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Are streamflow recession characteristics really characteristic?

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Abstract

Streamflow recession has been investigated by a variety of methods, often involving the fit of a model to empirical recession plots to parameterize a non-linear storage-outflow relationship. Such recession analysis methods (RAMs) are used to estimate hydraulic conductivity, storage capacity, or aquifer thickness and to model streamflow recession curves for regionalization and prediction at the catchment scale. Numerous RAMs have been published, but little is known about how characteristic the resulting recession models are to distinguish characteristic catchment behavior. In this study we combined three established recession extraction methods with three different parameter-fitting methods to the power-law storage-outflow model to compare the range of recession characteristics that result from the application of these different RAMs. Resulting recession characteristics including recession time and corresponding storage depletion were evaluated for 20 meso-scale catchments in Germany. We found plausible ranges for model parameterization, however, calculated recession characteristics varied over two orders of magnitude. While recession characteristics of the 20 catchments derived with the different methods correlate strongly, particularly for the RAMs that use the same extraction method and while they rank the catchments relatively consistent, there are still considerable differences among the methods. To elucidate this variability we discuss the ambiguous roles of recession extraction procedures and the parameterization of storage-outflow model and the limitations of the presented recession plots. The results suggest strong limitations to the comparability of recession characteristics derived with different methods, not only in the model parameters but also in the relative characterization of different catchments. A multiple methods approach to investigate streamflow recession characteristics should be considered for applications whenever possible.

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1 Introduction

Recession analysis methods are widely used to investigate the storage-outflow relationship of catchments. As in rainless periods streamflow originates solely from stored water in a catchment (aquifers, soils, lakes, etc.) the shapes of these recession curves should be characteristic for a specific catchment. If this is the case, then they could be used for low flow prediction and estimation of total dynamic storage. Generally, low flow at the catchment scale is examined with baseflow separation techniques, low flow frequency analysis, low flow indices and recession analysis methods, which have been comprehensively reviewed by Hall (1968), Tallaksen (1995), Smakhtin (2001) and Dewandel et al. (2003). There are large differences in these low flow analysis methods that often employ subjective or somehow imprecise graphical approaches (e.g. master recession curves, matching strip, recursive filters, threshold determination for low flow indices, dependence on a certain recession starting point with variable initial catchment conditions, etc.). For instance, Anderson and Burt (1980) have shown that graphical plotting techniques can lead to biased recession characteristics and even semi-logarithmic plotting is more appropriate to describe single recession events than a general storage-outflow behavior. To analyze streamflow recessions individually instead of collectively ignores the variability of storage depletion, which is represented by numerous recession events and not by one single event.

To overcome most of these restrictions Brutsaert and Nieber (1977) presented a method to parameterize a power-law storage-outflow model based on the Boussinesq equation, which described flow from an unconfined aquifer into the adjoined stream (Hall, 1968). For that purpose the negative decline in discharge ($-\mathrm{d}Q/\mathrm{d}t$) ($\mathrm{mm\,d^{-2}}$) is plotted versus discharge (Q) ($\mathrm{mm\,d^{-1}}$) to eliminate time as a reference, hereafter referred to as "recession plots" following Kirchner (2009). This allows analyzing catchment-specific streamflow recessions collectively and to derive storage-outflow relationships correlated to aquifer hydraulic properties solely by the means of discharge Q as a function of storage S ($\mathrm{mm\,d^{-1}}$). In absence of aquifer recharge or leakage and when precipitation P (mm d^{-1}) and evapotranspiration (mm d^{-1}) is negligible or very small compared to discharge Q (Kirchner, 2009), the water balance equation, can be used to relate change in storage S (mm d^{-1}) directly to discharge Q:

$$\frac{dS}{dt} = -Q. \quad (1)$$

Consequently a power law relationship between $-dQ/dt$ and discharge Q:

$$-\frac{dQ}{dt} = aQ^b \quad (2)$$

with factor a (mm$^{(1-b)}$ d^b) and exponent b (–) allows for both linear ($b = 1$) and non-linear ($b \neq 1$) storage-outflow relationships (Brutsaert and Nieber, 1977; Wittenberg and Sivapalan, 1999; Rupp and Selker, 2006a; Krakauer and Temimi, 2011).

With that power law relationship (Eq. 2) a variety of hydraulic aquifer properties can be represented and analyzed by recession plots. The plots are best shown on log-log-scale, because both $-dQ/dt$ and Q typically span several orders of magnitude during recessions (Kirchner, 2009). However, a reliable and unique description of catchment-specific recession behavior is still challenging, because first, a specific extraction procedure is required to obtain a characteristic recession plot and second, a method to fit the power-law relationship to derive storage-outflow model parameters has to be chosen.

Some studies have used additional rainfall data to obtain recession plots to exclude streamflow recession during periods with precipitation (Moore, 1997; Kirchner, 2009; Ajami et al., 2011; Shaw and Riha, 2012). However, when local rainfall data is missing or seems to be imprecise the declining parts of hydrograph ($dQ/dt < 0$) can be used to identify streamflow recessions (Brutsaert, 2008; Palmroth et al., 2010). Early stages of these recessions are often excluded to avoid the influence of preceding storm and surface runoff. Commonly at least the first 5 days of periods with declining streamflow are removed from analysis (e.g. Brutsaert and Nieber, 1977; Szilagyi and Parlange, 1998; Peña-Arancibia et al., 2010), but also studies can be found that eliminated an interval between 1 and 10 days (Zecharias and Brutsaert, 1988a; Vogel and Kroll, 1992; Parlange et al., 2001; Malvicini et al., 2005; van Dijk, 2010; Wang and Cai, 2010). Stall and Singh (1971) divided the declining hydrograph at the inflection point and analyzed only the latter part to reduce influence of surface flows at the beginning of recession. Other studies have extended this restriction and used only recessions that started two days after the inflection point (Wittenberg and Sivapalan, 1999; Wang and Cai, 2010). Moreover also a minimum recession length was established (Vogel and Kroll, 1992) to assure streamflow recession are connected to pure storage depletion (longer recessions) rather than to be influenced by surface or storm flow (shorter recessions). The threshold for this minimum length varied widely in published extraction procedures from 2 days (e.g. Mendoza et al., 2003), 3 days (Federer, 1973), 5 days (Aksoy and Wittenberg, 2011) up to 10 days (Vogel and Kroll, 1992) and it is often an issue of available streamflow recession data and regional hydrological and climatological properties.

