Master Recession Curve Parameterization Tool (MRCPtool): Different approaches to recession curve analysis

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ABSTRACT

Streamflow recession analysis is crucial for understanding how catchments release water in periods of drought and therefore is important for water resources planning and management. Despite there being several theories on how to model recession curves, few studies compare the different approaches to that problem. In this work, we developed the Master Recession Curve Parameterization tool (MRCPtool), which brings together a set of automated methods for the analysis of recession periods based on streamflow data. The methods include: (i) hydrograph separation using numerical filters; (ii) automatic extraction of recession periods; (iii) creation of the MRC with the matching strip method; (iv) creation of the MRC for different flow classes defined from the flow duration curve; (v) analysis of flow recession rates (−dQ/dt) as a function of flow (Q) and (vi) creation of the MRC from simulated recession curves with different analytical approaches, including linear and nonlinear models. The MRCPtool contains a graphical user interface developed in MATLAB software that facilitates the analysis of streamflow datasets. Finally, we present an example application of the MRCPtool using a streamflow dataset of 44 years. The MRCPtool is an open source tool that can be downloaded from the site: http://www.labhidro.ufsc.br/static/software/MRCPtool.rar.

1. Introduction

The understanding of streamflow recession periods is fundamental for water resources management as it controls uses such as water supply for human consumption, irrigation and hydropower generation. Since baseflow is maintained essentially by the groundwater component (Toebes and Strang, 1964), its analysis might also clarify the characteristics of unconfined aquifers and the storage and release properties of the watershed (Tallaksen, 1995). However, the low quality of the low flow data, the high variability of the recession curves and the limitations in some mathematical approaches might hinder the determination of the characteristic recessions of watersheds (Tallaksen, 1995; Lamb and Beven, 1997; Sujono et al., 2004).

Hydrograph separation is necessary in order to determine the baseflow component for the recession analysis (Stewart, 2015) and it can be achieved through the application of numerical filters (Lyne and Hollick, 1979; Arnold et al., 1995; Chapman and Maxwell, 1996; Eckhardt, 2005). Recession analysis is usually approached in three different ways: (i) analytical expressions for recession analysis (Boussinesq, 1904; Maillet, 1905; Coutagne, 1948; Tallaksen, 1995; Wittenberg, 1999); (ii) graphical methods for master recession curve (MRC) determination (Snyder, 1939; Toebes and Strang, 1964; Toebes et al., 1969; Tallaksen, 1995; Sujono et al., 2004); (iii) parameterization based on the flow recession rates (−dQ/dt) as a function of flow (Q) (Brutsaert and Nieber, 1977; Kirchner, 2009; Stewart, 2015). The MRC emerged as an alternative to overcome the variability of each individual recession period, since it considers several curves extracted over a long period. The matching strip method is the most prominent method for the MRC determination (Snyder, 1939; Toebes et al., 1969; Nathan and McMahon, 1990; Lamb and Beven, 1997; Posavec et al., 2006, 2010).

It is a graphical method based on the overlap of curves in which individual recession segments are plotted and adjusted to form a single recession curve representative of long data series (Snyder, 1939).

The MRCs are limited in the representation of storage variation, making it difficult to identify the transition point of quick and slow flow components (Jones and McGilchrist, 1978; Anderson and Burt, 1980). The parameterization based on Q and dQ/dt (Brutsaert and Nieber, 1977) provides an analysis that considers that flow variability. Kirchner (2009) uses a least squares regression with different sets binned mean flows (BINS), weighted by the square of the standard error of the

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1 Development of MRCPtool (code and graphical user interface) and writing of the manuscript.
2 Advisor who contributed technical support and critical analysis to the development of MRCPtool and writing of the manuscript.

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mean flow bin. The different methods have limitations suggesting that if used together they can improve the interpretation of the recession behavior at watershed scale (Stoelzle et al., 2013). While there may be significant differences in the recession characteristics derived from different methods, there are few studies comparing the different recession models and how each approach influences the recession analysis (Stoelzle et al., 2013). The advance of computational resources has provided the development of toolboxes that combine different methods of recession analysis, allowing for consistent evaluations of watersheds characteristics and the comparison of different analytical parameterization (Posavec et al., 2006; Esparza et al., 2017).

