baseflow: a MATLAB and GNU Octave package for baseflow recession analysis

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Summary

baseflow is a MATLAB® (MATLAB, 2022) toolbox designed for baseflow recession analysis, a technique used in hydrologic science to infer aquifer properties from streamflow (Brutsaert & Nieber, 1977). By leveraging widely-available streamflow data, baseflow can be used to estimate aquifer properties such as hydraulic conductivity and drainable porosity over the modern instrumental stream gage record. The toolbox is intended for analysis of measured streamflow values recorded on a daily timestep, and is tailored for shallow, unconfined riparian aquifers that discharge groundwater laterally into adjacent streams. Additionally, baseflow can analyze the collective behavior of individual hillslope aquifers constituting hydrologic catchments, known as "watersheds", from a nonlinear dynamical systems perspective (Kirchner, 2009). The toolbox incorporates recent advances in baseflow recession analysis (Cooper et al., 2023; Dralle et al., 2017; Roques et al., 2017) to enable objective estimations of aquifer properties, and their sensitivity to methodological decisions, at both hillslope and catchment scales.

Statement of need

Baseflow is a vital component of streamflow sourced exclusively from aquifer discharge, rather than surface sources such as rainfall, lake drainage, or managed reservoir release (Hall, 1968). Baseflow essentially reflects the delayed release of groundwater storage into streams, and sustains water availability during dry seasons, especially in regions with limited surface water storage (Cooper et al., 2018). Baseflow is therefore important for managing water scarcity, and understanding the baseflow recession process is a central task in hydrologic science (Hall, 1968; Kirchner, 2009; Troch et al., 2013).

The baseflow recession curve captures the decline in streamflow during low-flow periods (Brutsaert & Nieber, 1977). Parameters derived from this curve can be used to estimate unconfined aquifer properties, including hydraulic conductivity, drainable porosity, and the saturated zone thickness (Brutsaert & Lopez, 1998; Rupp & Selker, 2006b; Troch et al., 1993). Detecting baseflow segments from measured streamflow data, however, is a complex task that requires signal processing, curve fitting, and parameter estimation algorithms, further complicated by measurement error and noise (Dralle et al., 2017; Rupp & Selker, 2006a).
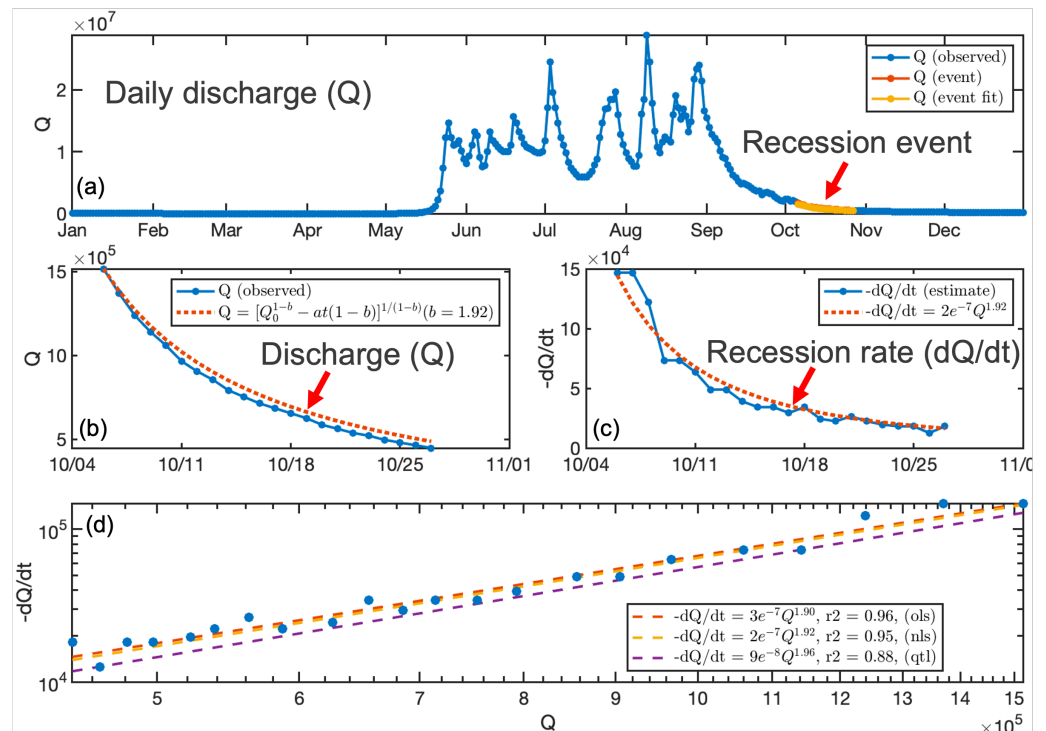
Figure 1: Example of baseflow recession analysis using the 'baseflow' toolbox. (a) Daily discharge hydrograph for the Kuparuk River, Alaska recorded at United States Geological Survey gage 1596000 and one detected recession event. (b-c) Observed and fitted discharge values (Q) and their rate of change ($-\mathrm{d}Q/\mathrm{d}t$) for the event highlighted in (a). (d) Log-log relationship between Q and $-\mathrm{d}Q/\mathrm{d}t$, comparing three fitting methods to estimate parameters a and b: ordinary least squares (ols), nonlinear least squares (nls), and quantile regression (qtl).

