# Use of Combined Recession Curves Analyses of Neighbouring Karstic Springs to Reveal Karstification Degree of Groundwater Springing Routes

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**Abstract** In the southern part of the Slovenský Kras Mts., positioned on the territory of Hungarian–Slovak transboundary karstic hydrogeological structure of Dolný vrch/Alsóhegy, several karstic springs occur. Hydrograph recession curves from nine gauged springs on the Slovak part of the transboundary aquifer were analyzed. Individual springs were classified by typical groundwater depletion hydrograph into categories by typical depletion equations. These were also assigned to the different lithostratigraphic limestone types occurring in the springing areas and assumed recharge areas. Previous hydrogeological mapping had first indicated a suspicion on the possible linking of groundwater from the two individual springs, to be only the two surface appearances of the same springing groundwater in the neighbouring springs. By coupling the outflowing volumes of the two springs together, and analyzing the resulting new time series, new classification of subregimes could be done. Surprising new facts were revealed about the analysed pairs of springs, which primarily were not recognized as connected branches of one spring. Summation of discharged volumes into one entity lead in two cases to discovery of apparent presence of turbulent flow subregimes on the recession curves. Two branches of one outflow from the recharge area exist there; one of them usually represents the lower branch with "baseflow" and another, the upper one, is the overflow spring. This also influences the aspects of groundwater-sensitivity-to-pollution, and also gives unexpected hopes for further speleological investigations nearby.

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# 1 Geographical and Hydrogeological Background

Karstic area of the Slovenský Kras Mts. (southern Slovakia) contains also the Slovak/Hungarian transboundary karstic hydrogeological structure of Dolný vrch/Alsóhegy (Fig. 1). The total area of this structure is 46.70 km$^2$, the Slovak part outcrops on the 21.63 km$^2$. The structure itself is formed mainly by Wetterstein type of limestones. Relatively impervious rocks, delineating the karstic structure itself – the Lower Triassic shales, sandstones and claystones form the underbed/barrier to the groundwater flow, on which the majority of springs appear. The springs are on the Slovak part of this transboundary karstic aquifer mentioned together with ID (number), under which they are registered by the Slovak Hydrometeorological Institute (SHMÚ), the institution that regularly monitors the discharge of the springs on weekly and in some cases on daily bases since the 1960s (Malík & Vojtková 2006).

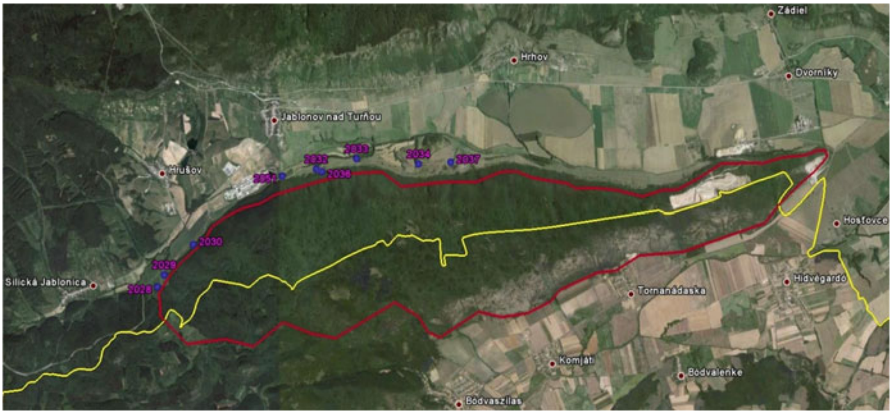


**Fig. 1** Location of the Dolný vrch/Alsóhegy transboundary Slovak/Hungarian hydrogeological structure in Europe. Springs monitored by the Slovak Hydrometeorological Institute in the NW part of the structure are *blue points*, structure delineation in *dark violet line*, state boundaries in *yellow line*. The coordinates of the centre of the area are N 48.5710° and E 20.7267°