Variation of storage-outflow model parameterization results from different parameter fitting methods to the recession plots. Although the non-linear, power law relationship can be expressed as a linear model in log-scaled recession plots, one has to decide in which way parameters a and b should be fitted to recession data. With a linear storage-outflow model ($b = 1$) recession analysis methods might be better comparable among each other, but a fixed slope may not represent dynamic catchment behavior over a wide range of recession flows (Tallaksen, 1995). However, Wittenberg (1999) concluded that a fixed $b = 1.5$ seems to be a standard power exponent for unconfined aquifers and Wittenberg and Sivapalan (1999) suggested that this assumption is more physically realistic than a linear storage-outflow relationship. Brutsaert and Nieber (1977) argued that lower envelopes (with fixed slopes $b = 1$, 1.5 and 3) would represent the smallest $-\mathrm{d}Q/\mathrm{d}t$ for a certain Q and therefore is a characterization of a non-linear and catchment-specific storage depletion from aquifers. One should note that evapotranspiration may cause faster streamflow recession (Federer, 1973) and a lower envelope will represent a more resilient storage-outflow relationship, whereas

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an upper envelope with a maximum observable rate of streamflow decline (Zecharias and Brutsaert, 1988a; Rupp and Selker, 2006a) will estimate faster recessions, e.g. due to evapotranspiration from groundwater.

Apart from envelopes numerous studies have implemented a linear model fitting obtained by least square fit through all recession data or binned means in order to focus more on the average recession behavior of catchments (Vogel and Kroll, 1992; Kirchner, 2009; Krakauer and Temimi, 2011). Fitting a linear regression through all data points in a recession plot gives the same weight to all $-\mathrm{d}Q/\mathrm{d}t$ values for a certain Q. Alternatively, a "binning" procedure that divides recession plots in different segments by splitting the range of log-Q into several parts has been employed (Kirchner, 2009). For each part (*bin*) averaged values of $-\mathrm{d}Q/\mathrm{d}t$ and Q can be calculated separately and thus, leads to a partitioning of recession behavior according to certain streamflow rates. The mean values of $-\mathrm{d}Q/\mathrm{d}t$ and Q of a variable amount of bins can then be used to fit the linear model. For example, binning was used by Parlange et al. (2001) to illustrate the sensitivity of the linear model's parameterization to the choice of lower compared to upper envelopes. Palmroth et al. (2010) presented an approach to combine lower envelope and binning by the means of a boundary line analysis adopted from Schäfer (2000). The authors calculated a slightly upshifted "lower" envelope to receive a relationship between $-\mathrm{d}Q/\mathrm{d}t$ and Q, which is not influenced by the lowest $-\mathrm{d}Q/\mathrm{d}t$ values in the recession plot. Those lowest values of $-\mathrm{d}Q/\mathrm{d}t$ could be an issue of streamflow measurement's precision. A scatter in recession plots might be produced by multiples of the minimum rate of $-\mathrm{d}Q/\mathrm{d}t$ (Rupp and Selker, 2006a), especially in the case of low streamflow. Consequently Kirchner (2009) used binned means and standard errors for $-\mathrm{d}Q/\mathrm{d}t$ and Q to fit an empirical function weighted by the reciprocal of the squared standard errors and to reduce the influence by highly uncertain data points. This procedure was since then successfully applied for different purposes (i.e. Krakauer and Temimi, 2011; Staudinger et al., 2011; Ajami et al., 2011).

Not only have a variety of adaptations of the original method by Brutsaert and Nieber (1977) good applicability, but these were applied to various catchment types with

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different catchment areas and different physiographic, geological, and climatic characteristics including in humid (Troch et al., 1993), in tropical (Peña-Arancibia et al., 2010), in semi-arid (Mendoza et al., 2003; Ajami et al., 2011) and sub-artic (Lyon et al., 2009) regions. Furthermore methods were applied to catchments with different landuse characteristics such as forested catchments (Parlange et al., 2001), deforested catchments (Malvicini et al., 2005), mountainous catchments (Zecharias and Brutsaert, 1988a; Teuling et al., 2010) and also explicitly in small catchments (Krakauer and Temimi, 2011).

The variety of applicability can also be seen in studies which estimated aquifer thickness (Dewandel et al., 2003), mountain block recharge (Ajami et al., 2011), catchment-scale evapotranspiration (Szilágyi et al., 2007; Palmroth et al., 2010) or permafrost thawing rates (Lyon et al., 2009). Other authors detected trends in groundwater storage (Brutsaert and Sugita, 2008) or quantified human influences on low flows (Wang and Cai, 2009). Kirchner (2009) demonstrated that with a recession analysis method the preceding precipitation amount is quantifiable. All these studies used slightly different adaptations of the original recession analysis method proposed by Brutsaert and Nieber (1977) and may therefore result in recession characteristics that are more dependent on the methodology rather than the catchment characteristics.

Nevertheless, a considerable number of studies have shown that streamflow recession characteristics could be related to catchment characteristics (see Price, 2011, for recent review), but regional generalizations of this relationship are still challenging (e.g. Gottschalk et al., 1997; Smakhtin, 2001; Aksoy and Wittenberg, 2011). Some of the issues are that often only one recession analysis method has been applied or sensitivity of modified analysis methods have been tested only in one catchment. More often streamflow recession analysis methods are adjusted for a specific case of application or a distinct set of catchments. However, when storage-outflow behavior is solely analyzed with streamflow data multiple methods approaches have been suggested to overcome potential uncertainty of a single recession analysis method (Halford and Mayer, 2000).

