Resources of groundwater, harmonized at Cross-Border and Pan-European Scale

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Deliverable 5.3

Karst aquifer typology tool

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SUMMARY

Fractured limestones, dolostones and chalks, all susceptible to karstification processes, form important groundwater resources, but often with a complicated flow regime that includes both fast flow routes that makes them vulnerable to pollution, and slow baseflow 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 evaluating their vulnerability to pollution. Classically, due to their high degree of heterogeneity, understanding of karst aquifer hydrogeology relies on the monitoring of the main spring outlets of the aquifer, considering these as the best proxy to characterize the karst system as a whole. Most karst classifications rely on these measurements and use spring time series data. Work package 5 of the GeoERA RESOURCE project (also called 'CHAKA') focuses on typologies/classifications for karst and chalk aquifers in order to improve their management. The objective of GeoERA RESOURCE WP5 is to test and evaluate analytical and assessment methods and come up with an improved characterization framework and typology of karst and chalk aquifers. These methods are tested on pilot areas within different countries across Europe. The operational objective is to provide a set of management recommendations associated with the different types of karst/chalk aquifers in order to assist management by multi-disciplinary teams including water operators, planners, engineers, government, scientists, farmers, land-owners and politicians and other operators in charge of karst aquifers in the context of karst hydrogeology and land use management.

The review of the state of the art of karst aquifers typology methods provided (i) the list of the various conceptual models describing the hydrogeology of karst aquifers and (ii) the existing classification typologies applied to time series data (Hakoun et al. 2020). The latter mainly rely on spring discharge 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.

The most used method in the world has been developed by A Mangin (1975) and has been commonly applied in France, Spain, Belgium, Greece and Croatia in order to classify karst aquifers. It provides information on infiltration processes in the vadose zone of the karst aquifer and groundwater flow into the saturated zone. An Excel based data treatment tool has been developed in order to compute the necessary metrics for the application of this methodology, and other times series analytical approaches.

This hydrodynamic typology is usually applied by karst experts but is not always fully understood by water operators and management authorities. The latter are more interested in the capability of an aquifer to provide good quality water in large quantities. This requires assessing the volume of water stored in the aquifer, the capacity of the aquifer to retain it and the vulnerability of this aquifer to pollution. The operational objective is to provide to water operators a classification methodology which relies on indicators of the main characteristics of karst/chalk aquifers that are highly important for groundwater resource management. Two main classical management issues in relation with aquifer characteristics have been identified:

- the first one is related to the quantity of water that the aquifer is able to store and provide for different usages
- the second one is linked to the quality of water that the aquifer can supply and is dependent on the vulnerability of this aquifer to pollution and the potentially polluting activities that are occurring in the catchment of the spring or borehole.

In this project, we have investigated methods of classifying karst aquifers with regard to management issues: (i) water reserves evaluation, (ii) flow regulation capacity and (iii) vulnerability assessment. The classification methodology has been developed to allow its usage with varying data availabilities, although

the amount and variability of available data will increase the reliability level of the resulting class obtained using the methodology.

The characteristics of the hydrodynamics typology and management classifications are summarized at FIGURE 1.

	Approach	
Question	Hydrodynamics typology	Management classifications
Who?	Scientists / Karst experts	Engineers / water operators / government / planning and policy makers / landowners
Why ?	Characterize karst aquifer structure and hydrogeology	Identify good quality and large quantity groundwater resources Propose management recommendations
How?	Discharge time series analysis	Catchment characteristics Discharge (+other) time series analysis
What ?	Infiltration and vadose zones responses	Vulnerability GW reserve

FIGURE 1: TABLE OF THE MAIN CHARACTERISTICS OF THE DIFFERENT TYPOLOGY/CLASSIFICATION APPROACHES

The application of the hydrodynamics typology allowed us to characterize the hydrodynamic processes of the case study sites, identifying karst and chalk aquifers with high or low dynamic volumes and fast or slow infiltration processes.

Then, three management classifications have been applied to the case studies. Method 1 describes the level of intrinsic vulnerability of the aquifer to pollution. It uses characteristics of the aquifer such as the presence of karst features, and indicators of fast flows at the spring. The method was adapted for application to boreholes, and tested on 20 Chalk borehole abstractions. The method gives results which are consistent with the conceptual understanding of the karst aquifers in which it has been applied. The limestone springs and borehole abstraction have the highest scores, which is consistent with the generally higher degree of conduit development in limestone aquifers. Dolomite karst generally has less extensive karstic development than limestones and the dolomite springs have medium vulnerability and scores that are at the lower end of those observed in the limestone springs, which is consistent with this. However, there are only 3 dolomite spring examples, and these were selected because they are known to have a subdued discharge response to rainfall and are therefore likely to have lower vulnerability than the limestone case study sites. Further study of dolomite springs is needed to determine the range which occur and is likely to include springs which fall into both the high and low vulnerability classes. The results for 20 Chalk borehole sites indicated a wide range of vulnerabilities, and were mostly lower than results for more classically karstic limestones, which is consistent with our understanding of the lower degree of karstification in the Chalk.

The method 2 classification is a mixed methodology which combines the vulnerability level estimated using method 1 (on the Y axis of a scatter plot) with an indicator of the capacity of the aquifer to regulate groundwater flow (on the X axis of a scatter plot). For the X axis two indicators are proposed: the memory effect and the KGWAI (Karst GroundWater resource Availability Index). The first combines the memory effect with additional information on the average discharge rate at the spring (indicated by the size of the point on the scatter plot) while the second one integrates both the memory effect and the average discharge. The results show the method produces results which are consistent with the conceptual understanding of the karst aquifers in which it has been applied.

The method 3 classification is an alternative method which also combines information about the vulnerability (V) and the storage capacity (regulation capacity RC) of the aquifer using a scatter plot diagram. It also provides information on the average discharge rate at the spring (size of the dots) and on the reliability of the results (colors of the dots).

The following management recommendations have been identified: sustainability assessment, source protection zones, vulnerability mapping, active and passive management, early warning systems and mitigation measures. They can be recommended according to the position of the spring in the classification scatter plots. The objective is to propose well suited recommendations for each case study as shown in Figure 46. The more vulnerable and less well regulated in terms of resources the aquifer is, as demonstrated by the classification methods, the more aquifer management recommendations there are.

These methods are a promising first attempt at karst classification aimed at water management issues based on the case studies available for the CHAKA project. Most of the case studies are within more classically karstic aquifers, and therefore further work is needed to assess the applicability of the methods to karst aquifers such as the Chalk with lower levels of karstification. Most of the case studies are spring sites rather than boreholes and therefore the application of the methods to boreholes also needs further investigation. Methods 1 and 3 identify a number of important physico-chemical parameters measured at spring and borehole sites that can indicate high vulnerability of karst sites. However, there remain some uncertainties about the thresholds and interpretation of these physico-chemical parameters, and further research using large datasets from a wide range of karst aquifers is needed to improve the vulnerability classifications.

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1 INTRODUCTION

1.1 Context: Work Package 5 (CHAKA) of GeoERA RESOURCE project

Work package 5 of the GeoERA RESOURCE project (also called 'CHAKA') focuses on typologies for karst and chalk aquifers. Fractured limestones, dolostones and chalks, all susceptible to karstification processes, form important groundwater resources, but often with a complicated flow 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 evaluating their vulnerability to pollution. Classically, due to their high degree of heterogeneity, understanding of karst aquifer hydrogeology relies on the monitoring of the main spring outlets of the aquifer, considering these as the best proxy to characterize the aquifer as a whole. Most karst classifications rely on these measurements and use spring time series data.

Phase 1 of WP5 has produced a review of the state of the art of existing classifications and typologies applied to karst aquifers (Deliverable 5.1 of GeoERA RESOURCE project; Hakoun et al. 2020). Phase 2 was dedicated to the identification and characterization of case studies and the development and testing of new karst classification methodologies. The case studies are described in Deliverable 5.2 of GeoERA RESOURCE project (Maréchal et al. 2020), and here we present classification methodologies and the results of their application to the case study sites.

1.2 Why specific management is needed for karst and chalk aquifers

Karst landscapes are some of the most beautiful and unique landscapes in the world. They are also one of the most fragile and vulnerable landscapes. Karst landscapes require specific, integrated and sustainable management in order to preserve and protect these invaluable resources.

Karst aquifers are extremely important water resources in terms of quality and quantity. According to Ford and Williams (2007) approximately 20-25% of the world's population depends of groundwater from karst aquifers. In some regions such as the Dinaric karst region in Europe and Southwest China karst 50% of the water supply or more comes from karst aquifers (Chen et al, 2017). Groundwater from karst aquifers is one of the most important drinking water resources in Europe and is it is critical that these aquifers are protected and sustainably managed.

Karst landscapes are priceless resources. The largest springs are found in karst aquifers and they therefore can be the source of many rivers. They usually provide an important baseflow to rivers and lakes and there generally is a high connectivity between surface water and karst aquifers. They give rise to unique calcium-rich groundwater dependent ecosystems. Indeed, many karst landscapes are rich in Special Areas of Conservation and other protected sites. Karst landscapes both above and below ground host large number of rare and protected species.

Karst landscapes are very important for geo-tourism. About 150 million tourists visit caves annually and many other unique karst landscapes, providing vital support to national economies (iyck2021.org). They are also significant cultural and archaeological sites. Indeed, more than 50 of UNESCO World Heritage Sites are karst, and are listed for reasons, such as landscape, culture and biodiversity.

The ever increasing global population and the increasing demand for water puts more and more pressure on this valuable resource and the rivers and ecosystems that it sustains. These pressures are also increasingly impacted by climate change and changes in global precipitation patterns due to climate change will have an especially significant impact on karst aquifers, which are generally characterized for their sensitivity to recharge events. In periods of intense rainfall flooding is becoming more common. Three main impacts due to climate change are identified: (1) the predicted increase in high intensity precipitation events which will increase flooding from increased rapid transfer through karst systems, and (2) the impacts on supply due to these changed precipitation patterns resulting in less baseflow in karst springs (3) the reduction in available karst groundwater resources in areas where recharge is reduced (either through less rainfall or more evapotranspiration). Increasing populations will also have significant impact on these supplies especially in prolonged periods of drought and with increasing irrigation demands.

These aquifers are complex, and difficult to understand and model. Due to the distinct characteristics of karst aquifers, such as extreme heterogeneity, anisotropy and high contrast hydraulic conductivity, they are often difficult to understand and predict. As karst and caves are often hidden features in a landscape they can remain under researched and poorly managed. Few water resource managers and scientists are appropriately trained and applying conventional aquifer methods can have disastrous consequences.

Karst landscapes are extremely vulnerability to pollution. The very nature of karst, which aims to direct surface water into the ground as quickly as possible, means karst aquifers can be easily contaminated. Influent karst landforms, such as sinking streams and dolines means pollutants from large areas can be funneled rapidly into the aquifer. These landforms can often mean the by-passing of any overlying protection material, such as superficial deposits. Thus, pollutants can enter the aquifer very quickly and with little or no filtration. Once in the aquifer, karst conduits allow the rapid transport of these contaminants and can convey them large distances of up to hundreds of kilometers in short spaces of time. This coupled with the poorly understood and unpredictability of karst aquifers makes managing a contamination event extremely difficult. Many pollutant incidents go undetected until it is too late. This can result in detrimental effects on the human and other ecological communities who depend on these karst water supplies. Increasing populations also means there is ever growing conflict of interests between land use demands.

Optimal management of karst aquifers requires an informed understanding of the workings of the karst system and its relations with associated surface waters and ecosystems. These workings are unique to each individual karst environment.

1.3 Content and objective

The objective of GeoERA RESOURCE WP5 is to test and evaluate monitoring and interpretation methods and come up with an improved characterization framework and typology of karst and chalk aquifers. These methods are tested on pilot areas within the different countries across Europe. The operational objective is to provide a set of management recommendations associated with the different types of karst/chalk aquifers in order to assist management by water operators, government, planners, engineers, scientists, farmers, land-owners and politicians in the context of karst hydrogeology.

This report constitutes the third Deliverable (D5.3.) of this work package. An application of classical karst typologies is applied to the European case studies in order to characterize their hydrodynamics (section 3). Then, three new classifications for groundwater resource management are proposed, and applied to the case studies (section 4). A set of recommendations for the groundwater management is proposed (section 5) according to the different types of aquifers.

2 KARST/CHALK AQUIFERS HYDROGEOLOGY

2.1 Karst Aquifer

On a small scale, karstified carbonate basins contain heterogeneous aquifers conceptualized by the notion of triple porosity (Bakalowicz, 2005; Goldscheider and Drew, 2007). The three types of porosities are: (1) micropores that develop during the genesis of the carbonate rock, (2) small fissures and fractures that develop due to tectonic processes, and (3) large fractures and conduits that develop due to karstification (Bakalowicz, 2005). The first two porosities are usually referred to as the matrix, while the latter are called (karst) conduits. These three types of porosities result in a strong heterogeneity of water flow at the surface and in the subsurface (Bakalowicz, 2005). This heterogeneity, shown in FIGURE 2, results in preferential infiltration through the soil/epikarst compartment and rapid transfer through the subsurface karst drainage network. The recharge zone is divided into an autochthonous zone where infiltration is favored (directly on limestone outcrops connected to the karstic spring) and an allochthonous zone where the favored surface runoff (on low permeability formations drained by the aquifer) infiltrates quickly via losses directly in the conduit network. This type of recharge makes it possible to distinguish unary karsts fed solely by autochthonous recharge from binary karsts fed by both autochthonous and allochthonous recharge (Marsaud, 1996).

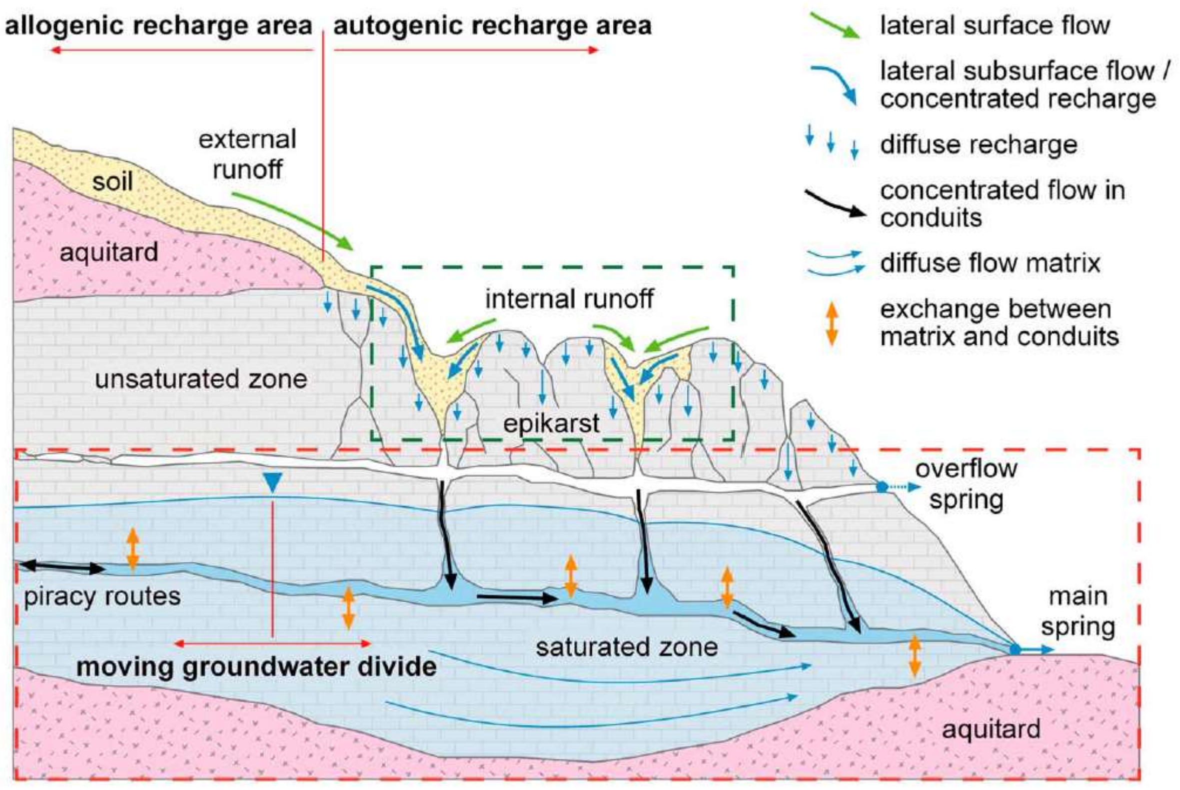


FIGURE 2: CONCEPTUAL MODEL OF A KARST SYSTEM INCLUDING ALL CHARACTERISTIC KARST PROCESSES; DARK GREEN AND RED DASHED LINES REPRESENT THE SOIL/EPIKARST AND THE GROUNDWATER SUBSYSTEMS (FROM HARTMANN ET AL., 2014).