# 2 Recession Curves Analyses

In this study, simple Maillet's exponential description ($Q_\mathrm{t} = Q_\mathrm{o} \cdot \mathrm{e}^{-\alpha \cdot t}$) of laminar subregimes is used (Maillet 1905). Using only the Reynold's number (usually technically difficult) it is possible to distinguish the presence of laminar or turbulent flow of water (groundwater/flow in karst channels). Kullman (1990) offers a simplified method of turbulent flow identification. The linear turbulent model ($Q_\mathrm{t} = Q_\mathrm{o} \cdot (1 - \beta \cdot t)$) for turbulent flow supposed for karstic channels as described by Kullman (1990, 2000) is used within this study. Several both laminar and turbulent subregimes may exist in one aquifer, and its discharge can be described by superposition of several appropriate equations. Hydrograph recession curves can be used for analyses of type and properties of a karstic aquifer (Kullman 2000), as well as for estimation of regional karstification degree and groundwater sensitivity to pollution (Malík 2007). The basis of this method, which is used for the assessment of the degree of the rock disruption and karstification, were described by Kullman

**Table 1** Equations of recession curves of springs monitored in the Dolný vrch/Alsóhegy area

| SHMÚ No. (Fig. 1) | Site and spring's name | Final discharge equation |
|---|---|---|
| 2028 | Hrušov – Studňa pri hradnom buku | $Q_t = 1.5 \cdot e^{-0.008 \cdot t} + 25.0 \cdot e^{-0.055 \cdot t}$ |
| 2029 | Hrušov – Čierna studňa | $Q_t = 0.35 \cdot e^{-0.0031 \cdot t} + 8.0 \cdot e^{-0.047 \cdot t}$ |
| 2030 | Hrušov – Jarček | $Q_t = 0.80 \cdot e^{-0.003 \cdot t} + 13.0 \cdot (1 - 0.02 \cdot t) + 22 \cdot (1 - 0.12 \cdot t)$ |
| 2032 | Jablonov nad Turňou – Köszörű | $Q_t = 17.0 \cdot e^{-0.005 \cdot t} + 20.0 \cdot e^{-0.011 \cdot t}$ |
| 2033 | Jablonov nad Turňou – Tapolca | $Q_t = 24 \cdot e^{-0.01 \cdot t} + 70 \cdot (1 - 0.0147 \cdot t) + 160 \cdot (1 - 0.045 \cdot t) + 790 \cdot (1 - 0.14 \cdot t)$ |
| 2034 | Hrhov – Körkút | $Q_t = 0.15 \cdot e^{-0.008 \cdot t} + 1.1 \cdot e^{-0.045 \cdot t}$ |
| 2036 | Jablonov nad Turňou – Köszörű občasný | $Q_t = 30.0 \cdot (1 - 0.0109 \cdot t) + 120.0 \cdot (1 - 0.016 \cdot t) + 146.0 \cdot (1 - 0.058 \cdot t)$ |
| 2037 | Hrhov – Žmaň | $Q_t = 2.7 \cdot e^{-0.024 \cdot t}$ |
| 2051 | Jablonov nad Turňou – Za mostom | $Q_t = 3.0 \cdot e^{-0.036 \cdot t} + 12.0 \cdot e^{-0.18 \cdot t}$ |
| 2032 + 2036 | Jablonov nad Turňou – Köszörű + Köszörű občasný | $Q_t = 12.0 \cdot e^{-0.003 \cdot t} + 130.0 \cdot e^{-0.05 \cdot t} + 500.0 \cdot (1 - 0.04 \cdot t)$ |
| 2028 + 2029 | Hrušov – Čierna studňa + Studňa pri hradnom buku | $Q_t = 2.0 \cdot e^{-0.0055 \cdot t} + 5.0 \cdot e^{-0.033 \cdot t} + 14.0 \cdot (1 - 0.07 \cdot t)$ |