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Based on these experiences we ask the question, how uncertain a relationship between catchment characteristics and streamflow recessions derived by a single recession analysis method with specific assumptions and simplifications will be? To our knowledge no systematic comparison of different recession analysis methods has investigated this question and approaches to quantify the uncertainty of the choice of recession analysis method are still missing. In this study we combined three established recession extraction methods with three different parameter-fitting methods to the power-law storage-outflow model. The objectives of our study are:

1. to compare the range of recession characteristics that result from the application of these different recession analysis methods,

2. to elucidate the relative roles of extraction procedures and parameterization method for the storage-outflow model on the recession characteristics and

3. to test the effect of applying different recession analysis methods to distinguish recession characteristics of a regional set of streamflow records.

2 Methods

To ensure comparability of the recession analysis methods we followed Brutsaert and Nieber (1977) to pair streamflow $Q = (Q_{t-1} + Q)/2$ and streamflow recession rates $\mathrm{d}Q/\mathrm{d}t = Q_{t-1} - Q$ consistently. We then implemented three established recession analysis procedures: the Vogel method (Vogel and Kroll, 1992), the Brutsaert method (Brutsaert, 2008) and the Kirchner method (Kirchner, 2009). Each consists of a specific extraction procedure and a specific parameter fitting by means of herein called "linear regression", "lower envelopes" and "binning", respectively. Hence, the combination of extraction procedures and model parameterization lead to nine specific recession analysis methods (RAMs), whereas originally the Vogel method uses a linear regression, the Brutsaert method a lower envelope and the Kirchner method the binning procedure for model parameterization.

2.1 Recession extraction

The Vogel method selects recession segments from the decreasing parts of 3-day moving averages of streamflow. These segments must have a minimum length of continuous 10 days and the decline in discharge for two consecutive data values has to be smaller than 30 %. Furthermore the first 30 % of every recession segment is excluded to avoid the influence of storm- and surface-runoff at the beginning of streamflow recessions. The Brutsaert method omits non-recession parts from hydrograph with a rule-base procedure. Data points within a recession segment have to comply with the following criteria: no values with positive or zero $\mathrm{d}Q/\mathrm{d}t$ are allowed, also three data points after the last and two data points before the first positive or zero $\mathrm{d}Q/\mathrm{d}t$ are eliminated. Additionally a fourth data point is excluded after major events. Due to no further specification in this study a major event was defined as streamflow values greater than the 30 % exceedance frequency ($Q30$) during the period of record. Further on the Brutsaert method eliminates data points followed by values with a larger $-\mathrm{d}Q/\mathrm{d}t$ in order to exclude sudden anomalies and the ups and downs of $\mathrm{d}Q/\mathrm{d}t$ values during a recession. In contrast to these procedures the Kirchner method uses all pairs of streamflow data Q and $\mathrm{d}Q/\mathrm{d}t$ during dry periods. Due to lack of precipitation and evapotranspiration data this method was adapted for data points with negative values of $\mathrm{d}Q/\mathrm{d}t$. A functional relationship between $-\mathrm{d}Q/\mathrm{d}t$ and Q is determined based on ranges (bins) of Q, i.e. sorted averages of $-\mathrm{d}Q/\mathrm{d}t$ in certain ranges of Q. Working from the highest to the lowest values of logarithmic Q, bins with at least 1 % of streamflow range are delimited to calculate the corresponding mean and standard error for $-\mathrm{d}Q/\mathrm{d}t$ and Q. Each bin then contains enough points that the half of mean ($-\mathrm{d}Q/\mathrm{d}t$) is larger than its standard error.

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2.2 Parameterization of storage-outflow model

The power law relationship between $-\mathrm{d}Q/\mathrm{d}t$ and streamflow Q (Eq. 2) can be log-transformed to

$$\log\left(-\mathrm{d}Q/\mathrm{d}t\right) = \log(a) + b\log(Q) \quad (3)$$

to derive $\log(a)$ ($\mathrm{mm}^{(1-b)}\,\mathrm{d}^b$) as intercept and b (–) as slope of the best fit linear regression in place of a non-linear storage-outflow function (Brutsaert and Nieber, 1977; Wittenberg and Sivapalan, 1999). The Brutsaert method suggests a lower envelope to parameterize the recession model, which in this study was fitted by means of a quantile regression (Koenker and Bassett, 1978) with 5 % of the points below it to take unavoidable errors into account. The Vogel method instead uses a linear regression through all data points by ordinary least squares regression. The Kirchner method fits a least squares regression through the binned means, weighted by the square of the standard error of each binned average (Kirchner, 2009). Due to the fact that this weighting is based on the previously calculated standard error of the binned means we followed Krakauer and Temimi (2011), who have suggested a minimum data points' quantity in each bin. In order to calculate weights for each bin in each catchment we have to define a minimum amount of binned data points ($n = 6$). Figure 1 illustrates an example of the applied RAMs and the different recession plots.

2.3 Recession characteristics

As a disjoint interpretation of the recession parameters a and b may be misleading, we computed two established recession characteristics to evaluate the impact of the parameterization on the prediction of streamflow recession. Recession time T_R (d) is defined as the time interval in which streamflow declined from median flow (*Q50*) to a low flow threshold (*Q90*). Storage depletion S_R (mm) is the cumulative summation of streamflow solely related to storage outflow. Starting with catchment-specific median flow *Q50* as initial streamflow both recession characteristics were calculated as

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a general solution of Eq. (3) in respect to time t with:

$$Q(t) = Q_o e^{-at}, \qquad \text{if } b = 1,$$

$$Q(t) = \left(Q_o^{1-b} - [1-b]\ \text{at}\right)^{\frac{1}{1-b}}, \qquad \text{if } b \neq 1, \qquad (4)$$

whereas a and b are the fitted recession parameters (Szilagyi and Parlange, 1998). Note that in the first case with $b = 1$ the storage-outflow model is an exponential decay function. Numerous comparable solutions for storage-outflow based on non-linear relationships between storage and discharge can be found in literature (e.g. Brutsaert and Nieber, 1977; Tallaksen, 1995; Moore, 1997; Wittenberg, 1999).

2.4 Comparison among recession analysis methods (RAMs)

The distribution of the nine different derived model parameters a and b and the recession characteristics T_R and S_R for the 20 streamflow records were assessed for similarities and differences. A Student's t-Test was performed to test whether the mean T_R and mean S_R of two RAMs differ significantly from each other (with 95 % confidence interval, $p < 0.05$). The method-specific variability of T_R and S_R is evaluated with the help of boxplots spanning interquartile range with whiskers extending to upper and lower 5 % percentiles.

