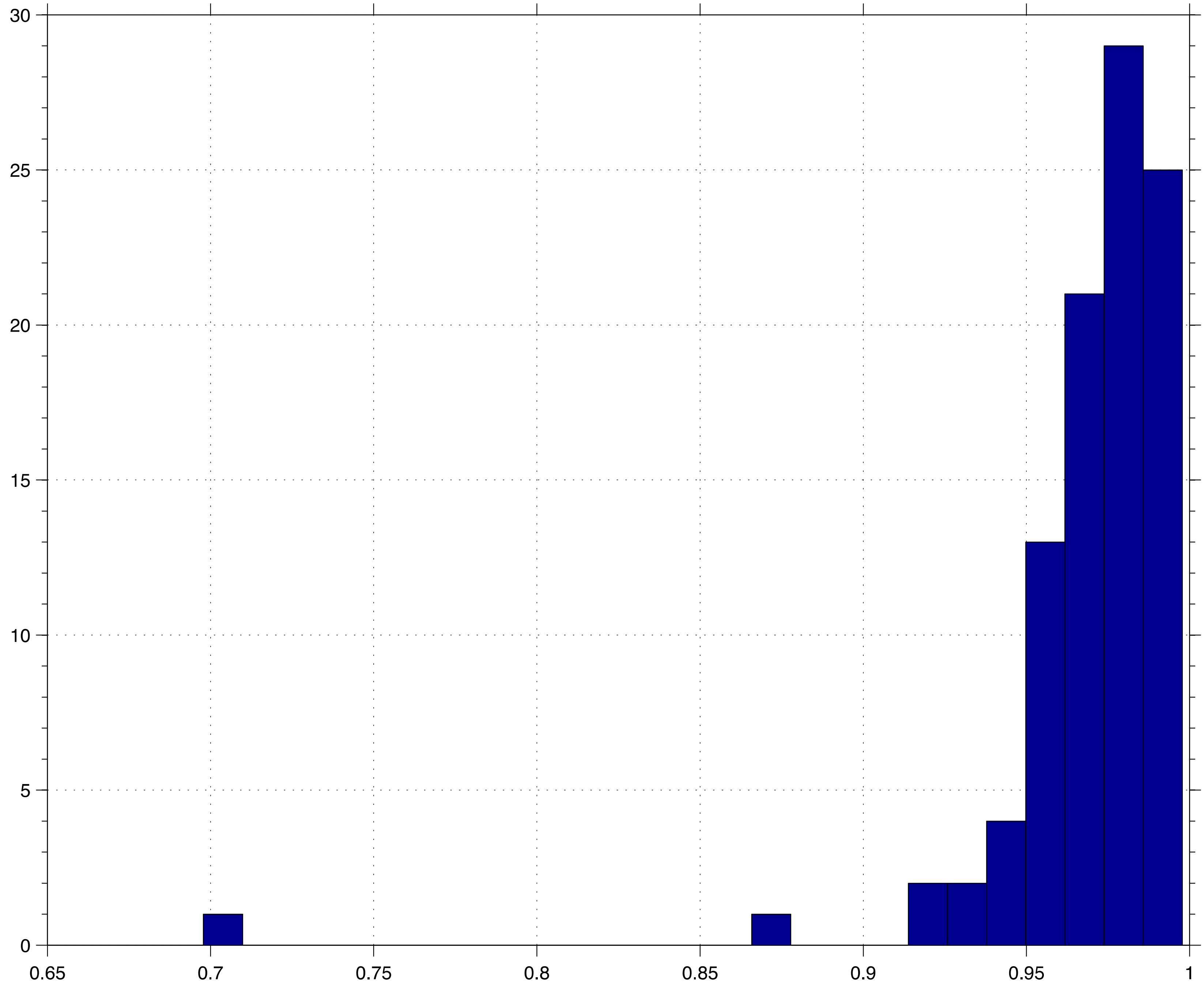
Recession Analysis

- **Alpha is estimated through a very simple recession analysis, in a single MATLAB function call, but virtually any method could be applied.**
  - **Periods where base flow (using BFI) = streamflow are determined**
  - **A minimum number of consecutive days of declining streamflow (*NR* = 3 days) isused to calculate an alpha value.**
  - **The alpha values and distribution statistics are passed back to the main code.**
  - **The median alpha is used.**



