Establishing the European Geological Surveys
Research Area to deliver a Geological Service for
Europe

RESOURCE Project

Deliverable 5.1

Karst typology in Europe: state of the art

Authors and affiliation: Hakoun, V. (BRGM), Bailly-Comte V. (BRGM), Charlier JB. (BRGM), Herms I. (ICGC), Hickey C. (GSI), Pardo-Igúzquiza E. (IGME), Stroj A. (HGI), Van Vliet M. (TNO), Vernes R. (TNO), Maréchal, JC. (BRGM)

E-mail of lead author:
v.hakoun@brgm.fr

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SUMMARY

Work package 5 of GeoERA RESOURCE project focuses on typologies for karst and chalk areas. Fractured limestones, dolostones and chalks, all susceptible to karstification processes, form important groundwater resources, but often with complicated hydrodynamic regimes. Complexity and heterogeneity of groundwater flow in karst aquifers limit the use of classical methods for assessing the water reserves volume or evaluating their vulnerability. Classically, due to their high degree of heterogeneity, understanding of karst aquifer hydrogeology relies on the monitoring of the main outlet of the aquifer, considering it as the right proxy in order to characterize the karst as a whole entity. Typical karst classifications rely on these measurements according to available data time series. The objective of Resource-WP5 is to test and evaluate monitoring and interpretation methods to come up with an improved characterization framework and typology that will be tested on pilot areas across Europe.

Task 1 (5.1) of WP5 is dedicated to the state of the art of existing methods/approaches and conceptual models usually applied to karst aquifers in Europe. The analysis has been extended to the whole world as worldwide citations have been collected and analyzed. The present report constitutes the deliverable 5.1. of RESOURCE project, describing a summary of the state of the art of karst hydrogeology typology. Chapters 2 and 3 of this deliverable constitute the core of the report including a list and description of the main classification methods/tools applied to karst aquifers. It is organized according to two main parts. Chapter 2 provides a list of the various conceptual models describing the hydrogeology of karst aquifers. Chapter 3 provides the existing classification typologies applied on data time series. The latest mainly rely on flow data that are used to identify and enhance several hydrodynamic behaviors: (i) baseflow/quickflow contribution to the spring; (ii) infiltration flow processes; (iii) dynamic volume stored in the saturated part of the system; (iv) possible existence of interflows from and to the system; (v) transit times evaluation.

Appendix 1 of the report contains a survey of present usage regarding the monitoring of karst aquifers among the Eurogeosurveys involved in this WP.

In the next steps of RESOURCE-WP5, these methods will be applied to the case studies identified by the Eurogeosurveys that are partners of this project. A comprehensive analysis of all the produced criteria/parameters will be carried out in order to identify useful versus redundant information. The final objective is to come up with a harmonized and up to date way of classifying karst aquifers with regard to management issues such as (i) water reserves evaluation (ii) flow regulation capacity and (iii) vulnerability assessment. For that purpose, a shared tool will be developed in a user-friendly system in order to implement the selected methods.

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1 INTRODUCTION

1.1 Context : Work Package 5 - CHAKA

Work package 5 of GeoERA RESOURCE project focuses on typologies for karst and chalk areas. Fractured limestones, dolostones and chalks, all susceptible to karstification processes, form important groundwater resources, but often with a complicated regime that includes both fast flow routes that makes them vulnerable to pollution, and slow baseflows of older uncontaminated water that mixes at the springs and wells. This complexity and heterogeneity of groundwater flow in karst aquifers limits the use of classical methods applied to porous aquifers for assessing the water reserve volume or evaluate their vulnerability. Classically, due to their high degree of heterogeneity, understanding of karst aquifer hydrogeology relies on the monitoring of the main outlet of the aquifer, considering it as the right proxy in order to characterize the karst as a whole. Usual karst classifications rely on these measurements according to available data time series. Resource-WP5 will test and evaluate monitoring and interpretation methods to come up with an improved characterization framework and typology that will be tested on pilot area across Europe.

1.2 Objective

Task 1 (5.1) of WP5 is dedicated to the state of the art of existing methods/approaches and conceptual models usually applied to karst aquifers in Europe. The analysis has been extended to the whole world as worldwide citations have been collected and analysed. The present report constitutes the deliverable 5.1. of RESOURCE project, describing a summary of the state of the art of karst aquifers typology and conceptual models in karst hydrogeology.

Chapters 2 and 3 of this deliverable constitute the core of the report including a list and description of the main classification methods/tools applied to karst aquifers. It is organized according to two main parts:

- Chapter 2: description of conceptual models applied to karst aquifers
- Chapter 3: description of classifications based on metrics applied to time data series.

These classifications and tools will be used in the following tasks of the WP.

Appendix 1 of the report contains a survey of present usage regarding the monitoring of karst aquifers among the Eurogeosurveys involved in this WP.

2 STATE OF THE ART OF CONCEPTUAL MODELS

Karst aquifers offer a broad diversity of structure and functioning in diverse environments. Thus several classifications were designed to order these systems according to soft and hard information. These classifications can be based on conceptual models for recharge, aquifer structure, functioning, hydrodynamic and/or hydrochemical variables such as spring discharge and electrical conductivity of water among others. Classifications based on conceptual models involve field knowledge which may be unknown at the time of the study (e.g. depth of karstification) and some information regarding spring discharge. Some complementary classifications based on quantitative metrics may be applied to better characterize the water resources of the aquifer.

2.1 Karst system functioning

The first classification is based on a conceptual model regarding the structure of the conduit system (its spatial organization) and flow efficiency. The classification is presented in Table 1. Based on field observations and water level and/or flow rate measurements, three types of aquifers can be identified (Marsaud, 1997): fissured carbonated aquifers, karst systems and non-functional systems.

		karst functioning	
		no	yes
karst structure	no	fissured carbonated aquifers **type 1**	no karst functioning when karst stucture is missing
	yes	non functional karst systems **type 3**	karst system *sensu stricto* **type 2**

Table 1: karst classification based on structure and flow efficiency functioning (Marsaud, 1997).

2.2 Spatial distribution of recharge

The second classification is a binary approach that conceptualizes the spatial distribution of the recharge area. For this classification, one has to identify whether some external catchment significantly contributes to recharge or not. This contribution may stem from a catchment having a different lithology and feeding the karst system through point recharge (i.e. river loss), as illustrated in *Figure 1*. In such case, the system is named binary. Otherwise, without external recharge, the system is unary. Identifying if the system is binary or unary helps interpret the temporal fluctuations of spring discharge or hydrochemistry. In particular for flood events, it helps identify whether flows from another catchment contribute significantly to flooding dynamics.

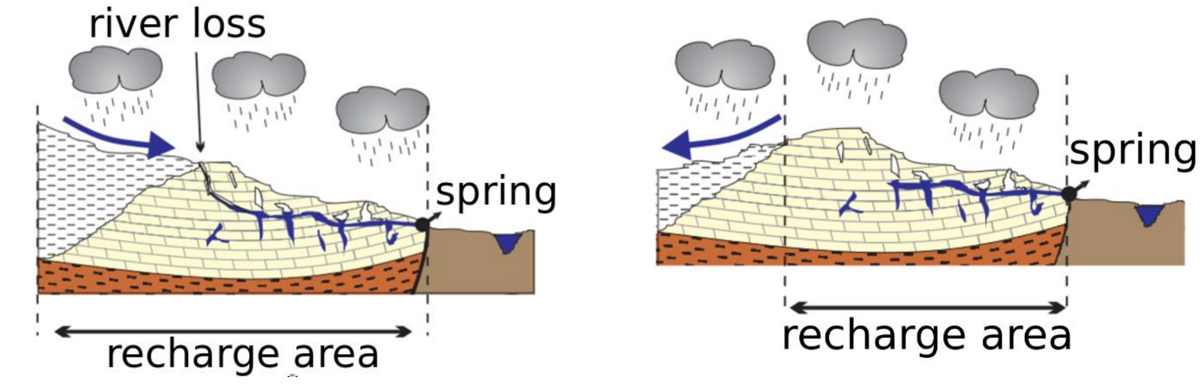


*Figure 1: **Left:** binary karst system where additional recharge stems from an upstream catchment. **Right:** unary karst system where recharge spreads over the karstified limestone only. Figure modified after Marsaud (1997).*

2.3 Karstification depth

The third type of classification relates to the depth of the karstification with respect to the main spring's altitude. Two cases may be found (*Figure 2*). When the karstification is solely present above (or at a similar altitude) the main spring, the system is of Jurassian-type. Otherwise, when the karst network extends significantly deeper below the spring altitude, the system is called of Vauclusian-type. Since Vauclusian-type aquifers may host important water resources below the spring level, identifying and reporting these types of aquifers is critical for water resources exploitation and management to differentiate aquifers with deep storage compartments.

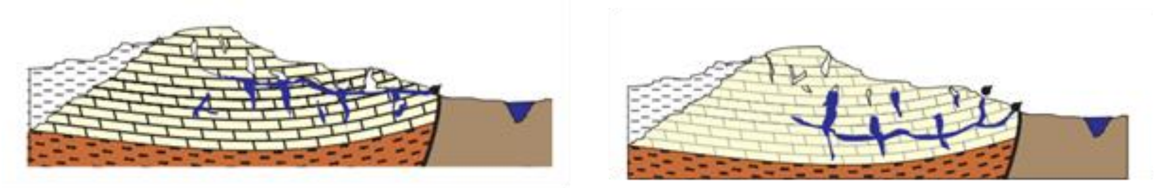


*Figure 2: **Left:** Jurassian-type karst system with conduit networks close to the spring altitude. **Right:** Vauclusian-type karst system with conduit network developed below the spring. Figure modified after Marsaud (1997).*

2.4 Multifactorial approaches

A complementary approach considers the type of flow occurring within a system. The three stages, shown in map view and cross section, are members of a continuum of karst evolution. These stages evolve from diffuse to conduit flow regimes for early to well-connected karst systems respectively. Black circles are springs and open circles indicate sinkholes where water infiltrates through localized recharge. Thick black lines correspond to karst conduits. Wiggly lines correspond to surface streams before their infiltration. Flow lines and equipotential lines are shown for diffuse and mixed flow, but the concepts of such lines is not applicable in a purely conduit system (Quinlan and Ewers, 1985).