A Spearman rank correlation coefficient (Spearman's rho) was calculated between the T_R and S_R of all pairs of catchments derived with all RAMs. If the predicted T_R und S_R are really characteristic for a catchment, the different recession analysis methods should rank the catchments similarly with respect to these predictions. Spearman's rho of 1 reveals the same order of all catchments, a coefficient of −1 the complete opposite order.

Besides the analysis of rank correlation we calculated the regression coefficient among all RAMs results. For example, a regression coefficient of 1 indicates not only the same order but also the same estimations for predicted storage depletion by two

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different RAMs, a coefficient of 0.5 or 2 quantify that one RAM compared to another RAM leads to halved or doubled amount of storage depletion, respectively.

3 Study sites and data

We used daily streamflow data (1971–2009) of 20 meso-scale catchments in the state of Baden-Württemberg in Germany (Fig. 2). They represent a wide range of physiographic and hydrogeological characteristics such as different geology, slopes or altitudes. Daily streamflow data in $m^3 s^{-1}$ were first converted to unit area runoff ($mm\,d^{-1}$). Streamflow in all catchments is near-natural with no known influence by dams, withdrawals, reservoirs or irrigation. Three streamflow records have one missing value, one record has 18 and one record has 247 days with missing streamflow values, which were excluded from the analysis.

4 Results

Combinations of 9 RAMs and streamflow data of 20 catchments led to 180 different recession model parameterizations. For simplification in the results section abbreviations are used for the different extraction procedures VOG (Vogel's method), BRU (Brutsaert's method) and KIR (Kirchner's method) as well as for the three methods of model fitting LE (lower envelope), REG (linear regression) and BIN (binning).

Intercepts a ranged (except for one outlier) from 0.001 up to 0.36 $mm^{(1-b)}\,d^b$ and slopes varied from 0.39 to 3.21 (Fig. 3a, b). We found a systematic order for parameters' medians within each extraction procedure. For intercept a the order is LE < REG < BIN, for slope b the order is LE > REG > BIN, except KIR estimates. LE model fitting led to notably smaller values for intercept a than all other methods, however, no clear pattern emerged for estimates of slope b.

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We identified inverse patterns to a in the results of recession time T_R (Fig. 3c) and storage depletion S_R (Fig. 3d). Values of T_R for all RAMs spanned two orders of magnitude from a few days up to almost one year. This can be shown in highly variable T_R for LE (62–342 days) with similar medians 105.5 days (VOG), 119.5 days (BRU) and 123.5 days (KIR) among the extraction procedures. However, REG and BIN model fitting with VOG and BRU extraction procedures led to shorter T_R of around three weeks (18.5 to 24.5 days), whereas KIR resulted in very quickly receding recessions with medians from 7 to 11 days. Accordingly to T_R large S_R was found for LE (up to 425 mm) as well as smaller values especially for KIR.BIN down to almost 1 mm (Fig. 3d). Generally, LE generated approximately six fold longer recession times and larger storage depletions than the other model fitting methods. It also can be shown that apart from LE model fitting KIR led to slightly shorter recession times T_R, thus, also smaller storage depletions S_R were found.

The t-test (values not presented) identified two groups with a significantly similar mean S_R ($p \leq 0.05$). The first group contains any particular combination of VOG.REG, VOG.BIN, BRU.REG and BRU.BIN ($n = 6$). The second group contains the RAMs with LE model fittings: VOG.LE, BRU.LE and KIR.LE ($n = 3$). These groups can also be seen in the boxplots for calculated storage depletion (Fig. 3d). The remaining 27 RAM combinations had statistically different means of S_R.

In addition to the values, we distinguished the RAMs by how they order the calculated recession characteristics (e.g. storage depletion) of the 20 streamflow records. Spearman's rho (ρ) values that compare the catchments' ranking according to the recession characteristics T_R and S_R are shown in Table 1. Spearman's rho for all pairs of RAMs ranged from 0.31 up to 0.91 for T_R and from 0.57 up to 0.96 for S_R. Hereinafter we focus the analysis on S_R, because the results for T_R are comparable. Values of ρ were all positive, hence indicated a positive correlation between all RAMs. The most consistent ranking was found within each extraction procedure regardless of which model fitting method was used. Mean Spearman's rho is highest within KIR ($\bar{\rho} = 0.92$), but ranking is also relatively good for BRU ($\bar{\rho} = 0.88$) and VOG ($\bar{\rho} = 0.82$). In contrast to the relationships for the same extraction procedure the $\bar{\rho}$ is smaller for the different model fitting methods (each $\bar{\rho} < 0.82$) with order of rank correlations BIN > REG > LE. But, more importantly we found weak to medium rank correlations ($\bar{\rho} = 0.73$) among the three originally published combinations of recession extraction and model fitting (Vogel method with linear regression, Brutsaert method with lower envelope, Kirchner method with binning).

The regression coefficient, i.e. the slope of a linear regression between two RAMs can be used to further quantify the relationship between different RAMs (Fig. 4). The coefficient varied two orders of magnitude for S_R. Strong linear relationships with a regression coefficient between 1.28 and 0.77 can be found between VOG.REG, VOG.BIN, BRU.REG and BRU.BIN (mean $R^2 = 0.94$). The relationships between the three originally published methods were notably weaker (mean $R^2 = 0.73$). Model fitting by linear regressions or binning combined with Kirchner's extraction method generally led to smaller S_R in comparison to all other RAMs (values < 1.0 in the columns KIR.REG and KIR.BIN in Fig. 4). Many RAMs differ by a factor of more than 5 (or less than 0.2) among storage depletion for the 20 catchments (Fig. 4).