The classical conceptual models of karst hydrogeology give to the unsaturated zone (UZ) a transfer role, and to the saturated zone (SZ) a storage role. The latter is mainly ensured by the fissured matrix. The hydrodynamics response of the karst aquifer to rainfall is usually divided into two components:

- The baseflow which lasts throughout the year, and comprises the slow contribution from the saturated zone;
- The quickflow which generally occurs over a few days in response to rainfall, and is the fast contribution from the infiltration zone to the spring

The relative importance of the quickflow and baseflow components is a very important parameter of karst hydrodynamics, with a strong effect on both aquifer water availability and resilience to droughts, and aquifer vulnerability (Padilla et al. 1994).

2.2 Chalk Aquifer

The Chalk is an unusual karst aquifer in which cave development is limited, but networks of solutional fissures and conduits too small for humans to enter are common (Maurice et al., 2006; MacDonald et al., 1998; Maurice et al., in review). In some countries (e.g. the Netherlands) there are almost no known karstic caves in the Chalk. Cave development is most extensive in the French Chalk where short caves are fairly common in some areas, and include a few examples of over 1 kilometer in length (Rodet, 1985 and 2007; Ballesteros et al., 2020). In England around 45 small karst caves have been documented in the Chalk; the most extensive being Beachy Head cave with a length of ~350 m (Reeve, 1981).

The Chalk provides an important water supply across much of Northwest Europe; and is found in the UK, France, Belgium, the Netherlands, Denmark and Sweden (Downing et al., 1993). The Chalk was formed in the Cretaceous period between ~99 and 65 million years ago (Downing et al., 1993); and comprises a fine grained very pure limestone of ~ 98 % calcium carbonate (Allen et al., 1997). It has a high matrix porosity (average 34% in England, Bloomfield et al., 1995), although very low matrix permeability due to the small size of the pore throats (Price, 1987). There is a dense primary fracture network with spacings of ~0.1 to 1 m (Price et al., 1976; Bloomfield et al., 1996; Zaidman et al., 1999). The unmodified fracture component of the Chalk aquifer typically has a hydraulic conductivity of ~ 0.1 m/day and a transmissivity of ~ 20 m^2/day (Price, 1987). However, median transmissivity of 2100 pumping tests in the English Chalk is 540 m^2/day, with many sites having transmissivities of 1000 m^2/day (Macdonald and Allen, 2001). This high transmissivity arises due to the karstic properties of the Chalk: the potential for solutional enlargement of the primary fractures to form networks of larger fissures and conduits.

Karstic development in the Chalk occurs through classical stream sink-spring karst network development; and also through mixing dissolution which enables the formation of solutional networks at all depths throughout the aquifer and in the absence of point recharge (Farrant et al., 2021). Where surface karst occurs in the Chalk, it is generally on a much smaller scale than observed in more classical karst aquifers, but small surface karst features can be very common. In England there are many hundreds of small karst stream sinks, generally associated with the geological boundary with the overlying Paleogene deposits which enable runoff which sinks at the boundary. The development of surface karst features is very variable in the Chalk. For example, in some areas of England, associated with the Chalk-Paleogene margin, there are extremely high densities of surface karst features (Maurice et al., 2006); whilst in other areas stream sinks and dolines are absent. However, recent studies suggest that there is considerable evidence for karst and rapid groundwater flow throughout the Chalk in England, even in areas away from obvious surface karst (e.g. Maurice et al., in review; Foley and Worthington, 2021; Maurice et al., 2020). This evidence includes the presence of large springs, sudden reactivation of ephemeral springs; losing rivers on outcrop Chalk; high yields from abstractions; indicators of rapid groundwater flow at chalk abstractions; and tracer tests indicating rapid groundwater flow velocities. Maurice et al. (in review) present groundwater velocities for 97 individual tracer connections in the English Chalk. Tracer tests from stream sinks demonstrate velocities of 1000s m/day over distances of up to 19 km; while those from boreholes demonstrate velocities of 100s m/day. These tracer tests demonstrate rapid groundwater flow to abstraction boreholes as well as to springs which formed the natural karst outlets. There has been even more extensive tracer testing in the French Chalk, where tracer tests have been routinely used for catchment delineation in the Chalk and demonstrate rapid flows, often of 1000 m/day (Rodet, 1985; Gombert et al., 2010).

Karst processes in the Chalk result in high vulnerability to pollution, and the potential for pollutants to be transported long distances and into different topographical catchments. However, the Chalk also has very high storage (Allen et al., 1997) and some long (decades) residence time groundwaters as indicated by sampling of CFCs and Sf_6 (e.g. Gooddy et al., 2006). The high matrix porosity, dense fracture network, and the solutional enlargement of many features to a small extent, rather than a few to a larger extent results in a higher degree of protection than in more classical karst aquifers. There is potential for contaminant attenuation via diffusion and dispersion, especially in the unsaturated zone (Foster, 1993).

2.3 Karst Aquifer Management Questions

The management of karst aquifer must be examined in terms of quantity and quality (Bakalowicz 2005).

2.3.1 Quantity: sustainability of supply

The sustainability of karst aquifer must consider the resource value of the aquifer as well as the entire ecosystem services provided by these aquifers. Method 2 and method 3 of CHAKA both address the sustainability element of karst aquifers. Understanding the relationship between baseflow and quickflow, recession and storativity is essential in determining if current abstractions and other ecological water needs are sustainable. It is essential to be able to assess the groundwater volume reserve and the renewable resource. This information will guide the water operators in the quantitative management of the resource, for optimizing water abstraction throughout the year.

2.3.2 Quality: karst specific groundwater vulnerability

Groundwater vulnerability is a term used to represent the natural geological characteristics that determine the ease with which groundwater may be contaminated by human activities (European Commission, 2021). Groundwater vulnerability can be intrinsic or specific. Intrinsic vulnerability embodies the characteristics of the intrinsic geological and hydrogeological features at a site that determine the ease of contamination of groundwater. Specific vulnerability is used to define the vulnerability of groundwater to a particular contaminant and is usually calculated by the combination of the intrinsic vulnerability with an indicator (proxy) of the specific pollutant of interest.

The groundwater vulnerability concept is based largely on the question 'can water and contaminants move in the subsurface materials (soil and subsoil) and get down to groundwater easily?'

The vulnerability category assigned to a site or an area is thus based on the relative ease with which infiltrating water and potential contaminants may reach groundwater in a vertical or sub-vertical direction. As all groundwater is hydrologically connected to the land surface, it is the effectiveness of this connection that determines the relative vulnerability to contamination. Groundwater that readily and quickly receives water (and contaminants) from the land surface is considered to be more vulnerable than groundwater that receives water (and contaminants) more slowly, and consequently in lower quantities. Also, the slower the movement and the longer the pathway, the greater is the potential for attenuation of many contaminants (DELG/EPA/GSI 1999). Conceptually therefore, the vulnerability can be related to the recharge acceptance rate or the recharge potential at any given site or area:

- In areas where recharge occurs more readily, a higher quantity of introduced contaminants will have access to groundwater;
- In areas where recharge is rapid, contaminants may quickly enter groundwater.

As karst areas are known for their heterogeneity, complexities and ease at which water (and contaminants) can move from the land surface to the aquifer, groundwater vulnerability mapping in karst areas must include some assessment of the karst properties of the aquifer and the characteristics of karst groundwater recharge, such as at karren and bare rock surfaces, sinking streams, swallow holes and dolines or other karst depressions (FIGURE 3).

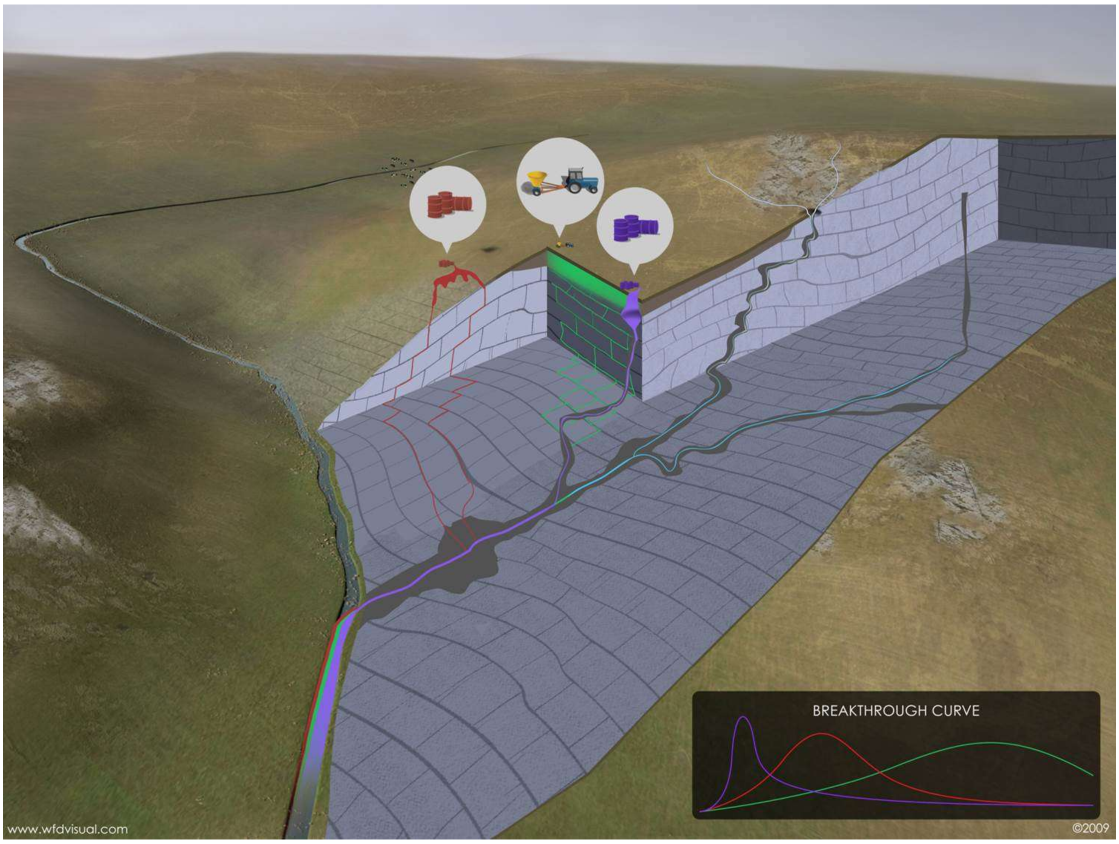


FIGURE 3: THE VARYING BREAKTHROUGH RATES AND CONCENTRATIONS FOR CONTAMINATION EVENTS ON DIFFERENT KARST ENVIRONMENTS, RED - LIMESTONE PAVEMENT, GREEN – COVERED KARST WITH THICK SUPERFICIAL DEPOSITS AND PURPLE – DIRECTLY INTO DOLINE BY PASSING THE OVERLYING DEPOSITS. (WWW.WFDVISUAL.COM/ GSI)

3 HYDRODYNAMIC TYPOLOGY OF KARST/CHALK AQUIFERS

3.1 Introduction

The review of the state of the art of karst aquifers typology methods provided (i) the list of the various conceptual models describing the hydrogeology of karst aquifers and (ii) the existing classification typologies applied to 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.

In this section, after a brief presentation of karst and chalk aquifers specific hydrodynamics, an application of the most common hydrodynamics typology (Mangin 1975, updated by El-Hakim and Bakalowicz, 2007) is applied to all the case studies of this project.

The CHAKA project includes three Chalk case studies – a small spring in an area of the Chalk of the Netherlands with little evidence of karst; and two sites in different areas of the Chalk of Southern England where karst features are well documented and tracer tests have demonstrated rapid groundwater flow over many kilometers to the study sites which comprise one very large spring and one abstraction borehole. In the CHAKA project the new spring classification systems are applied to the Chalk case study sites, and a classification system specific to Chalk boreholes is proposed and applied to 20 sites. However, given the highly variable nature of Chalk karst, the small number of sites considered, and the continuing uncertainties about the karstic functioning of the Chalk aquifer, we recommend that further work is conducted to improve the assessment and classification of karst in the Chalk and other similar aquifers where cave development is limited, and there appears to be a lower level of karstification than in more classical limestone karst.

3.2 Development of a new tool

3.2.1 Specifications of the new tool

The state of the art presented in the Deliverable 5.1 (Hakoun et al., 2020) highlights numerous methods of karst aquifer characterization that are based on spring hydrograph analyses, from time series analysis like correlatives and spectral analyses to discharge frequencies distribution analysis and recession curves analyses. In addition, Mangin (1975) already proposed a method for karst aquifer classification based on the analysis of spring recession curves.

It has been decided, as a first step, to apply these different methods to the case studies of the CHAKA project in order to have a first classification which bring together all the case studies. The objectives of this tool are therefore:

- to apply peer-reviewed methods of hydrograph analysis that can bring useful parameters for karst aquifer classification,
- to allow each team of the CHAKA project to easily carry out the requested calculations, through a simple tool that can be shared between all partners.

A Microsoft Excel application has been created to perform all these results, considering that all partners of the project, and also most of end-users, will easily use it.

This tool is named “XLKarst”. It has been developed in Visual Basic for applications with Excel Office 2016 within Windows 10, but compatibility issues have been solved with older version from the 1998 one.

All the computations are done in the Excel environment using two new menus that appear in the Add-Ins Menu:

- A Time Series Analysis menu for some statistical analyses, including univariate and bivariate correlation and spectral analysis,
- a Discharge menu for recession curves analysis and cumulative frequency analysis of discharge using normal and semi-normal probability plots (FIGURE 4).

A third menu "Info" gives some information on the XLKarst tool, including a reference to the GeoERA project.