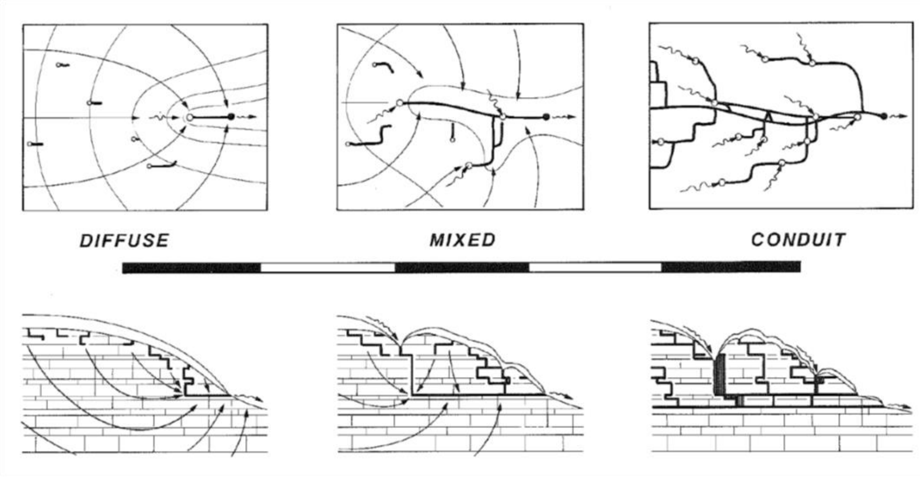


Figure 3: Diffuse flow, mixed flow and conduit flow karst systems, from (Quinlan and Ewers, 1985)

Karst functioning and individual components which describe flow, storage and recharge and discharge processes were summarized by several authors. In particular, Quinlan et al., (1991) propose a classification based on flow, storage, recharge and vulnerability. This classification is illustrated on Fig. 4 with a four dimension diagram.

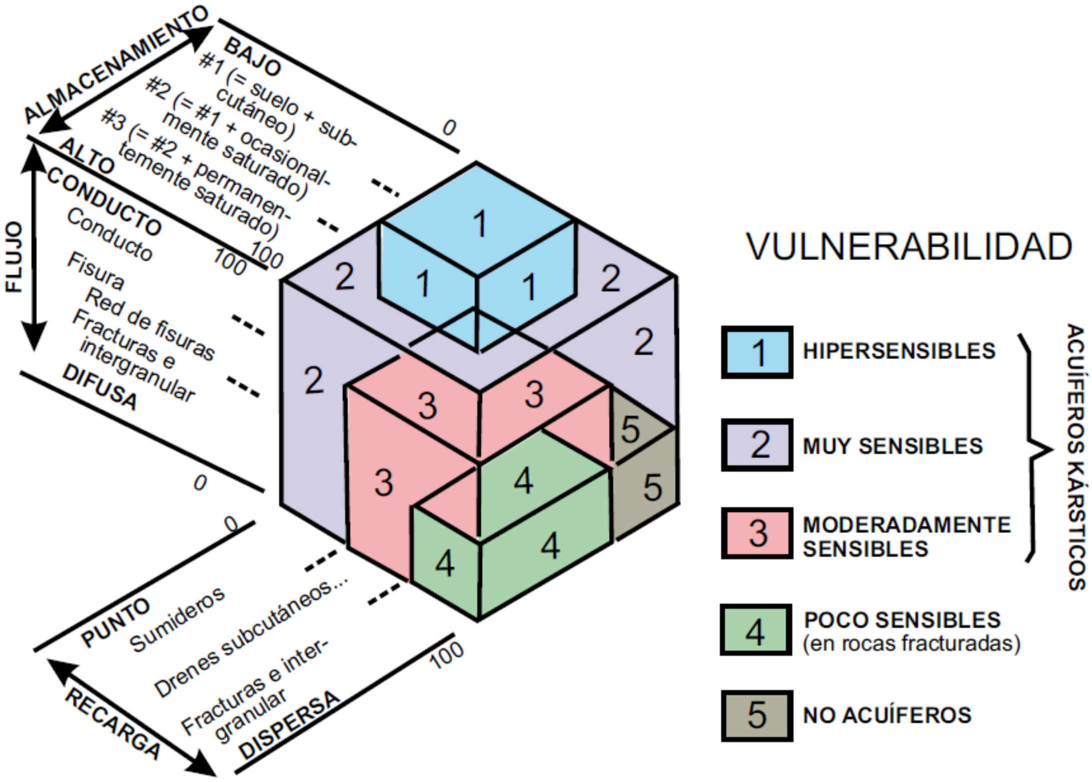


Figure 4: Four dimension diagram providing a generic framework for karst classification based on flow, storage, recharge and vulnerability (after (Pulido, 2014; Quinlan et al., 1991)) .

Leaving aside the vulnerability factor, several authors propose classifications based on multiple compartments including recharge type (e.g. Mangin, 1975; Smart and Hobbs, 1986). Smart and Hobbs (1986) considered recharge, storage and transmission to be the important end members, that need to be considered separately. They used hydrographs to demonstrate the independent effects of recharge, storage and flow on karst spring discharge (*Figure 5*). They argue that information on all three factors; recharge, storage and transmission should be gathered, as analysis of the hydrograph alone can be misleading. This is demonstrated by the fact the hydrographs produced for an aquifer with concentrated recharge, high storage and diffuse flow could produce an almost identical hydrograph to an aquifer with diffuse recharge, high storage and concentrated flow.

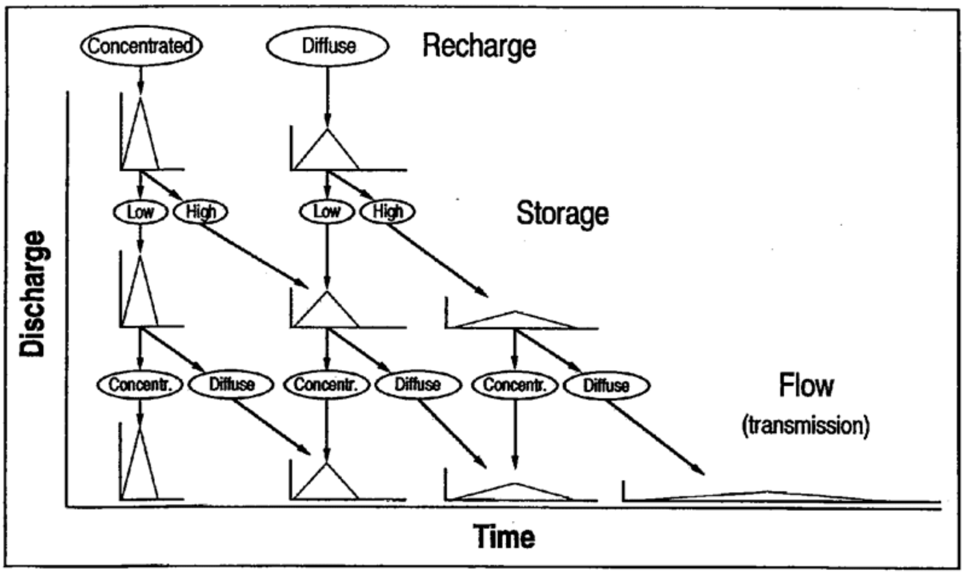


Figure 5: recharge, storage and transmission end members from hydrograph analysis (after Smart and Hobbs 1986)

In particular, (Mangin, 1975) and (Ford and Williams, 2007) proposed two similar classifications which are illustrated in Fig. 5. These figures show the variety of flow, storage and discharge processes, together with their location, which may occur in a given system. While these generic classifications result from years of debate between hydrologists and account for critical components (i.e. factors), examples of inter system comparison according to these classifications is yet to be found in the literature.

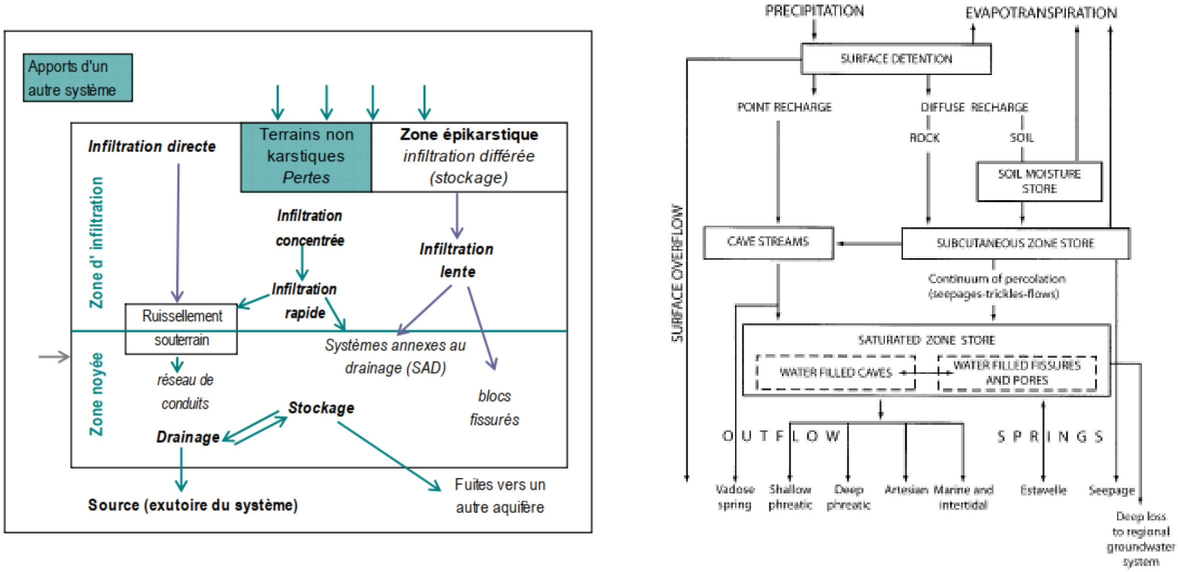


Figure 6: Conceptual models of karst system functioning accounting for flow, storage and recharge processes. Functioning diagram on the left and right from Mangin (1975) and Ford and Williams (2007) respetively

2.5 Engineering and speleomorphological classifications

Several classifications based on geomorphological aspects were devised for engineering purposes (e.g. Fookes and Hawkins (1988) and Fookes (1997)), to identify which geohazards a civil engineer would encounter in karst terrains. Note the recent review of Gutiérrez et al. (2014) summarizing karst related geohazards. *Figure 7* shows the recent classification of Waltham and Fookes (2003) who described five classes characterizing karst terrains "in terms of complexity and difficulty to be encountered by the foundation engineer". The progressive transition through these classes focuses on the specific properties of three main objects: caves, sinkholes and rockhead relief (the upper horizon of outcropping limestone rock, i.e. the epikarst). The first class of karst "kI" shows caves of little size and no sinkhole or upper fractured layer. In contrast, the last class "kV" shows caves of large diameter (with collapsed ceiling), buried sinkholes with subsiding sediments and pinnacles. While this classification addresses geomorphological aspects, it does not account for flow, storage and recharge processes nor vulnerability. Alternate approaches based on geomorphology were devised to classify geometries of karst conduit networks. As we shall see next, an intrinsic characteristic of such classifications is to account for self-organization created by flow and dissolution processes.