Recently Esparza et al. (2017) developed a toolbox in MATLAB that contains some of the most useful methods for analyzing recessions based on analytical expressions (Boussinesq, 1904; Maillet, 1905; Coutagne, 1948; Wittenberg, 1999) used for recession analysis and also the methodology proposed by Brutsaert and Nieber (1977). Posavec et al. (2010) developed an automated method for separating MRCs into two or three parts determined from a flow duration curve. They use five different regression models for the creation of MRCs in which the resulting parameters are always described by an exponential model. An integrated comparison option of graphical methods of MRC (Posavec et al., 2006) and the analytical expressions (Stoelzle et al., 2013) would allow for a better understanding of streamflow recession periods.

We have developed the Master Recession Curve Parameterization tool – MRCPtool in MATLAB that allows for a comparison between recession analysis methods and its parameterization based on different analytical models. The tool has a graphical user interface (GUI) which offers automated resources to perform: (i) hydrograph separation using numerical filters; (ii) automatic extraction of recession periods; (iii) creation of the MRC with the matching strip method; (iv) creation of the MRC for different flow classes defined from the flow duration curve; (v) analysis of flow recession rates \( \frac{dQ}{dt} \) as a function of flow \( Q \); and (vi) creation of the MRC from simulated recession curves with different analytical approaches, including linear and nonlinear models.

2. The Master Recession Curve Parameterization tool (MRCPtool)

The Master Recession Curve Parameterization tool (MRCPtool) brings together a set of automated resources for the analysis recession period based only on streamflow data. The methods include: (i) application of numerical filters for hydrograph separation (Lyne and Hollick, 1979; Chapman and Maxwell, 1996; Eckhardt, 2005), (ii) extraction from periods of recession, (iii) creation of MRCPs, (iv) segmentation of MRCPs from the flow duration curve, (v) analysis of flow recession rates \( \frac{dQ}{dt} \) as a function of flow \( Q \) with linear regression model, and (vi) creation of MRCPs from simulated recession curves with different analytical approaches including a linear (Maillet, 1905) and non-linear models (Boussinesq, 1904; Coutagne, 1948; Wittenberg, 1999). For the optimization of the parameters of the models we use the ‘Nonlinear Least Squares’ method with the ‘Trust-Region’ algorithm of MATLAB. The tool has a graphical user interface (GUI), a parameter reporting system with outputs in .txt format and automatic image saving that facilitates the comparative analysis.

2.1. Baseflow separation methods

Flow separation filters can be used to obtain the baseflow from a time series of discharge. The MRCPtool presented in this paper contains the following numerical filters:

Lyne and Hollick (1979)
\[
B_i = \frac{1}{2} \left[ 1 + \frac{1}{a} (Q_i - Q_{i-1}) \right].
\]

Chapman and Maxwell (1996)
\[
B_i = \frac{a}{2 - a} B_{i-1} + 1 - a \frac{Q_i}{2 - a}.
\]

Eckhardt (2005)
\[
B_i = \frac{(1 - BF_{max}) a B_{i-1}}{1 - a BF_{max}} + (1 - a) BF_{max} Q_i.
\]

where \( B_i \) is the baseflow at time \( i \), \( a \) is the parameter of the filters which can be determined by \( e^{-\frac{t}{\alpha}} \) where \( k \) is the recession constant and \( dt \) is the time interval between \( i \) and \( i+1 \), \( Q \) is the total flow rate and \( BF_{max} \) is the maximum baseflow index. It is assumed that if \( B_i \geq Q_i \) the flow rate at time \( i \) is equal to \( Q_i \). Fig. 1 exemplifies the separation of flows by the application of the Lyne and Hollick numerical filter.

2.2. Analytical expressions for the estimation of recession curves

The methods of recession analysis are based on analytical expressions that describe the recessions over time, providing parameters to characterize the relationship between storage and flow in river basins. The following are the analytical expressions that are part of the computational tool developed in this work.

