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AS SIMPLE AS POSSIBLE? DROUGHT RECOGNITION BASED ON STREAMFLOW RECESSION

MICHAEL STOELZLE (1), KERSTIN STAHL (1), MARKUS WEILER (1)
(1): Institute of Hydrology, University of Freiburg, Fahnenbergplatz, 79098 Freiburg i.Br., Germany

Nature and society are affected by droughts and low flows even in a water-rich region like Baden-Wuerttemberg in Southern Germany. Low flow is a result of water depletion of surface and subsurface reservoirs during times of low or no precipitation. This depletion is visible in the recession limb of the hydrograph. Streamflow during drought flow recession is hence a proxy to understand the drainage behavior of the storages in a catchment. In this study three storage-streamflow relationships were derived from streamflow recessions of six meso-scale catchments. Different approaches exist to fit regressions through plots of streamflow versus its daily rate of change. Three were tested to evaluate whether the fitted parameters can provide the core of a simple, conceptual model for low flow prediction. We found, that the differences in these predictions highlight the variability caused by the different recession analysis methods. In fact this variability may mask a specific catchments storage-outflow due to physiography and hydrogeology. As drought sensitivity depends on several factors, especially on storage characteristics, this conceptual model is an expandable tool, which may be regionalized to help the assessment of the potential drought hazards in different catchments.

INTRODUCTION

According to WMO [1] recession models are straightforward tools to predict low flows at the catchments scale. However, as a core of an early recognition model for low flows such a tool must be based on a representative functional storage-outflow relationship. Streamflow recessions occur during rainless periods. In these times streamflow originates from subsurface reservoirs (e.g. groundwater) within a catchment. Thus, when precipitation, withdrawals and evaporative losses from groundwater are negligible or several orders of magnitude smaller than the recession flow, streamflow can be described by a storage-outflow relationship. This functional relationship can be analyzed using solely streamflow data, which is readily available and is both measured with higher accuracy and less influenced by spatial variability than precipitation or evapotranspiration measurements. Since Brutsaert & Nieber [2] introduced a simple and straightforward method to analyze storage-outflow behavior of catchments, many applications of this and comparable methods have been published, perhaps most comprehensively by Kirchner [3] using recession analysis to "do hydrology backward". The underlying idea is to extract recession segments from declining hydrographs and plot the streamflow values (Q) against their corresponding rate of change ($-\mathrm{d}Q/\mathrm{d}t$) on log-log-plots in order to derive a functional relationship between storage and outflow (streamflow).

Recent applications of recession analysis are manifold: detection of trends in groundwater storage [4] and storage variability in small catchments [5], estimation of catchment-scale evapotranspiration [6,7], human interferences on low flows [8] or seasonal behavior of recession flow for intermittent streams [9]. Beyond applied recession analysis, methodical improvements include the introduction of a variable time increment, which is scaled to a specific rate of change in flow [10] and furthermore a recession analysis method for fragmentary streamflow data [11]. However, all of these applications adapted the recession analysis method proposed by Brutsaert and Nieber [2] to quantify components of the water balance at the catchment scale. Hence, a multitude of variations of recession analyses exists, thus introducing considerable uncertainty into applications. This study aims to compare three published recession analysis methods [3,4,12] and to quantify the impact the choice of method has on low flow prediction.

DATA

To apply recession analysis methods we used daily streamflow datasets (1971-2009) of six meso-scale catchments, which are located in southwest Germany (Table 1). Streamflow in these catchments is near-natural, i.e. it is not influenced by irrigation, withdrawals, dams or reservoirs. The catchments differ in their dominant geology as well as their area, slope, and altitude.

Table 1. Basic physiographic and hydrogeological characteristics of the six catchments.