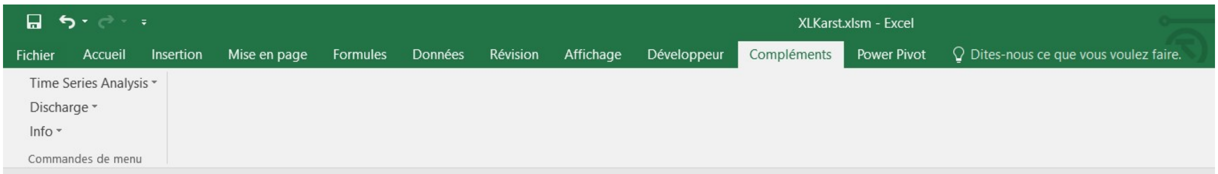


FIGURE 4: STATISTICS SUMMARY FOR THE IRONSELLE KARST SPRING (FR) USING THE XLKARST TOOL

3.2.2 Times Series Analysis menu

The Time Series Analysis menu first allows to compute the main statistical descriptors that are commonly used to describe a discharge time series, with a focus on methods dedicated to karst hydrology, as listed by the CHAKA Deliverable 5.1 (Hakoun et al., 2020). Among them, one can easily compute the coefficient of variation, the spring variability coefficient (SVC, Flora, 2004), the Base Flow Index (BFI) based on the Lyne and Hollick (1979) filter following the standard approach of Ladson et al. (2013), the memory effect (Mangin, 1984), the regulation time (Mangin, 1984) and a new parameter σ250/σ (%) that will be presented and discussed in the following chapter.

The FIGURE 5 shows an example of results from the Ironselle karst spring (FR), for which the BFI is high, which is illustrated by the red curve that theoretically represents the baseflow dynamics as proposed by the Lyne and Hollick (1979) digital filter. One can change the filter parameter (a=0.91 by default in cell C21) to compute other estimates of the BFI, which automatically update the baseflow curve (red curve in FIGURE 5).

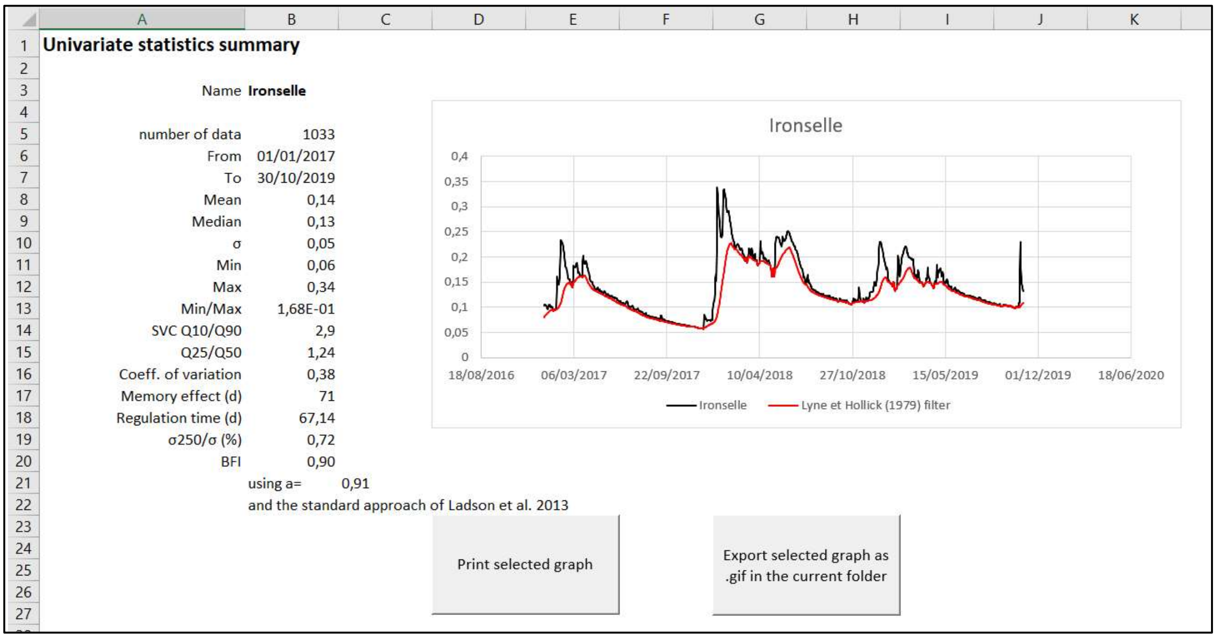


FIGURE 5: STATISTICS SUMMARY FOR THE IRONSELLE KARST SPRING (FR) USING THE XLKARST TOOL

The statistics summary can also be performed on a list of time series at the same time to get a table of results for all the time series.

The second sub-menu of the Time Series Analysis menu enables correlation and spectral analysis. It computes simple (univariate time series) and cross-correlograms (bivariate time series) and their respective discrete Fourier transforms following Jenkins and Watts (1968) methodology, as proposed by Mangin (1984). An example of cross correlogram and cross-spectrum analysis is shown for the Fontaine de Nîmes (FR) case study (FIGURE 6).

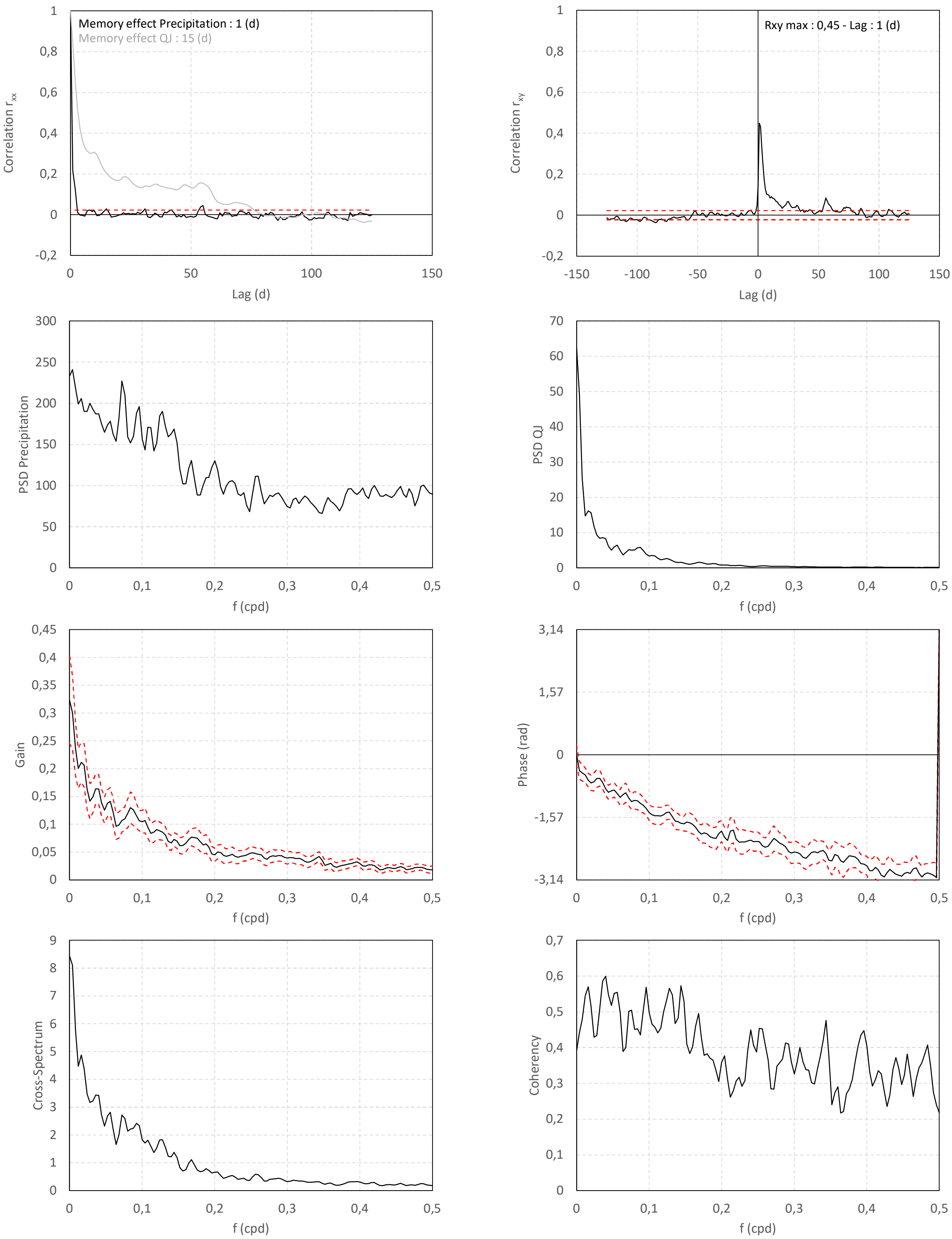


FIGURE 6: CORRELATION AND SPECTRAL ANALYSIS OF THE FDN (FR) DISCHARGE TIME SERIES

Discharge analysis menu

3.2.2.1 Recession curves analysis: Assessment of recession parameters

The first sub-menu of the Discharge menu allows the analyses of recession curves of karst springs using the method proposed by Mangin (1975), as described in the Deliverable 5.1 (Hakoun et al. 2020).

The method proposed by the XLKarst tool asks for 2 parameters in order to automatically select the flood recession curves: A minimal flood peak (Flood Peak parameter), and a minimal duration between two successive flood peaks (LAG parameter). For instance, with the parameters Q=6 m^3/s and LAG = 60 days, only flood recession with a flood peak higher than 6 m3/s and without any increase of discharge higher than 6 m^3/s during at least 60 days will be selected. This is what has been chosen for the selection of flood recessions shown on **FIGURE 7** with the example of the FdN (FR) case study: 19 recessions curves have been selected and labelled from the flood peak (red dot) to the end of the recession (white dot) corresponding to the minimal value between two recession curves.

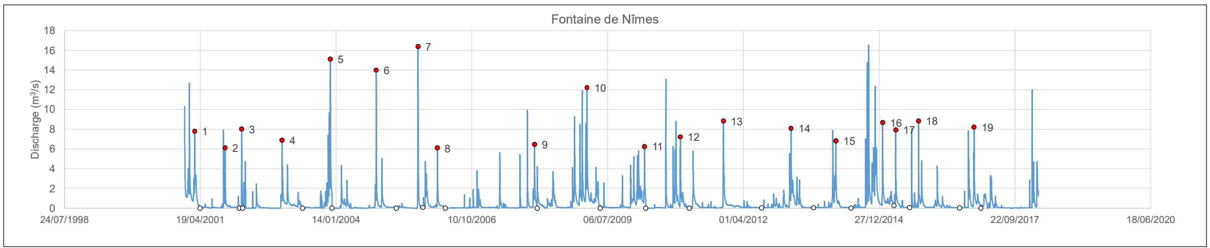


FIGURE 7: RECESSION CURVES SELECTION (WITH NUMBERED FLOOD PEAKS)

The user can manually modify this selection, either by removing a recession curve. For instance, the third one in **FIGURE 7** cannot be analyzed due to a lack of data. This recession curve should be removed if the lacking data cannot be corrected.

Then, the user has to edit each recession curve to get the recession curves parameters. An “Edit” button is used to select each recession by its number in a new spreadsheet. The **FIGURE 8** shows an application with the recession #15 shown on **FIGURE 7**.

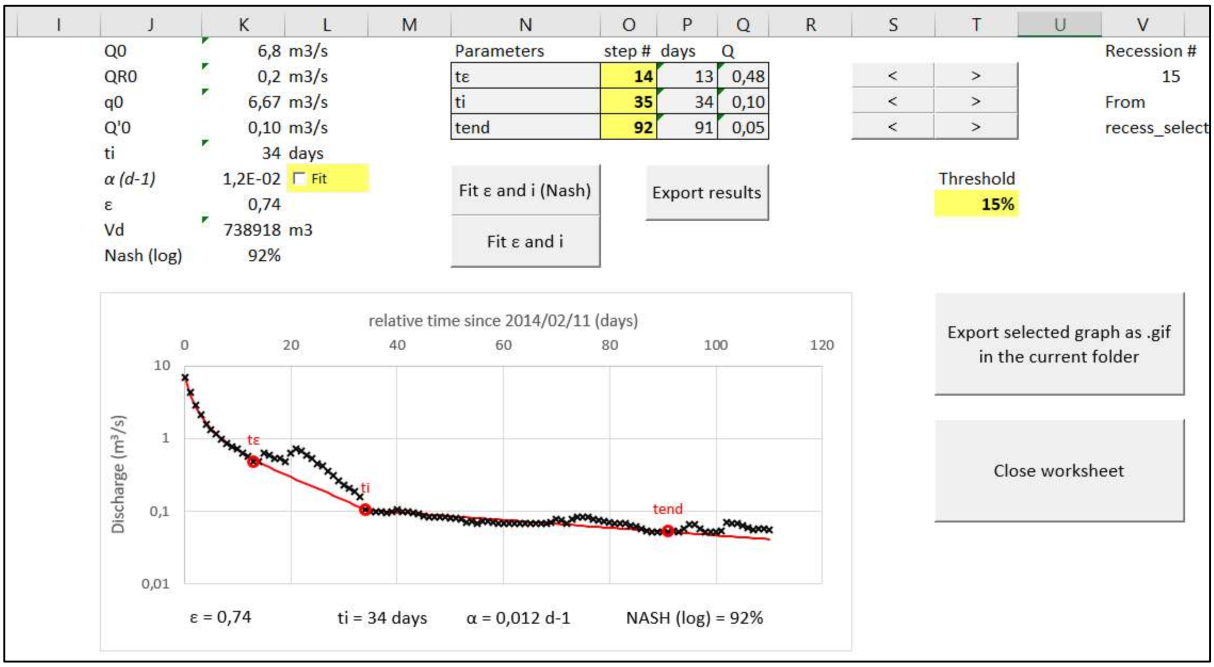


FIGURE 8: VIEW OF THE RECESSION CURVES EDITOR, THE PARAMETERS TO BE MODIFIED BY THE USER ARE IN YELLOW

The fitting process of the recession model is mainly based on the calibration of 2 parameters:

- The time *ti* when the Maillet's law (exponential decrease) applies. The choice of *ti* automatically defines the value of the recession coefficient computed from *ti* to *tend*, the latter defining the last measurements to take into account. There are two options for computing *α*, either by regression of the linearized exponential function to be fitted from *ti* to *tend*, or by direct computation of the slope between the two points of coordinates (*ti, log(Q(t=ti))* and (*tend, log(Q(t=tend)*), where *tend* is the last point that is used for the recession curve calibration. The user can choose between these two options by the "Fit" cursor in column L, FIGURE 8. By default, "Fit" is unchecked and the direct computation based on the slope is used since it is less sensitive to secondary flood events.
- The time *tε*, which defines the length of the discharge time series that is used for the calibration of the homographic function. The tool automatically computes the *ε* coefficient between *t=0* to *t=tε* using the regression of the linearized homographic function (Mangin, 1975).

This calibration procedure can be done manually using buttons to easily move forwards and backwards the *ti*, *tε* and *tend* parameters. The Nash coefficient computed with the log of the discharge is also automatically computed as a criteria of calibration efficiency.

Two automatic calibration procedures are also proposed: the first one computes the Nash coefficient on the log of the discharge values for all the values of *te* and *ti*, and keep the values that corresponds to the highest Nash coefficient. This approach can be used to discuss the sensitivity of the parameters to be fitted, but it often gives poor results for recession curves influenced by secondary recharge events.

The other calibration procedure allows for finding the value of *ti* so that the modeled curve passes through the maximum of measured points: by default, each modeled value (in log) deviating from the measured value (in log) by less than 10% will be taken into account to appreciate the efficiency of the calibration. This percentage can also be modified by the user from the spreadsheet (a value of 15% was used in FIGURE 8, see "Threshold" in the T column). Then, once *ti* is fixed, the Nash coefficient is used to find the best value of *tε*. This procedure is much more efficient and is less influenced by recharge events during the recession.