10^4
10^3
10^2
04/01/07
07/01/07
10/01/07
01/01/08
04/01/08
07/01/08
10/01/08


4.2
4
3.8
3.6
3.4
3.2
3
2.8
2.6
2.4
2.2
2
4
6
8
10
12


30
25
20
15
10
5
0
0.65
0.7
0.75
0.8
0.85
0.9
0.95
1

Beta (BFI_{max})

- Eckhardt (2005) proposed BFI_{max} be estimated by a priori according to the predominant geological characteristics of the drainage basin
- Comparisons of the filtering method with conventional separation methods on watersheds in Pennsylvania, Maryland, Illinois and Germany:
  - BFImax =0.80 for perennial streams with porous aquifers
  - BFImax =0.50 for ephemeral streams with porous aquifers
  - BFImax =0.25 for perennial streams with hard rock aquifers.

BFI and Recession Analysis

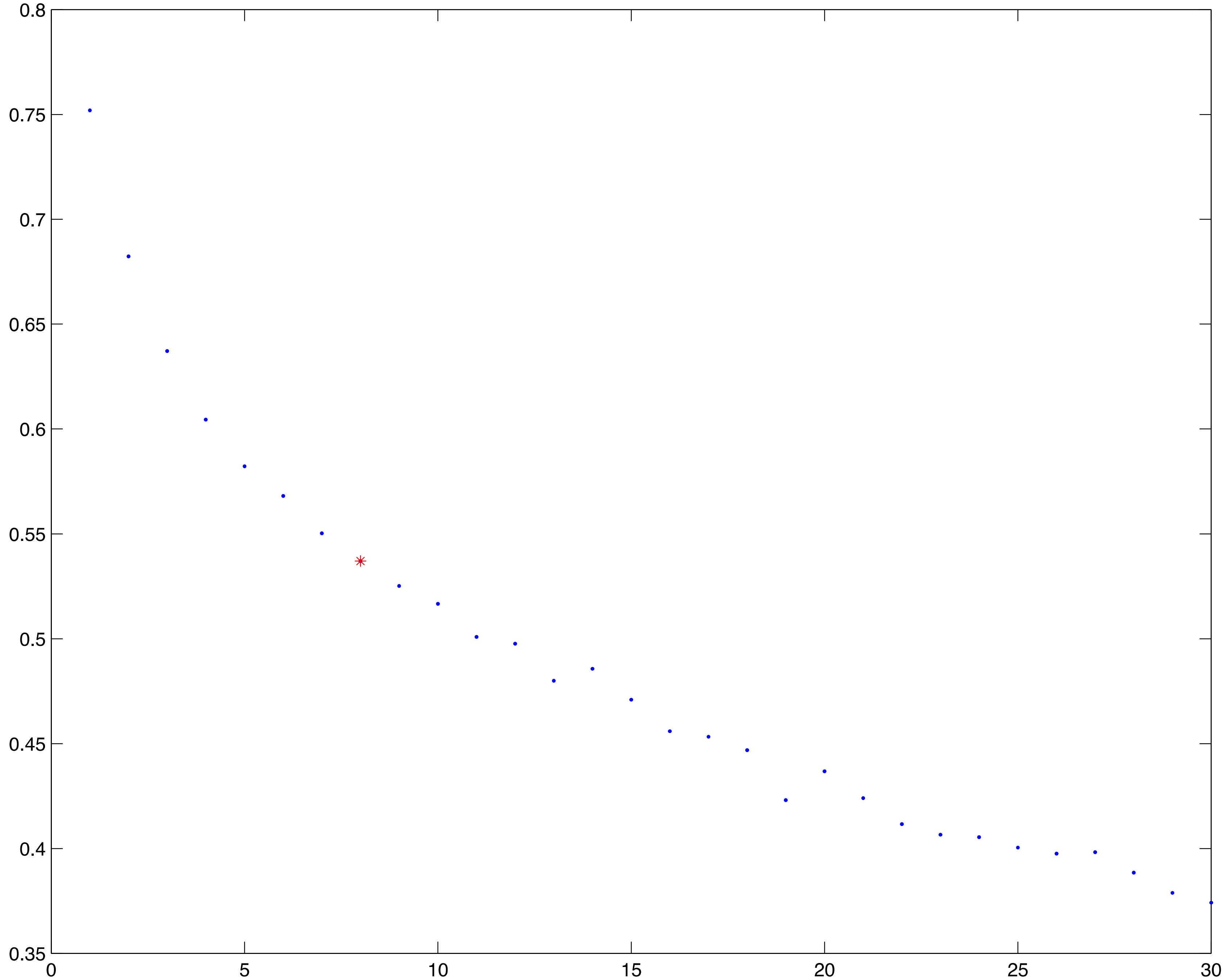
- The BFI (Base-Flow Index) method is a widely used computerized graphical method based on determination of local minima.
- It has been suggested that application of the BFI method could be useful in determining periods of base flow for recession analysis (David Wolock, USGS, written communication, 2014).