Catchment	Area [km^2]	Mean altitude [m]	Altitude range [m]	Mean slope [%]	Dominant geology	Q50/Q95 [-]
Kinzig	954.6	600	175-1082	23.4	metamorphic	3.11
Lauchert	451.7	761	585-953	9.7	limestone	2.27
Eyach	328.5	625	397-998	12.5	limestone	3.13
Dreisam	272.7	778	317-1495	29.3	metamorphic	7.17
Enz	218.9	723	361-995	20.4	sandstone	2.27
Fichtenberger Rot	125.7	463	338-603	11.7	sandstone	2.48

METHODS

Streamflow recession analysis assumes a water balance equation where streamflow Q is solely related to change in storage,

$$\Delta S = P - E - Q \mid_{\mathrm{P \ll Q, E \ll Q}} \quad (1)$$

where ΔS is the change in stored water volume [mm] in the catchment. Precipitation P [mm] and evapotranspiration E [mm] are zero or very small in comparison to Q [mm]. Hence, streamflow Q is a function of storage S:

$$Q = f(S) \ . \tag{2}$$

With this relationship streamflow (Q) is directly related to changes in storage (*-dQ/dt*). Under the assumption of a non-linear storage-outflow relationship the rate of change in streamflow can be described as a function of streamflow [2],

$$-dQ/dt = aQ^b \ . \tag{3}$$

A characteristic recession behavior of each catchments can be estimated with parameters a [$L^{3(1-b)}T^{b-2}$] and b [-] by fitting a linear regression to the combined sample of all recession segments:

$$\log(-dQ/dt) = \log(a) + b\log(Q) \ . \tag{4}$$

We applied three methods of recession extraction and parameter fitting. Pairs of –dQ/dt and Q for all recession segments lead to method- and catchment-specific shapes of each individual recession plots. The Vogel method [12] selects recession segments out of a decreasing 3-day moving average. Recessions must have a minimum length of 10 days and the first 30% of every recession segment are removed in order to exclude the influence of surface-flow or storm-flow. Furthermore the decrease between two consecutive streamflow values has to be smaller than 30%. The parameters for the non-linear storage-outflow model were obtained by linear regression through all points in the –dQ/dt versus Q plot. The Brutsaert method [4] eliminates recession segments by a rule-based procedure. The segments must comply with the following criteria: no positive dQ/dt and no positive dQ/dt within the next two days, no peak flow in the last three days, no major events in the last four days, and no sudden anomalies while streamflow declines. In this study, a major event was defined as streamflow values greater than 30% exceedance frequency (Q30). Finally, a linear regression was fitted to a lower envelope (quantile regression with 5% of the points below). The last method by Kirchner [3] initially uses all negative dQ/dt values within a streamflow time series. Starting with the highest 1% of log-transformed streamflow values a corresponding mean for this range (bin) is calculated, then a mean is calculated for the next 1%, and so forth. In order to get representative means the Q-bins can be widened until the standard error in the associated –dQ/dt bin is less than half its absolute mean value. Finally, a linear regression is fitted to the bins, weighted by inverse variances of each binned –dQ/dt in order to reduce the influence of highly uncertain values in the regression.
The models obtained with the three recession analysis methods were then used to predict the evolution of 50-day low flows in the study catchments. We used a solution of Eq. (3) with respect to time t proposed by Szilagyi and Parlange [13] to calculate low flows Q_t starting with median flow (Q50) for Q_0:

$$Q(t) = \left(Q_0^{1-b} - (1-b)at\right)^{\frac{1}{1-b}}, \text{with } b \neq 1 \tag{5}$$

As both parameters *a* and *b* influence the modeling and the value of intercept *a* depends on the derived slope *b*, in order to compare the different models' applicability we calculated the streamflow half-life period $T_{1/2}$ [*d*] [4,14]. We also analyzed the differences of the streamflow 10-days, 20-days, and 30-days into the predicted recessions. Finally, the ratio *Q*50/*Q*95 (Table 1) represents the variability of low flow excluding effects of catchment area [1].

RESULTS

The three different methods extracted very different samples of recession segments from the streamflow series (Fig. 1a). Only the Kirchner method included all negative d*Q*/d*t* values as recession data. The Kirchner and Brutsaert methods include early parts of recession flow with steeper slopes. These extracted sequences have larger values of –d*Q*/d*t* than those extracted by the Vogel method, which considers only consecutive segments of recession flow with more moderate –d*Q*/d*t* values (Fig. 1b). The merged recession segments and derived functional relationships between –d*Q*/d*t* and *Q* are shown in Fig. 2. For the Kirchner method we used 71 (Enz catchment) up to 84 (Eyach catchment) binned means for the linear regression. Brutsaert's 5% lower envelope lead generally to steeper relationships in comparison to the Vogel or Kirchner method, because streamflow values are linked with significantly lower d*Q*/d*t* values, apparent in smaller values for *a* and larger values for *b* for all catchments.

