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Scaling behavior of the fluctuations in stream flow at the outlet of karstic watersheds, France

D. Labat [a,*], J. Masbou [a], E. Beaulieu [a], A. Mangin [b]

[a] Géosciences Environnement Toulouse - UNIVERSITE DE TOULOUSE-CNRS-IRD-OMP, 14 Avenue Edouard Belin, 31400 Toulouse, France
[b] Station d'Ecologie Experimentale CNRS, Moulis 09200, France

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SUMMARY

This contribution presents a study of discharge variability at two karst springs outlet in southwestern France and aims at presenting the Detrended Fluctuation Analysis (DFA), which method is not very usual in hydrology, to the community interested in investigating the scaling behavior of karst hydrological responses. Several studies have already highlighted the existence of a power law scaling behavior in the spectral variance distribution of hydrological signals such as rainfall rates, stream flow and groundwater levels. This power law behavior provides evidence for characteristic scales that correspond to different physical responses of the system depending on its complexity and occurring at distinct temporal scales. We derive in this contribution particular scaling behavior of karstic watersheds, in particular, the assessment of time interval of karstic watershed responses to rainfall. Based on DFA analysis and relying on a unique high resolution long-term discharge database, we provide evidence for a scaling behavior in the response of two French karstic watersheds. The DFA analysis of discharge time series fluctuations at daily, half hourly and 3-min sampling rate allows to detect scaling behavior in the fluctuation of karstic stream flow from 1 h up to 100-h, from 100-h up to 1-year time scales and for scales larger than 1 year. The DFA analysis can also be useful in investigating groundwater levels or chemical conductance time series scaling behavior and deserves to be more largely disseminated in hydrology as valuable complement to Fourier or wavelet analyses.

1. Introduction

Karstic aquifers constitute a freshwater resource still under exploited. Their complex characteristics make their exploitation more complicated than other porous or fractured aquifers. However, as water flows through pores and fractures, the spatial distribution of micro- and macro-porosity caused by the state of limestone dissolution, and inherent in a karstic aquifer, causes water to flow into drains and conduits connected to large water reserves (Labat et al., 2000). Therefore, the dissolution makes karstic watersheds as spatially heterogenous groundwater systems characterized by an inherent temporal unstationarity and nonlinearity of their hydrological response. Effectively, the existence of combined rapid infiltration via boreholes and delayed infiltration via epikarstic soil combined with diphasic flow in the unsaturated zone leads to a nonlinear response reflecting the large diversity of pathways connecting the surface with springs that involves complex hydraulic connections in the saturated zone.

This extreme variability over a wide range of spatial and temporal scales naturally suggests applying scaling methods in their hydrogeological analysis. Spectral and wavelet analyses have already proven their efficiency to highlight periodicities and/or non-stationarities in the hydrological response of karst systems (Labat et al., 2000). However, these periodicities do not often give relevant information on the scaling behavior of karst systems. Multifractal analyses could provide a valuable alternative but are still not widely used in hydrology and hydrogeology mainly because the rather difficult interpretation of their results (Tessier et al., 1996; Labat et al., 2002 among others).

We propose here the first application in karst hydrogeology of the Detrended Fluctuation Analysis (DFA) that have already proven its efficiency in DNA analysis, medicine, finance and weather records for example (Peng et al., 1994; Maraun et al., 2004, Kantelhardt et al., 2002, 2003 among others).

Karst scaling analysis is dedicated to highlight in the temporal fluctuation of the discharge at the outlet of the spring the different temporal scales that could be related to the physical structure of the karst. Then, that allows inferring some hypothesis on the physical processes related to these temporal scales and in a last step to propose relevant modeling approaches in accordance with these temporal scales. Scaling analyses must rely on a valuable and

* Corresponding author. Address: Géosciences Environnement Toulouse – GET, 14 Avenue Edouard Belin, 31400 Toulouse, France. Tel.: +33 5 61 33 25 12; fax: +33 5 61 33 25 60.
E-mail address: labat@get.obs-mip.fr (D. Labat).

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extended database at different sampling rate. Here, DFA is applied to uninterrupted discharge time series measured at the outlet of two French karstic watersheds at three sampling time (3-min, 30-min and daily average discharge) on different periods from 2 up to 40 years for the daily discharge time series.

After an overview of the DFA analysis principles and its applications in hydrology, we will show its specific application to karst spring discharge time series. Finally, we highlight the main results of the scaling analyses and discuss plausible hydrogeological implications in term of karst scaling analysis.

2. Detrended fluctuation analysis

The simple Detrended Fluctuation Analysis (DFA) and Multifractal Detrended Fluctuation Analysis (MFDFA) have proven their efficiency in Earth Sciences for example revealing potential temporal correlation in atmospheric pollution time series (Varotsos et al., 2005; Zhu and Liu, 2003; Zhu and Zeng, 2006) or in geophysics (Alvarez-Ramirez et al., 2009, 2010; Ida et al., 2005; Telesca and Lapenna, 2006; Telesca and Lasaponara, 2006). It has also been already used in exploring groundwater dynamics (Li and Zhang, 2007, Little and Bloomfield, 2010) and river stream flow records (Koscielny-Bunde et al., 2006; Kantelhardt et al., 2003, 2006; Livina et al., 2003, 2007; Matsoukas et al., 2000; Mohaved and Hermanis, 2008; Wang et al., 2008; Zhang et al., 2008, 2009, 2011). The series are first deseasonalized e.g. the seasonal component is removed from the original series in order to address the correlations. Indeed, periodicities make it more difficult to determine potential power law behavior (Chen et al., 2002; Hu et al., 2001; Kantelhardt et al., 2006; Maraun et al., 2004; Bashan et al., 2008). In practice, it consists in removing the interannual mean from the data series (for example, the mean daily interannual value is removed from a given daily data). Then, the deseasonalized time series to be analyzed, noted here $x(k)$ is first integrated to determine the "profile" $y(i)$:

$$y(i) = \sum_{k=1}^{i}(x(k) - \langle x \rangle) \tag{1}$$

where $\langle x \rangle$ is the mean of the time series. Then, the integrated $y(i)$ time series is divided into non-overlapping boxes of equal duration. In each box of duration n, a least squares polynomial fit is applied to the data in order to represent the trend in that box. Then, we detrend the integrated time series, $y(i)$, by subtracting the local linear or polynomial trend, $y_n(i)$, in each box. The root-mean-square fluctuation of this integrated and detrended time series is given by

$$F(n) = \left[\frac{1}{N}\sum_{k=1}^{N}[y(k) - y_n(k)]^2\right]^{1/2} \tag{2}$$

Linear, quadratic or higher order polynomial fit can be used for the fitting procedure, leading to so called DFA1, DFA2 analyses. Since the detrending of the time series is done by substraction of the fits from the profile, these methods differ in their capability of eliminating trends in the data. For example, in mth order DFA, trend of order m in the profile and of order m-1 in the original records are eliminated. This computation is repeated over all time scales (box sizes) to characterize the relationship between $F(n)$, the average fluctuation, and the box size, n. Typically, $F(n)$ will increase with box size. A linear relationship on a log–log plot indicates the presence of power law (fractal) scaling. Under such conditions, the fluctuations can be characterized by a scaling exponent α corresponding to the slope of the line relating log $F(n)$ to log(n) (Peng et al., 1994, 1995). The scaling exponent α can be explaining the behavior of time series as $0 < \alpha < 0.5$ indicates anti-correlation, $\alpha = 0.5$ indicates white noise, $0.5 < \alpha < 1$ indicates correlated time series, $\alpha = 1$ indicates $1/f$ pink noise, $1 < \alpha < 1.5$ indicates random walk and $\alpha \sim 1.5$ indicates Brownian noise.

3. Detrended fluctuation analysis in hydrology

Since we assume that DFA is less known than for example spectral or wavelet multiresolution analyses, Table 1 constitutes a summary of the most recent applications of DFA and MFDFA analyses that focused on rainfall, stream flow and groundwater level fluctuations. The reader is highly incited to refer to these contributions in order to get an overview of the main applications of DFA in hydrology. The most striking results consist in the existence for stream flow time series of a pronounced cross over at intermediate scales, typically for scales from 1 week to several weeks. The DFA exponent shows a high variability for temporal scales inferior to a week from 0.8 to 1.64 but a lower variability at larger scales with a DFA exponent systematically inferior to one related to the interannual discharge variability.

However, these analyses deal with the scaling analysis of the discharge fluctuations of large basins and therefore do not apply for small size watersheds. Moreover, none of these studies focused on karstic watersheds. Only a few ones dealt with a fine hourly sampling rate of rainfall or stream flow and we found only a few publication that focus on ground water levels and base flow hourly fluctuations DFA analysis.

4. Karstic watershed data

The methods presented above are applied to stream flow time series at the outlet of two karstic springs of the Pyrénées Mountains (Ariège): the Aliou and the Baget springs (Fig. 1). The main hydrological and geomorphological characteristics of these karstic basins are presented in Table 2 and have already been documented by Labat et al. (2000, 2002). The Aliou and Baget watersheds are physically similar and owing to the geographic proximity of these mid-altitude basins, one can consider that they are under the influence of the same rainfall input function, measured at the meteorological station of Antichan (Ariège – Pyrenees). For these two watersheds, long and uninterrupted chronological series of daily rainfall and daily stream flow have been collected over a period of almost 40 years. Both basins are characterized by rapid and unexpected swells of runoff. For example, Aliou watershed which is known as extremely karstified with a very short time response (less than a day) exhibits a discharge increase from 0.1 m^3/s to nearly 30 m^3/s in as little as 8 h followed by a decrease about as quick. A daily sampling rate would not be adequate to convey the temporal structure of such sharp rises and falls. Therefore, a 30-min sampling time has been adopted since the beginning of the 1990s. Recently, a 3-min sampling rate has been implemented at the outlet of the Baget karstic watershed in order to deal with high-resolution karst hydrodynamic but we will see that a 30-min sampling rate is definitely the best compromise in term of hydrogeological information.

Fig. 2 displays a visualization of the daily and 30-min sampling rate Aliou and Baget springs discharge time series and Fig. 3 displays a visualization of the 3-min sampling rate Baget spring discharge time series. Detailed information about the hydrological dataset is given in Table 2. Concerning Aliou watershed, we have at our disposal a daily discharge time series extended from 10/04/1964 up to 12/01/2011 corresponding to 15,253 successive daily data. Then, three 30-min sampling rate discharge time series are also available over the 1992–2011 period, the largest discharge time series corresponding to 122,125 successive data. Concerning Baget watershed, we have at our disposal a daily discharge time