BFI Algorithm

1. The mean daily streamflow record is divided into non-overlapping blocks of *N* days.
2. The minima for each of these blocks (Q1, Q2, Q3…Qn) is calculated.
3. Consider in turn the minima (Q1, Q2, Q3,), (Q2, Q3, Q4)…(Qi-1, Qi, Qi+1) etc. In each case, if *f* × central value < outer values, then the central value is an ordinate for the base-flow line. The variable *f* is referred to as the turning point test factor (0.9). Continue this procedure until all the data have been analyzed to provide a derived set of base flow ordinates QB1, QB2, QB3…QBn which will have different time periods between them.
4. By linear interpolation between each QBi value, estimate each daily value of QB1…QBn.
5. If QBi > Qi then set QBi = Qi.
6. Calculate VB the volume beneath the base flow line between the first and last base flow turning points QB1…QBn.
7. Calculate VA the volume beneath the recorded mean daily flows Qn for the period QB1…QBn. The Base Flow Index (BFI) is then VB/VA.

Optimizing N

- The value for *N*, which defines the width of non-overlapping periods used in the BFI method, typically is set to a value of 5 days.
- Wahl and Wahl (1995) point out, however, that the value of *N* can be optimized by computing the long-term average BFI value (i.e., percentage of base flow in total flow) for a range in *N* values, and then identifying the break point in the relationship between the *N* and long-term average BFI values.
- In this study, the break point was determined by (1) computing long-term average BFI values for a range (1-30) of N values and then (2) using a MATLAB script “knee_pt.m” (Dmitry Kaplan, 2012) to determine the break point in the piecewise linear relationship.



0.8
0.75
0.7
0.65
0.6
0.55
0.5
0.45
0.4
0.35
0
5
10
15
20
25
30

Optimal Hydrograph Separation

Rimmer and Hartmann (2014) proposed an optimal hydrograph separation filter that optimizes the value of β using geochemical data and a mass balance approach. The approach minimizes the value of the root-mean-square error (RMSE) $E(\beta)$, defined as:

$$E(\beta) = \left[\sum_{j=1}^{n} \left[C_{obs_j} - C_{sep_j}(\beta) \right]^2 \right]^{1/2}$$

where:

$$C_{sep_j} = \frac{C_B Q_{B_j}(\beta) + C_S Q_{S_j}(\beta)}{Q_j}$$

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

Modeling C_B

- **Base-flow *SC* (C_B) may be approximated as a sine/cosine function of time:**
  - **incorporate expected seasonality in base-flow SC;**
  - **remove outliers, such as road-salt spikes;**
  - **The resultant errors will impact parameter estimation and model fit.**
- **Base-flow *SC* (C_B) may be approximated in a manner similar to the manual approach taken by Sanford and others (2012):**
  - **Fitting may remove spurious values; the filtered data could then be modeled using the approach above or some other approach;**
  - **the advantage of filtering is that spurious values of SC do not effect the error statistics and optimization.**
- **A time series of C_B may be approximated using smoothing or other approaches.**