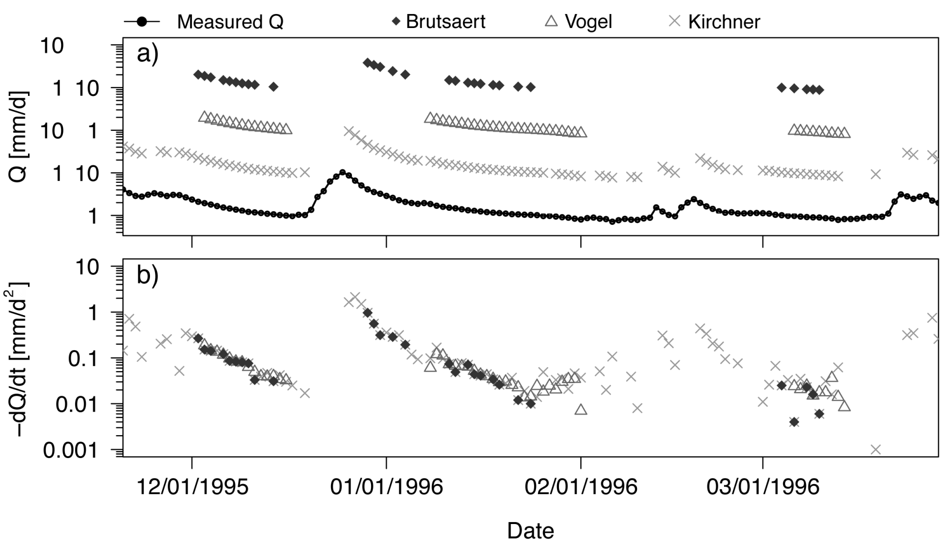

Figure 1: Observed streamflow (Kinzig catchment) and recession segments extracted with the three different methods (a) and resulting –d*Q*/d*t* values (b).

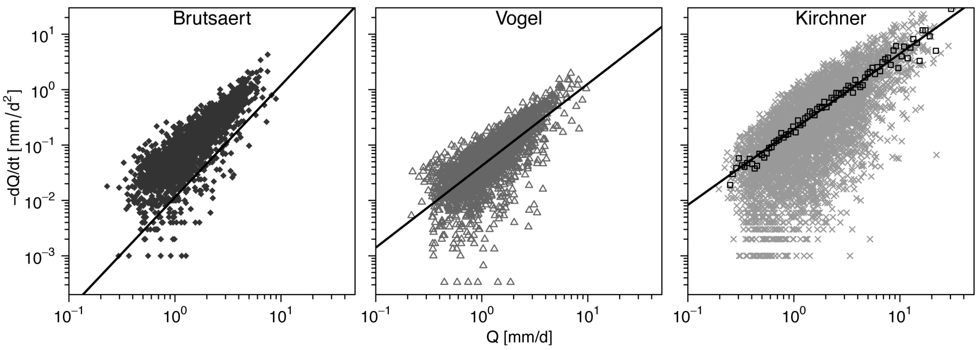

Figure 2: Recession streamflow (Q) versus rate of change (–d*Q*/d*t*) for the Kinzig catchment and three recession extraction methods. The straight lines show the fitted lines to derive intercept and slope of the parameters *a* and *b*.

Distinguishing between the Vogel and Kirchner methods is more difficult as both methods use a mean linear functional relationship. Kirchner give more weight to smaller –d*Q*/d*t* values. Thus, the Vogel method resulted in steeper linear regressions and consequently higher *b*-values. As a result the parameters for the non-linear storage-outflow differ significantly among the three methods. The differences between the Brutsaert and Vogel methods result in a spread of 0.15 to 0.47 mm/d for the prediction of 30-day low flow values in all catchments.