Based on the 20 streamflow records we were able to group the different RAMs by the derived recession characteristics. Lower envelopes consistently lead to significantly longer recession times (median 104 days) and larger storage depletions (median 61 mm). While fitting by linear regression and binning resulted in shorter median recession times of 20 and 17 days and corresponding median storage depletions of 11 and 9 mm, respectively, the relative ranking of these values was consistent for the different extraction methods constituting the RAMs. Interestingly, regression coefficients near 1.0 between both VOG.REG and BRU.REG as well as between VOG.BIN and BRU.BIN indicated that here the calculated recession characteristics are dominated more likely by model fitting method than by the extraction procedure. In contrast to these findings we identified a ranking among extraction methods (BRU > VOG > KIR) when estimating storage depletion with lower envelope fittings (means of 100, 82 and 55 mm for the 20 catchments).

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5 Discussion

5.1 Range of recession characteristics

The RAMs used in this study were all applicable to all streamflow records and the derived ranges of intercept and slope are in the range of literature values and can be interpreted in the lights of both storage-outflow behavior and catchment characteristics. Brutsaert and Nieber (1977) stated that values of b from 1 for late recession segments (long-time behavior) to 3 for early stages of recession (short-time behavior) are in a physically reasonable range. They identified decreasing slope b in power law storage-outflow relationships as a function of continuous drawdown, whereas Rupp and Selker (2006b) summarized that the range of slope b may be used for aquifer characterization as values ranging from 1 to 2 indicated sloping aquifers and from 1.5 to 2 horizontal aquifers. If we consider the upper and lower 10 % of calculated values to be outliers, in this study slope b ranged from 1.1 to 2.1 with an average of 1.55. Other studies have found comparable ranges of slope b for different purposes, e.g. between 1 and 1.6 (Palmroth et al., 2010), approximately 2 (Biswal and Marani, 2010; Shaw and Riha, 2012) or even higher than 2 (Szilágyi et al., 2007). In fact individual recession events often have larger slopes b, but those are concealed in recession plots which contain all recession events (Rupp et al., 2009; Biswal and Marani, 2010; Shaw and Riha, 2012). The resulting flattening of fitted models compared to individual events' recession slopes is a limitation of the presented RAMs based on recession plots.

Similar to the slopes the derived intercepts are in the range of literature values (e.g. Szilágyi et al., 2007; Palmroth et al., 2010; Shaw and Riha, 2012). Generally, the intercept can be seen as an estimator of storage volume whereas derived slopes are more related to the rate and dynamic of storage depletion. We have shown that the pattern of the derived recession characteristics (recession times and storage depletion) among the RAMs is linked more closely with the pattern of intercepts than with the distribution of slopes (Fig. 3). Small intercepts lead to longer recession times and larger storage depletions (e.g. RAMs with model fitting by lower envelope), whereas recession times

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and smaller storage depletions coincide with larger intercepts (e.g. RAMs with model fitting by binning). However, apart from these patterns the distribution of fitted intercepts a and slopes b lead to a wide range of recession times and storage depletions. The interquartile ranges of all calculated storage depletion and recession time values are higher than 90 mm and 70 days, respectively. The variation of these recession characteristics over two orders of magnitudes can be seen as an estimation of RAMs' uncertainty.

5.2 Roles of extraction procedure and parameterization method

Both the extraction procedure and the model fitting method to parameterize a storage-outflow relationship can cause the uncertainty of comparable RAMs. To elucidate the parameterization we investigated the different extraction procedures and fitted models. The ratio of analyzed streamflow data to total time-period length differs notably among the three recession extraction procedures: 32 % (Kirchner), 13 % (Vogel) and 7% (Brutsaert). The smaller amount of data within Vogel's and Brutsaert's procedures is mainly caused by the required minimum length of recession segments and the strict elimination of non-recession parts. Furthermore, both procedures exclude 3–4 days of early recession stages, thus recessions have to prolong at least 4–5 days to be considered. However, RAMs with Kirchner's extraction procedure take early stages of recession into account and consequently lead to shorter recession times and smaller storage depletions no matter which model fitting method is used.

Parameters estimated by linear regression and binning show that the upper parts of recession plots (with higher $-\mathrm{d}Q/\mathrm{d}t$ from early recession stages) influence the fitted parameters. Brutsaert and Lopez (1998) have shown that these upper parts are shaped by early stages of recession, and thus are sensitive to excluded initial recession parts (1–6 days). Vogel and Kroll (1992) discussed whether slope b can be a function of the removed fraction (0–80 %) of early recessions and found lower values for b and more scatter with an increasing fraction. Zecharias and Brutsaert (1988a) concluded that an upper envelope is sensitive to length of eliminated early stage, because additionally

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excluded two and five days reduced the fitted slopes by 30 % and 55 %, respectively. In light of these outcomes we assume that for all fitted models a smaller slope b generally lead to a higher intercept a and hence to larger storage depletion. Accordingly, the average calculated storage depletion for Vogel's and Brutsaert's RAM was 16 mm and 7 mm for Kirchner's RAM using linear regression fitting. In other words, the decrease of storage depletion by more than 50 % can be attributed to approximately 3–4 days of early stage recession, which is neither considered by Vogel's nor Brutsaert's extraction method. Furthermore, Zecharias and Brutsaert (1988a) suggested that although early stages were eliminated various short-time effects like stormflow from the farthest parts of a catchments can contribute to the downstream outlet as a lagged signal, thereby distorting the late-time storage-outflow behavior.

The influence of the model fitting method on the intercept a is pronounced with generally higher values for linear regression and binning, because the regression line is shifted upwards compared to the lower envelope fit. Consequently, RAMs with linear regressions represent more averaged storage-outflow relationships, recession times and storage depletions, which are notably more influenced by the wider scatter of recession plots than lower envelopes. A very selective extraction methods like Brutsaert's leads to very specific recession plots and thus further focuses the storage-outflow model parameterization, e.g. by excluding the early stage of a recession. Similarly, a weighted linear regression like Kirchner's through a catchment-specific amount of bins can also focus parameter estimation, e.g. by weighting smaller $-\mathrm{d}Q/\mathrm{d}t$ values and thus reducing influence of higher $-\mathrm{d}Q/\mathrm{d}t$ values, which in turn could represent early stages of recession. The highest Spearman's rank correlations among the RAMs based on Kirchner's extraction procedure suggest that for the estimation of relative recession characteristics for a set of catchments depends more on the amount of data in recession plots than on the choice of a fitting model.