As an example, both automatic procedures have been used for the recession curve shown in FIGURE 8. The best result given by the second calibration procedure gives the red point that is shown on the sensitive analysis according to the *ti* parameter in FIGURE 9. Visual inspections also show that the parameters given by the red point, which is shown in FIGURE 8, gives the best calibration, although a higher Nash criteria could be computed for higher *ti* values. This illustrates that the Nash coefficient computed with the log of the discharge is a first step to optimize the recession curve, but it cannot be used alone to get the best parameter calibration.

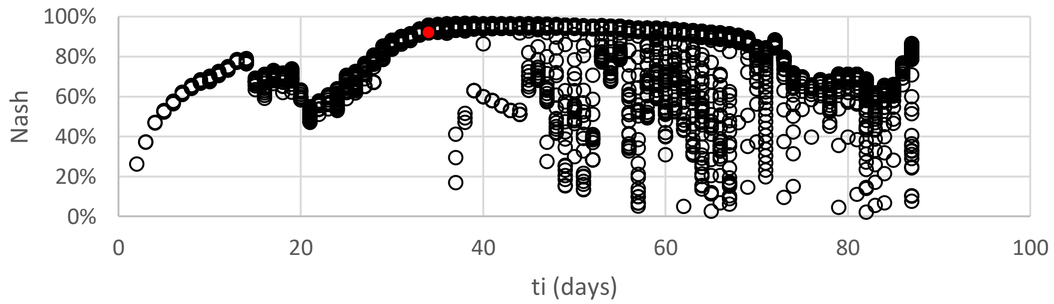
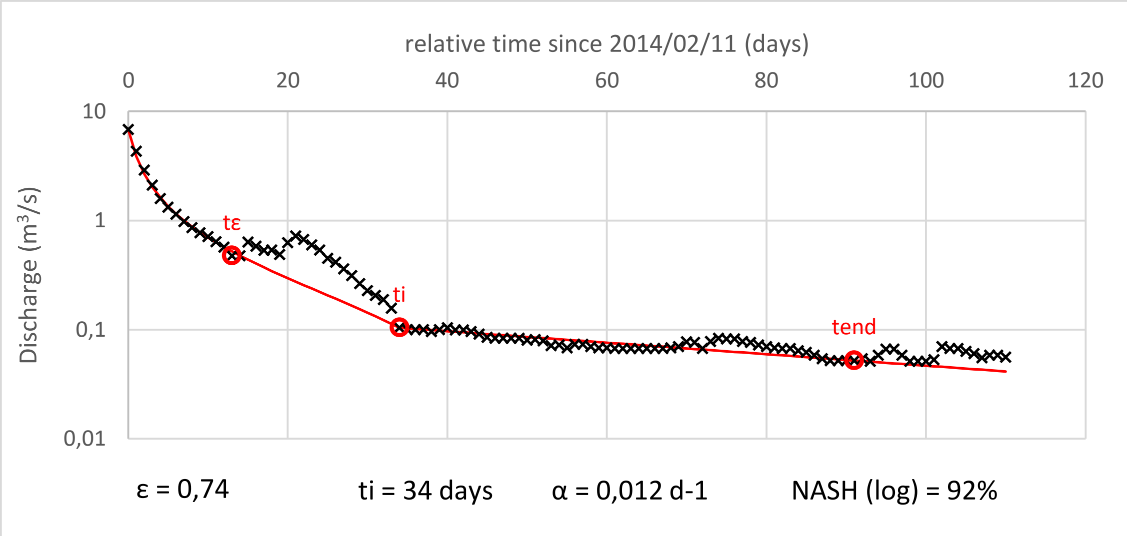


FIGURE 9: SENSITIVE ANALYSIS ACCORDING TO THE "t_i" PARAMETER

FIGURE 10 shows the final results given by the XLKarst tool, one using a logarithmic scale for the discharge, and another one using a linear scale, along with the values of the main recession parameters and the Nash criteria.



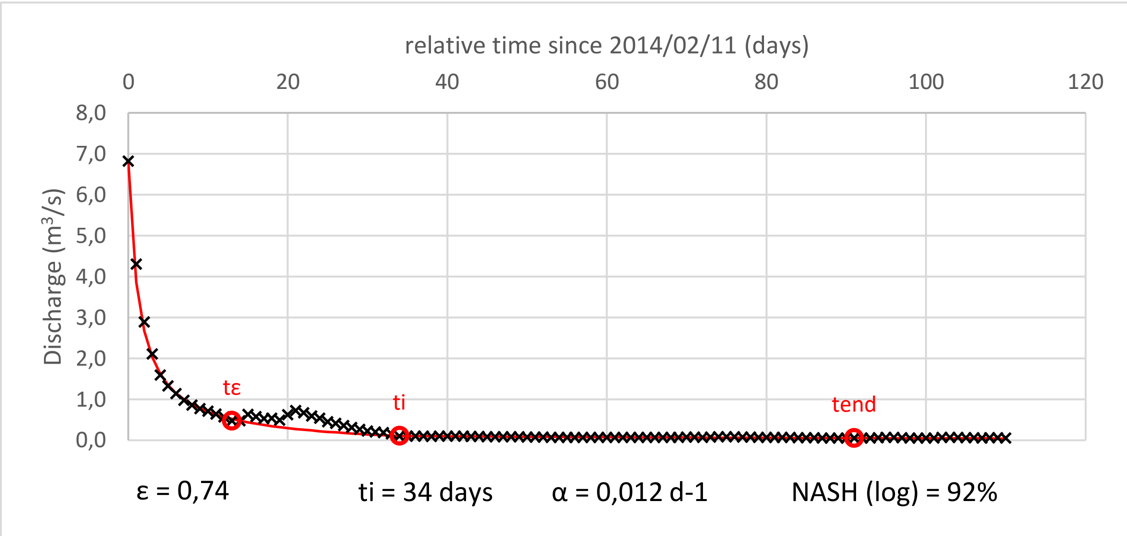


FIGURE 10: RESULTS OF THE RECESSION CURVE CALIBRATION FOR THE RECESSION#15, FDN (FR)

By clicking on the "Export Results" button, the user goes back to the spreadsheet showing the list of the recession curves. All the recession parameters are saved in a table, and the modeled curves are also added on the main graph showing all the recession curves. The user can also zoom on a given flood recession to better see the model adjustment (**FIGURE 11**).

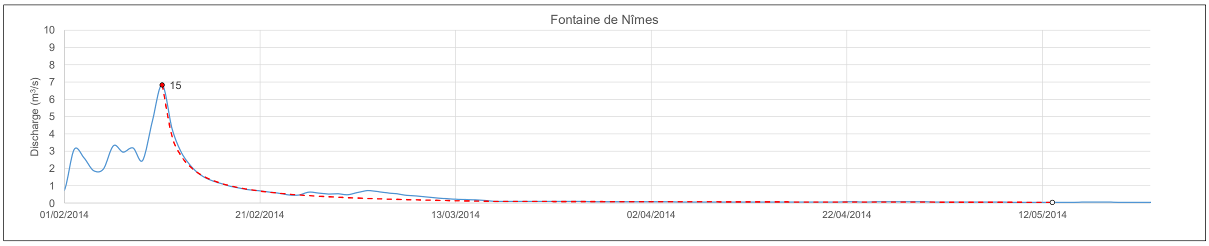


FIGURE 11: ZOOM ON THE 15TH RECESSION CURVES SHOWING THE MODEL ADJUSTMENT (RED DASHED LINE) TO THE MEASUREMENTS (BLUE LINE)

The parameters that are stored in the table are named according to Mangin (1975):

- Q_0 (m^3/s) is the flood peak at the beginning of the recession, i.e. at *t=0*.
- Q_{R0} (m^3/s) is the value of the modeled discharge using the Maillet's law at *t=0*. It is a fictive discharge that theoretically represents the discharge coming from storage at the beginning of the recession. It is used to compute the infiltration rate q_0.
- q_0 (m^3/s) is the initial infiltration rate, computed as the difference between Q_0 and Q_{R0}.
- Q'_0 (m^3/s) is the discharge at $t=t^i$, i.e. when recharge of the phreatic zone is supposed to stop and the Maillet's law applies.
- t_i (d) represents the duration of the infiltration after which the baseflow can be modeled by the Maillet's law.
- α (d-1) is the recession coefficient used in the Maillet's law.
- ε is the non-dimensional coefficient of "heterogeneity" used in the homographic function that is chosen by Mangin (1975) to describe the flood recession dynamics still influenced by the recharge event, i.e. for *0<t<ti*.
- V_d (m^3) is the dynamical storage volume, which represents the volume of water coming from the phreatic zone that flows to the spring. It is assessed by integration over time of the Maillet's law. Some authors compute this integration between *t=0* to *+∞* (see for instance Bakalowicz et al., 2004) while Mangin (1975) recommends to start this computation at *t=ti*, considering that the discharge evolution coming from the phreatic zone is unknown from *t=0* to *t=ti*. The calculation of *Vd* by the XLKarst tool follows the recommendation of Mangin (1975), which gives $V_d = 86400\frac{Q'_0}{\alpha}$, with V_d in m^3, Q'_0 in m^3/s and α in d^{-1}.

3.2.2.2 Recession curves analysis: Classification

The recession parameters estimation is used by Mangin (1975) for the classification of karst aquifer, which is presented in the Deliverable 5.1 (Hakoun et al. 2020):

Mangin's classification is used to compare several aquifer systems with respect to their recharge and storage processes at a daily time step. It is based on two indices: *i* and *k*, which describe an infiltration delay and how the aquifer system regulates flow respectively:

- The Y axis represents the infiltration delay, which is a non-dimensional parameter denoted *i*. It is computed for each recession curves using $i = \frac{1-2/t_i}{1+2\varepsilon}$, and the mean value is reported for the classification,
- The X axis represents the regulating power (Mangin, 1975), denoted *k*. It is computed as the ratio of the largest value of V_d to the mean annual volume computed over the hydrological cycles that are used for the recession curve analysis. *k* was proposed by Mangin (1975) as a non-dimensional parameter lower than 0.5 for well karstified systems and ranging from 0.5 to 1 for poorly karstified systems.

- 5 domains were defined by Mangin (1975) to describe the hydrodynamic functioning of a karst system based on the analysis of discharge time series and tracer tests from 5 karst springs in France:
  - 1: $k < 0.5$ and $i > 0.5$: domain of complex karst systems, largely extended with several sub-systems and/or thick infiltration zone;
  - 2: $k < 0.5$ and $0.25 < i < 0.5$: systems with a karst conduit system more developed in their upper part than in parts close to their spring, and characterized by a delayed recharge because of either non-karstic terrains, snow or sediment cover;
  - 3: $k < 0.1$ and $i < 0.25$: intensely karstified systems in the downstream part of the system, with a well-developed conduits system directly connected to the spring;
  - 4: $0.1 < k < 0.5$ and $i < 0.25$: systems with a well karstified infiltration zone and a large phreatic zone;
  - 5: $k > 0.5$: porous and fissured aquifers.
- More recently, El Hakim and Bakalowicz (2007) consider *k* as a proxy for the mean residence time of water in the phreatic zone, allowing *k* to be higher than one in their classification to account for karst systems with very large regulating power. k>1 characterizes karst systems with a deep phreatic zone, partly or totally confined underneath impermeable sediments, and largely karstified during previous karstification phases.
- In addition, the classification proposed by El-Hakim and Bakalowicz (2007) expresses *k* in a logarithmic scale.

Both initial (Mangin, 1975) and modified (El-Hakim and Bakalowicz, 2007) classifications are proposed by the XLKarst tool, which also allows to change the size of the points according to the mean discharge value.

3.2.2.3 Cumulative frequency analysis

The second sub-menu of the Discharge menu allows to perform a cumulative frequency analysis of discharge using normal and semi-normal probability plots on a linear or logarithmic scale of the discharge. The user has to choose the discretization of the histogram that will be reported in a probability plot, as well as the minimal value to consider in order to discard the lowest flow values controlled by the recession dynamics.

The user can also choose between the semi-normal and the normal statistic law, the semi-normal being the one recommended by Mangin (1975) for the analysis of karst spring hydrographs.

For instance, the cumulative frequency analysis of daily discharge at the Waldbachursprung Sp. (Austria) is shown on FIGURE 12 for discharge classes of 0.1 m^3/s. The curve clearly shows a breakpoint in a semi-normal probability plot that is a typical consequence of overflow spring(s) activation for a discharge higher than 10 m^3/s. This overflow functioning is one of the characteristics of a well-karstified karst system.

This cumulative frequency analysis is used for identifying the existence of specific flow regimes (example of overflowing spring) but is not used in the karst classification proposed later.

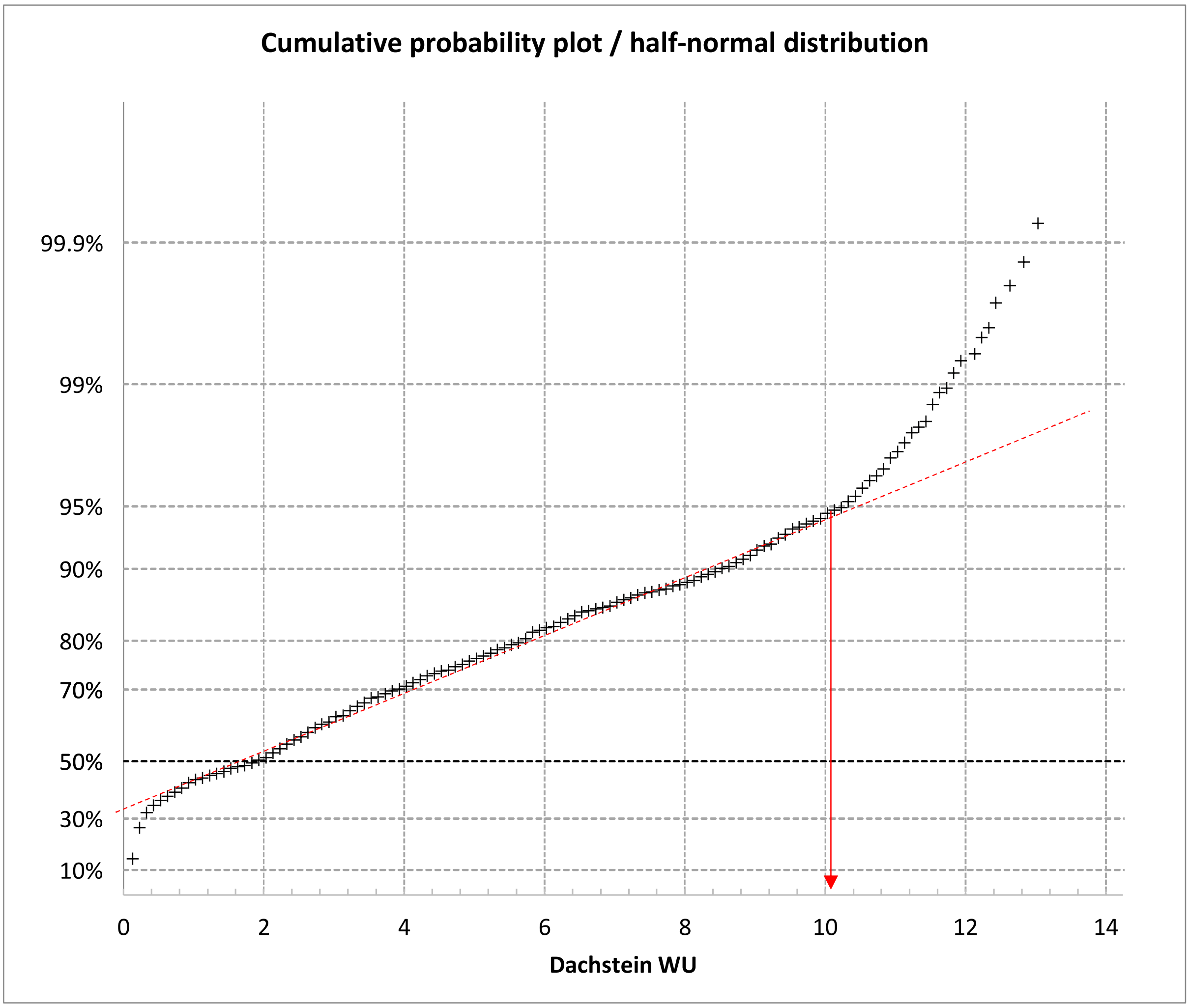


FIGURE 12: ZOOM ON THE 15TH RECESSION CURVES SHOWING THE MODEL ADJUSTMENT (RED DASHED LINE) TO THE FREQUENCY CURVE

3.3 Application to case studies

3.3.1 Results of the karst system classification using the Mangin (1975) method

The XLKarst tool has been used in the project to provide statistical parameters that will be used in the new methods of karst aquifer classification proposed in the GeoERA project. At this step, only the results given by the recession curves analysis will be shown and discussed as a starting point for further developments. The results are shown in for the 16 case studies. The analysis has been done on daily discharge time series, except for the BHS (UK) case study which is at a weekly time step. The 5 domains proposed by Mangin (1975) with the modification of the 5th domain proposed by El-Hakim and Bakalowicz (2007) are reported in the classification.