The `baseflow` API offers a user-friendly interface for essential baseflow recession analysis tasks, including event detection, parameter fitting, and visualization (Figure 1). The toolbox also addresses the nonlinear behavior of baseflow, which can arise due to rate-dependent hydraulic properties (Rupp & Selker, 2006b), or the nonlinear collective behavior of hillslope aquifer units that comprise watersheds (Harman et al., 2009). `baseflow` is primarily intended for hydrologic research, and provides a foundational tool for studying groundwater storage changes in Arctic and Subarctic regions affected by permafrost thaw (Cooper et al., 2023). The toolbox also includes several interactive notebooks that introduce linear and nonlinear reservoir theory, serving as educational resources for hydrologic science.

State of the field

Several publicly available software packages provide standardized methods for baseflow recession analysis (Arciniega-Esparza, 2018; Dralle et al., 2017; Gnann et al., 2021). These tools focus on estimating the canonical parameters of the event-scale recession equation (1), which relate the rate of change of streamflow to streamflow itself:

$$-\frac{\mathrm{d}Q}{\mathrm{d}t} = aQ^b \tag{1}$$

where Q is streamflow, t is time, and recession parameters a and b determine the shape of the recession curve (Figure 1). Several well-known solutions to the one-dimensional lateral groundwater flow equation for unconfined aquifers can be written in the same form as Equation 1.

Parameters a and b can be regarded as lumped coefficients from which various aquifer properties can be recovered (Brutsaert & Nieber, 1977; Rupp & Selker, 2006b; Troch et al., 1993).

Two MATLAB-based toolboxes for baseflow recession analysis are available to our knowledge. The HYDRORECESSION (Arciniega-Esparza et al., 2017; Arciniega-Esparza, 2018) toolbox provides methods to detect recession events and fit Equation 1, organized around a graphical user interface (GUI). Relative to HYDRORECESSION, the baseflow toolbox offers additional features for aquifer property estimation, such as saturated aquifer thickness, hydraulic conductivity, and drainable porosity. HYDRORECESSION and baseflow both provide methods for fitting both linear and nonlinear forms of Equation 1 based on alternative solutions to the one-dimensional lateral groundwater flow equation. baseflow could benefit from similar GUI capabilities, and the digital-filter baseflow separation methods available in HYDRORECESSION.

The Toolbox for Streamflow Signatures in Hydrology (TOSSH) (Gnann et al., 2021) provides recession event-detection and curve fitting algorithms but is broader in scope than both baseflow and HYDRORECESSION. For example, TOSSH provides automated estimation of several dozen quantitative streamflow metrics known as "hydrologic signatures", including recession parameters a and b. It provides a narrower toolkit for estimating a and b, and limited options for interpreting their values in terms of hydraulic groundwater theory. However, TOSSH provides a unique capability for interpreting a and b empirically in terms of hydrologic signatures. Although baseflow is designed for hillslope- and catchment-scale aquifer characterization, it could benefit from a broader scope that includes methods for quantifying evapotranspiration, which impacts estimates of a and b (Jachens et al., 2020).

Unique functionality: power-law scaling of recession parameters

The baseflow toolbox uniquely offers an automated Pareto distribution parameter-fitting module for aquifer characterization, motivated by a recent derivation of the Pareto transformation of Equation 1 (Cooper et al., 2023). To do so, the toolbox utilizes the function plfit (Clauset et al., 2009), translating its notation and functional forms to those of hydraulic groundwater theory. This probabilistic approach provides theoretically unbiased estimates of a and b for late-time aquifer drainage, which are necessary to obtain meaningful estimates of aquifer properties from baseflow recession analysis.

Software Availability

baseflow is on GitHub.

Acknowledgements

References

Arciniega-Esparza, S. (2018). *HYDRORECESSION*. MATLAB Central File Exchange, The MathWorks Inc.