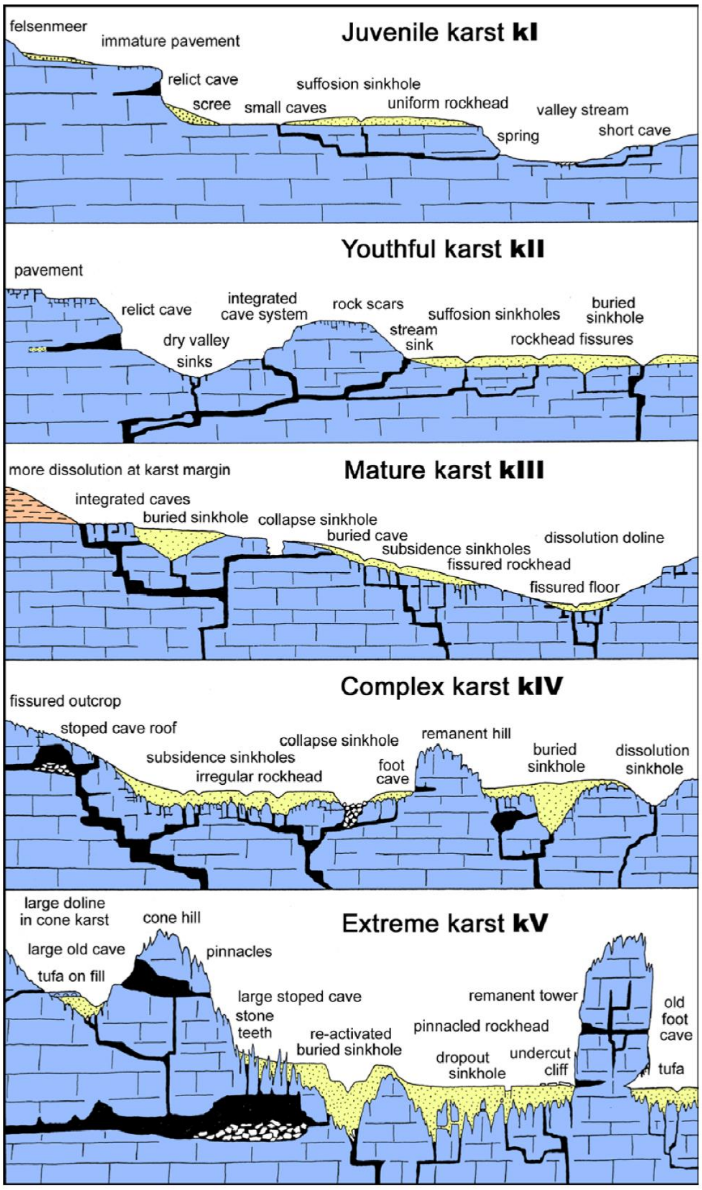


Figure 7: Five classes of karst terrain with varying characteristics of caves, sinkholes and rockhead reliefs for engineering applications (from Waltham and Fookes (2003)).

Since systematic explorations of caves during the 19th century, the geometries of caves have been classified with respect to their associated patterns and groundwater flow (Cvijić (1893), Martel (1921)). More advanced studies based on caves databases identified specific patterns of conduit networks (see Palmer (2010) for a review). A complementary set of approaches depicting regional scale groundwater flow were proposed by Grund (1903) and Katzer (1905) among others. Cvijic (1918) introduced a vertical zonation according tor three flow components: vadose, epiphreatic and phreatic. More recent approaches have identified the role of flow conditions (i.e. gradient, recharge, outlet location). Accounting for different recharge and karstification contexts, Jouves et al. (2017) proposed a generic conceptual model of cave networks based on a quantitative analysis of 3D maps of 26 natural systems. Figure 8 presents this model with four types of cave patterns, three vertical areas of flow (from top to bottom: vadose, epiphreatic and phreatic areas) components and different recharge contexts (top: irregular (localized) and diffuse and bottom: hypogenic). Since this classification aims to describe conduit networks structure, it disregards groundwater water storage processes.

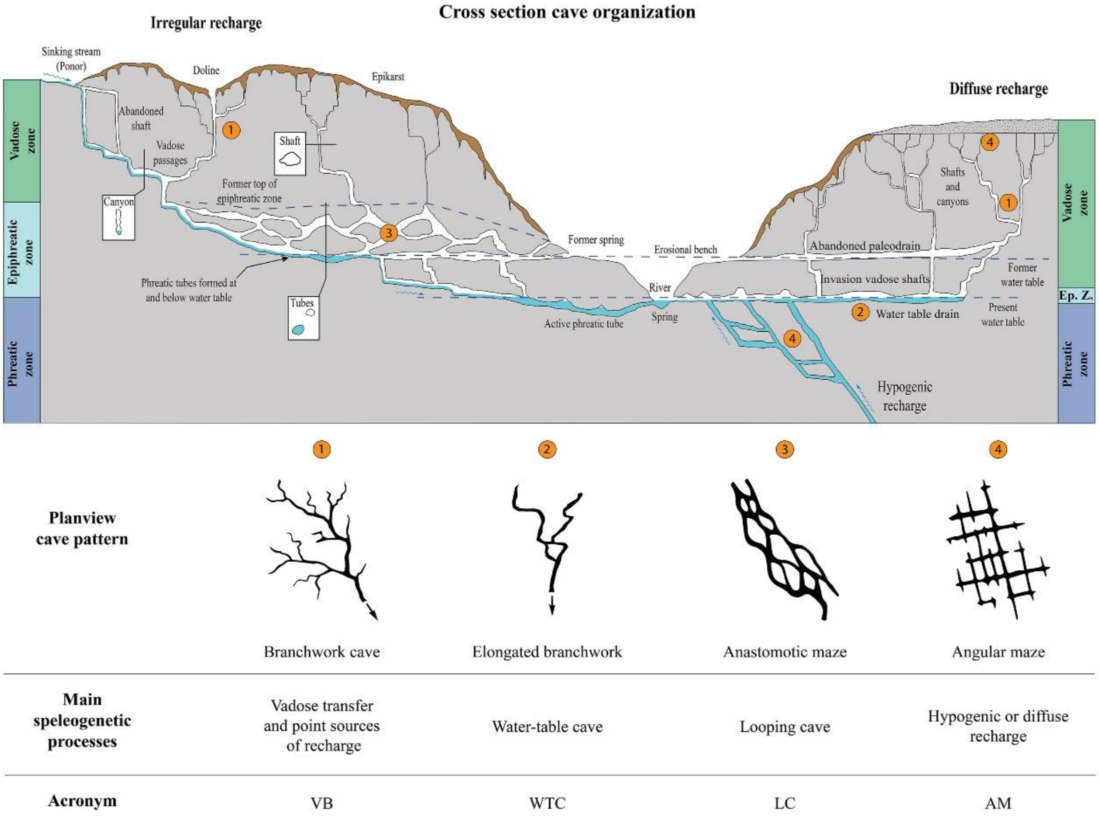


Figure 8: Classification of cave geometries and spatial organization accounting for boundary (recharge) and flow conditions (from Jouves et al. (2017)).

3 STATE OF THE ART OF METRICS CLASSIFICATION

Classically, due to their high degree of heterogeneity, understanding of karst aquifer hydrogeology relies on the monitoring of the main outlet of the aquifer, considering it as the right proxy in order to characterize the karst as a whole entity (

Figure 9). Until now, the proposed approach has focused on discharge time series analysis using several types of tools (spectral analysis, recession curve analysis). The output is then used to propose a typology of karst aquifers based on metrics classification: see Mangin (1974) for example. During the last decades, additional variables such as temperature, turbidity, electrical conductivity, and others (

Figure 9) were measured. These new variables provide promising information about the karst hydrodynamics and vulnerability that should be used in order to propose a new and more complete typology of karst aquifers.

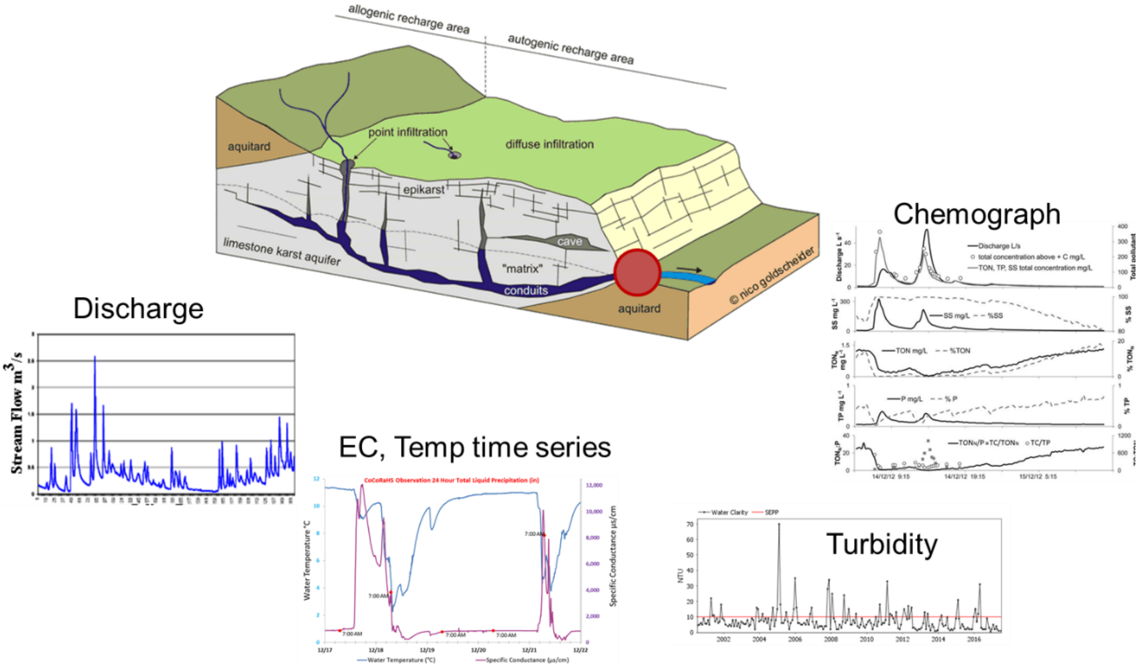


Figure 9: schema of a karst aquifer monitored at its main outlet for discharge, EC or temperature, turbidity and chemistry.

