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 $r_{\text{Lin}} < 0.7$, 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 \( V_{\delta^{18}O} \) 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 \( V_{\delta^{18}O} \) 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 (\( V_{\delta^{18}O} \)) 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

<table>
<thead>
<tr>
<th>study sites</th>
<th>Austria</th>
<th>Israel 1/2</th>
<th>Palestine</th>
<th>Spain</th>
<th>Switzerland</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start</td>
<td>01.10.2002</td>
<td>01.10.1989</td>
<td>01.10.1989</td>
<td>01.10.2007</td>
<td>01.10.2004</td>
</tr>
<tr>
<td>discharge</td>
<td>daily</td>
<td>daily</td>
<td>monthly</td>
<td>daily</td>
<td>daily</td>
</tr>
<tr>
<td>δ¹⁸O</td>
<td>irregular</td>
<td>irregular</td>
<td>-</td>
<td>weekly to monthly</td>
<td>-</td>
</tr>
<tr>
<td>NO₃</td>
<td>weekly</td>
<td>weekly to monthly</td>
<td>-</td>
<td>weekly to monthly</td>
<td>-</td>
</tr>
<tr>
<td>SO₄</td>
<td>weekly</td>
<td>daily to weekly</td>
<td>-</td>
<td>weekly to monthly</td>
<td>-</td>
</tr>
</tbody>
</table>

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: $L_{NO_3}$ 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

<table>
<thead>
<tr>
<th>Deviation of signatures</th>
<th>Unit</th>
<th>Study site</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Austria</td>
</tr>
<tr>
<td>$S_{HF}$ [%] / [l s$^{-1}$]</td>
<td>7.59 / -0.32</td>
<td>2.67 / -0.12</td>
</tr>
<tr>
<td>$S_{MF}$ [%] / [l s$^{-1}$]</td>
<td>-1.16 / 0.01</td>
<td>-3.47 / 0.03</td>
</tr>
<tr>
<td>$S_{LF}$ [%] / [l s$^{-1}$]</td>
<td>0.22 / -0.01</td>
<td>49.29 / -0.48</td>
</tr>
<tr>
<td>$R_{Q,100}$ [%] / [-]</td>
<td>12.15 / 0.05</td>
<td>13.98 / 0.08</td>
</tr>
<tr>
<td>$V_{d18O}$ [%] / [-]</td>
<td>27.53 / 0.09</td>
<td>n.a.</td>
</tr>
<tr>
<td>$L_{NO3}$ [%] / [d]</td>
<td>83.33 / 5</td>
<td>n.a.</td>
</tr>
<tr>
<td>$S_{SO4}$ [%] / [mg s l$^{-2}$]</td>
<td>9.19 / -0.01</td>
<td>n.a.</td>
</tr>
<tr>
<td>$B_{SO4}$ [%] / [mg l$^{-1}$]</td>
<td>0.75 / 0.00</td>
<td>n.a.</td>
</tr>
<tr>
<td>$B_Q$ [%] / [Mio m$^3$]</td>
<td>2.16 / 0.01</td>
<td>0.08 / 0.00</td>
</tr>
<tr>
<td>$E_Q$ [%] / [-]</td>
<td>-3.69 / -0.01</td>
<td>n.a.</td>
</tr>
</tbody>
</table>

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 time 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 $\leq$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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