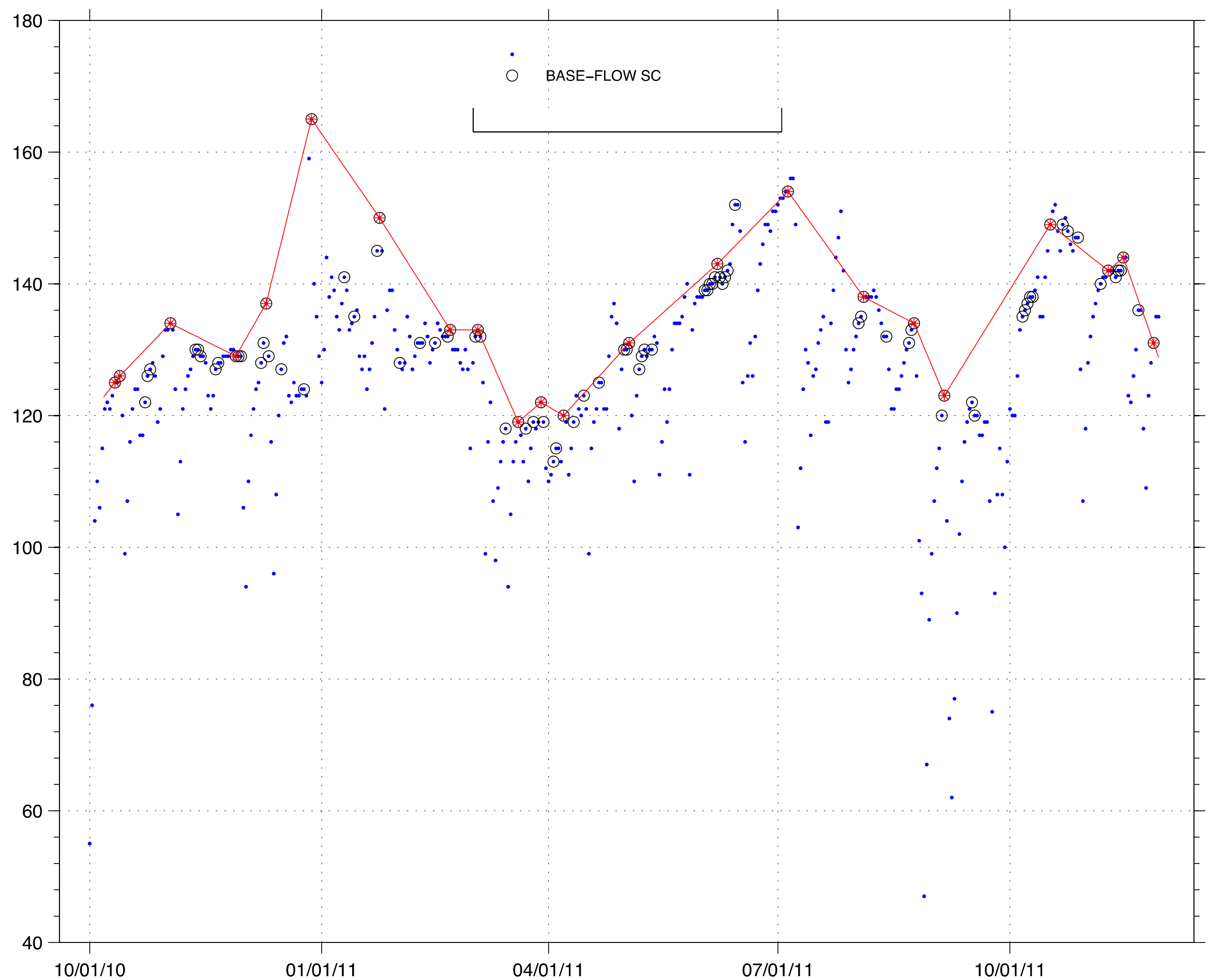
Sanford, W.E., Nelms, D.L., Pope, J.P., and Selnick, D.L., 2012, Quantifying components of the hydrologic cycle in Virginia using chemical hydrograph separation and multiple regression analysis: U.S. Geological Survey Scientific Investigations Report 2011–5198, 152 p.