3.1 Descriptive statistics of flow and electrical conductivity

Some basic statistics have been used to describe and compare karst spring discharges. Among them, specific statistics such as the mean annual flow, $\bar{q}$, and the maximum and minimum flow rates can be used for water balance and comparison among karst springs. Other specific metrics such as the ratio between the maximal and minimal discharges (variation index), $^{q_{max}}/_{q_{min}}$, and the coefficient of variation, $^{\sigma}/_{\bar{q}} \times 100$ or $^{(q_{max} - q_{min})}/_{q_{min}}$ x 100 (Meinzer, 1923).

3.2 Classification based on recession flow analysis

Regarding classifications based on quantitative metrics, the French geological survey applied Mangin's approach on many karst aquifers. The basis of the approach is to model the spring discharge curve after a flood peak (Mangin, 1970). The decreasing and recession limbs of the spring discharge are modeled as a sum of one (sometimes two, see Ladouche et al. (2006)) homographic function(s) ψ_t and an exponential function $\phi_{(t)}$:
$Q_{(t)} = \psi_{(t)} + \phi_{(t)}$.

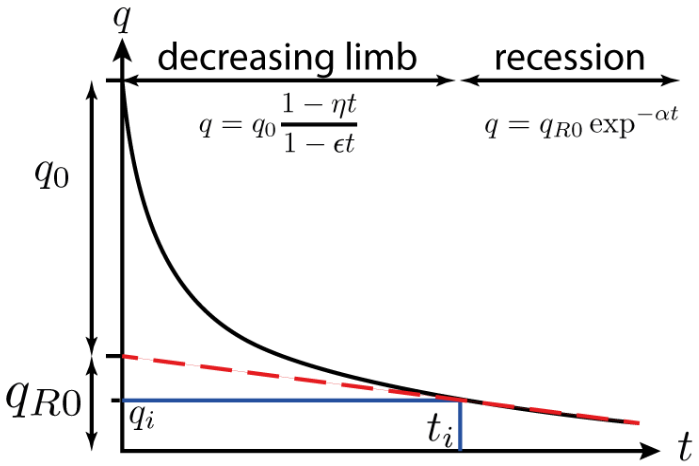


Figure 10: quantification of decreasing and recession limbs with a homographic and exponential function (Mangin, 1970, Crochet and Marsaud, 1997).

The former function $\psi_{(t)} = q_0 \frac{1-\eta}{1+\epsilon\, t}$ is fitted to the decreasing limb while the latter function (Maillet's law) $\phi_{(t)} = q_{R0} e^{-\alpha t}$ is fitted to the recession limb (see Figure 10 for details).

Mangin's classification is used to compare several aquifer systems with respect to their recharge and storage processes at a daily time step (Mangin A. , 1975). It is based on two indices: *i* and *k*, which describe an infiltration delay and how the aquifer system regulates flow respectively. The former index ranges between 0 and 1, it stems from the fitted homographic function when *t=2.* High *i* values (i → 1) relates to slow and complex infiltration processes, conversely small values relate to fast transfers to the saturated zone. It should be noted that *i* value can be significantly influenced by intensity and duration of the precipitation event, which results in its value inconsistency between different floods (Jeannin and Grasso, 1994).

The *k* index is the ratio between the dynamic storage volume and the mean annual volume flowing through the phreatic zone. The dynamic volume (V_D) is given by:

$$V_D = \int_0 q_i . e^{-at} = \frac{q_i}{\alpha} . c$$

in which q_i is the flow rate at the beginning of the recession period (see Figure 10). Thus, V_D can be calculated from the quantitative analysis of the recession period with Maillet's law (see above). Except for deep confined karst aquifers for which k>1 (e.g. El-Hakim and Bakalowicz (2007)), most aquifer systems have 0.01<k<1. The lower the k, the faster the mean transit time.

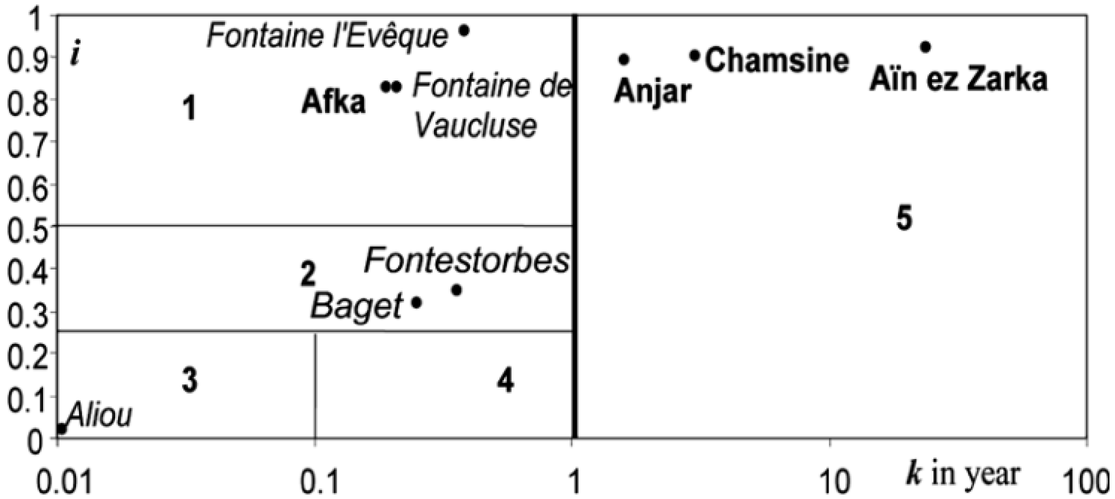


Figure 11: Classification of karst aquifers systems. Based on Mangin (1975) and modified for high i (>1) by El-Hakim and Bakalowicz (2007).

The dependence of recession coefficient on aquifer properties follows two fundamentally different principles (Kovács et al., 2005):

The matrix-restrained flow regime (MRFR) is controlled by the hydraulic parameters of the low-permeability medium. This case can be mathematically characterized by the drainage of a homogeneous block. It is a characteristic of mature karst systems under baseflow conditions

The conduit influenced flow regime (CIFR) is mainly controlled by the conductive capacity of the conduit system. CIFR is typical during the baseflow of fissured systems or weakly karstified systems, defined as early karst systems.

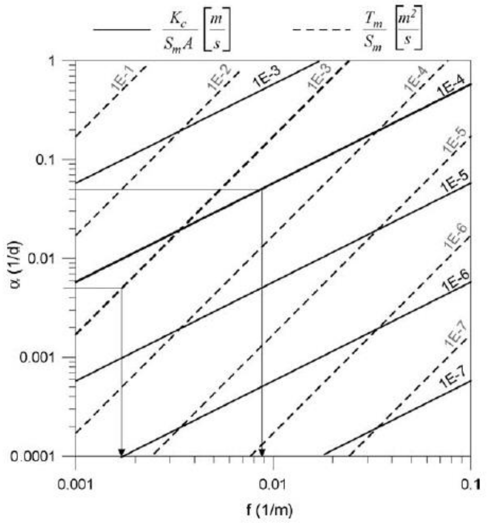
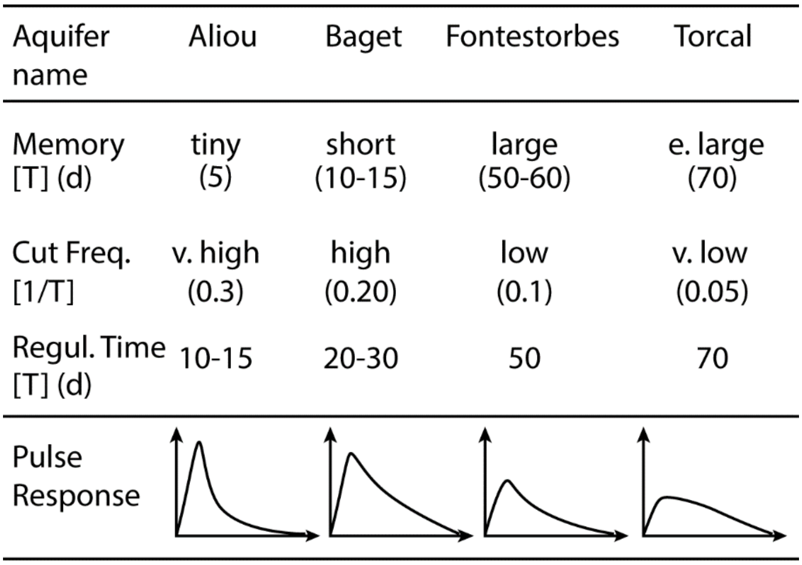


Figure 12: relationship between aquifer hydraulic and geometric parameters and baseflow recession coefficient, from (Kovács et al., 2005).

3.3 Classification based on correlation analysis

An additional classification combines expert knowledge and time series statistics, it considers the correlation function and spectrum of the signal of the spring discharge. Their characteristics are associated to a few "typical" karst aquifers which structure and functioning are well understood (Alain Mangin, 1984). Briefly, the typology ranges from flashy systems (e.g. Aliou) with short transit times to inertial systems with long transit times (e.g. Torcal). These two end-members and the characteristics of intermediate types are summarized on Figure 13. Examples of applications to other French, Belgian, Greek and Spanish karst systems can be found amongst others in (Hanin, 2010; Larocque et al., 1998; A. Mangin, 1984; Marsaud, 1997; Meus, 1993; Padilla and Pulido-Bosch, 1995; Panagopoulos and Lambrakis, 2006)



Aquifer name	Aliou	Baget	Fontestorbes	Torcal
Memory [T] (d)	tiny (5)	short (10-15)	large (50-60)	e. large (70)
Cut Freq. [1/T]	v. high (0.3)	high (0.20)	low (0.1)	v. low (0.05)
Regul. Time [T] (d)	10-15	20-30	50	70
Pulse Response				

Figure 13: Classification based on correlation and spectral analyses of discharge time series (Crochet and Marsaud, 1997; Alain Mangin, 1984)

3.4 Classification based on ranked discharge rates

Ranking and analyzing daily averages of discharge rates can be used a semi-quantitative tool to characterize the functioning of a karst system. Based on the sharp slope changes of the cumulated distribution function (CDF) of daily averages of discharge (Mangin, 1971)(Alain Mangin, 1984) , one may identify several hydraulic behaviors: temporal changes in the recharge area due to leakage from or to? or influx of water to the system, overflow springs functioning, errors of gauging station measurements, an approximate discharge value below which base flow conditions occur. Figure 14 summarizes five frequent cases affecting the CDFs of daily averages of discharge together with typical interpretations.

