Supplement to Hartmann et al. “Process-based karst modelling to relate hydrodynamic and hydrochemical characteristics to system properties”

1 Regionalization of karst system signatures by simple climatic and topographic descriptors

In addition to the relations between the parameters of the VarKarst model and the karst system signatures, relations between the signatures and climatic and topographic descriptors of the karst systems were explored. Doing so, insights were gained about their transferability to ungauged catchments and hence about their potential to facilitate the application of karst models at ungauged karst systems.

1.1 Methodology

If it is possible to regionalize the system signatures the relations between model parameters and system signatures can be used to apply the karst model at ungauged karst systems. Preceding studies (e.g. Sawicz et al., 2011; Yadav et al., 2007) already showed that regionalisation of system signatures by climatic factors and landscape properties is possible. To find out whether this approach is also adequate for our karst systems, we will try to link mean precipitation, mean temperature and altitude difference of the karst systems (Table 1 in the manuscript) with the observed karst system signatures. Unfortunately, most of the descriptors used in other studies (Yadav et al., 2007) are based on the knowledge about the location and size of the catchment. In most cases they cannot be used for karst systems, because spatial information about their subsurface catchment area is seldom available (Goldscheider and Drew, 2007).

1.2 Results

Disregarding all relationships with $r_{Lin} < 0.7$, we obtain six relations between climatic and topographic descriptors and system signatures (Figure 1). The autocorrelation of discharges $R_{Q,100}$ and the annual water balance B_Q show a certain correlation with the altitude difference at the study sites, but regarding the locations of the different crosses in Figure 1, two different patterns may be abundant. For $R_{Q,100}$, a negative correlation for small altitude differences, and a positive correlation for large altitude differences was found. For B_Q, the two positive correlations are indicated, one with a steep slope and one with a flat slope. The $\delta^{18}O$ variability $V_{\delta 18O}$ and the Q-NO_3 cross-correlation L_{NO3} are correlated to both mean annual precipitation and mean annual temperature. However, also these relationships are not well pronounced both visually and in terms of their linear correlation coefficients ($r_{Lin} \leq 0.81$ with $p \leq 0.12$).

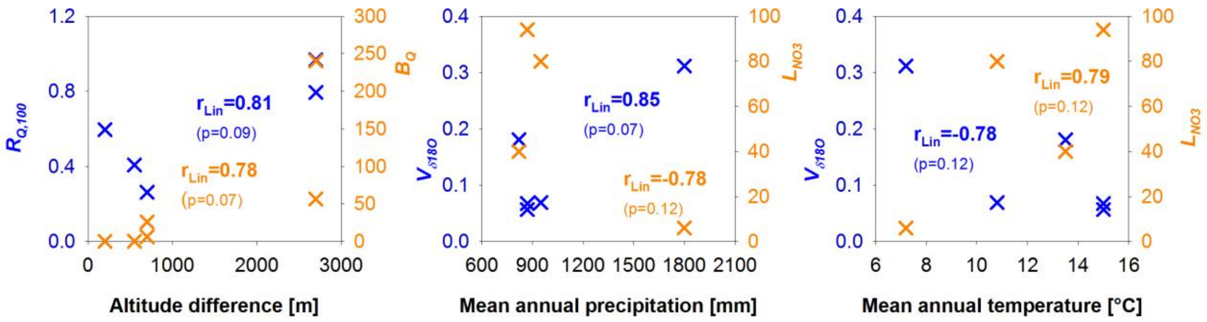

Figure 1: Relations between climatic factors and landscape properties and system signatures that have an $r_{Lin} > 0.7$.

1.3 Discussion

Figure 1 shows that correlation between some of these descriptors and the system signatures could be found: The larger the altitude difference, the larger were the memory effect $R_{Q,100}$ and B_Q. However, for $R_{Q,100}$ the relation reverses for small altitude differences. Hence, the appearing correlation might just be coincidence. The same may true for B_Q, which seems to have two correlations, one with a steep and one with a flat slope. Its positive slope may be explained by the fact that large altitude differences often go along with large recharge areas. Annual precipitations show a positive correlation to $V_{\delta 18O}$ and a negative correlation to L_{NO3}. Both can be explained by the faster dynamics going along with more water input to the systems. For the same reason, same signatures are related to the mean annual temperature in the opposite way, since higher temperatures often go along with lower precipitation. All apparent relations are not very strong (r_{Lin} = 0.76-0.85, p = 0.07-0.12, Figure 1). In addition, only one of the hereby found system signatures ($V_{\delta 18O}$) was also identified to be correlated with system properties expressed by the model parameters. Hence, the relations between karst system signatures and climatic and topographic descriptors of the karst systems found in this work are (1) too weak and (2) not complete enough to allow a regionalisation of system signatures and, therefore a model application in ungauged karst basins.

2 Evaluation of stability of karst system signatures by split sample test

Since large parts of the analysis are based on the assumption that the karst system signatures represent the long-term characteristically behaviour of the karst systems, a split sample test was performed to check them for their stability.