- Maillet (1905) — assumes a linear relationship between storage and flow \( S = k Q \) so that the recession curve can be adjusted by an exponential model as follows:
\[
Q_i = Q_0 e^{-at},
\]

where \( Q_i \) is the flow rate at time \( i \); \( Q_0 \) is the initial flow rate; \( a \) is the parameter to be adjusted.

- Boussinesq (1904) — proposes the analytical solution of the non-linear differential flow equation assuming a Depuit–Boussinesq aquifer model.
\[
Q_i = Q_0 (1 + nt)^{-2},
\]

where \( n \) is the parameter to be adjusted.

- Coutagne (1948) — assumes that \( dq/dt = -a Q^b \), whose analytical solution when \( b \neq 1 \) is expressed by:
\[
Q_i = \left[ Q_0^{1-b} - (1-b)at \right]^{1/(1-b)}.
\]

when \( b = 1 \), we use Eq. (4). Where \( Q_i \) is the flow rate at time \( i \); \( Q_0 \) is the initial flow rate; \( a \) and \( b \) are the parameters to be adjusted.

- Wittenberg (1999) — assumes a non-linear reservoir \( S = a Q^b \) when \( b \neq 1 \), so that the analytical expression can be expressed as follows:
\[
Q_i = Q_0 \left[ 1 + (1 - b) Q_i^{(1-b)/a} \right]^{1/(b-1)},
\]

when \( b = 1 \), we use Eq. (4). Where \( Q_i \) is the flow rate at time \( i \); \( Q_0 \) is the initial flow rate; \( a \) and \( b \) are the parameters to be adjusted. The expression \( dq/dt = -a Q^b \) assumed by Coutagne (1948) can also be written in the linearized form by means of logarithmic transform as follows:
\[
\log \left( \frac{dQ}{dt} \right) = \log(a) + b \log(Q),
\]

so the parameters \( a \) and \( b \) can be determined by linear regression using the \( \log(-dQ/dt) \) Vs \( \log(Q) \) ratio proposed in Brutsaert and Nieber (1977).

2.3. Extraction of recession curves

The methods for the extraction of the recession curve approximate the recession periods from historical flow series. In order to extract the recessions, we developed an automated form that uses the basic principles presented by Vogel and Kroll (1992) and Brutsaert and Nieber (1977) in determining the decreasing parts of the streamflow series. Vogel and Kroll (1992) select recession segments from the decreasing parts of the flow after applying a 3-day moving average. They
recommended to exclude 30% of the data corresponding to the largest flows of each recession segment to avoid the influence of the quick flow components (also referred to as surface flow). They assumed that the recession segments should have a minimum length of 10 days with a rate of change between consecutive flows of less than 30%. Brutsaert and Nieber (1977) consider that the recession curves are composed of the set of flows in which \( \frac{dQ}{dt} < 0 \). They exclude data that cause atypical slopes \((dQ_{i+1}/dt > dQ_i/dt)\) followed by the exclusion of the last three and the first two data points of each recession segment.

In order to extract the recessions, we developed an automated form that uses the basic principles presented by Vogel and Kroll (1992) and Brutsaert and Nieber (1977) in determining the decreasing parts of the streamflow series. Our method differs in that instead of defining maximum limits or to perform data deletion from the recession segments we use the prior application of flow separation filters so that the recession curves are drawn from the baseflows. The process of extracting the recession curves considers the baseflows from the numerical filter to determine the beginning and end of each recession period. However, we left in the MRCPtool an option to extract recession periods directly from the total flow series without the use of a filter.

The MRCPtool provides the identification of the recession curves according to the following assumptions:

- Baseflow is predominant in the recession periods so that whenever possible we should use a numerical filter before the extraction of the recession curves. To determine the baseflow, MRCPtool provides the choice of three numerical filters presented in Section 2.1. Each filter can lead to different results depending on the parameters used, therefore, care must be taken in the application. We suggest that the filter should be chosen according to the user needs and to the characteristics of the study region, if possible it is advised to compare the different approaches.
- To suppress the noise contained in the streamflow data series, a moving average of 3 points is applied. MRCPtool allows one to set the amount of times the moving average will be applied.
- Recession periods are considered to occur when rates of change between consecutive flows are less than zero \((dQ/dt < 0)\).
- The minimum duration for recessions should be informed, and can be defined as 10 days according to Vogel and Kroll (1992), 6 to 7 days according to Brutsaert and Nieber (1977) or can be defined based on the observation of the behavior of the streamflow series and specific meteorological variables for each case studied.