With the low flow prediction we identified three classes of storage-outflow behavior with flat (Brutsaert), medium (Vogel) and steep recession curves (Kirchner). Based on these classes the recession behavior of the six catchments can be grouped. The first group with the Enz and Lauchert catchments shows a relatively slow recession behavior with streamflow half-life periods of more than 200 days (Brutsaert method), approximately 40 days (Vogel method) and 9 days (Kirchner method) (Fig. 3a and 3b). The Brutsaert and Vogel methods derived recessions do not decline under *Q*95 streamflow within 50-days. For both catchments the spread between the different recessions increases from 0.7 and 0.32 mm/d for 10-day low flow to 0.97 and 0.51 mm/d for 30-day low flow, respectively. In the second group with the Kinzig and Fichtenberger Rot catchments this spread is 0.88 and 0.48 mm/d, whereas the streamflow half-life periods here are mostly comparable (2-3 months with the Brutsaert method down to 3 days with the Kirchner method) (Fig. 3c and 3d). The third group with the Eyach and Dreisam catchments shows not only the steepest recessions and smallest streamflow half-life periods: From about 40 days (Brutsaert) to 12 days (Vogel) to 2 days (Kirchner)), but also a relatively small decrease of the spread between the methods with 0.3 (10-day) to 0.27 mm/d (30-day) and from 0.9 to 0.66 mm/d (Fig. 3e and 3f). Furthermore, differences between the recession analysis methods can be distinguished for the relative streamflow values after 20-days, which represent the streamflow exceedance frequency ranges of Q55-Q67 (Brutsaert), Q73-Q88 (Vogel) and lower than the measured minimum streamflow (Kirchner).