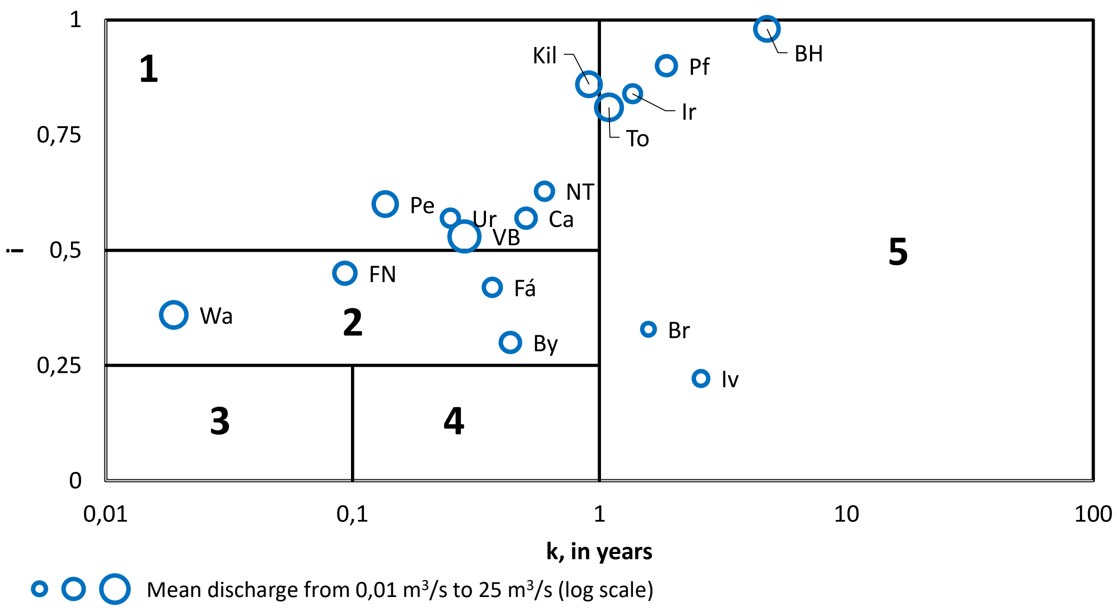


FIGURE 13: RESULTS OF THE MANGIN'S CLASSIFICATION FOR THE 16 CASE STUDIES OF THE CHAKA PROJECT

This classification shows that most of the case studies fall in the first domain, which is, for k<1 and i>0.5 the domain of complex karst systems, largely extended and made up of several sub-systems. Some karst systems show a higher karstification degree and fall in the second domain. Several karst systems show however a high regulating power (k in X axis), which define a poorly karst system (0.5<k<1) and even a non-karstic system (porous or fissured aquifer) according to Mangin (1975) for k>1. El-Hakim and Bakalowicz (2007) however propose to add the 5th domain to include karst system with a deep phreatic zone, partly or totally confined underneath impermeable sediments, and largely karstified during previous karstification phases. This description applies for the Killeglan case study (Kil, IR), but cannot explain the results for the Tonkovic karst system (To, Cratia) or dolomitic and karstified karst systems like the Ironselle (Ir, FR), the Ivanscica Sp. (Iv, Croatia) or the Pfannbauernquelle (Pf, Austria). In addition, the karst systems developed in chalk (BH, UK and Br, NL) also show high values for *k*.

For systems with high regulation power, it can be difficult to describe the first part of the recession, before the exponential decreasing limb, because the infiltration rate (q_0) would be negative. This implies a 0 value for ε, and somehow arbitrary value of I that only depends on the time t_i. For instance, the values found for the St Brigida Sp. system (Br, NL) or the Ivanscica Sp. (Iv, Croatia) can be discussed and could be interpreted differently.

3.4 Conclusion

This classification enables a description of the hydrodynamics properties of the karst system. High values of *i* and *k* may suggest favorable conditions for karst groundwater resource exploitation. A high value of i means that the decrease of the discharge is relatively small 2 days after the flood peak, which mean that the infiltration is somehow delayed through the infiltration zone, while a high value of *k* means that there is a high baseflow component with a high proportion of the discharge derived from long term storage as opposed to rapid infiltration. These characteristics provide the aquifer with a degree of resilience to precipitation variability and drought.

However, the mean discharge of the karst system is also a primary factor for groundwater resource availability, which is not considered in this classification. A high value of i suggests that there is a long delay between precipitation and response in the aquifer and therefore the aquifer may be less vulnerable to pollution. However, this classification provides only limited information on karst groundwater vulnerability to pollution, which is important for the protection of drinking water supplies and the management of source catchments.

4 CLASSIFICATION OF KARST/CHALK AQUIFERS FOR GROUNDWATER RESOURCE MANAGEMENT

4.1 Introduction

The hydrodynamic typology applied in the previous section is usually applied by karst researchers to compare karst springs but is not generally used by water operators and management authorities. From the perspective of water providers, the main interest is the capability of an aquifer to provide good quality of water in large quantities. This implies questions about the volume of water stored into the aquifer, and the vulnerability of this aquifer to pollution. The objective of the geoera CHAKA project is is to provide water providers and regulators with a classification method which uses indicators that are important for groundwater resource management and provision. Two main classical management issues in relation with aquifer characteristics have been identified:

- the quantity of water that the aquifer is able to store and provide
- the quality of water that the aquifer can supply which is dependent on the vulnerability of this aquifer to pollution.

In this chapter, we propose three types of karst aquifer classification based on different kinds of data. They are illustrated on FIGURE 14. Method 1 uses information on the catchment coupled with indicators measured on a spring or well in order to assess the intrinsic vulnerability of the aquifer to pollution. Method 2 combines method 1 with additional information from discharge time series. Method 3 describes the vulnerability and regulation capacity of karst/chalk aquifers using several time series (discharge and several physio-chemical parameters). These three methods are described and applied to the case studies below.

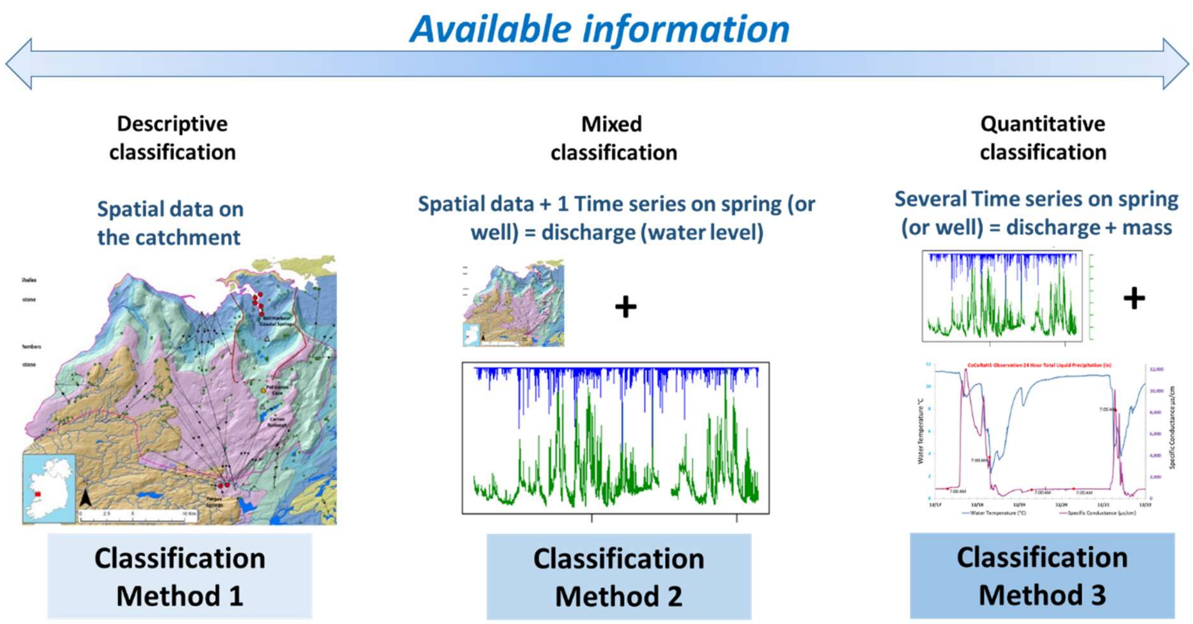


FIGURE 14: KARST/CHALK AQUIFERS CLASSIFICATION ACCORDING TO THE TYPE OF DATA USED

4.2 Method 1: Classification of karst aquifer intrinsic vulnerability to pollution

4.2.1 Method description

The aim of this method is to use multiple criteria to assess the intrinsic vulnerability of a spring or borehole in a karst aquifer to pollution. By intrinsic vulnerability we mean the vulnerability of the spring or borehole that arises due to the karstic nature of the aquifer which enables rapid groundwater flow through connected networks of solutional fissures, conduits and caves, whatever the nature of the pollutant. Focused recharge in karst is demonstrated to be a key feature of risk of contamination (Hartmann et al., 2021). Intrinsic vulnerability does not consider the risk of pollution of a spring or borehole due to long-term land use practices within the catchment. Karst networks may provide varying degrees of attenuation via dispersion into smaller voids and the intrinsic vulnerability depends on how much flow occurs rapidly through connected networks of larger voids or the rate at which water and contaminants can enter these voids. This classification uses parameters which are indicative of this vulnerability.

This method has been principally developed for application to springs, as most of the CHAKA project case studies are karst springs. It can be applied to any spring regardless of the amount of data available, including those springs with no time series data. Where time series data are available, the outputs from this method are combined with discharge time series data in Method 2, to provide a more comprehensive assessment of karst aquifers including both intrinsic vulnerability and reserve assessments.

Method 1 is applied to all CHAKA sites, but it should be noted that there are only two chalk springs, and given how different chalk is to other karst aquifers (Section 2.2.2), further work would be recommended to develop the most appropriate method for the Chalk. A modified version of the method for application to abstraction boreholes is also presented and tested on 20 boreholes from the English Chalk (Section 3.2.3). Further work is also recommended to develop the most appropriate classification for boreholes because the method has only been tested on these 20 boreholes in one area of the Chalk and has not been tested on limestone karst aquifers.

4.2.1.1 General principles

The method considers 6 (for springs) or 7 (for borehole abstractions) parameters which are indicative of vulnerability and are detailed below. For each parameter a score of 1 (low vulnerability), 2 (moderate vulnerability), or 3 (high vulnerability) is assigned. For each spring or borehole abstraction, the average score from all parameters is used as an overall indicator of the vulnerability. Sites with average scores ≥ 2.5 are considered to have high vulnerability, those with scores 1.5 to 2.5 are considered moderately vulnerable, and those with scores < 1.5 are considered low vulnerability.

4.2.2 Parameters (Intrinsic vulnerability indicators) for springs

Surface karst

Surface karst features result in high vulnerability as they are indicative of connected karstic flowpaths through the unsaturated zone, and enable pollutants to travel rapidly from the surface to the saturated zone. The surface karst scores are:

- *Surface karst features with direct water input present in catchment = high vulnerability, Score 3*

- *Surface karst features with no obvious water input present in catchment = moderate vulnerability, Score 2*
- *No surface karst features present in catchment = low vulnerability, score 1*

Surface karst features that provide the highest vulnerability are those in which there is an obvious direct water input into a karst feature. This includes karst stream and river sinks in which all surface water from the stream or river enters the ground, and which may or may not be via a doline, blind valley or a swallow hole. It also includes rivers which have sections in which there are large losses to the karst aquifer indicated by river flow gauging, or where rivers have dry sections due to losses to the karst aquifer (e.g. Sefton et al., 2019). The category also includes artificial point input soakaways into the karst aquifer which have capacity to take large flows (e.g. >1 l/s), because these are likely to be feeding into karstic pathways enabling rapid flow through the unsaturated zone. Sites should be assigned to the high vulnerability category where any of these features are present within the catchment, including those that are only hydrologically active following rainfall.

Surface karst features with no obvious water input (dolines and dissolution pipes) may still be indicative of rapid flowpaths through the unsaturated zone and their presence suggests some vulnerability to pollution. Therefore, where these are present, the spring should be assigned to the moderate vulnerability class.

Cave development

Conduits are solutionally enlarged voids which enable rapid groundwater flow through the aquifer, and when they are large enough to enter, they are usually termed caves. Information on caves is generally known through speleologists exploration. Therefore, this parameter can be used in most cases. Karst aquifers have very variable degrees of cave and conduit development. For example, in the CHAKA project there are limestones in the classical karst with very large-scale cave systems that extend for 10s of kilometers with dimensions in places of many 10s meters. In contrast the Chalk aquifer of England has very little cave development, although smaller conduits are common (Section 2.2.2). For the assessment of the “Cave development” criteria, it is assumed that the more extensive the cave development is, the more vulnerable the aquifer will be. Therefore, an assessment of the degree of cave development (i.e. conduits that are large enough for humans to enter and are therefore indicative of a greater degree of conduit development) is used for assessing the aquifer vulnerability. The cave development scores are:

- *Caves > 1 km in length present in the catchment = high vulnerability, score 3*
- *Caves < 1 km in length present in the catchment = moderate vulnerability, score 2*
- *No caves present in the catchment = low vulnerability, score 1.*
-

Water quality indicators of rapid groundwater flow

The “water quality” parameter assumes that evidence from chemical, physicochemical, or ecological measurements that is indicative of rapid groundwater flows can be used as a proxy of vulnerability of groundwater to pollution due to the presence of karstic flowpaths enabling the rapid groundwater flow.