Biases in model fitting are manifold. For instance, lower envelopes can be affected by the precision of streamflow measurements (Rupp and Selker, 2006a). Multiples of the lowest detectable $-\mathrm{d}Q/\mathrm{d}t$ value produce some times a horizontal scatter in recession

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plots which influence the parameterization of the storage-outflow model. In Fig. 1 we illustrated that a horizontal scatter for small $-dQ/dt$ in recession plots can be detected most frequently by using Kirchner's and rarely by Vogel's extraction procedure. Vogel's moving average seems to reduce this scatter, whereas Kirchner's extraction method leads to a more extensive scatter caused by considering all negative dQ/dt. To reduce the influence of scatter on lower envelopes Rupp and Selker (2006a) suggested to enlarge the time-step for calculating $-dQ/dt$ and average Q until the decline in streamflow is higher than measurement precision of streamflow. This scatter reduction in recession plots might improve model fit and was successfully applied in a number of studies (e.g. Clark et al., 2009; Palmroth et al., 2010; Ajami et al., 2011; Staudinger et al., 2011).

However, fitting by lower envelope is not only sensitive to the precision of streamflow measurements, but also might also be influenced by the proportion of analyzed streamflow data in the recession plots. The number of recession data points that remained under the lower envelope differs among the RAMs with a maximum of 99 for the Brutsaert extraction method (minimum 7, average 48) based on all catchments (each with a 38-year daily streamflow record). In other words, a very selective extraction procedure like Brutsaert's can lead to recession plots shaped by only 1 % of all streamflow data and lower envelopes with around 0.35 % of all streamflow data below them. As these remaining data points may be extracted from only a few recession events, we see an issue of balancing selectivity of an extraction procedure against the reliability of derived storage-outflow relationships. Other studies have fitted lower envelopes with 3–10 % of data points, depending on data availability or to test the sensitivity of lower envelopes related to derived intercepts (Troch et al., 1993; Szilagyi and Parlange, 1998; Malvicini et al., 2005).

Finally, the relative roles of extraction procedure and model fitting can be elucidated with an analysis of Kirchner's RAMs. Kirchner (2009) argued that the influence of highly uncertain points has to be reduced to find representative values for certain ranges of $-dQ/dt$ and Q. Subsequently, bins with smaller standard errors gain more weight, which typically can be found for lower values of $-dQ/dt$. In other words, lower bins have more influence on regression than bins with higher Q values. Nevertheless one might argue that streamflow measurement is less precise for lower Q values, while early stages of recession with higher Q do not reflect undistorted storage depletion. The faster drainage characterized by the RAMs that used binning has two reasons: Kirchner's extraction procedure considers the early stages of recession and the weighted linear regression (through the binning) leads more often to reduced slopes b, which in turn resulted in higher intercepts a.

5.3 The effect of different RAMs to distinguish catchments' recession characteristics

Variations in the derived parameters a and b will influence common applications of RAMs that rely on characteristic recession behavior of catchments. The results of recession analysis are often related directly to physical characteristics such as drainable porosity, hydraulic conductivity, aquifer thickness and other basin-wide hydraulic or geomorphological parameters such as drainage area or stream length (Brutsaert and Nieber, 1977; Zecharias and Brutsaert, 1988b; Parlange et al., 2001; Dewandel et al., 2003; Mendoza et al., 2003). Beyond that RAMs are often used to estimate recession behavior over different scales (e.g. hillslopes) (Clark et al., 2009; Wang, 2011) or to characterize storage capacity (Sayama et al., 2011), recession timescales (Brutsaert, 2008; Krakauer and Temimi, 2011) or the temporal variability of aquifer response (Brutsaert and Lopez, 1998). In these applications, the choice of RAM will directly influence the estimated properties of water availability. Our results suggest that in such applications a range of recession characteristics determined with a multiple-RAM approach may be appropriate to quantify the uncertainty of the derived characteristics.

Intercepts as parameters of recession models have been related to catchment characteristics such as drainage density or geomorphic properties for regionalization purposes and estimation in ungauged catchments (e.g. Vogel and Kroll, 1992; Tague and Grant, 2004; Brutsaert, 2008; Aksoy and Wittenberg, 2011). In this study we found that the derived intercepts vary by a factor of 20 (Fig. 3a), thus a regionalization of recession

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behavior with related catchment characteristics may result in at least the same uncertainty. Fixed slopes of approximately $b = 1.5$ have been suggested to calibrate parameter a and to regionalize non-linear storage-outflow (Wittenberg and Sivapalan, 1999), but one should note that for the RAMs in this study the slopes differ notably between 1 and 2. Some studies have linked slopes b to the spatial scale and found that a linear relationship for storage-outflow ($b = 1$) was suitable for hillslopes, but turned more and more into non-linear behavior ($b > 1$) with increasing catchment scale (Clark et al., 2009; Harman et al., 2009). We found no systematic pattern between slopes b and catchment area (not shown) although area often has been identified as catchment characteristic for regional low-flow regression models (Eng and Milly, 2007). This may be due to the non-characteristic results of a RAM caused by aquifers' heterogeneity or the unknown number of aquifers that contribute recession streamflow among the catchment set (Ajami et al., 2011).

Recession characteristics have also been used for catchment classification (Wagener et al., 2007; Carrillo et al., 2011; Sawicz et al., 2011), especially with a view to a heuristic understanding of the interaction between climate (in terms of available precipitation and changing evapotranspiration rates), transferable catchment characteristics and the corresponding streamflow dynamics. While absolute values of the recession characteristics may not be so important for such applications, the analysis of Spearman's rank correlation coefficient and the regression coefficient between characteristics obtained with different RAMs has elucidated differences in the relative values. Generally, the bundle of methods leads to a relatively consistent ranking of recession time and storage depletion among catchments, but apart from their order a high variability in calculated recession characteristics could be found (e.g. median storage depletion for each of the nine RAMs leads to an maximum difference between Vogel's lower envelope and Kirchner's binning of 67 mm and to a moderate Spearman's rank correlation coefficient). These differences have the potential to hamper a robust classification and its interpretation as every statistical classification is based on relative similarities and differences. The found uncertainty could be seen as a limitation

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for regionalization, because it has shown a wide range of recession characteristics calculated for one specific catchment with particular physical characteristics.