93 Arciniega-Esparza, S., Breña-Naranjo, J. A., Pedrozo-Acuña, A., & Appendini, C. M. (2017).
94 HYDRORECESSION: A Matlab toolbox for streamflow recession analysis. *Computers &*
95 *Geosciences*, *98*, 87–92. https://doi.org/10.1016/j.cageo.2016.10.005

96 Brutsaert, W., & Lopez, J. P. (1998). Basin-scale geohydrologic drought flow features of
97 riparian aquifers in the Southern Great Plains. *Water Resources Research*, *34*(2), 233–240.
98 https://doi.org/10.1029/97WR03068

99 Brutsaert, W., & Nieber, J. L. (1977). Regionalized drought flow hydrographs from a mature
100 glaciated plateau. *Water Resources Research*, *13*(3), 637–643. https://doi.org/10.1029/
101 WR013i003p00637

102 Clauset, A., Shalizi, C. R., & Newman, M. E. J. (2009). Power-Law Distributions in Empirical
103 Data. *SIAM Review*, *51*(4), 661–703. https://doi.org/10.1137/070710111

104 Cooper, M. G., Schaperow, J. R., Cooley, S. W., Alam, S., Smith, L. C., & Lettenmaier, D. P.
105 (2018). Climate Elasticity of Low Flows in the Maritime Western U.S. Mountains. *Water*
106 *Resources Research*, *54*(8), 5602–5619. https://doi.org/10.1029/2018WR022816

107 Cooper, M. G., Zhou, T., Bennett, K. E., Bolton, W. R., Coon, E. T., Fleming, S. W., Rowland,
108 J. C., & Schwenk, J. (2023). Detecting Permafrost Active Layer Thickness Change
109 From Nonlinear Baseflow Recession. *Water Resources Research*, *59*(1), e2022WR033154.
110 https://doi.org/10.1029/2022WR033154

111 Dralle, D. N., Karst, N. J., Charalampous, K., Veenstra, A., & Thompson, S. E. (2017). Event-
112 scale power law recession analysis: Quantifying methodological uncertainty. *Hydrology and*
113 *Earth System Sciences*, *21*(1), 65–81. https://doi.org/10.5194/hess-21-65-2017

114 Gnann, S. J., Coxon, G., Woods, R. A., Howden, N. J. K., & McMillan, H. K. (2021). TOSSH:
115 A Toolbox for Streamflow Signatures in Hydrology. *Environmental Modelling & Software*,
116 *138*, 104983. https://doi.org/10.1016/j.envsoft.2021.104983

117 Hall, F. R. (1968). Base-Flow Recessions—A Review. *Water Resources Research*, *4*(5),
118 973–983. https://doi.org/10.1029/WR004i005p00973

119 Harman, C. J., Sivapalan, M., & Kumar, P. (2009). Power law catchment-scale recessions
120 arising from heterogeneous linear small-scale dynamics. *Water Resources Research*, *45*(9).
121 https://doi.org/10.1029/2008WR007392

122 Jachens, E. R., Rupp, D. E., Roques, C., & Selker, J. S. (2020). Recession analysis revisited:
123 Impacts of climate on parameter estimation. *Hydrol. Earth Syst. Sci.*, *24*(3), 1159–1170.
124 https://doi.org/10.5194/hess-24-1159-2020

125 Kirchner, J. W. (2009). Catchments as simple dynamical systems: Catchment characterization,
126 rainfall-runoff modeling, and doing hydrology backward. *Water Resources Research*, *45*(2).
127 https://doi.org/10.1029/2008WR006912

128 MATLAB. (2022). *Version: 9.13.0.2126072 (R2022b)*. The MathWorks Inc.

129 Roques, C., Rupp, D. E., & Selker, J. S. (2017). Improved streamflow recession parameter
130 estimation with attention to calculation of - dQ/dt. *Advances in Water Resources*, *108*,
131 29–43. https://doi.org/10.1016/j.advwatres.2017.07.013

132 Rupp, D. E., & Selker, J. S. (2006a). Information, artifacts, and noise in dQ/dt - Q recession
133 analysis. *Advances in Water Resources*, *29*(2), 154–160. https://doi.org/10.1016/j.
134 advwatres.2005.03.019

135 Rupp, D. E., & Selker, J. S. (2006b). On the use of the Boussinesq equation for interpreting
136 recession hydrographs from sloping aquifers. *Water Resources Research*, *42*(12), W12421.
137 https://doi.org/10.1029/2006WR005080

138 Troch, P. A., Berne, A., Bogaart, P., Harman, C., Hilberts, A. G. J., Lyon, S. W., Paniconi, C.,
139 Pauwels, V. R. N., Rupp, D. E., Selker, J. S., Teuling, A. J., Uijlenhoet, R., & Verhoest, N.

E. C. (2013). The importance of hydraulic groundwater theory in catchment hydrology: The legacy of Wilfried Brutsaert and Jean-Yves Parlange. *Water Resources Research*, *49*(9), 5099–5116. https://doi.org/10.1002/wrcr.20407

Troch, P. A., Troch, F. P. D., & Brutsaert, W. (1993). Effective water table depth to describe initial conditions prior to storm rainfall in humid regions. *Water Resources Research*, *29*(2), 427–434. https://doi.org/10.1029/92WR02087