Fit Base-Flow SC

- The second approach involves identifying SC values on base-flow days (according to the optimized BFI method), and using an algorithm to identify peaks (thought to represent base flow) in the record.
- These peaks are used to generate daily interpolated base-flow SC values.
- Estimate/optimize:

$\beta \quad C_S$

Example SCfit



C_B: sin-cos Function(s) of Time

- **Base-flow C_B:**

$$C_{B_j} = \bar{C}_B + C_B^{*s}\left[\sin\left(2\pi\left(t_j - t_0\right)/365.25\right)\right] + C_B^{*c}\left[\cos\left(2\pi\left(t_j - t_0\right)/365.25\right)\right]$$

$$C_{B_j} = \bar{C}_B + C_B^{*s}\left[\sin\left(2\pi\left(t_j - t_0^s\right)/365.25\right)\right] + C_B^{*c}\left[\cos\left(2\pi\left(t_j - t_0^c\right)/365.25\right)\right]$$

- **Estimate/optimize:**

$$\beta \quad C_S \quad \bar{C}_B \quad C_B^{*s} \quad C_B^{*c} \qquad t_0 \;[\; t_0^c \quad t_0^s \;]$$

Example sin-cos Fit

Results – 47 Sites

- Criteria for model acceptance
  - Beta optimized (not at limits)
  - Nash-Sutcliffe efficiency > 0.3
- 34 acceptable (21 unique, 7 nonunique)
  - 25 Scfit (19)
  - 6 sin-cos (2)
  - 3 sin-cos2 (0)