2.1 Methodology

We first split the available time series into equal or almost equal parts (Table 1), depending on the length of the record. Since seasonality has a strong impact on the hydrological and hydrochemical behaviour, we only considered complete hydrological years. Then, the karst system signatures were calculated again applying the equations in Table 3 of the manuscript on the shortened time series.

Table 1: Shortened time series used for the split sample test; note that for the Swiss site, no hydrochemical data could be considered because it was only available for one hydrological year

	study sites				
	Austria	Israel 1/2	Palestine	Spain	Switzerland
Start	01.10.2002	01.10.1989	01.10.1989	01.10.2007	01.10.2004
End	30.09.2004	20.09.1994	20.09.1994	30.09.2009	30.09.2005
discharge	daily	daily	monthly	daily	daily
$\delta^{18}O$	irregular	irregular	-	weekly to monthly	-
NO_3	weekly	weekly to monthly	-	weekly to monthly	-
SO_4	weekly	daily to weekly	-	weekly to monthly	-

2.2 Results

The majority of the signatures do not deviate more than 20% from their original signature values. However, there are a number of exceptions: L_{NO3} shows always a deviation >30% and often the slopes of the flow duration curves show deviations >20% especially for the Spanish and Israeli 1 sites.

Table 2: Results of the split sample test; deviations from the system signatures obtained by the complete time series are given as relative deviations [%] and as absolute deviations

Deviation of signatures	Unit	Study site					
		Austria	Switzerland	Spain	Palestine	Israel 1	Israel 2
S_{HF}	[%] / [l s^{-1}]	7.59 / -0.32	2.67 / -0.12	-99.74 / 1.17	16.61 / -0.39	37.89 / -0.14	17.61 / -0.48
S_{MF}	[%] / [l s^{-1}]	-1.16 / 0.01	-3.47 / 0.03	14.63 / -0.33	-53.58 / 0.31	-56.90 / 0.18	-8.94 / 0.07
S_{LF}	[%] / [l s^{-1}]	0.22 / -0.01	49.29 / -0.48	37.98 / -0.69	17.99 / -0.56	26.94 / -0.43	44.51 / -0.76
$R_{Q,100}$	[%] / [-]	12.15 / 0.05	13.98 / 0.08	-107.40 / -0.28	n.a.	3.01 / 0.03	-0.29 / 0.00
V_{d18O}	[%] / [-]	27.53 / 0.09	n.a.	7.62 / 0.01	n.a.	-8.06 / -0.01	6.90 / 0.00
L_{NO3}	[%] / [d]	83.33 / 5	n.a.	90.00 / 36	n.a.	98.94 / 93	31.91 / 30
S_{SO4}	[%] / [mg s l^{-2}]	9.19 / -0.01	n.a.	28.45 / -0.06	n.a.	5.96 / -0.01	4.38 / -0.05
B_{SO4}	[%] / [mg l^{-1}]	0.75 / 0.00	n.a.	10.06 / 0.16	n.a.	4.30 / 0.06	2.75 / 0.13
B_Q	[%] / [Mio m³]	2.16 / 0.01	0.08 / 0.00	20.71 / 5.40	-10.64 / -0.66	4.31 / 10.37	-8.90 / -5.04
E_Q	[%] / [-]	-3.69 / -0.01	n.a.	-114.46 / -1.89	-9.56 / -0.10	-44.39 / -0.16	-8.97 / -0.11

2.3 Discussion

None of the karst system signatures found by the split-sample test had exactly the same value as the original signature found by the whole timer series. Because of the natural variability of the karst systems, this is no surprise, especially when the total length of time series is only 3 years (Spanish and Austrian sites). Hence, a deviation of ≤20% may still be regarded as "stable" compared to the original signature value. But larger deviations indicate instability of the signature. This is the case for L_{NO3}, were deviations >30% were found, for the Israeli 1 site even in the range of 3 months. Figure 2 in the manuscript shows that the cross-correlations coefficients obtained for the different sites are sometimes irregular (Austrian and Spanish sites) or very flat (Israeli 1 site). So small changes in the data used for their calculation may result in strong changes in the timing of the maximum cross-correlation. For that reason, conclusions drawn by the value of L_{NO3} or by sensitivity of the parameters to L_{NO3} should be considered with strong care. The strong deviations found for some of the slopes of the flow duration curves may be attributed to extra-ordinary wet or dry years that are either included or disregarded in the split-sample time series (e.g. Spanish site, wet hydrological year 2010/11, see Hartmann et al. (2013); Israeli sites, wet hydrological year 1990/91, dry hydrological year 1998/99, see Rimmer and Salingar (2006)). The analysis in our study considers the entire available time series of discharges and therefore the longest possible time period to reflect the hydrological variability of the karst systems. However, the split- sample test shows that the adequateness of the flow duration curves to represent the long-term characteristic behaviour of the discharge dynamics is dependent of the length of the available record and the number of extreme events it is containing (Singh and Bárdossy, 2012).

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