Finally, implications exist for application of low flow forecasting based on recession characteristics. For this task the application of multiple parameter sets (derived from the use of different RAMs) as an ensemble forecast is a feasible option, although the uncertainty will be very large (Stoelzle et al., 2012) and the range of predictions may potentially become non-specific to the catchment.

6 Conclusions

We tested the effect of different recession analysis methods to distinguish recession characteristics in a regional set of streamflow records caused by particular catchment characteristics. The results of this study suggest four main conclusions.

The bundle of established RAMs produces a high variability of recession parameter values and derived recession characteristics. While the different RAMs rank the catchments relatively consistent, systematic variations in particular regarding the absolute values exist among the methods making it difficult to distinguish recession characteristics among the catchments.

The roles of recession extraction procedures and fitting method for parameterization of storage-outflow models are complex and the interaction of the recession analysis components has various effects on the derived recession characteristics. We suggest paying attention to the extraction of different stages of recession, but also the physical meaning of different fitting methods (e.g. lower envelopes representing slowly receding streamflow recessions) as they focus on a specific storage-outflow relationship. Furthermore, reconsidering single recession events or a master recession may be a possibility to validate parameterization of RAM derived by recession plots (Shaw and Riha, 2012).

We suggest that the limited comparability of recession characteristics derived with different RAMs elucidate a considerable uncertainty of individual analysis methods and

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thus recommend a multiple method approach to investigate streamflow recession characteristics whenever the application allows the use of multiple solutions.

The majority of the tested RAMs are too specific to reflect all catchment characteristics that control recession behavior. Possible specific catchment characteristics are blurred by the variability of parameters from different RAMs. The uncertainty may hence be too high for the regionalization of streamflow recession behavior or for catchment classification based on recession analysis.

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Table 1. Spearmans's rank correlation coefficient (ρ) for recession times T_R (above diagonal) and storage depletions S_R (below diagonal) calculated for pairs of all RAMs.

	Recession time T_R								
Storage depletion S_R	VOG LE	0.77	0.66	0.80	0.74	0.58	0.63	0.31	0.52
	0.83	VOG REG	0.91	0.70	0.89	0.73	0.64	0.63	0.53
	0.70	0.92	VOG BIN	0.61	0.84	0.80	0.62	0.73	0.54
	0.83	0.67	0.57	BRU LE	0.83	0.62	0.66	0.41	0.71
	0.80	0.73	0.66	0.92	BRU REG	0.86	0.76	0.69	0.65
	0.79	0.81	0.78	0.82	0.89	BRU BIN	0.73	0.70	0.55
	0.72	0.86	0.90	0.71	0.79	0.91	KIR LE	0.69	0.62
	0.66	0.84	0.87	0.70	0.79	0.91	0.96	KIR REG	0.58
	0.62	0.78	0.82	0.74	0.79	0.84	0.89	0.91	KIR BIN

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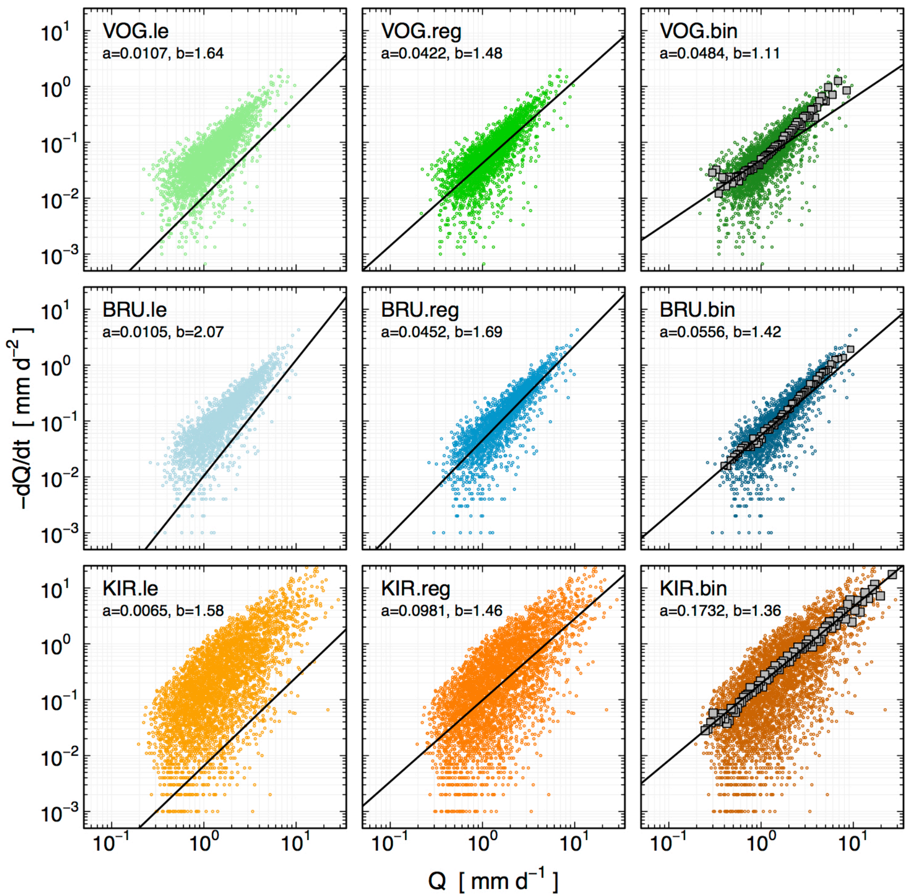

Fig. 1. Recession plots with intercepts *a* and slopes *b* for three extraction procedures (VOG, BRU, KIR) and three different fitted models (lower envelope, linear regression, binning). Daily streamflow data from the Kinzig catchment.