There are a number of water quality parameters which are indicative of a component of rapid groundwater flow (and hence vulnerability) at a spring. These include (but are not restricted to):

(1) Substances which are rapidly degraded in the subsurface and would not be present in longer residence time groundwater. For example, bacterial contaminants such as coliforms which

only survive around 4 days to 4 weeks within groundwater (Lewis et al., 1980, reported in MacDonald et al., 1998); and some rapidly degrading pesticides (e.g. Metaldehyde which is reported to have a half-life of around 12 days (AERU, 2017)).

(2) Turbidity caused by transport of sediment in karstic voids. Turbidity occurs due to karst processes where there is rapid transport of sediment from surface karst features to the spring, or where flow is rapid enough to re-suspend sediment within the aquifer which was previously deposited in karstic conduits (Massei et al., 2003). Turbidity can also occur due to non karst processes, such as in the Chalk where very fine chalk particulate matter can cause turbidity. Turbidity due to karst could be determined by analysis of the particles producing the turbidity. In some cases, Specific Electrical conductance (SEC) measurements could also be used to identify sediment transported from the surface where there is a decrease in SEC during the turbidity event, as this decrease in SEC indicates transport of fresher surface water (Fournier et al., 2007).

(3) Salinity occurring within a short time of road salt applications.

(4) Salinity indicating saline intrusion over long distances.

(5) Water quality indicating connectivity with a surface river (i.e. clear evidence from water chemistry/ecology analyses that the abstraction contains a component of river water e.g. the presence of parameters/concentrations observed in river water but not in groundwater, or the presence of surface water organisms)

The water quality indicator scores are:

- *More than one indicator of rapid flow present at the spring = High vulnerability, Score 3*
- *One indicator of rapid flow present at the spring, = moderate vulnerability, Score 2*
- *No indicators of rapid flow present at the spring, but monitoring conducted = Low vulnerability, Score 1.*

Sites should only be assigned to the low or medium vulnerability class where sufficient data are available to make the assessment: as a minimum at least two rapid flow water quality indicators (e.g. coliforms and turbidity) monitored to a sufficient degree to be confident that they are not present at the site.

Where no or insufficient water quality data are available, this parameter should be excluded from the assessment until further data are available.

Coliforms

The “Coliforms” parameter assumes that the more coliforms that are present in groundwater, the higher the intrinsic vulnerability of the aquifer. The rationale for this is outlined here.

The “water quality” parameter outlined above only considers the presence or absence of different water quality indicators of rapid groundwater flow, and does not consider how much of the pollutant is present at the spring. However, the concentrations/amount of the substance present may also reflect the intrinsic vulnerability of the karst system. Karst systems in which there is a high proportion of rapid flow and/or there is little attenuation along the flowpath result in much higher concentrations of pollutants at the spring. These springs are therefore intrinsically more vulnerable to pollution than those in which there is attenuation via dispersion/dilution into smaller voids, and dilution of the rapid flow component with longer residence time groundwater, resulting in low pollutant concentrations at the spring.

Assessing this is difficult because pollutant concentrations may reflect the intrinsic vulnerability of the aquifer, but could also reflect the pollutant source term, and depend on pollutant loads in the catchment. If there are high concentrations of a substance present which is indicative of rapid groundwater flow, then this implies low potential for attenuation and high vulnerability. However, if low concentrations are present this could either reflect low intrinsic vulnerability or low pollutant loads in the catchment. Nevertheless, there is evidence that karst aquifers generally have higher concentrations of pollutants indicative of rapid flow than other types of aquifer (Sinreich et al., 2014), and it appears that high concentrations of parameters such as coliforms and turbidity are likely to be indicative of the intrinsic vulnerability of a karst system. Considering 20 borehole abstractions from the English Chalk (Section 3.2.3), very large variations in coliform counts are observed (0 to 38700 cfu/100mls). The highest coliform counts occurred at sites where there was other evidence for high vulnerability (stream sinks present in the catchments and rapid flow indicated from tracer tests). Although no land use data have been considered, there appear to be many potential coliform sources throughout the chalk outcrop, from both urban and agricultural sources, which might imply that variations in coliform counts reflect the intrinsic vulnerability of the chalk karst aquifer. This is also supported by the highly variable nature of chalk karst with some areas devoid of surface karst features, and hence where it might be expected that there is higher potential for attenuation, resulting in lower vulnerability. However, in many catchments not all surface karst features have been identified, and additionally rapid flow from the surface is not always via obvious karst features. High concentrations of pollutants that indicate rapid groundwater flow are therefore a useful additional parameter to consider in assessing vulnerability.

Of all the water quality parameters that indicate rapid groundwater flow, coliforms are the most straightforward to interpret and are routinely monitored at abstractions (in the UK at least), and they are therefore included as a parameter in the assessment of vulnerability with the following scores:

- *Maximum coliform counts > 1000 cfu/100 mls = high vulnerability, score 3*
- *Maximum coliform counts 10 to 1000 cfu/100 mls, = moderate vulnerability, score 2*
- *Maximum coliform counts < 10 cfu/100 mls = low vulnerability, score 1, if sufficient sampling coverage following rainfall events*

The threshold values were determined from the ranges of coliforms that are observed in karst aquifers.

Because coliforms occur in response to rainfall events the number of samples and frequency of monitoring will affect the maximum coliform count observed. It is therefore recommended that sites are only assigned to the low vulnerability category if there is high confidence that there has been sufficient sampling: for example if there are more than 500 samples spanning at least one wet season, or there is good sample coverage following rainfall events.

Where coliforms have not been monitored this parameter should be excluded from the assessment. This parameter should also be excluded if there is insufficient sample coverage to determine the likely maximum coliform counts, but in this case because coliforms have been detected their presence would still be an indicator of rapid flow for the “water quality” parameter discussed above.

Tracer tests indicating rapid groundwater flow

Tracer tests are extremely useful for assessing vulnerability as they provide direct evidence for rapid groundwater flow impacting a spring.

Relating particular tracer velocities to levels of vulnerability is difficult as any successful tracer test could be interpreted as being indicative of intrinsic aquifer vulnerability, and at sites where tracer tests have been undertaken they do not provide information on all the flow to the spring or borehole. In addition, there are many different types of tests: Those that inject and/or monitor directly into a karst feature (stream sink injections and spring monitoring points); and those that inject or monitor boreholes in the saturated zone which are unlikely to intersect the main conduit systems directly. One approach to determining thresholds would be to use observed tracer velocities in karst aquifers (e.g. from Worthington and Ford, 2009), and the Chalk (Maurice et al., in review), and divide these up to enable a classification based on relative vulnerability from observed data. However, for water management purposes, the more important question is: what are the risks to groundwater quality due to the intrinsic nature of the aquifer? Even the lower velocities observed in tracer tests in karst are indicative of high vulnerability. Nevertheless, we can make the assumption that, the more rapid the flow, the more vulnerable the aquifer is likely to be.

Tracer recoveries can also provide an indication of high vulnerability because high recoveries indicate low attenuation within the aquifer and increased vulnerability to pollution. A high tracer recovery is expected where there is a well-developed karst drainage structure, with focused groundwater flows that converge on the spring with low dispersion and diffusion into smaller voids. Sites with lower groundwater velocities (10-500 m/day), but combined with low tracer attenuation (> 5 % tracer recovery) are therefore assigned to the high vulnerability category 3.

Low recoveries (< 5 %) may be indicative of high attenuation in the aquifer through dispersion and diffusion into smaller voids surrounding the main karstic conduit networks, and dilution with water from these smaller voids. However, the low tracer recoveries could also be due to rapid tracer transport to other groundwater outlets, and therefore are not used here as indicators of low vulnerability.

We use the following groundwater velocity vulnerability indicator scores to reflect the increased vulnerability of sites where tracer tests reveal rapid flow, with consideration of tracer recoveries where available:

- *Tracer velocity of > 500 m/day; or velocities of 10-500 m/day combined with tracer recoveries > 5 % = high vulnerability, score 3*
- *Tracer velocity of 10 to 500 m/day with no tracer recovery data, or with tracer recovery < 5 % = moderate vulnerability, score 2*
- *Tracer tests with no tracer recovery from all stream sinks in the catchment or from at least 3 different injection points if no stream sinks present = low vulnerability, score =1*

The tracer velocity assessment should be based on first arrival of tracer where available, but if first arrival information is not available, can be based on time to peak concentration. The vulnerability scores should be applied based on tracer tests to the spring in question.

To assign a spring to the low vulnerability category there must be high confidence that sufficient tracer testing has been undertaken to demonstrate low vulnerability. Therefore, tracer tests should be conducted from all streams/rivers that sink within the catchment; or if none are present, from at least 3 other injection sites (which could be boreholes, dolines or soakaways) shown to provide appropriate geographical coverage of the catchment. There needs to be high confidence that monitoring was conducted for a long enough period of time and with sufficient frequency to be confident in the negative result.

Sites where no or insufficient tracer tests have been conducted should not be assigned a score for this parameter, as it remains unknown whether future tests would reveal a rapid flowpath.

Spring Discharge response

The "Spring discharge response" parameter assumes that rapid increases in spring discharge following rainfall indicate fast flow transfer, and that this can be interpreted as a proxy of high vulnerability to pollution. A rapid spring response may be due to direct transfer of recharge water from the surface, but also to a piston flow response. In either case the rapid response implies a rapid influx of water to the subsurface in the infiltration zone which enables rapid transport of any pollutants within the recharge water. This will reach the spring more quickly in the case of a direct transfer response than with a piston flow response. A better assessment of spring vulnerability can be made by establishing the proportion of rapid flow discharging from the spring. This can be estimated using time series analysis which is considered in detail in methods 2 and method 3 (Sections 3.3 and 3.4). To enable discharge to be considered at sites with no/limited frequency time series data, a descriptive method is used here to assess aquifer vulnerability based on spring discharge responsiveness:

- *Rapid response of spring observed within 24 hours of rainfall = high vulnerability, score 3*
- *Response of spring observed within more than 24 hours = moderate vulnerability score 2*
- *No discernible short-term responses to rainfall = low vulnerability, score 1*

The scores can be applied based on qualitative observations. However, in cases where it is considered uncertain which of these categories the spring is in, no score should be assigned.

4.2.3 Application to CHAKA case study springs

The results of Method 1 for the GEOERA case study springs are shown in Figure 15. In addition to the original case study springs which are detailed in the case study report, Deliverable 5.2 (Maréchal et al., 2020), three additional dolomite springs have been included: the Pfannbauernquelle spring in Austria, Ironselle spring in France, and Ivanscica spring in Croatia.

The majority of the CHAKA case study springs have high scores, and are classed as high vulnerability, with 4 sites scoring 3 for all available parameters indicating the highest vulnerability score possible. This is consistent with the type of karstic springs that were selected as case studies for this project, with many of them being in classically karstic areas.

There are two case study springs from the Chalk which have very different characteristics. The Bedhampton and Havant springs in the UK Chalk are very large springs (combined mean flows of > 1000 l/s) with very clear evidence of karst: surface karst features (stream sinks) are present in the catchment; tracer tests demonstrate rapid flow of several kilometers per day to the springs over distances of many kilometers; and there are strong water quality indicators of high vulnerability. This case study site scores 2.5 and is classed as high vulnerability. The main reason that the score is not as high as many of the limestone case study springs is that there is no known cave development in the catchment, which is consistent with the very limited cave development that occurs in the English Chalk. In contrast the St Brigida spring in the Netherlands Chalk is a smaller spring (0 to 55 l/s) with no water quality indicators of rapid groundwater flow in an area where there is no evidence of stream sinks or dolines. Whilst the flows that are observed require a connected network of karstic solutional fissures and conduits, it appears that this spring has low intrinsic vulnerability with scores of 1 for all available parameters. It should be noted that groundwater analysis of this spring show high nitrate concentrations as well as presence of pesticides (Dimethylsulfamide, Metolachlor, metabolites desphenyl-chloridazon and methyl-desphenyl-chloridazon). The low vulnerability of this spring compared to the other case studies is related to point-source and accidental pollution, not to long-term and diffuse pollution due to agriculture activities.

The three dolomite springs that have been added to the CHAKA study have somewhat lower scores (ironselle 2.4; and Pfannbauernquelle 2.0; Ivanscica 1.4) than many of the limestone springs and are classified as having moderate (Ironselle and Pfannbauernquelle) or low (Ivanscica) intrinsic vulnerability.

Country/Region	Site name	Surface karst	Caves	Water quality	Coliforms	Tracer tests	Discharge	Average score	Vulnerability Class
France	Fontaine de Nimes	3	3	3	-	3	3	**3.0**	**High**
Austria	Waldbachursprung	3	3	3	-	3	3	**3.0**	**High**
Hungary	Naga-Tohonya	3	3	-	-	3	-	**3.0**	**High**
Bosnia and Herzogovina	Vrelo Bune	3	3	-	-	3	3	**3.0**	**High**
Croatia	Gacka Pecina spring	3	2	3	-	3	3	**2.8**	**High**
UK	Bedhampton and Havant	3	1	3	3	3	2	**2.5**	**High**
Croatia	Gacka Tonkovic spring	3	2	2	2	3	3	**2.5**	**High**
Czech Republic	Bull Rock	3	3	2	1	3	3	**2.5**	**High**
Ireland	Killeglan	3	1	3	3	3	2	**2.5**	**High**
Spain	La Farara	2	2	3	-	-	3	**2.5**	**High**
France	Ironselle	2	3	2		3	2	**2.4**	**moderate**
Catalonia	St Quinti & Cardener	2	2	-	-	-	3	**2.3**	**moderate**
Romania	Grota Ursului	3	3	2	1	2	3	**2.3**	**moderate**
Austria	Pfannbauernquelle	2	2	-	-	-	2	**2.0**	**moderate**
Croatia	Ivanscica springs	1	1	2	1		2	**1.4**	**low**
Netherlands	St Brigida	1	1	1	-	-	1	**1.0**	**low**

FIGURE 15: TABLE OF RESULTS OF METHOD 1 FOR THE CHAKA CASE STUDY SPRINGS

4.2.4 Application to borehole abstractions

4.2.4.1 Method

Borehole abstractions differ from springs as boreholes do not generally directly intersect the main cave and conduit systems within the aquifer, but intersect smaller solutional fissures and conduits. However, the fissure and conduit network supplying the borehole abstraction may be extensive (especially where boreholes have high yields/transmissivity), and they may therefore have high vulnerability to subsurface activities. These networks may also be connected to the main cave and conduit networks within the aquifer and/or to surface karst features, resulting in especially high vulnerability. The vulnerability assessment for springs is modified for borehole abstractions to account for this different setting and is as follows.

Surface karst

As for springs:

- *Surface karst features with direct water input present in catchment = high vulnerability, Score 3*
- *Surface karst features with no obvious water input present in catchment = moderate vulnerability, Score 2*
- *No surface karst features present in catchment = low vulnerability, score 1*

Caves

As for springs:

- *Caves > 1 km in length present in the catchment = high vulnerability, score 3*
- *Caves < 1 km in length present in the catchment = moderate vulnerability, score 2*
- *No caves present in the catchment = low vulnerability, score 1.*

Conduits

An additional parameter is included for borehole abstractions to reflect the additional information that may be available through borehole imaging which shows the types of features that are contributing flow to the borehole and can reveal large fissures and conduits. The scores for this parameter are based on the assumption that the larger the conduits, the more extensive the conduit network is likely to be:

- *Conduits/solutional fissures with diameters/apertures > 10 cm = high vulnerability, score = 3*
- *Conduits/solutional fissures with diameters/apertures 2 to 10 cm = moderate vulnerability, score = 2*
- *Conduits/solutional fissures with diameters/apertures < 2 cm = low vulnerability, score 1*

Where possible other borehole data (flow logging, dilution tests or electrical conductivity/temperature logging) should be used to verify that the conduits/solutional fissures are flowing.