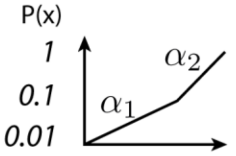
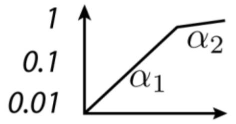
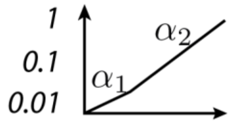
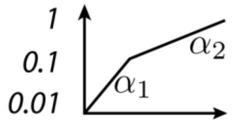
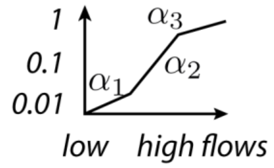
Breakup location and slopes	Schematic	Interpretation
high probabilities $\alpha_1 < \alpha_2$		Over flow spring functioning Leakage to other system Temporary storage Gauging station flooded or leaking
$\alpha_1 > \alpha_2$		Influx from other system Gauging station influenced by other sources
low probabilities $\alpha_1 < \alpha_2$		Water reserves build up
$\alpha_1 > \alpha_2$		Influx from reserves of a previous hydrologic cycle
$\alpha_1 < \alpha_2$ and $\alpha_2 > \alpha_3$		Water stored during early discharge and release during baseflow

Figure 14: Summary of sorted discharge main cases and interpretation (modified after Crochet and Marsaud (1997); Mangin (1971)).

3.5 Classification based on numerical models

Lastly, a recent study of Baudement (2018) compares the estimated lumped coefficients of fast and slow discharge reservoirs used in several models simulating spring discharges (Figure 15). While these results seem model dependent and that equifinality may be an issue (see Guinot et al. (2011); Mazzilli et al. (2013); Mazzilli, Guinot, and Jourde (2012)), this study shows for the first time that considering mean daily flow rates for flashy systems may not be appropriate, because their fast recession coefficient is greater than 1 day^{-1}. In addition, it shows that the comparison may be a diagnostic tool for flow processes, it could help identify inertial (e.g. Dardennes) and flashy systems (e.g. Lez). This approach could be improved by using the same numerical model for all systems which would render the results somehow comparable.

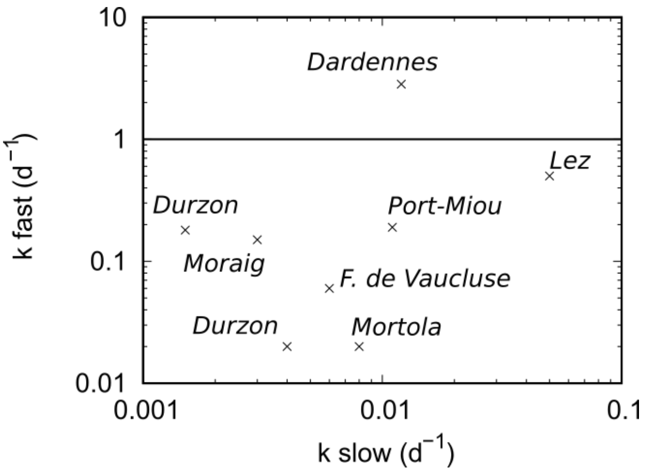


Figure 15: Dependence between fast and slow reservoir coefficient used in karst spring discharge modeling in the Mediterranean (Baudement, 2018).

A “model based system identification” has been suggested to identify among a set of models, devised for solute transport and flow simulations, a plausible model for karst processes (Hartmann et al., 2013). The approach is based on an advanced procedure that involves 1) modeling flow and solute transport ($\delta^{18}O$; SO_4 and NO_3 concentrations) and evaluating model performance with multi-objective criteria -- linked to system signatures, 2) evaluating parameter identifiability and 3) combining the modeling and parameter evaluation steps to identify a functioning model of the system. Figure 16 illustrates examples of five model structures for a system with two springs. These models differ by the way the duality of flow is accounted for, in particular the strong or weak exchange flow between reservoirs.

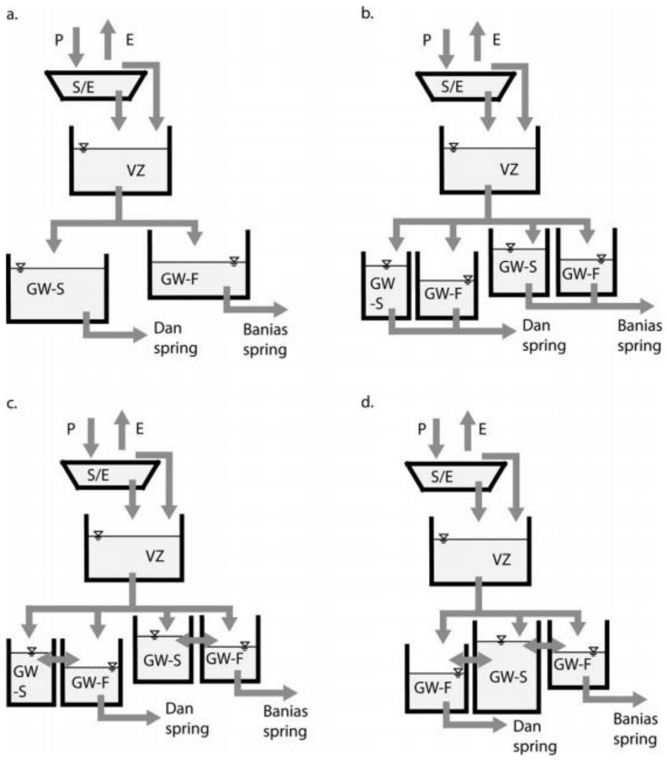


Figure 16: Different model structures: (a) single reservoir model, (b) two reservoirs model, (c) two reservoirs model with exchange flow, (d) shared two reservoirs model with exchange flow, from Hartmann et al. (2013).

3.6 Classification based on chemo- and thermographs

Early works of Jakucs (1959) considered the information content of time series of hydrochemical variables at karst springs - coined chemographs by the similarity of discharge measurements and hydrographs - to characterize karst systems responses to recharge. When temperature is the observed variable considered, temperature time series are named thermograph.

Chemograph analysis may be applied to any chemical variable, examples include among others water hardness and electrical conductivity of water that inform the water's mineralization. An example of chemograph is shown on *Figure 17*. The figure shows calcium and discharge time series' evolutions according to two contrasted behaviors: concomitant low and high variability after a recharge event. These contrasted responses stem from recharge and flow types: diffuse and concentrated respectively (Jakucs, 1959). Their statistics (mean, variance, coefficient of variation and density functions – detailed below) were linked to karst functioning and aquifer structure; from diffuse to conduit flow types (e.g. (Bakalowicz, 2015; Bakalowicz and Mangin, 1980; Shuster and White, 1971). Note that some authors argued that chemical variability may be linked to recharge distribution (i.e. proportion of allogenic recharge), instead of flow conditions in an aquifer (Atkinson, 1977a, 1977b; Jakucs, 1959; White, 2002; Worthington et al., 1992).

Figure 18 shows three typical behaviors for the time series of concentration values for a chemical compound (and discharge) after a recharge event. Accordingly, three patterns are described:

1) a simultaneous decrease and increase of the concentrations and discharge variable respectively -- a pattern linked to mixing which enhance dilution effects;
2) a two phase pattern in which concentrations increase and then decrease -- a pattern linked to a "piston-like" effect that pushes more mineralized water followed by "mixed/diluted" water;
3) an almost flat signal with low variability of concentrations illustrating low mixing and reactions/dilution processes.

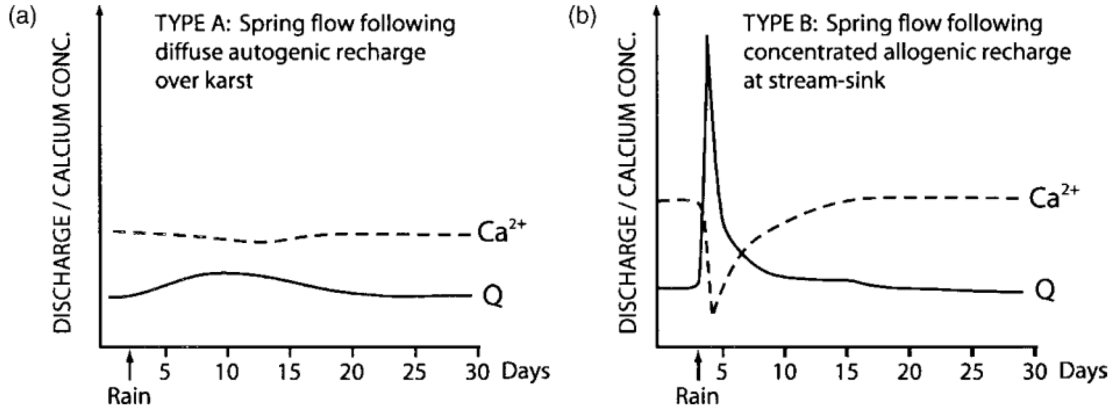


Figure 17 : Examples of chemograph evolutions after a rain event with interpretations regarding contrasting recharge situations (left: diffuse; right: localized recharge). From Jakucs (1959) in (Ford and Williams, 2007).

