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Single event time series analysis in a binary karst catchment evaluated using a groundwater model (Lurbach system, Austria)

C. Mayaud [a,*], T. Wagner [a], R. Benischke [b], S. Birk [a]

[a] Institute for Earth Sciences, University of Graz, Heinrichstraße 26, A-8010 Graz, Austria
[b] Department of Water Resources and Environmental Analytics, Institute for Water, Energy and Sustainability, Joanneum Research Forschungsgesellschaft mbH., Elisabethstraße 18/II, A-8010 Graz, Austria

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SUMMARY

The Lurbach karst system (Styria, Austria) is drained by two major springs and replenished by both autogenic recharge from the karst massif itself and a sinking stream that originates in low permeable schists (allogenic recharge). Detailed data from two events recorded during a tracer experiment in 2008 demonstrate that an overflow from one of the sub-catchments to the other is activated if the discharge of the main spring exceeds a certain threshold. Time series analysis (autocorrelation and cross-correlation) was applied to examine to what extent the various available methods support the identification of the transient inter-catchment flow observed in this binary karst system. As inter-catchment flow is found to be intermittent, the evaluation was focused on single events. In order to support the interpretation of the results from the time series analysis a simplified groundwater flow model was built using MODFLOW. The groundwater model is based on the current conceptual understanding of the karst system and represents a synthetic karst aquifer for which the same methods were applied. Using the wetting capability package of MODFLOW, the model simulated an overflow similar to what has been observed during the tracer experiment. Various intensities of allogenic recharge were employed to generate synthetic discharge data for the time series analysis. In addition, geometric and hydraulic properties of the karst system were varied in several model scenarios. This approach helps to identify effects of allogenic recharge and aquifer properties in the results from the time series analysis. Comparing the results from the time series analysis of the observed data with those of the synthetic data a good agreement was found. For instance, the cross-correlograms show similar patterns with respect to time lags and maximum cross-correlation coefficients if appropriate hydraulic parameters are assigned to the groundwater model. The comparable behaviors of the real and the synthetic system allow to deduce that similar aquifer properties are relevant in both systems. In particular, the heterogeneity of aquifer parameters appears to be a controlling factor. Moreover, the location of the overflow connecting the sub-catchments of the two springs is found to be of primary importance, regarding the occurrence of inter-catchment flow. This further supports our current understanding of an overflow zone located in the upper part of the Lurbach karst aquifer. Thus, time series analysis of single events can potentially be used to characterize transient inter-catchment flow behavior of karst systems.

1. Introduction

Karst aquifers are of primary importance for supplying drinking water to nearly 25% of the world's population (Ford and Williams, 2007), but their significant reserves are highly vulnerable to contamination and to industrial or intensive agricultural land use. Because karst is a highly heterogeneous environment comprising aperture diameters varying over more than five orders of magnitude (from fracture openings less than 1 mm in the limestone matrix to conduits of more than 10 m width in large caves) there is a need to develop and improve existing tools helping to better understand the processes governing the hydrodynamic behavior of karst systems. As not more than a few percent of a karst aquifer are generally mapped (or explored), it can be defined as grey/black-box system, where the input is routed through to the output without a direct observation of the water transfer. Thus, indirect methods of characterization have been developed to obtain a maximum of information from the karst systems. They are mostly focused on the comparison between the available input

* Corresponding author. Tel.: +43 316 380 87 29; fax: +43 316 380 98 70.
E-mail address: cyril.mayaud@uni-graz.at (C. Mayaud).

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and output data and include hydrograph and chemograph analyses using discharge, specific electric conductivity, water temperature, chemical parameters, isotopes and tracer experiments (e.g., Bakalowicz, 2005; Geyer et al., 2013; Kresic and Stevanovic, 2010; Pinault et al., 2001; Rehrl and Birk, 2010).

Time series analysis are signal processing methods belonging to this category, and are mostly used to improve the understanding of the hydrological behavior of karst systems. Mangin (1984) was the first to apply them to the field of karst hydrology. He compared the autocorrelation and power spectral density functions of the discharge of three Pyrenean karst aquifers under the same climatic conditions and deduced that their different responses were due to different degrees of karstification and storage capacities. Larocque et al. (1998) extended the analysis to a broader dataset (piezometric level, water discharge at the inlet and outlet, precipitation, specific electrical conductivity and water temperature) combined with new methods such as cross-correlation, cross-spectral density, coherence function, gain and phase functions, and proved their usefulness for the purpose of water management. Panagopoulos and Lambrakis (2006) applied time series analysis to two Greek karst aquifers well-known for their different karstification and found that the different results were in agreement with the differences in karstification. More recently Bailly-Comte et al. (2008) applied these methods to a small Mediterranean karst system and highlighted the interactions between the karst aquifer and an overflow river. Kovačič (2010) applied autocorrelation, cross-correlation, power spectral density and coherence function to the complex Unica river catchment and improved the understanding of its hydrodynamic behavior, allowing the differentiation of flow paths using two datasets of different time scale. Time series analysis were also successfully used by Amraoui et al. (2003), Bailly-Comte et al. (2011), Bouchaou et al. (2002), Jemcov and Petrič, (2010), Genthon et al. (2005) and Massei et al. (2006) using a broader dataset (rainfall, specific electric conductivity, turbidity, water temperature) and different methods (e.g. spectral and wavelet analyses).