Water quality indicators of rapid groundwater flow

As for springs:

- *More than one indicator of rapid flow present at the spring = High vulnerability, Score 3*
- *One indicator of rapid flow present at the spring = moderate vulnerability, Score 2*
- *No indicators of rapid flow present at the spring, but monitoring conducted = Low vulnerability, Score 1.*

Coliforms

As for springs:

- *Maximum coliform counts > 1000 cfu/100 mls = high vulnerability, score 3*
- *Maximum coliform counts 10 to 1000 cfu/100 mls, = moderate vulnerability, score 2*
- *Maximum coliform counts < 10 cfu/100 mls = low vulnerability, score 1, if sufficient sampling coverage following rainfall events*

Tracer tests indicating rapid groundwater flow

As for springs:

- *Tracer velocity of > 500 m/day;* ***or*** *velocities of 10-500 m/day combined with tracer recoveries > 5 % = high vulnerability, score 3*
- *Tracer velocity of 10 to 500 m/day with no tracer recovery data, or with tracer recovery < 5 % = moderate vulnerability, score 2*
- *Tracer tests with no tracer recovery from all stream sinks in the catchment or from at least 3 different injection points if no stream sinks present = low vulnerability, score =1*

Transmissivity/pumping rate

For abstraction boreholes, there is no comparable parameter to spring discharge. However, borehole abstractions with higher transmissivity (or pumping rate) are likely to be fed by more extensive networks of conduits and fissures and hence have higher vulnerability (Foley and Worthington, 2021; Maurice et al., in review). The vulnerability assessment scores are:

- *T > 5000 m^2/day or pumping rate > 100 l/s; likely to be supplied by extensive connected conduit/fissure system, score 3.*
- *T 100 to 5000 m^2/day, pumping rate 10 to 100 l/s likely to be supplied by connected conduit/fissure system, score 2.*
- *T < 100 m^2/day or pumping rate < 10 l/s; likely to be supplied by poorly connected conduit/fissure system, score 1*

The lower transmissivity threshold value of 100 m^2/day is based on the observation by Price (1987) that the approximate transmissivity of the unmodified network in the Chalk is 20 m^2/day and an assumption that therefore once transmissivity exceeds 100 m^2/day there is likely to be a reasonably extensive well-connected solutional network. The upper threshold of 5000 m^2/day represents transmissivities which are likely to be associated with larger aperture solutional features (Maurice et al., in review); and are at the upper end of transmissivities observed in aquifers (MacDonald and Allen,

2001) and are likely to be associated with the most extensive rapid groundwater flow. However, there is considerable uncertainty about what threshold should be used for this parameter, and it may be more appropriate to consider boreholes with transmissivity of > 1000 m^2/day as high vulnerability. Further work is recommended to investigate the most appropriate transmissivity thresholds for assessing intrinsic vulnerability. Pumping rates are based on the range of pumping rates commonly observed at abstraction boreholes with these sorts of transmissivities (e.g. Maréchal et al., 2008).

4.2.4.2 Application to CHAKA case studies

There are only two borehole case study sites in the CHAKA project: one Chalk site in the UK and one limestone site in Slovenia. Both sites have high scores and high vulnerability (Figure 16). The Slovenian site has fairly limited data with results for only three parameters, which all score 3. The Essendon chalk site has several indicators of karst and high vulnerability including surface karst in the catchment, tracer tests to the abstraction indicating rapid groundwater flow of several km/day over distances of several kilometers, and extensive evidence of rapid groundwater flow indicated by water quality.

Country/Region	**UK**	**Slovenia**
Site name	**Essendon**	**Klarici**
Surface karst	3	3
Caves	1	3
Conduits	2	-
Water quality	3	-
Coliforms	3	-
tracer tests	3	-
T/yield	3	3
Average	2.6	3
Vulnerability	high	high

FIGURE 16: TABLE OF RESULTS OF METHOD 1 FOR THE TWO CHAKA BOREHOLE CASE STUDIES

4.2.4.3 Application to Chalk boreholes

In order to investigate the classification of boreholes further, the system was applied to 19 other borehole sites in the Chalk of Southern England which have been relatively well characterized during work by the British Geological Survey for Affinity Water. The sites cannot be named for confidentiality reasons, but the results for the 20 sites (including Essendon which is site 1) are shown in Figure 17. These show that there is a much wider range of vulnerability than observed in the CHAKA springs. Scores for the Chalk boreholes range from 1.5 to 2.57. Most of these chalk borehole abstractions fall in the medium vulnerability category, but there are some with high vulnerability and one with low vulnerability.

Site	Surface karst	Caves	Conduits	Water quality	Coliforms	Tracer tests	Transmissivity/yield	Average score	Vulnerability
3	3 (hc)	1 (hc)	-	3 (hc)	3 (hc)	-	3 (lc)	2.6	High
1	3 (hc)	1 (lc)	2 (lc)	3 (hc)	3 (hc)	3 (hc)	3 (mc)	2.57	High
2	3 (hc)	1 (hc)	-	3 (hc)	3 (hc)	3 (hc)	2 (lc)	2.5	High
5	3 (hc)	1 (hc)	-	-	3 (hc)	-	3 (lc)	2.5	High
8	3 (hc)	1 (hc)	-	-	3 (hc)	-	3 (lc)	2.5	High
4	3 (hc)	1 (hc)	2 (lc)	3 (hc)	3 (hc)	2 (mc)	3 (lc)	2.43	Medium
9	3 (hc)	1 (hc)	-	3 (hc)	2 (hc)	-	2 (mc)	2.2	Medium
10	3 (hc)	1 (hc)	-	3 (hc)	1 (hc)	-	3 (mc)	2.2	Medium
6	3 (hc)	1 (hc)	-	-	2 (mc)	-	2 (lc)	2	Medium
7	3 (hc)	1 (hc)	-	-	2 (mc)	-	2 (lc)	2	Medium
13	2 (lc)	1 (hc)	2 (lc)	2 (mc)	2 (hc)	-	2 (mc)	1.83	Medium
15	3 (hc)	1 (hc)	2 (lc)	2 (mc)	1 (hc)	-	2 (mc)	1.83	Medium
18	2 (lc)	1 (hc)	2 (lc)	2 (mc)	2 (hc)	-	2 (lc)	1.83	Medium
14	2 (lc)	1 (hc)	-	2 (hc)	2 (hc)	-	2 (mc)	1.8	Medium
19	1 (hc)	1 (hc)	-	3 (lc)	2 (hc)	-	2 (mc)	1.8	Medium
20	2 (lc)	1 (hc)	-	2 (hc)	2 (hc)	-	2 (lc)	1.8	Medium
12	2 (hc)	1 (hc)	2 (lc)	2 (mc)	1 (hc)	-	2 (lc)	1.67	Medium
17	2 (lc)	1 (hc)	2 (lc)	2 (hc)	1 (hc)	-	2 (lc)	1.67	Medium
11	2 (lc)	1 (hc)	-	2 (lc)	1 (hc)	-	2 (lc)	1.6	Medium
16	2 (lc)	1 (hc)	2 (lc)	1 (hc)	1 (hc)	-	2 (mc)	1.5	Low

(hc = high confidence, mc = medium confidence, lc = low confidence, with lc)

FIGURE 17: TABLE OF RESULTS OF METHOD 1 FOR 20 CHALK BOREHOLES IN SOUTHERN ENGLAND

At many sites, it was not difficult to assign a score to the surface karst parameter, and there is high confidence in the assigned score. However, at a number of sites there is low confidence in the scores. At five of the sites (numbers 11,16,17,18 and 20) this is because there are reported to be "possible small stream sinks" in the catchment; but there is insufficient evidence to be certain. These sites are assigned a score of 2 which presumes that there are not stream sinks present. However, if stream sinks are identified through further work at these sites the score may increase to 3. At two sites (13 and 14) there are dissolution pipes present but no dolines or stream sinks. These sites are assigned a score of 2 as dissolution pipes are indicative of solutional processes. However, many may be formed by in situ weathering processes, filled with low permeability material, and without solutional fissures beneath them. If further work on these features demonstrates that they are not associated with increased vulnerability, the score may be reduced to 1.

All the Chalk borehole sites scored 1 for cave development, which is consistent with the limited cave development in the English Chalk. The only site with low confidence is Essendon (site 1). The Water End Swallow Holes which lie within the catchment (and have been traced to the Essendon Abstraction) have been excavated by speleologists to reveal caves of a few metres in length. This was not considered sufficient cave development to justify a score of 2 but it is possible that longer caves may be discovered in future.

At all sites where a score was assigned for "conduits" observed in borehole images there is low confidence in the score. This is because there are no measurements of the size of the solutional features that have been observed in the boreholes, and in many cases the descriptions of the borehole images are vague with the terms "fissure", "conduit" and "cavity" being used interchangeably. The category is retained in the classification as it is a useful indicator of karstic development and the potential for rapid flow to abstraction boreholes, but further work is needed to obtain better information at abstraction sites to determine where larger conduits and fissures are present.

At many sites there is high confidence in the water quality scores. However, at 4 sites (12, 13, 15, 18) there is medium confidence in the scores because of uncertainty about the turbidity that is present. These sites have been assigned a score of 2 which assumes there is only one rapid flow indicator present. The turbidity was not counted as an additional indicator of rapid flow because the levels of turbidity were relatively low, and it is uncertain whether the turbidity is due to transport of sediment due to karst processes. If future studies suggest that there is turbidity due to karstic transport of sediment, then the water quality scores will increase to 3 for these sites. There is low confidence in the score assigned to site 11 as only 6 out of ~750 samples detected coliforms and the count was only 1 cfu/100 mls which might suggest false positives and there are no other indicators of rapid flow present (which would mean the score should be lowered to 1). There is also low confidence in the water quality score for site 19. At this site the turbidity is generally low and as at sites 12, 13, 15 and 18 it is unclear whether higher turbidity is due to karst. However, nitrate is reported to fluctuate in response to rainfall, and therefore this site is assigned a water quality score of 3. However, the relationships between rainfall and nitrate in the Chalk are complex, and it may be that future work suggests that the nitrate responses are not indicative of rapid pollutant transfer in which case the score will reduce to 2.

There is generally high confidence in the scores assigned to the coliform parameter, as there are likely to be sufficient samples to have detected higher counts. At two sites (6 and 7) there is only medium confidence as there have been fewer than 500 samples collected. However, at these sites the sample numbers are still reasonably high (440 and 320 respectively), and likely to have included periods following rainfall, and therefore it is considered unlikely that further sampling would result in an increase in the vulnerability score.

There are no tracer data available for most sites. Site 4 is assigned to the medium vulnerability category based on the tracer velocity of 120 m/day and there is only medium confidence in this score, as there has only been one test conducted and future tests might demonstrate more rapid groundwater flow and result in a score of 3.

There is generally low or medium confidence in the scores assigned for the transmissivity/pumping rate parameter. This is because of the uncertainty regarding the most appropriate thresholds for this category, and also because many of the transmissivities are based on modelled values rather than pumping tests, and the maximum possible pumping rates at the sites has not been considered for this assessment.

4.2.5 Discussion and Conclusion

The Method 1 intrinsic vulnerability results for all the different types of sites are shown in FIGURE 18. This shows that the limestone springs (red triangles) and the single limestone borehole abstraction (orange circle) have the highest vulnerability. The three dolomite springs (brown triangles) have moderate or low vulnerability, whilst the two Chalk springs (green triangles) are very different, with one site with high vulnerability and one site with low vulnerability. The Chalk boreholes (green circles) have very variable scores, ranging from high vulnerability to low vulnerability.

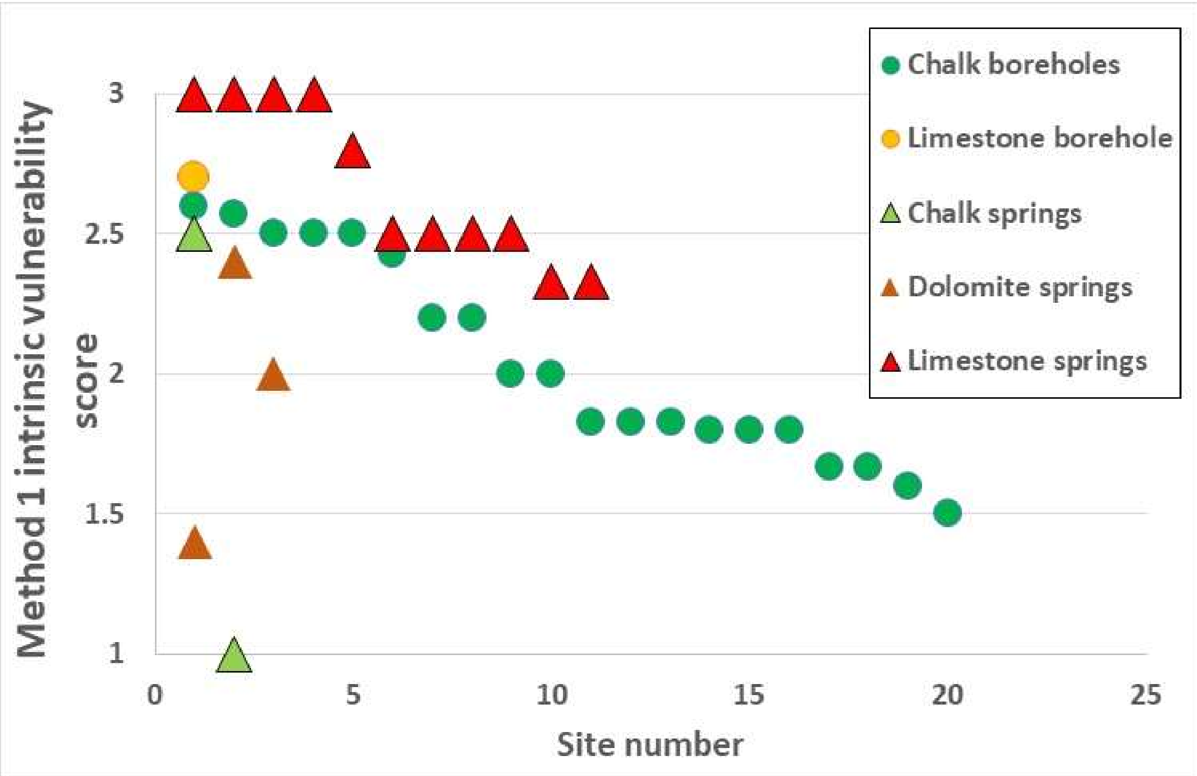


FIGURE 18: RESULTS OF THE METHOD 1 INTRINSIC VULNERABILITY CLASSIFICATION

The method has been designed based on parameters that provide evidence of intrinsic vulnerability. Therefore, because karst aquifers are inherently vulnerable, we would expect high vulnerability scores at most sites. From a water management perspective, it would not be useful to take all karst sites and use a relative assessment of vulnerability to determine cut-off points for classes of high, medium and low vulnerability. Indeed, there is an argument that sites that score more than 2 should perhaps be classified as highly vulnerable as at least one parameter has a high vulnerability score of 3 (in which case there could be a fourth class of extremely vulnerable for those sites that score >2.5 as these would have high vulnerability scores of 3 for most parameters).