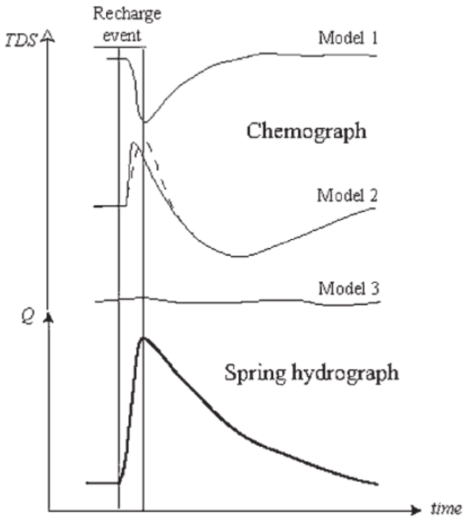


Figure 18: Three patterns of chemograph observed at a spring during a flood event, from (Bakalowicz, 2005)

Thermal fluctuations of water together with discharge observed at karst springs may be used to constrain and identify conduit geometries and transport processes. Since heat is only useful when convective transport precludes in aquifers (Manga, 2001), it appears that thermal tracing seems an appropriate method to trace flow processes fingerprints in karst conduits mainly dominated by advective transport. Luhmann et al. (2011) determined four patterns for karst spring thermographs. A summary flow chart of these patterns is presented in *Figure 19*. These patterns split between two types of flow paths: with ineffective heat exchange (e.g. conduits) and effective heat exchange (e.g. small fractures). In the former type, the water's temperature is different from the rock's temperature. Conversely for the latter type, the water's temperature equilibrates with the rock's temperature. Thus, the four patterns divide between event scale variability, seasonal variability, changing and constant aquifer temperatures for karst systems located in southeastern Minnesota (USA). It is noted that a thermograph pattern may be non-unique for a specific site because one or another pattern may be linked to –varying- recharge modes. Covington et al. (2012) further investigate spring thermal variability using mathematical models, and calculate characteristic length scales for the propagation of thermal (and electrical conductivity) signal in conduits (Covington et al., 2012)

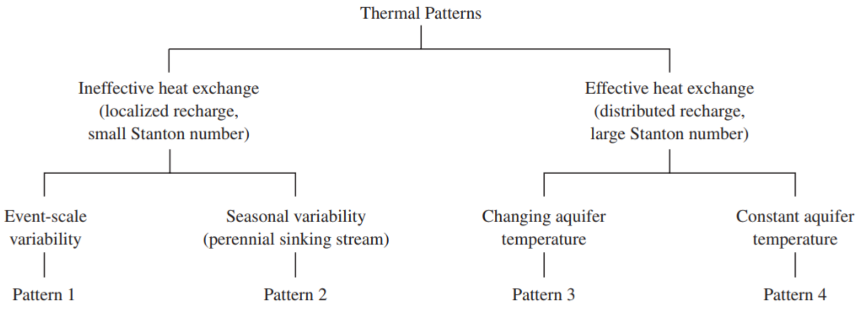


Figure 19 : Flow chart summary and patterns for heat transport in karst springs (Luhmann et al. 2011).

3.7 Classification based on water mineralization statistics

Considering a hydrochemical variable such as electrical conductivity as a random variable over a hydrologic cycle allows constructing an "annual" density function. Its shape can be used to assess qualitatively the degree of functioning for a system. When the hydrochemical time series shows little variability (see model 3 on *Figure 18*), the density function is Gaussian shaped – solute transport occurs in well-mixed conditions and the karst functioning is likely limited. Though, enhanced mixing conditions may occur in karst systems with meanders. In contrast, time series showing variability, with peaks of low/high EC values (see models 1 and 2 on *Figure 18*), create singular density functions with multiple modes – solute transport occurs in incomplete mixing conditions; a specificity of karst functioning.

Figure 20 shows examples of electrical conductivity density functions for several porous and carbonate aquifers. On the one hand, EC's density functions of porous aquifers (e.g. the Evian Cachat spring, France) are bell shaped (Gaussian). On the other hand, EC's functions of karst springs (e.g. Las Hountas, Baget river in France) are skewed (asymmetric) and often show several local maxima. These singularities make the use of the coefficient of variation inaccurate (because the standard deviation metric assumes a Gaussian distribution) for multimodal distributions and one should favor using density functions to better represent the variability of the variable EC (Bakalowicz and Mangin, 1980). Though, the variability can be approximated with CV and be used as a first indicator (Quinlan et al., 1991). By extension it may be used as a first indicator of varying karst structures (Shuster and White, 1971). Both White (1999) and Worthington et al (1992) support Smart and Hobbs model and advise caution in the use of CV (coefficient of variation) values as indicators of karst flow type as they recognise that a low CV does not necessarily imply the absence of conduit flow and that the use of CV seems to work best when applied to small drainage basins in temperate climates.

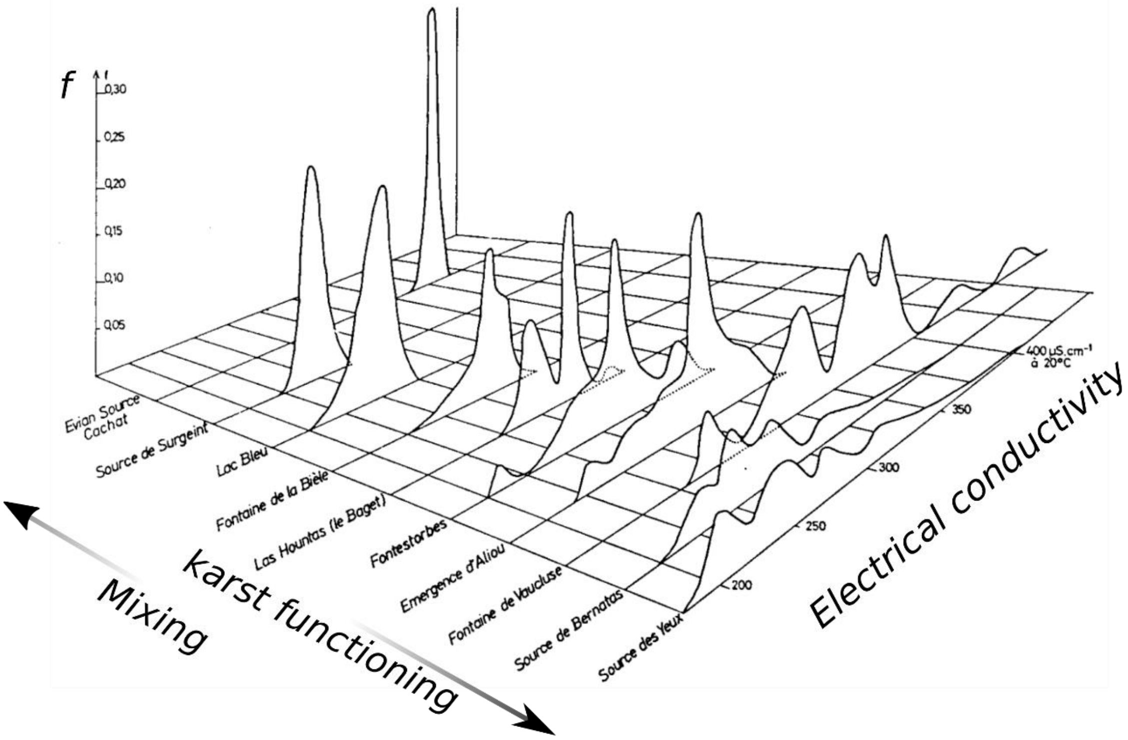


Figure 20: Comparison of density functions of electrical conductivity from several springs. Gaussian shaped density linked to porous aquifers: Evian, Surgeint and Lac Bleu; Other types of density functions linked to karstified aquifers, all other springs. Modified from M Bakalowicz and Mangin (1980).

3.8 Classifications using isotopes and age tracers

In principle, information about travel times and transport can be derived from stable and radioactive isotopes measured in chalk or karst springs. For example, Barbieri et al. (2005) use stable isotopes (^{2}H, ^{18}O and ^{87}Sr/^{86}Sr) and hydrochemistry monitoring for groundwater dynamics analyses in a karst aquifer. They related the signals of ^{18}O to the elevation of spring water recharge, linking depleted ^{18}O to high-elevation recharge at the dolomite reefs and enriched signals to recharge at lower elevation in debris slopes. Herms et al. (2019) used a combination of stable isotopes and modeling approaches to estimate mean transit times in the pilot karst system of Port del Comte in Spain. Van der Velde et al. (2018) used long term datasets of river discharge, evapotranspiration, and water quality, complemented by an extensive set of cosmogenic radioactive and stable isotopes (^{3}H, ^{2}H, ^{18}O, ^{22}Na, ^{35}S), revealing a component of old water discharging in the Californian Sierra Nevada. Recently, in the GeoERA context, we explored the use of low-resolution ^{3}H time series in the Dutch chalk system (Broers and Vliet, 2018; Van Vliet and Broers, 2019) following lumped parameter models first developed by (Maloszewski and Zuber, 1996, 1998) and applied by Morgenstern et al. (2010). A convolution of tritium time series in precipitation and a range of travel time models gives a range of travel time distribution models that fit the measured ^{3}H concentrations (see figure 20). Various combinations of the travel time in the unsaturated zone and the mean travel time in the saturated zone can be assumed. A Piston Flow model (PF) is used for the vertical flow in the unsaturated zone and an exponential model (EM) for the saturated flow. Possible combinations:

- PF model: unsaturated zone delay 0, 5, 10, 20 and 40 years
- EM model: saturated flow Mean travel time (MTT) of 1, 2, 4, 6, 8,10, 15, 20, 25, 30, 40, 50, 60, 80,100 years

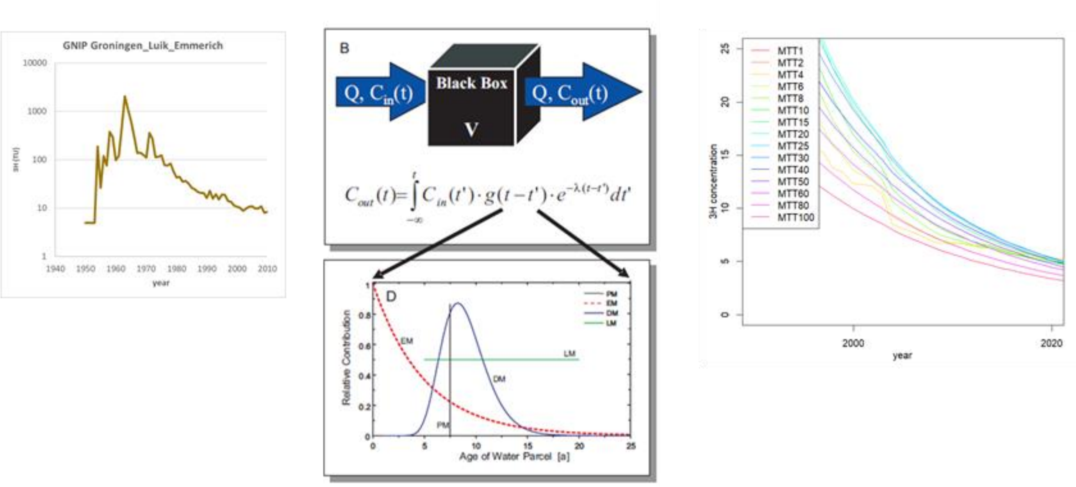


Figure 21 : Figure left: input data of tritium concentrations in precipitation based on Global Network of Isotopes in Precipitation data (GNIP), figure in middle: convolution of the tritium time series in precipitation for a range of travel time distributions, Figure right: convoluted ^{3}H response for all models with 5 year piston flow and 15 possible EM models with with a range of MTT's (1 -1 00 years).