An example of recession curve extraction is shown assuming the baseflows determined with the Lyne and Hollick streamflow separation filter (Fig. 1).

### 2.4. Automated MRC method

For the creation of the master recession curves we use the Matching Strip Method which consists of overlapping the individual recession curves to create a single curve that can represent the general behavior of the recessions of the entire streamflow data. We have developed an automated method to perform the recession curves overlay process that performs the following steps:

1. Imports previously extracted and saved recession curves into the database;
2. Sort the recession curves by the minimum values.
3. The recession curves are moved horizontally until the position of the minimum value of each recession coincides with the position of the corresponding value in the immediate lower curve.

The method also allows the creation of MRCs with recession curves belonging to different flow classes. The procedure of class determination for the MRC is performed by manual selection of the intervals in the flow duration curve. There is an option to manually edit MRC or to exclude recessions with discrepant data.
2.5. General considerations for the graphical user interface

All steps of recession analysis can be performed through the graphical user interface (GUI) (Fig. 2). Each item of Fig. 2 is described below.

A — Select data: button that opens the window for locating data files that must be in .xlsx or .xls format. The location window allows you to browse and select files in any folder on your computer.

B — Separation of flows: allows the application of numerical filters of hydrograph separation. If the numerical filter parameter is not known one can use the MRC analysis made with unfiltered flow data to make a first approximation of the filter application parameter to separate the base flows and repeat the procedure.

C — Extracting recessions: allows to identify the recession curves from streamflow time series.

D — Methods: Using a combo box, you can choose between 4 recession analysis methods. The following methods are available:

• Matching Strip Method — provides automated construction of the MRC by overlapping curves in which individual recession segments are plotted and adjusted horizontally to overlap forming a single recession curve. As results, we obtain graphical and numerical outputs generated from the MRC analysis with parameter adjustments by four different analytical expressions presented in Section 2.2.

• Matching Strip Method with the classified method — is an automated method of creating MRCs for different flow classes where intervals are selected manually from a flow duration curve with the help of the graphical interface shown in Fig. 2b. As a result, graphical and numerical outputs of the MRC analyzes are generated for each flow class. Each MRC can be analyzed by different parameterization methods including analytical expressions and the log(−dQ/dt) versus log(Q) method that provides the comparison between the results of a linear regression model applied to describe recessions of each class, the MRC data and the flows belonging to the binned data obtained according to Kirchner (2009). All fitted expressions are displayed graphically and the parameters are shown in the statistics list and can be saved as a report in .txt format.

• Method log(−dQ/dt) Vs log(Q) — provides the use of the relation between the flows and the respective decline rates to obtain parameters characteristic of the recessions considering Eq. (8). The choice of this method allows generating graphs containing adjustments by linear regression for different sets of recession data. The adjustments are made to data sets containing (i) all recessions (ii) MRC data and (iii) BIN data. Results can be saved as a report in .txt format or in graphics (.png or .fig).

• MRC simulation method — adjusts all the recession curves individually and then generates the MRCs with the simulated recession curves. The analytical models available for the simulation of the recession curves and the MRC are presented in Section 2.2. The log(−dQ/dt) versus log(Q) method can also be applied to all simulated recessions and MRCs. The results are displayed graphically and in the form of list of parameters displayed in the statistics window. They can be saved in .txt format with the graphics saved in .png and .fig (editable in MATLAB) formats.