	Alpha	Beta	CS	N-S Efficiency
Min:	0.86	0.43	49	0.30
Max:	0.98	0.94	388	0.85

OPTIMAL HYDROGRAPH SEPARATION: 01487000

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Alpha = 0.972

Beta = 0.836

CS = 95.9

BFI N Value = 7

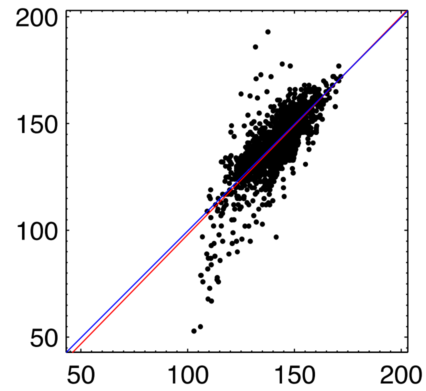
BFI f Value = 0.9

Root Mean Square Error = 378

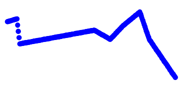
Nash–Sutcliffe Efficiency 0.59

Beta Bounds: 0.4:0.95

CS Bounds: 53:193



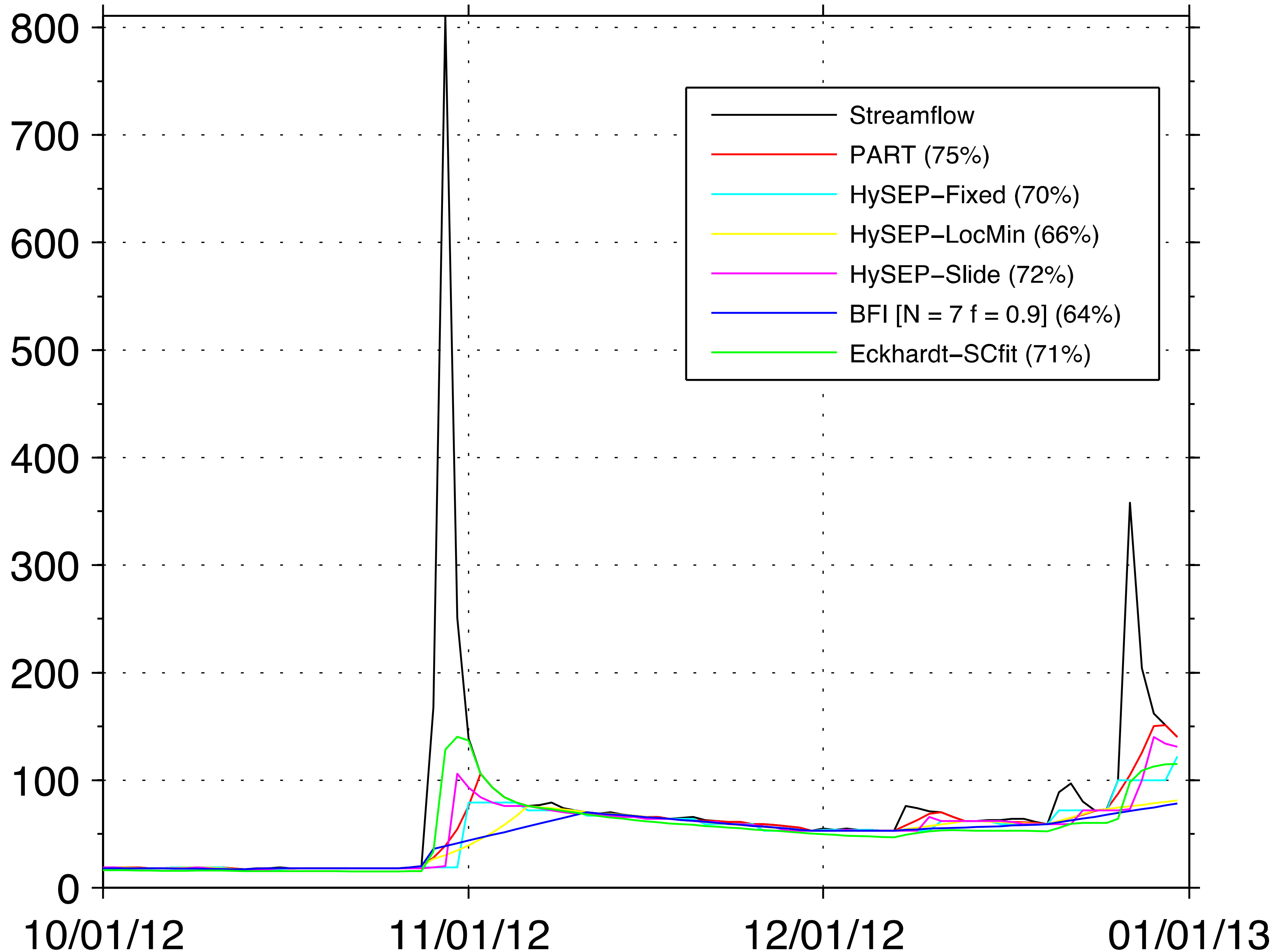
Model: SCfit



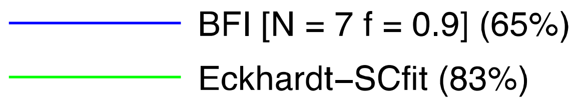