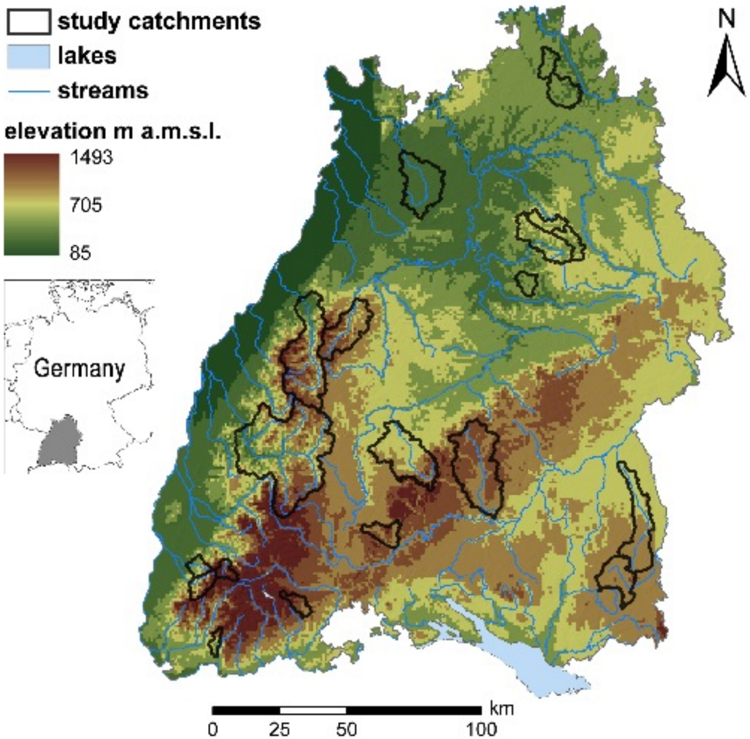

Fig. 2. Outlines and position of the 20 study catchments in Baden-Württemberg, Germany. Material from d-maps.com is used for the thumbnail map of Germany (http://d-maps.com/m/allemagne/allemagne15.pdf).

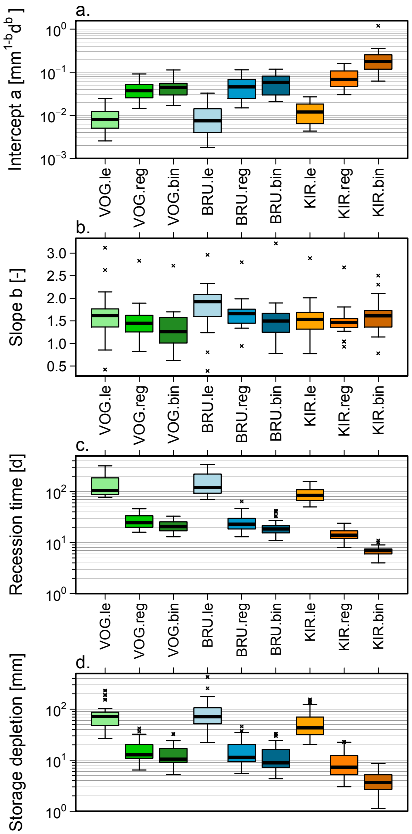

Fig. 3. Distributions of intercept a **(a)**, slope b **(b)**, recession time T_R **(c)** and storage depletion S_R **(d)** for the study catchments grouped by RAMs. Boxplots spanning interquartile range with whiskers extending to upper and lower 5 % percentiles (crosses denote outliers).

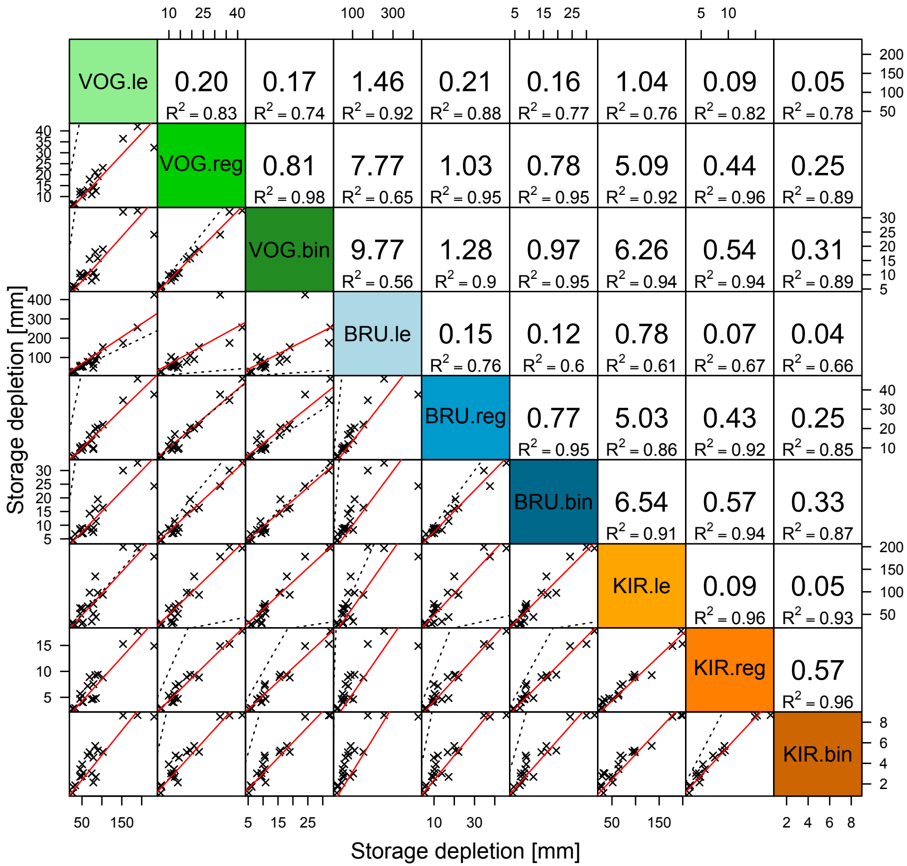

Fig. 4. Below diagonal: scatterplots for calculated storage depletion from each combination of RAMs with a linear regression (red line) and the 1 : 1-line (dashed line), above diagonal: corresponding slope and adjusted R^2 of the linear regression.