E — Statistics: presents a list of the results of the analysis of the recession curves containing the values of the parameters adjusted for different analytical models with the respective 95% confidence intervals. The values of coefficient of determination (R²), the Sum of Squares due to Error (SSE), adjusted R² and Root Mean Squared Error (RMSE) are also reported. The confidence intervals for the adjusted coefficients are given by:

\[ CI = c_j \pm t_{1-\alpha/2} \sqrt{S_j}, \]  

where \( c_j \) are the coefficients produced by the fit,  \( t \) depends on the confidence level and is calculated using the inverse of Student’s t cumulative distribution function, e \( S_j \) is a vector containing the diagonal elements of the covariance matrix for the estimated coefficients \( (\hat{X}^T \hat{X})^{-1} S_j \). In a linear fit, \( X \) is the design matrix, while for a non-linear fit \( X \) is the Jacobian matrix of the adjusted values in relation to the coefficients. \( X^T \) is the transpose of matrix \( X \), and \( s^2 \) is the mean squared error (https://uk.mathworks.com/help/curvefit/confidence-and-prediction-bounds.html). The report button generates files in .txt format. Along with the reports, figures are saved automatically.

F — Recessions: lists all of the recessions identified in the flow data series. When a recession is selected in the list the editing options allow to exclude or move the recession appear if any MRC method is being used.

G — Graph window: Graphics outputs main window.

H — Curve movement: allows you to move the recession curves to manually correct possible imperfections in the MRCs. To move a curve you must select it in the list of recessions (to see the numbering of the recession curves you must check the checkbox Number Recessions). This feature can only be used with methods that involve creating or viewing MRCs.

I — Graph properties: allows direct editing of graphical properties including axis titles and scales and unit conversion. It also offers the options of inserting recession numbering in the MRC and making editable figures generated in external graphic windows that allow you to take advantage of native MATLAB graphics editing capabilities.

J — Select fit view: allows to choose the analytical expressions (Section 2.2) that will be used in the recession analysis.

K — Select plot type and View: this option appears only when Matching Strip Method (Classified) is selected in Methods (shown in topic D). The combo box Select plot type allows you to choose between viewing the MRC or log(−dQ/dt) versus log(Q) and the combo box View allows to choose the class to be visualized.

In addition to the functions described above, MRCPtool provides the import and export of MRCs during analysis. The Export MRC and Import MRC options are available from the File menu in the upper left corner of the tool. The Export MRC function exports the MRC (complete or the selected Class in the combo box View) under analysis. If you want to start the analysis from a previously saved MRC you can use the Import MRC option. After opening the MRC file, all recession curves will be displayed in the recession list (described in topic F) and all analysis methods can be applied.

3. Example: determination of the parameters of a MRC from flow data in a river basin

In this work we used 44 years of daily streamflow data to exemplify the use of the MRCPtool. The following describes some of the results that can be obtained with the tool.

In Fig. 1a we show the series of flow data after the application of the Lyne and Hollick (1979) flow separation filter. For this example we used the numerical filter parameter \( a = 0.9925 \) which by visual interpretation best suited the determination of the base flows (Fig. 1a). The flows used to identify the recession curves were the base flows determined with the Lyne and Hollick (1979) filter after the application of a moving average, an example of a recession curve is shown in Fig. 1c. We defined that the curves would have a minimum duration of 10 days. In all, 82 recession curves have been identified (this number can be increased if the moving average is applied more than once or if the minimum duration is decreased).

In Fig. 3b we show the MRC obtained with the matching strip method and using the analytical expressions presented in Section 2.2. The methods of Coutagne and Wittenberg describe a behavior similar to the adjustment by the Maillet method that assumes a linear reservoir.
The Boussinesq method better adjusts the larger flows and in this case did not fit the behavior of the MRC.

The fitted parameters of the MRC (Fig. 3b) are presented in Table 1. It can be seen that the parameter $b$ with a 95% confidence interval can assume a value of 1 so that the Eqs. (6) and (7) of 2 parameters can be replaced by Eq. (4) with only 1 parameter. Therefore the baseflow in the basin can be well described by the analogy with a linear reservoir. However, low flows less than $1\text{ m}^3/\text{s}$ exhibit a different behavior which is best described by a nonlinear model.