**Table 2** Karstification degree of the monitored springs in the Dolný vrch/Alsóhegy hydrogeological structure

| SHMÚ No. (Fig. 1) | Site and spring's name | Karstification degree |
|---|---|---|
| 2034 | Hrhov – Körkút | 3.7 |
| 2037 | Hrhov – Žmaň | 2.3 |
| 2028 | Hrušov – Studňa pri hradnom buku | 3.7 |
| 2029 | Hrušov – Čierna studňa | 3.0 |
| 2030 | Hrušov – Jarček | 8.0 |
| 2032 | Jablonov nad Turňou – Köszörű | 3.7 |
| 2033 | Jablonov nad Turňou – Tapolca | 6.0 |
| 2036 | Jablonov nad Turňou – Köszörű občasný | 10.0 |
| 2051 | Jablonov nad Turňou – Za mostom | 4.7 |
| 2032 + 2036 | Jablonov nad Turňou – Köszörű + Köszörű občasný | 5.5 |
| 2028 + 2029 | Hrušov – Čierna studňa + Studňa pri hradnom buku | 5.5 |

(1990, 2000). Karstification degree is understood as a level of endogenous karst development, which – for the phreatic and epiphreatic zone – can influence the mode of groundwater upwelling from the karst system (Malík 2007).

In the case of Dolný vrch/Alsóhegy hydrogeological structure, the previous analyses of springs' recession curves had revealed presence of several discharge subregimes, including turbulent ones. In the Table 1, recession curves analyses undertaken on individual springs are shown as resulting equations.

Differences in character of individual depletion hydrographs enabled also the assessment of the anticipated extent of karstification of the rock environment between groundwater infiltration in the catchment area and its springing (outflow) in the individual springs (Table 1). According to Malík (2007), the karstification degree there is within the range of 2.3 to 10.0 (Table 2).

In the same way, for the purposes of regional comparison, the mean ranking can be linked to certain aquifer types, based on the results of individual spring's evaluation. In this way, Wetterstein limestones aquifer can be characterized by "4.7" degree as rock environment with anticipated existence of crushed water-bearing zones (e.g. fault zones) or by dense network of open small fissures in combination with simple, partly (perennially) phreatic conduit system of considerable extent (e.g. with open karstified fault in the vadose zone; Kullman 1990).

## 3 Discharge Coupling

Previous hydrogeological mapping had first indicated the possible linking of groundwater from the two individual springs as only two surface appearances of the same springing groundwater in the neighbouring outlets. In the case of the northern part of the Dolný vrch/Alsóhegy hydrogeological structure, springs 2032 Köszörű + 2036 Köszörű občasný near Jablonov nad Turňou and 2028 Studňa pri hradnom buku + 2029 Čierna studňa near Hrušov seemed to be close enough to start further investigations. Counting the outflowing volumes of these two pairs of springs together, and analyzing resulting new time series, new classification of subregimes could be done (Fig. 2, Tables 1 and 2 – lower part). Outflows from the aquifer in the area of spring's outlets (2032 + 2036) and (2028 + 2029) are both characterised by the "5.5" degree. Regime of groundwater discharge is mathematically expressed by superposition of two exponential and one linear equations (Table 1, last rows). Groundwater regime type is a combination of one sub-regime with turbulent flow (with short-term influence) and two sub-regimes with laminar groundwater flow. Discharge coefficients in individual sub-regimes are high (Table 1), which indicates very high permeability and low storativity of rock environment. Discontinuities in the rock environment can be described as affected by extensive deformation, with a majority of open, medium size, both not karstified and karstified fissures, in the phreatic zone of the fissure karst groundwater reservoir and with smaller influence of connected conduits.