Until now, time series analysis were mostly applied to time-periods covering a period of 1 year or more (Eisenlohr et al., 1997; Kovačič, 2010; Larocque et al., 1998; Mangin, 1984; Panagopoulos and Lambrakis, 2006). Only a few studies (e.g. Bailly-Comte et al., 2008; Budge and Sharp, 2009; Covington et al., 2009, 2012; Valdes et al., 2006) applied the methods at a very short -or single event time scale to provide information about the hydrodynamic behavior of a karst system for short periods. Indeed, as opposed to long-term time series analysis, which is recommended to provide information about the "average" aquifer behavior/properties (Kovačič, 2010; Panagopoulos and Lambrakis, 2006), single event analysis has the potential to show how the system reacts at the scale of a single event only (Bailly-Comte et al., 2008; Covington et al., 2009, 2012; Valdes et al., 2006). This is of primary importance, because karst aquifers are highly dynamic non-linear systems whose behavior may evolve or vary temporarily depending on the hydrological conditions within the system (Mayaud et al., 2013; Wagner et al., 2013).

As demonstrated by the examples cited above, time series analysis has been frequently applied to karst catchments. Although the results from these applications were found to be in qualitative agreement with field observations, it has only rarely been attempted to verify the interpretation more quantitatively by applying the methods to synthetic catchments represented by a numerical model, where aquifer properties and hydrological stresses are known in detail. This approach was followed by Eisenlohr et al. (1997) who evaluated the results from times series analysis using a numerical groundwater flow model. These authors concluded that the results were not only dependent on the system geometry but also on the frequency and type (allogenic vs. autogenic) of the recharge events and on their intensity. In addition, an inappropriate length of the analyzed time series may cause errors in the interpretation. Jeannin and Sauter (1998) concluded that these methods were inappropriate without knowledge of the investigated area to characterize the underground geometry of karst aquifers. Nevertheless, Larocque et al. (2000) applied successfully autocorrelation and cross-correlation analysis to numerical data of a groundwater model representing the Larochefoucault karst aquifer (France). Later, Budge and Sharp (2009) applied short term cross-correlation analysis to a simplified synthetic MODFLOW catchment in order to develop a conceptual understanding of the Barton springs–Edwards aquifer. Their results showed that the cross-correlation was dependent on the input data but also on the geometrical properties of the aquifer.

The purpose of this paper is to improve the interpretation of time series analysis at the scale of single events in karst catchments that are characterized by the existence of a localized recharge component from a sinking stream and by temporarily varying drainage pattern due to the overflow from one spring catchment to another. This involves the need to investigate how physical characteristics of the karst system are reflected in the results from the time series analysis. To this end, two methods, autocorrelation and cross-correlation, are applied to a well investigated field site, the Lurbach karst system (Austria), where an overflow from one sub-catchment to another one is reported by numerous tracer experiments, and to a synthetic karst catchment represented by a numerical groundwater flow model, which accounts for the most relevant features of the field site in a simplified manner.

2. Approach

The following subsection 2.1 provides a brief introduction into the two time series analysis methods that are examined in this paper. These methods are evaluated in parallel using both a field site and a synthetic karst catchment represented by a numerical groundwater flow model, which are both described in the subsequent subsections 2.2 and 2.3, respectively. If the time series analysis of the synthetic and the field case yield comparable results, similar aquifer properties and geometries of the overflow section present in the model can be deduced for the Lurbach system.

2.1. Methods

2.1.1. Autocorrelation

The autocorrelation function examines how a value depends on the preceding values over a period of time. This function is represented with a correlogram. The slope of the correlogram is determined by the response of the system to an event. If the event has only a short-term influence on the response of the karst system, the slope of the correlogram will decrease steeply and quickly. In contrast, if the system is influenced by an event for a long time, the slope of the correlogram will decrease slowly. Generally the length of the influence of an event is given by the "memory effect" which is according to Mangin (1984) the lag number when $r(k)$ reaches the value of 0.2. The formula for autocorrelation is (Larocque et al., 1998; Mangin, 1984):

$$r(k)\frac{C(k)}{C(0)} \tag{1}$$

with

$$C(k) = \frac{1}{n}\sum_{t=1}^{n-k}(x_t - \bar{x})(x_{t+k} - \bar{x}) \tag{2}$$

where k is the time lag and varies from 0 to m. According to Mangin (1984) m has to be taken as 1/3 of the length of the whole dataset to avoid stability problems.