The Fig. 3c shows the relationship between $\log(-dQ/dt)$ and $\log(Q)$ for all curves recession (gray dots) for data BINs (black squares) and MRC data (red circles). The linear regression for all recessions is similar to the application considering only the BIN data, but the adjustment of the MRC data is shifted downwards influencing the parameter $a$ (intercept) and presents a similar slope, this is explained by the fact that the MRC considers only the smallest flows of each recession curve.

In Table 2 we present the parameters obtained by linear regression corresponding to the adjustments shown in Fig. 3c. The BIN data provide an adjustment that represents the set of all the data with greater influence of the high flows, but the MRC allows adjusting the recessions giving greater weight to the low flows that commonly occur in periods of drought and are a determining factor for the sizing of hydraulic systems and water supplies.

Another important aspect shown in Fig. 3b is the different behavior of the flows smaller than $1\text{ m}^3/\text{s}$, indicating that it would be interesting

![Fig. 2. Graphical user interface (GUI) of the MRCPtool. (a) Main window and (b) GUI for the classification of master recession curves.](image)
Fig. 3. Master Recession Curves (MRC) and graphs of the relation \(\log(-\frac{dQ}{dt})\) versus \(\log(Q)\) before and after MRC segmentation. (a) Flow duration curve used for creating MRC; (b), (d) and (f) show the MRCs and the adjustments by the analytical expressions of Maillet, Coutagne, Boussinesq and Wittenberg; (c), (e) and (f) relation \(\log(-\frac{dQ}{dt})\) versus \(\log(Q)\) where the data were adjusted by linear regression considering the all recessions data (gray dots), BIN data (black squares) and MRC data (red circles). (b) and (c) use all the recession curves, (d) and (e) use the recession curves belonging to MRC with flow rates greater than 0.43 m\(^3\)/s and (f) and (g) use the recession curves belonging to MRC of flows smaller than 0.42 m\(^3\)/s with a range of values extended to the beginning of the first recession curve (flow rate \(\approx 1\) m\(^3\)/s).

Table 2

<table>
<thead>
<tr>
<th></th>
<th>Parameter</th>
<th>MRC</th>
<th>BINs</th>
<th>Recessions</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>(CI_{0.05})</td>
<td>(0.070;0.075)</td>
<td>(0.067;0.076)</td>
<td>(0.072)</td>
</tr>
<tr>
<td>b</td>
<td>(CI_{0.05})</td>
<td>(0.864;0.897)</td>
<td>(0.856;0.916)</td>
<td>(0.881)</td>
</tr>
<tr>
<td>RMSE</td>
<td></td>
<td>0.276</td>
<td>0.096</td>
<td>0.284</td>
</tr>
<tr>
<td>(R^2)</td>
<td></td>
<td>0.810</td>
<td>0.973</td>
<td>0.884</td>
</tr>
</tbody>
</table>

Table 2: Parameters adjusted by linear regression considering all flows of the recession curves (Recessions), BIN data and MRC data where \(CI_{0.05}\) and \(CI_{0.05}\) are the 95% confidence intervals for parameters \(a\) and \(b\) respectively.

to analyze the MRC by separating the flow rates in two or more classes. In Fig. 3a we present the flow duration curve used to visualize the flows and to select the intervals that define the classes for the separation of the MRC by means of the method of separation of MRC available in the tool that we present. The red vertical line was marked on \(Q_{90}\) to separate the data set into two classes where class 1 is in the flow range [97.61, 0.42] (Fig. 3d) which behaves similarly to a linear reservoir and class 2 in the interval [0.43, 3.75e−05] (Fig. 3f) where the adjustment of the data is more influenced by the low flows and has non-linear behavior.