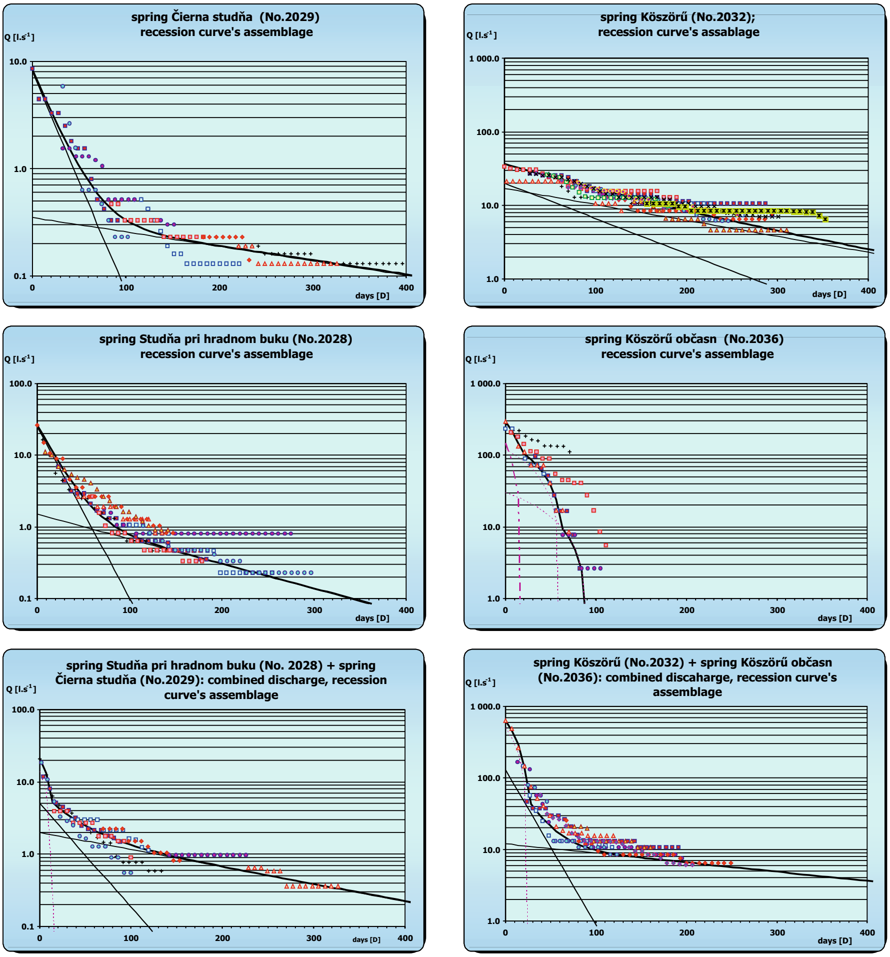


**Fig. 2** Recession curves of the individual outflows and of the coupled discharges (total sum of discharges) analysed for the cases of springs Studňa pri hradnom buku (No. 2028), spring Čierna studňa (No. 2029), Köszörű (No. 2032) and Köszörű občasný (No. 2036), situated in the NW part of the Dolný vrch/Alsóhegy transboundary Slovak/Hungarian hydrogeological structure. Individual decreasing discharge series are drawn by different marking, the final evaluation was done on the base assemblage of individual recession curves from the different dry periods. *Thick lines* represent the final assessment of recession curve, based on equations shown in Table 1. *Thin lines* represent estimated subregimes. Both equations and their representation by lines were created manually by help of MS Excel macro developed in Geological Survey of Slovak Republic, using the "maximum allowed accession"

## 4 Conclusions

Recession curves analyses of discharge time series observed on individual springs can be used for estimation of regional karstification degree. In some cases of analysed pairs of springs (previously not recognized as connected branches of one spring), surprisingly new facts can be revealed. Being classified as individual springs, with only the presence of laminar subregimes in their recession curves (i.e., with low karstification degrees), summation of discharged volumes into one entity may lead into discovery of apparent presence of turbulent flow subregimes on the recession curves. In the hydrogeological structure of Dolný vrch/Alsóhegy, two such cases were found. These springs can be therefore considered as two branches of one outflow from the hydrogeological structure. One of them usually represents the lower branch with the “baseflow”, another, the upper one, is the overflow spring. These complex relationships bring more light in the aspects of groundwater sensitivity to pollution in such cases, and also give unexpected hopes for further speleological investigations nearby.

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