The outcomes of these theoretical models were compared with the measured tritium at the springs, optimizing for a best fit between measurements and models. Different combinations of MTT and PF delay give highly different ^{3}H changes over 2001-2009-2017 (see figure 21). The unsaturated zone (PF model delay) has a large effect on ^{3}H evolution and peak. It determines the moment at which ^{3}H discharges and the amount of decay before saturated flow starts.

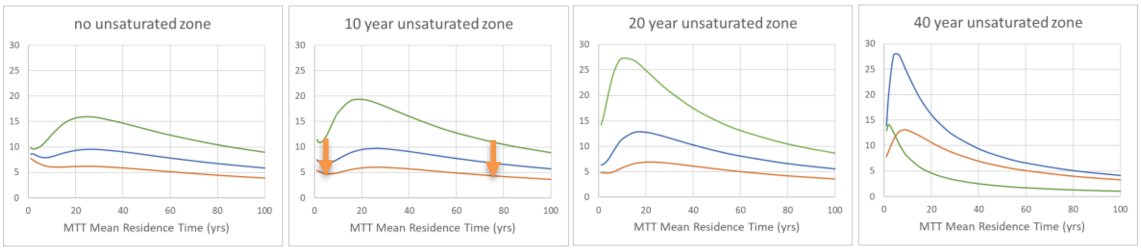


Figure 22 : Change of the tritium concentration as a function of the mean travel time in the EM model (MTT) and the delay in the unsaturated zone.

For RESOURCE WP5, we systematically sampled 15 chalk springs sampled in the most southern part of the Netherlands, Zuid-Limburg in order to quantify the travel time distributions (TTD) of the springs and to gain insight in the variation of nitrate. Leaching of fertilizers and manure in the catchment area of the springs typically led to nitrate exceeding the WFD threshold of 50 mg/l. Figure 22 gives one example of the best fitting ^{3}H convolution models to the measured 3H concentrations. The best fit model would represent a system with 20 years delay in the unsaturated zone and a mean travel time of 80 years in the saturated chalk. Best-fit TTD models were subsequently convoluted with a time series of nitrate leaching from the soil zone, yielding a reconstruction and forecast of nitrate concentrations at the springs.

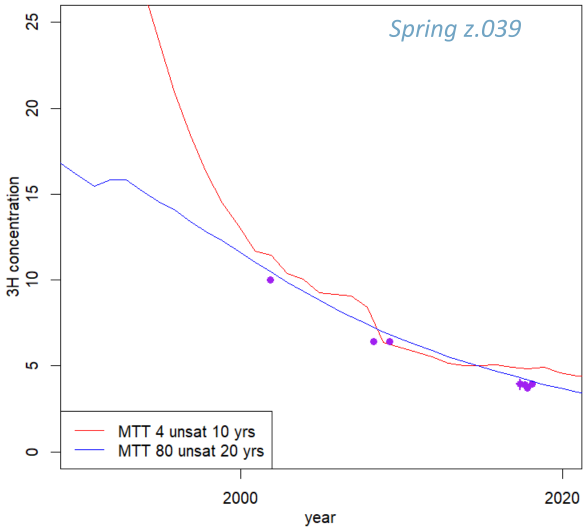


Figure 23 : The best old and young tritium model for springs.

4 CONCLUSION

This review of the state of the art of karst aquifers typology methods provides (i) the list of the various conceptual models describing the hydrogeology of karst aquifers and (ii) the existing classification typologies applied on data time series. The latest mainly rely on flow data that are used to identify and enhance several hydrodynamic behaviors: (i) baseflow/quickflow contribution to the spring; (ii) infiltration flow processes; (iii) dynamic volume stored into the saturated part of the system (iv) possible existence of interflows from and to the system; (v) transit times evaluation.

In the next steps of RESOURCE-WP5, these methods will be applied and probably adjusted to the case studies identified by the Eurogeosurveys that are partners of this project and a comprehensive analysis of all the produced criteria/parameters will be carried out in order to identify useful versus redundant information. The final objective is to come up with a harmonized and up to date way of classifying karst aquifers with regard to management issues such as (i) water reserves evaluation, (ii) flow regulation capacity and (ii) vulnerability assessment. For that purpose, a shared tool will be developed under a user-friendly system in order to implement the selected methods. The classification methodology should be developed to allow it usage with varying data availabilities, while amount and variability of available data will increase the reliability level of the resulting class from the methodology.

5 APPENDIX

5.1 Appendix 1: survey results

In order to explore if the partners of the project study karst aquifers in a similar fashion, the task team developed a survey which was then submitted to all partners. Here below are provided the answers given by the geological surveys of nine partners – Austria, Bosnia and Herzegovina, Catalonia, Croatia, Czech Republic, France, Ireland, the Netherlands and Spain.

The survey contained the following five questions:

Question 1: high frequency measurements at the spring. Which parameters should be monitored? At which time step? What are the most reliable interpretation methods enabling aquifer flow and dispersion of contaminants characterization?

Question 2: low frequency measurements at the spring. What is the minimal frequency under which aquifer flow characterization is no longer possible?

Question 3: which parameter for which question? How can we mix hydrodynamic (water level, discharge rate) and physico-chemical (EC, temperature, turbidity) time series measurements? What amount of information provided by those time series is redundant and what amount is new and complementary?

Question 4: which are the hydrologic signatures of the different types of karst aquifers? Which global typology?

Question 5: which spatial distribution of measurements? How many measurements in wells (intercepting karst conduits or not), caves, overflow springs etc. are needed to capture the karst flow characteristics at the scale of the recharge area?

Geological survey of Austria

Answer to Q. 1: Data logger parameters: discharge, temperature, conductivity,
Answer to Q. 2: The quarterly sampling should cover the following parameter: T (°C), pH, Cond, O2, Ca, Mg, Na, K, Fe, Mn, HCO3, SO4, Cl, NO3, PO4, B, As, Pb, Cd, Cr, Cu, Ni, Hg, AOX, DOC, Tetrachlorethen, Trichlormethan, Atrazin, Desethylatrazin, DOC, O18, 2H, 3H/Helium
Answer to Q. 3: I would focus on well investigated karst areas where karstwater is used for drinking water and where we do have sufficient information.
Answer to Q. 4: Austrian karst aquifers are mainly linked to Mesozoic limestones, but also Paleozoic ones. I would suggest the Ca/Mg ratio and retention capacity to describe the impact of dolomites.
Answer to Q. 5: I would suggest sites where on site monitoring is present

Geological survey of Bosnia and Herzegovina

Answer to Q. 1: Measurement: discharge, temperature, conductivity, TDS, turbidity, nitrates, nitrites, ammonia
Answer to Q. 2: The minimum yield changes are in the July-September period. Measurements are possible in all hydrological periods.
Answer to Q. 3: Hydrodynamic and physico-chemical characteristics of we can link measurements at the source.The higher the discharge source has a lower temperature and conductivity water and higher blurry.
Answer to Q. 4: Karst aquifer are mesozoic limestone of the Dinaric Karst transboundary aquifer. Speed of liquid water in the Dinaric Karst are 0.002 – 55.2 cm/s; typically up to 5 cm/s, and depends mainly on the structural-geological conditions, the intensity of the karst processes and the hydraulic gradient.
Answerr to Q. 5: Frequency measurements every 15 days on "Vrelo Buna" in the course of one hydrological year.

Geological survey of Catalonia

Answer to Q. 1: It depends of the hydrogeological context, the issue you want to be answered, and the characteristics of the karst system for itself. Each case should be analyzed separately. It depends. I would suggest Q, Tº, CE, Ph, Eh at minimum always, and if it’s possible isotopes too (D, 18O). Time, as we comment, it depends, but between 15min to 1 hour rate at minimum.
About the method, it depends if you have the possibility to perform dye tracings test. If is not possible, I suggest combining classical semi-distributed hydrological model to calibrate the spring response to infer the recharge flow series with lumped parameter models for the interpretation of the kind of dispersion model (e.g. FlowPC) using environmental tracer data e.g. isotopes data

Answer to Q. 2: It depends of the hydrogeological context, the issue you want to be answered, and the characteristics of the karst system for itself. Each case should be analyzed separately. It depends. I would suggest no longer that 1 data/month, but it's difficult to generalize.
Answer to Q. 3: No answer was provided
Answer to Q. 4: We hope that the project should aim to help to determine this matter.
Answer to Q. 5: We would say that, it depends of the hydrogeological context and the issue you want to answered. It depends. Could be at regional or more local scale.

Geological survey of Croatia

Answer to Q. 1: Discharge is the basic parameter, all other parameters provide additional and valuable information, but depend mainly on possibility for obtaining them. Currently, the most convenient parameters for monitoring are temperature and electrical conductivity, followed by turbidity, oxygen saturation, total gas saturation, others??. Other parameters can be monitored in high resolution by employing automated samplers (relatively expensive). For karstic systems 1 hour time step is optimal, and once a day probably minimal for detailed interpretation/classification. More sparse measurements (e.g. monthly) can provide indication of the system properties. Interpretation methods mainly depend on data availability – from basic statistical parameters (low frequency data) to more advance time series analysis (high frequency data).
Answer to Q. 2: Probably once a month – for basic indication on the type of the aquifer/system.
Answer to Q. 3: Increasing number of monitored parameters increase reliability of final characterization/classification. Variability of parameters in comparison to variability of discharge should be examined, taking into account processes connected to particular parameters. Not sure if adding additional parameters can become redundant, especially in research of karst systems. Regarding our project, I think we should include in methodology all commonly monitored parameters (Discharge, SEC, T, turbidity, artificial tracers, Ca/Mg ratio, TOC; Nitrates, ???) in a way that they can be, but not need be included during classification process (as I already suggest at the Madrid meeting).
Answer to Q. 4: I think vulnerability (V) and regulation capacity (RC) are basic parameters for classification (especially regarding water resources management). So based on these parameters we can have four categories – (1) high V and low RC (systems with very low baseflow and pronounced response after the rainfall); (2) high V and high RC (similar as previous, but with considerable baseflow); (3) low V and high RC (attenuated response to rainfall, considerable baseflow); (4) low V and low RC (not sure if that type can exist – probably not). Regarding which monitoring parameter can be used for estimation of particular classification parameter – discharge dynamics for both parameters; while all the others manly for estimation of system vulnerability (i.e. characterization of infiltration and transport through the system). Additionally, maybe size of the system should be added in classification (regional, local, ??).

Answer to Q. 5: Similar to monitored parameters (question 3) – springs are the main monitoring points for classification of the global characteristics of the system, but additional monitoring sites increase level of knowledge and reliability of final classification. Probably, our methodology should be flexible also regarding the monitoring sites.