In Fig. 3d we show the adjustments of the MRC using the recession curves of class 1. It is possible to verify that the linear reservoir model (Eq. (4)) adjusts well to the data. In Fig. 3e we present the graph of the relationship between \(\log(-\frac{dQ}{dt})\) and \(\log(Q)\) for the data of the recession curves belonging to class 1 in which the adjustment for the data composing the MRC (red circles) was performed. Also shown are the adjustment for the BINs (black squares) data and for the flows belonging to the recess curves (gray dots). In Table 3 it is verified that the parameter \(b\) is close to 1 so that within a 95% confidence interval Eqs. (6) and (7) can be replaced by the Eq. (4) of only one parameter providing a good adjustment of the base flows above 0.43 m\(^3\)/s. In Fig. 3f we show the MRC adjustments for the flows of the recession
curves belonging to class 2 in which it is verified that the low flows (less than 0.43 m³/s for this example) does not have a good fit by means of the analytical expressions tested. In this case the best adjustment of the base flows can be obtained by means of the relation between \( \frac{\log(-dQ/dt)}{dQ/dt} \) and \( \log(Q) \) of the flows belonging to the MRC as shown in Fig. 3g.

It can be seen that the adjustment that considers all recessions (gray dots) and the adjustment of the BINs (black squares) in for the recession curve of class 2 have similar parameters that are more influenced by the high flows (Fig. 3g). On the other hand the adjustment of the data of the MRC (red circles) consider the smaller flows of each curve of recession providing a better approximation of the low flows.

In Table 4 it is verified that the base flows adjusted from the flows belonging to the MRC (Fig. 3f) have a lower inclination than the adjustments of the BIN data and the complete set of flows of the curves of recession, showing that the low flows vary more slowly and have non-linear behavior since \( b \neq 1 \). Thus, flows smaller than 0.43 m³/s can be represented by Eq. (6) with parameters adjusted by the ratio between \( \log(-dQ/dt) \) and \( \log(Q) \).

After verifying that the behavior of recession curves for the basin is predominantly exponential, we use the method of creating simulated MRCs that we provide in the tool to create an MRC from the individual adjustment of each curve of recession assuming that all are well represented by Eq. (4). Simulated recessions (in blue lines) and MRC (red circles) are shown in Fig. 4a.

In Fig. 4b we show the relationship between \( \log(-dQ/dt) \) and \( \log(Q) \) and the linear regression adjustments for the simulated recession curves, BINs data and simulated MRC. Fig. 4b shows how data adjustments would be made by assuming that all recession curves are represented by the exponential model characteristic of a linear reservoir. Thus, both the MRC and the BIN data have similar adjustments of the average flow behavior that can be verified in the Table 5.

The example above illustrates some of the applications of the tool developed in this work, and shows a way to study recession periods with different analytical approaches compared to automated methods of creating recession master curves (MRC) together with analysis of the relation between \( \log(-dQ/dt) \) and \( \log(Q) \). Graphical and numerical analyses allow to identify significant differences in flow behavior (standard changes) and to define classes for the application of different analytical approaches for the parameterization of MRCs and recession curves.

4. Conclusions

The MRC tool presented in this article provides the application of different methods of recession curve analysis in an easy and intuitive way through a graphical user interface developed in MATLAB software. It is an open-source tool that provides automated recursive curves assembly (MRC) capabilities and provides graphical visualization and numerical analysis of results with automatic report generation containing parameters adjusted by four different analytical expressions. The application of the tool and the basic procedures for the analysis of recession curves were demonstrated using an example case in which it is clear that the joint use of the different parameterization methods considering automated forms of MRC creation, the relation between \( \log(-dQ/dt) \) and \( \log(Q) \). Different types of analytical expressions can bring significant gains to the analysis of flows in recessions periods, allowing to compare results and to explore specific parts of the MRCs for pre-established flow classes based on the flow duration curve.

Acknowledgments

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Computer code availability

• Name of code: MRCPtool
• Developer: Tomas Carlotto
• Contact address: tomas.carlotto@posgrad.ufsc.br (T.Carlotto) and pedro.chaffe@ufsc.br (P.L.B Chaffe).
• Year first available: 2019
• Software required: MATLAB® version 2014b or later
• Program language: MATLAB®
• Program size: 300 kb
• Details on how to access the source code: the source files of the MRCPtool code can be downloaded from site: http://www.labhidro.ufsc.br/static/software/MRCPtool.rar. Source code and updates are also available at https://github.com/T-Carlotto/MRCPtool/blob/master/MRCPtool.rar in downloads.

References