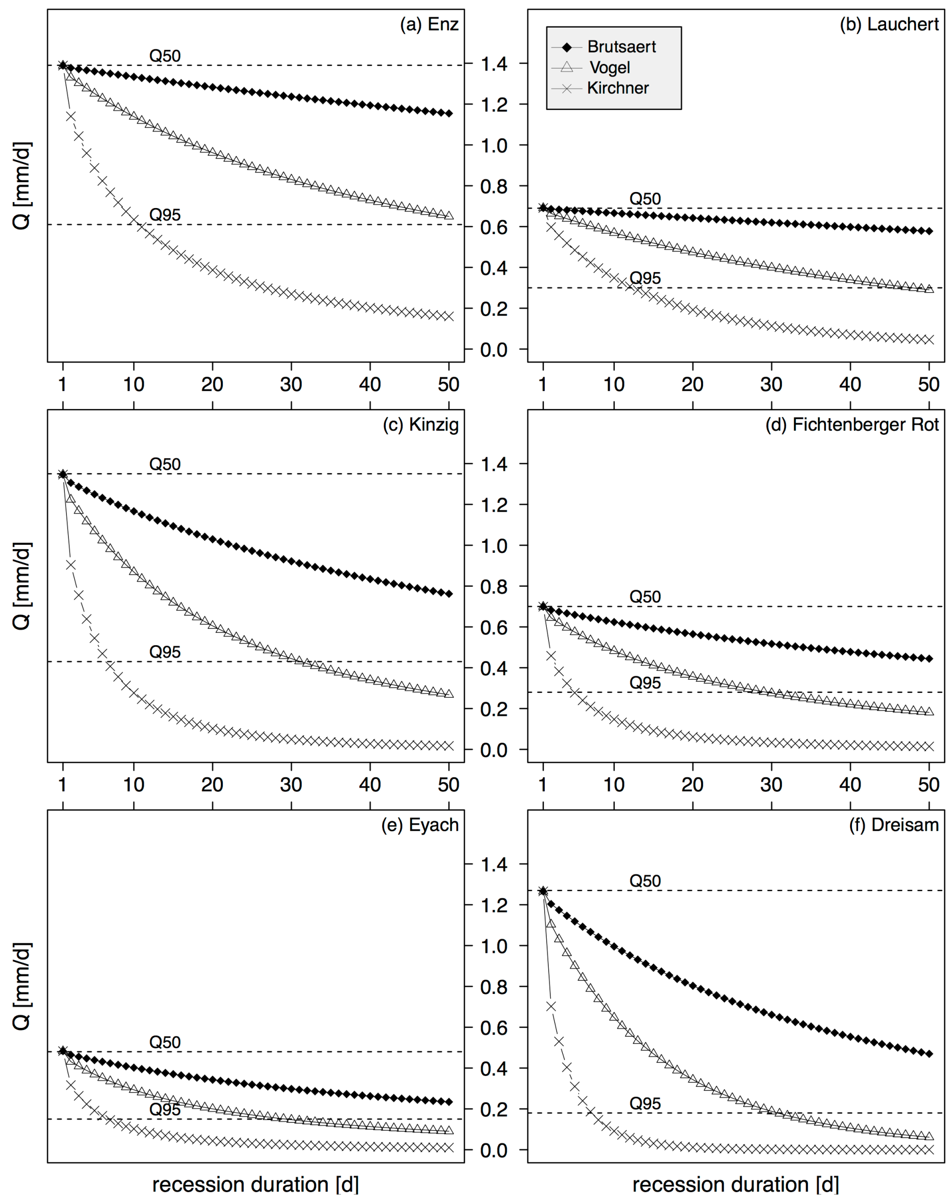

Figure 3: 50-day recession and low flow prediction with three models starting at the median flow (*Q*50).

In summary, we found, that the low-flow prediction models highlight the variability caused by the different recession analysis methods. However, the Brutsaert methods predicted moderate low-flows, whereas the Kirchner method exhausted storage-outflow within 10-15 days for all catchments.

DISCUSSION AND CONCLUSION

The strict implementation of the published extraction methods leads to method-specific datasets in the log-log-plots. As Kirchner [3] stated, one must carefully decide what parts of a declining hydrograph should be included as recession and how a reliable storage-outflow relationship should be derived. Rupp and Selker [10] intensively discuss the horizontal scatter in the log-log-plots for small values of $-\mathrm{d}Q/\mathrm{d}t$ caused by streamflow measurement accuracy and the time increment for which $-\mathrm{d}Q/\mathrm{d}t$ is calculated. However, the extraction procedures and this scatter influenced both the lower envelope in the Brutsaert method and the linear regression in the Vogel and Kirchner methods. Thus, the result of the prediction model depends strongly on the adopted method.

Furthermore, the derived non-uniqueness of recession characteristics also hampers attempts to find links to physiographic and hydrogeological catchment characteristics (Table 1). Such links have been suggested in the literature [2,11,12,14,15]. For Enz and Lauchert (Fig. 3a and 3b) for example which have very different slopes and geology, streamflow half-life is in the same order of magnitude, but the parameters a and b differ significantly, i.e. for the Brutsaert method the parameter a is 0.0027 and 0.0043 and b is 2.27 and 1.43, respectively, resulting in similar storage-outflow behavior. As Brutsaert [14] emphasizes, the lower envelope as a fitting function for storage-outflow modeling is only valid in relatively flat terrain. So the Brutsaert method only reflects storage-outflow from valley sections in the lower parts of mountainous catchments. Thus, a regression through all points of the log-log-plots, as used by Vogel and Kirchner, is a more representative method in order to predict low-flow in such catchments. As a consequence, recessions predicted with the Brutsaert method overestimate low flows especially for mountainous catchments. The steeper recessions of the Kirchner method caused by discharge shortly after rain events are responsible for quickly receding recessions. The Vogel method eliminates these early recession segments; hence, recessions predicted with this method are slower and in between the Brutsaert and Kirchner methods.

A reversal of the fitting procedures (lower envelope and mean linear regression) to derive a and b for the Brutsaert and Vogel methods revealed that the differences between resulting predictions of 30-day low flow are small. The maximum difference between the Vogel method (with 5% lower envelope) and the Brutsaert method (with a mean linear regression) is smaller than 0.08 mm/d for all catchments. Consequently, the fitting procedure appears to have more influence on the recession parameters, and therefore also on prediction of storage-outflow behavior than the extraction methods of recession segments, which leads to different log-log-plots. According to Smakhtin [15], we can classify the catchments into quickly (7-21 days as average streamflow half-life for Kinzig, Fichtenberger Rot, Eyach, and Dreisam) and slowly receding streams (up to 150 days as for Enz, and Lauchert).

Extracting recessions from hydrographs and fitting a non-linear storage-outflow model is a straightforward and suitable approach to derive a low flow prediction model. Whether the parameters vary systematically with physiographic and hydrogeologic characteristics of the catchments can be regionalized for application in ungauged catchments remains to be studied in particular in light of the non-uniqueness of the recession parameters. Thus, we conclude that an ensemble of different recession analysis methods may provide a better insight into the storage-discharge behavior of catchments and a more honest representation of the uncertainty of low flow predictions.

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