Geological survey of Czech Republic

Answer to Q. 1: Spring discharge, water temperature, water electric conductivity (and maybe pH) should be monitored. Concerning time step – depends on the reaction of the aquifer to the rainfall and on the water retention time in aquifer. However, continuous measurement, at least of the spring discharge, is optimal.
Answer to Q. 2: It is impossible to predict without knowledge of the reaction of the aquifer to the rainfall and of the water retention time in aquifer.
Answer to Q. 3: Perhaps we can correlate hydrodynamic characteristics as discharge rate with the water EC from the point of view of dilution during the high flow periods.
Answer to Q. 4: Not specified yet in Czech Republic karst areas.
Answer to Q. 5: Not possible to specify easily - depends on the type of karst structure and its recharge and on the possibility to measure all the inflow into it (allochtonous streams, rainfall infiltration, drainage from its surroundings) and many other factors.

Geological survey of France

Answer to Q. 1: Frequency rate are probably system dependent. High sampling/measurements rates of discharge (every 3 minutes) were reported by Labat et al; 2013 for the karst systems of Baget and Alliou in the French Pyrenees. Such high sampling rate was needed because thoses systems have fast (on the order of hour) discharge fluctuations during storm or snow melt events. A higher sampling rate, such as daily measurements, do not provide enough resolution to characterize the hydrological processes occurring over short time scales. Regarding the most reliable interpretation methods to characterize flow and dispersion, the study of recession curves and correlation analyses of discharge data shed light on the flow dynamics. Tracing tests help better delineate catchment areas, hydraulic connections and transit time distributions from one site to one or several observation sites for a given hydrological condition.
Answer to Q. 2: There are no studies related to a lower threshold (a low frequency) which would disable the characterization of karst spring discharge.
Answer to Q. 3: Data related to hydrodynamics only provide help shed light on pressure transfers, hydraulic properties of karst aquifers. Combined to recharge estimates one may obtain a water budget that is interesting to address water resources issues. Regarding hydrochemical data, EC is today a proxy relatively easy to measure at high frequency. It is an integrative measurement of mineralization, which is linked to water-rock interactions and water residence times. Identifying fluctuations in EC times-series

can help improve understanding a given aquifer system, and feed information for a conceptual model of flow and mass transport. Note that there might be karst system showing few EC fluctuations due to long residence times. Such information can only be revealed through monitoring.

Answer to Q. 4: This question is too broad and requires a definition of “types of karst aquifers”.

Answer to Q. 5: To answer this question, one requires a conceptual model for the given karst aquifer. Intuitively, one would first chose to measure the karst spring discharge. In addition, if the system appears to be recharged through point recharge and a (several) sinking stream(s), it is required to measure the river stage. In addition, it would be appropriate to identify monitoring wells to measure water well fluctuations. Finally, overflow springs may be monitored.

Geological survey of Ireland

Answer to Q. 1: Time step: It will be interesting to see this – the project should aim to determine this. For very flashy springs, ‘continuous’ (15 minutes – hourly) may be appropriate. In contrast, in springs emerging from aquifers with greater cover or less conduit development, hourly to a few-hourly to daily may be sufficient.

Parameters: flow is the most important parameter. However, it will be interesting to see what other parameters may act as a proxy sufficient for characterisation/ what level of characterisation can be achieved with them. Stable physico-chem parameters would be beneficial to explore. For example, temperature, electrical conductivity.

most reliable interpretation methods: don’t fully understand the question. GSI undertakes a lot of dye tracing to determine main flow paths, connections and directions, and straight line time of travel at different stages. We use various methods, including binary occurrence indicators (e.g. charcoal and optical brightener), manual sampling at various frequencies and automatic sampling.

Answer to Q. 2: Minimal frequency: the project should aim to determine this. Could be achieved by both downsampling and bootstrapping high resolution data, and also by comparison of pilot sites with more / less data acquisition.

Answer to Q. 3: Project should aim to determine this.

Answer to Q. 4: Project should aim to determine this.

Answer to Q. 5: Depends on the question being answered – regional or local study

Geological survey of the Netherlands

Answer to Q. 1: In the Netherlands, hydrogeological research on springs in limestone areas has been very limited so far. The chemical composition and the age of the spring water were the main point of focus; no high frequency measurements, for example of discharge, were carried out at the site of the springs. Therefore, based on this research, it is not possible to specify which parameters to measure and with what frequency.

Answer to Q. 2: Due to the limited amount of research done so far it is not possible to answer the question what the minimal frequency is under which the aquifer flow characterization is no

longer possible. On the other hand, we can provide an answer to the minimum frequency needed to chemically characterize the springs. With a frequency of 1x per 6 to 8 years for tritium, we can clearly define the travel time distribution. The hydro chemical data (nutrients, EC, pH, temperature) is measured 4 times a year to gain insight into the variation of the concentrations.
Answer to Q. 3: We cannot yet answer this question. The relationship between precipitation and discharge rate will provide insight into the hydrogeological system.
Answer to Q. 4: Project should aim to determine this.
Answer to Q. 5 Project should aim to determine this and depends on the question being answered (regional or local study).

Geological survey of Spain

Answer to Q. 1: Discharge rate is the most important and informative parameter. The minimum time step is 1 measurement per day. 1 measurement per hour is preferable. The ideal would be 1 measurement every 5 minutes. Conductivity and temperature are good complementary parameters. Any additional parameter will be a plus. The method of Mangin (1984) with flow rate and expert interpretation of the rest of the parameters is what has been done in Spain.
Answer to Q. 2: Any frequency of measurement with less than 1 measurement per day will introduce biases in the characterization as the main discharge peaks will be lost or damped.
Answer to Q. 3: Discharge rate is the customary parameter for an aquifer to be included in the classification. A methodology will be to classify the aquifer according to discharge rate, so we are sure that all the aquifers can be classifies. Conductividy, temperature, etc. can be used to refine the classification.
Answer to Q. 4: The aquifers will give an ouput signal to the input signal of recharge (effective rainfall) according to their karst development (good connection between the surface and the spring by a network of karst conduits), soil-epikarst thickness and vadose aquifer thickness. The answer will also be dependent on climatology.
Answer to Q. 5: In high relief karst systems there are no wells, but only the spring data. If there are well data they can be used.

Geological Institute of Romania

Answer to Q. 1: There are 2 types of objects that need to be monitored: wells and springs. The wells are of two kinds: water abstraction for potable water wells, which have a systematic monitoring system, and thermomineral water wells, which are not monitored. For the water abstraction for potable water wells type we shall obtain data monthly data for level, discharge, temperature, conductivity, major anions/cations. For the thermomineral water wells and for springs which are not monitored, we have sporadic historical data of expeditionary type.
Answer to Q. 2: Due to the limited amount of research done so far it is not possible to answer the question what the minimal frequency is under which the aquifer flow characterization is no longer possible.
Answer to Q. 3: We hope that the project should aim to help to determine this matter.

Answer to Q. 4: Given the variability of situations, it is first necessary to establish a conceptual model in each case, to determine the influence of each parameter, such as: recharge, storage, discharge.

Answer to Q. 5: It depends on the aquifer type. In our study case, where the aquifer is represented by Jurassic limestones situated in a platform region, the most relevant are measurements in wells. Due to the fact that there is an interaction between the Danube river and the aquifer, the flow of springs reflects this type of local interaction.

Geological Survey of Hungary

Answer to Q. 1: We believe that sampling rate depends on the karstification and hydraulic functionig of the system. While karstified systems require hourly or more frequent sampling frequency, unkarstified dolomitic systems with damped spring response might be analysed using daily data. For future monitoring we recommend at least hourly data for every system.

Answer to Q. 2: We believe that daily data is a minimum requirement. In certain highly karstified systems hourly dataset is needed as a minimum.

Answer to Q. 3: We believe that in ideal conditions basic physico-chemical parameters should be measured at the samling rate of discharge measurements.

Answer to Q. 4: Hydrograph decomposition together with physical hydrograph analysis can determine the dominant behaviour of the system. Recession coefficient, hydraulic diffusivity and conduit spacing togehter determine the flow behaviour of a carbonate system.

Answer to Q. 5: Conduit spacing can be determined from spring hydrograph analysis. Well hydrograph analysis can provide additional information about the variability of conduit spacing. The more data is the better.

Geological Survey of England

Answer to Q. 1: It depends on the question that is being asked. Parameters: Key parameters for characterizing karst and identifying where rapid flow is occurring are discharge (pumping rate and drawdown in boreholes), Turbidity, Coliforms, Specific Electrical Conductance, other low residence time indicators (such as pesticides that degrade in short timescales). Time step: The time step needs to be short enough to capture rapid responses of the karst system, so as short as possible, but at least hourly. Interpretation method: Depending on the question, a range of interpretation methods from simple to complex, could be required.

Answer to Q. 2: This may vary depending on the nature of the karst at the site in question. In slow responding karst systems daily measurements of some parameters may be sufficient, although more frequent measurements may be required initially to determine that there are no more rapid responses occurring. The length of the record may also be important, as longer datasets are more likely to capture rapid responses at lower frequencies. It is unlikely that weekly or monthly measurements will capture enough information to characterize karst systems.

Answer to Q. 3: Conceptual models of karst systems should be based on time series data from as many parameters as possible from the spring/borehole combined with geomorphological, hydrogeological and tracer data from the catchment. For the classification of sites a scoring system could be developed to provide multiple strands of evidence from the different datasets to characterize the nature of the karst at the site. For understanding the details of the response of an individual system and the details of the catchment area, more complex data analysis is required.

Answer to Q. 4: Many good karst typology classification systems have been proposed. They are perhaps more limited in karst aquifers with little or no cave development, where rapid flow and karst may be present but hard to identify.

For practical purposes of decision making for regulators/water companies etc. a quick and easy to apply classification system to determine the likely risk of rapid flow impacting the spring/borehole could be useful.

Answer to Q. 5: It depends on the question being asked. To understand the detail of the karst system a very dense network of monitoring sites (caves, boreholes, springs, swallow holes) may be needed. To classify a spring/abstraction borehole then the data requirements might depend on the type of karst aquifer. For example in classical karst, at a highly karstic site, data requirements may be small with clear evidence of high discharge and SEC fluctuations, and high turbidity/coliform presence enabling a quick classification of highly karstic/high risk. At the other end of the scale, for a Chalk spring/borehole in a catchment with no known cave development more data may be needed to provide evidence of the karst and enable the site to be assigned to an appropriate classification category.

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