OBSERVED SC

SIMULATED SC

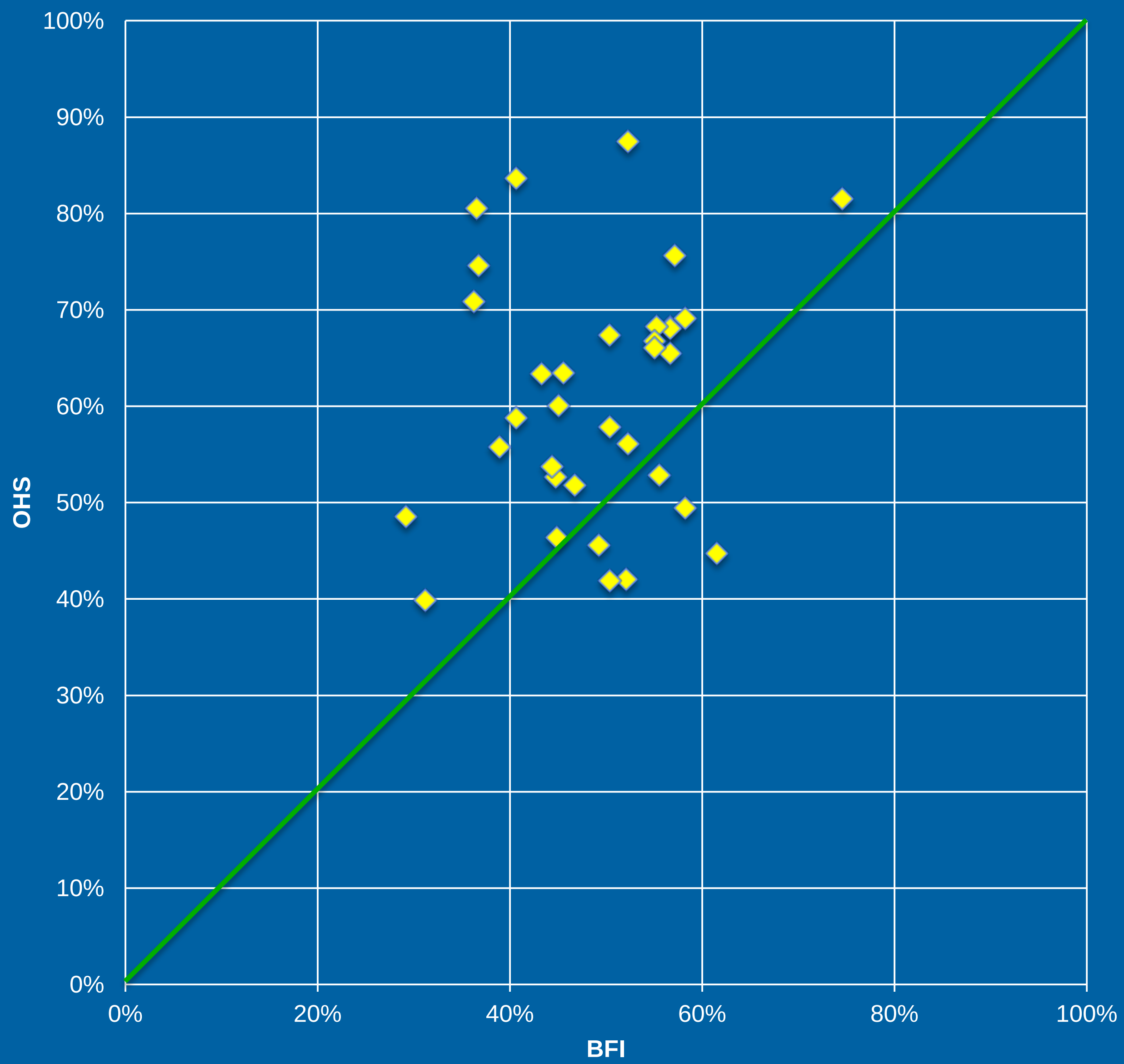
CALCULATED BASE–FLOW SC



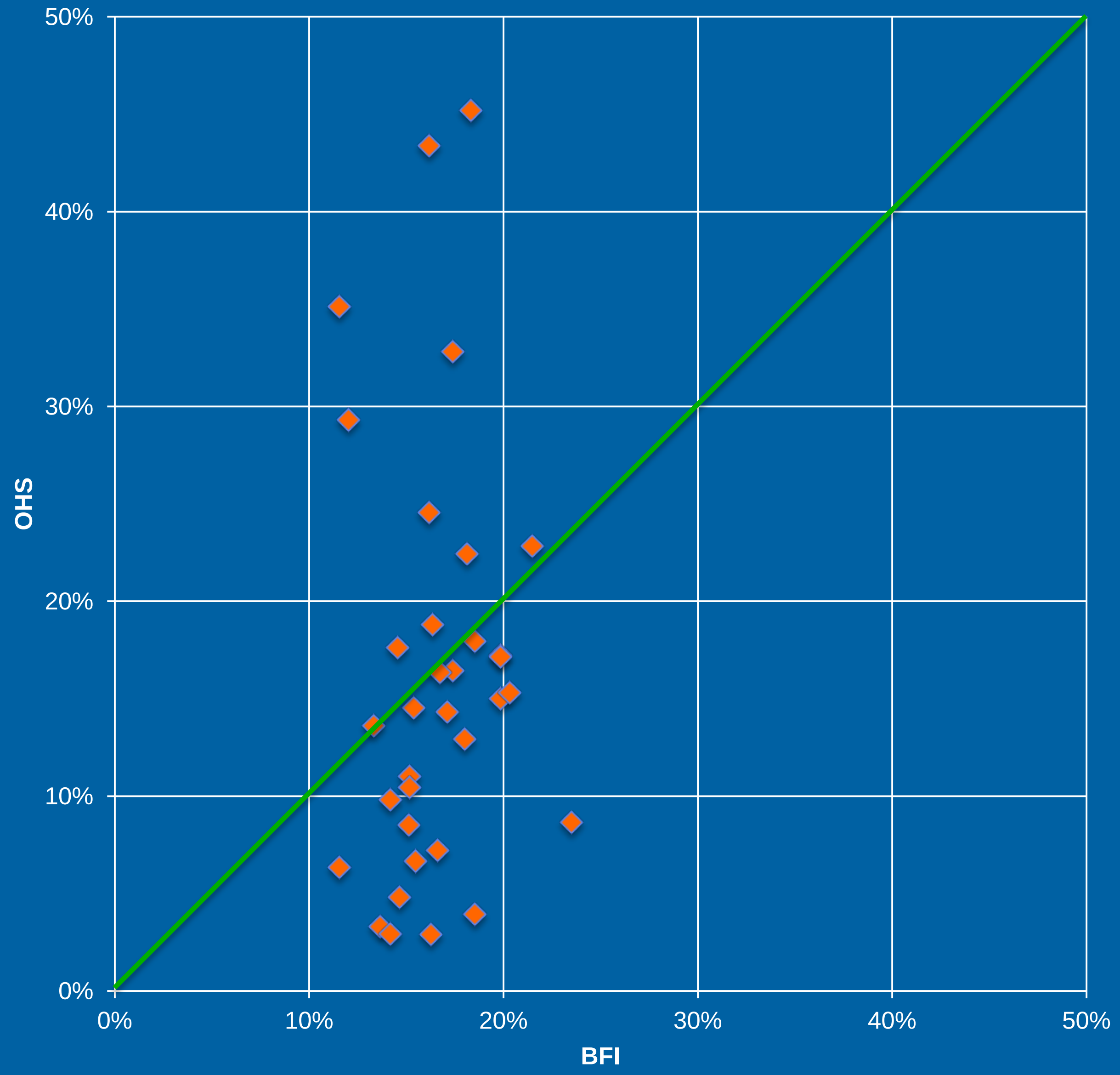
800
700
600
500
400
300
200
100
0
10/01/12
11/01/12
12/01/12
01/01/13
Streamflow
PART (75%)
HySEP−Fixed (70%)
HySEP−LocMin (66%)
HySEP−Slide (72%)
BFI [N = 7 f = 0.9] (64%)
Eckhardt−SCfit (71%)


BFI [N = 7 f = 0.9] (65%)
Eckhardt–SCfit (83%)

Base-Flow Index



Days at Base Flow



Summary and Conclusions

- **Base flow consists of diffuse groundwater discharge within a stream network that is routed to a point of measurement.**
- **Base flow sustains streamflow between precipitation events, maintaining ecologically-necessary flows, and providing water and chemicals to streams.**
- **Optimal Hydrograph Separation (OHS) combines a physically-based Recursive Digital Filter with Chemical Mass Balance (CMB).**
- **The approach allows opportunity for objective estimation of model parameters (α, β, chemical end-members).**

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