The method appears to produce results which are consistent with the conceptual understanding of the karst aquifers in which it has been applied. The limestone springs and borehole abstraction have the highest scores, which is consistent with the generally higher degree of conduit development in limestone aquifers. Dolomite karst generally has less extensive karstic development than limestones and both the dolomite springs have medium vulnerability and scores that are at the lower end of those observed in the limestone springs, which is consistent with this. However, there are only 3 dolomite spring examples, and these were selected because they are known to have a subdued discharge response to rainfall and likely to have lower vulnerability than the limestone case study sites. Further study of dolomite springs is needed to determine the range which occur and is likely to include springs which fall into both the high and low vulnerability classes.

As expected, the results for the Chalk springs and boreholes show generally lower vulnerability than those for the limestone springs. Given the small number of chalk springs (two), the highly variable nature of chalk karst, and the ongoing conceptual uncertainties regarding the nature of karst in the Chalk, it is recommended that further work is done both on the parameters and thresholds used in the classification for chalk springs, and in the assessment of the intrinsic vulnerability of chalk springs.

Considering the application of Method 1 to borehole abstractions, these first results show good promise. The classification produces a good range of vulnerability classifications for the Chalk boreholes which is consistent with the variable nature of chalk karst. However, the results are preliminary, there are limitations in the site data, and a few remaining uncertainties in the most appropriate parameter thresholds (as outlined in the sections above). In addition, all the Chalk borehole sites are in southern England, so further work is also recommended to verify this system for borehole abstractions in other areas. There is only one limestone borehole site in the study, with limited data, and further work is needed to verify that the classification system is appropriate for borehole abstractions in all karst areas. However, overall, the results for Method 1 are consistent with our understanding of the karst aquifers that have been used, and the results are promising as a method for classification of the intrinsic vulnerability of borehole abstractions and other types of karst including chalk and dolomite sites, as well as the limestone springs that form the main part of this study.

4.3 Method 2: Mixed classification using the method 1 plus a discharge time series

4.3.1 Method description

Method 2 aims at classifying karst/chalk aquifers using 2 axes related to:

- the vulnerability of the spring to pollution, for which the results of method 1 is used,
- the responsiveness of the karst spring, which will be used to characterize either the hydrodynamics of the karst system or the GW resource availability according to the objectives of the classification.

For the application of method 2, it is assumed that a long-term discharge time series is available, whatever the time step of this time series. This time series can thus be used to assess the responsiveness of the karst system. While Method 1 focused on parameters that describe mass transfer to assess the vulnerability to pollution, Method 2 focuses on pressure transfers through the analysis of discharge time series at the outlet of the karst system to describe the response to recharge events and quantify the GW resource availability. This is thus an intermediate method that require more data than method 1 (records of discharge time series at the spring), and enables both vulnerability and water resource availability to be assessed.

This method should be applicable whatever the time step of the discharge time series, which can be larger than one day for inertial karst system.

4.3.2 Selection of statistical parameters to characterize karst springs responsiveness

Various statistical parameters or proxies can be computed from a long-term discharge time series to characterize karst systems and assess the relative importance of groundwater derived from long term storage compared to that derived from fast infiltration. The previous report (Hakoun et al. 2020) describes numerous methods proposed by authors from a very simple approach (ratio of discharge values) to more complex approaches including correlation analysis and Fourier or wavelet transforms of the discharge time series.

The main objective is thus to select the statistical parameter that can be used to quantify the relative importance of baseflow to the total flow, assuming that the higher this is, the more consistent the available water supply will be and the more resilient it will be to variations in precipitation and drought (and hence the better the regulation capacity of the spring). Thus, all methods that can describe the relative importance of baseflow to total flow are potentially useful for the parameterization of Method 2. Based on a previous literature review, the main parameters that could be used to quantify this are:

- The coefficient of variation CV has been used to describe the responsiveness of karst springs (Mangin, 1975; Meinzer, 1923). This coefficient is computed as the ratio of the standard deviation of a time series to its mean value. It expresses the level of dispersion around the mean, whatever the frequencies.
- Spring Variability Coefficient (SVC, Flora, 2004), like the ratio of the minimum to the maximum daily discharge values can also be used to describe the discharge variations.
- The Base Flow Index (BFI) is computed as the ratio, in volume, of the baseflow to the total flow. A lot of baseflow separation methods exist to compute the Base Flow Index (BFI). Recently, Ladson et al. (2013) propose a standard approach using the Lyne and Hollick (1979) digital filter. The approach used a reflection of the time series of 30 days to address "warm up" issues, and 3 passes of the digital filter with a filter coefficient

ranging from 0.9 to 0.98. If this approach seems to address our main issue, it is sensitive to the choice of the filter coefficient, and requires daily data.

- The memory effect (Mangin, 1984) is computed as the time lag that is reached as the autocorrelation function of the discharge time series falls below the value 0,2. It somehow expresses the resilience of the karst system after a rain event and is used to compare the response time between karst systems.
- The regulation time is another parameter proposed by Mangin (1984) to quantify the length of the impulse response of the system, i.e. the duration beyond which the system no longer reacts to the rain event. It is the value of the Power Spectrum for f=0 when the Fourier transform of the autocorrelation function of the discharge time series is used, with a daily time step and a correlation length of 125 days. This means that this parameter actually expresses the relative contribution of "long term" processes to the total variance, where "long term" describe all processes with a period higher than 2*125=250 days.

These parameters require long term discharge time series, 3 hydrological cycles being often recommended, but results can be given when only one year is available. The BFI and the regulation time both require daily time series. The BFI parameter seems to be the only parameter that is bounded, since it ranges from 0 to 1, which is an interesting point for classification purposes. In fact, Mangin recommends using a daily discharge time series and to compute the autocorrelation function for lags lower than 125 days to limit seasonal influence. Thus, the regulation time and the memory effect both range from 0 to 125 days and can be divided by 125 to be expressed in %, ranging from 0 to 100%. As a result the coefficient of variation, SVC and other ratio of discharge values are the only parameters that are not bounded.

An additional statistical parameter has been used in this project based on a moving average filter. Indeed, the previous definition of the regulation time shows that it could be also computed using the variance or the standard deviation of a filtered time series compared to the variance or the standard deviation of a non-filtered time series, using a low-pass filter with a cut-off frequency of 250 days in that case. A 250 days moving-average filter is used in the following to compute the standard deviation of filtered times series. The ratio σ250/σ expresses in % the ratio of the standard deviation of each filtered time series to the one of the raw discharge time series. This ratio ranges from 0 to 1 and is theoretically related to the regulation time by the following relationship (Eq. 1), with *Treg* (days) the regulation time and *σ250/σ* (%) the new parameter based on a moving average filter according to the following equation:

$$Treg = 125 * \left(\frac{\sigma_{250}}{\sigma}\right)^2$$

Thus, like the regulation time, σ250/σ expresses the relative importance of long term processes to the total variance. While T_{reg} has been defined from results of correlative and spectral analysis at a daily time step, the ratio *σ250/σ* can be computed whatever the time step of the time series, assuming that this time step is short enough to capture most of discharge fluctuations. This will be discussed in the following using the Bedhampton Sp. case study.

All these parameters are easily computed using the "Statistics summary" menu of the XLKarst tool.

They will now be computed for a synthetical time series and for the various discharge times series of the CHAKA project in order to select the best parameter to use for the second axis of method 2.

4.3.3 Application to a synthetic dataset

Sinusoidal functions are used to represent synthetic spring hydrographs, and test the ability of various statistical parameters to describe the responsiveness of a karst system.

The use of two sinusoids like those shown on FIGURE 19 allow the computation of the coefficient of variation and the memory effect, as well as other statistical descriptors like the SVC, the minimum, the maximum, the mean, and ratios between them. The two time series shown on FIGURE 19 have been computed using two sinusoids with distinct periods (20 days and 120 days respectively), but with the same random noise (between 0 and 1) and the same long term (T=1200 days) sinusoidal trend[1]. The objective of this theoretical approach is to compare the results from time series characterizing different transfer time, and to discuss the ability of each statistical parameter to describe the responsiveness of a karst system.

From these two theoretical time series, we would expect to get a parameter that will clearly show that the grey (short period) time series characterizes a "spring" with a much higher "responsiveness", which is exemplified by the fast increase and decrease of the discharge in response to rainy events, while the black (long period) times series would characterizes a more inertial "karst" system.

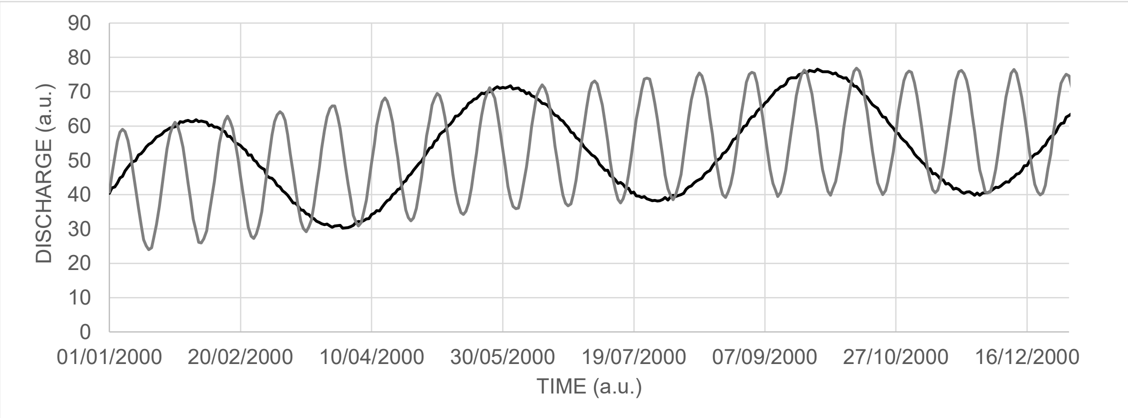


FIGURE 19: 2 EXAMPLES OF SYNTHETIC DISCHARGE TIME SERIES WITH SAME CV, SVC, MAX/MIN OR OTHERS RATIOS OF CENTILES, BUT 2 DISTINCT PERIODS (A.U. = ARBITRATRY UNIT)

The various statistical parameters and descriptors computed with the XLKarst tool from these two time series are all the same and fail to distinguish the two time series, except the memory effect.

Parameters dealing with data filtering (BFI, σ250/α and the regulation time) use techniques that theoretically allow to distinguish various component according to their frequencies, but a ratio is used to express the results, so that the two sinusoids cannot be finally distinguished. This

[1] Additional noise and long term trends are needed to be able to compute the variance spectra, and thus to compute the regulation time

result shows that the memory effect is the only parameter that should be used to describe the responsiveness of a karst spring.

4.3.4 Application to the CHAKA dataset

4.3.4.1 Dataset description and results

16 discharge time series have been provided by the various partners of the project. All these time series are daily, except the one from the BH case study which is weekly.

The results from the statistical analyses using the XLKarst tool are given in the Figure **20**.

Name	Killeglan	Nagy-Tohonya	Vrelo Bune	Byčí skála (Bull Rock)	Grota Ursului	Waldbach-ursprung	St Quinti and Cardener	Fontaine de Nîmes	St Brigida	La Fájara	Ivanscica springs	Tonkovic (Gacka riv)	Pecina (Gacka riv)	Bed-Hampton	Ironselle	Pfannbauern-quelle
Short-name	Kil	NT	VB	By	Ur	Wa	Ca	FN	Br	Fa	Iv	To	Pec	BH	Ir	Pf
Data	3165	10958	2191	3652	365	1420	2729	6309	2133	866	735	7305	7305	2884	1030	1342
From	01/01/2010	01/01/1964	01/01/2010	01/01/2009	01/10/1997	07/11/2012	13/06/2003	25/12/2000	22/06/1994	19/05/2015	01/03/2019	01/01/1997	01/01/1997	02/01/1961	04/01/2017	01/01/2014
To	31/08/2018	31/12/1993	31/12/2015	31/12/2018	30/09/1998	26/09/2016	01/12/2010	03/04/2018	23/04/2000	30/09/2017	04/03/2021	31/12/2016	31/12/2016	04/04/2016	30/10/2019	03/09/2017
Mean	1,02	0,11	24,26	0,29	0,06	3,00	0,30	0,55	0,01	0,12	0,05	3,66	1,55	1,11	0,14	0,29
Median	0,93	0,06	16,05	0,17	0,04	1,94	0,20	0,09	0,01	0,05	0,05	3,28	0,97	1,06	0,13	0,29
σ	0,58	0,13	23,95	0,39	0,06	3,28	0,28	1,32	0,01	0,16	0,00	1,62	1,58	0,26	0,05	0,02
Min	0,22	0,02	3,44	0,05	0,01	0,08	0,06	0,00	0,00	0,01	0,04	0,74	0,00	0,61	0,07	0,23
Max	4,50	1,14	133,90	7,65	0,64	14,24	2,54	16,50	0,06	2,24	0,06	13,70	10,60	1,96	0,34	0,34
Min/Max	0,05	0,01	0,03	0,01	0,02	0,01	0,02	0,00	0,00	0,01	0,71	0,05	0,00	0,31	0,21	0,69
SVC Q10/Q90	4,13	8,66	12,31	7,58	4,80	55,94	6,10	190,94	494,47	20,31	1,21	2,95	27,11	1,83	2,95	1,24
Q25/Q50	0,63	0,62	0,51	0,66	0,74	0,13	0,74	0,52	0,39	0,40	1,05	0,77	0,39	0,84	0,81	0,95
CV	0,57	1,24	0,99	1,37	1,11	1,09	0,93	2,41	0,86	1,38	0,07	0,44	1,02	0,24	0,37	0,08
ME (d)	73	85	57	32	14	66	47	13	125	35	76	82	53	98	73	87
RT (d)	77,86	51,42	46,96	29,85	5,02	56,10	47,12	20,06	116,44	32,57	78,32	59,80	47,42	*	66,54	82,16
σ250/σ (%)	0,75	0,63	0,60	0,50	0,16	0,63	0,58	0,38	0,95	0,47	0,78	0,68	0,60	0,85	0,71	0,78
BFI	0,86	0,69	0,66	0,65	0,59	0,62	0,75	0,38	0,92	0,65	0,97	0,86	0,64	*	0,90	0,98
RT (d) σ250/σ	71	49	46	31	3	50	43	18	113	27	76	57	45	90	64	76
Method 1	2,50	3,00	3,00	2,50	2,30	3,00	2,30	3,00	1,00	2,50	1,40	2,50	2,80	2,50	2,40	2,00
KGWRAI	0,54	0,42	0,62	0,31	0,15	0,57	0,37	0,21	0,19	0,27	0,33	0,65	0,48	0,63	0,41	0,51
Relat ME (%)	0,58	0,68	0,46	0,26	0,11	0,53	0,38	0,10	1,00	0,28	0,61	0,66	0,42	0,78	0,58	0,70

FIGURE 20: RESULTS OF THE STATISTICAL ANALYSIS FROM THE XLKARST TOOL USING THE 16 DISCHARGE TIME SERIES OF THE CHAKA PROJECT. * REQUIRES DAILY DATA. ME: MEMORY EFFECT. RT: REGULATION TIME. KGWRAI: KARST GW RESOURCE AVAILABILITY INDEX.

The use of a theoretical time series show that the memory effect is the only parameter that should be used to describe the responsiveness of a karst spring. Consequently, the application to real case studies from the CHAKA project allows to compute various statistical parameters that will be compared to the value of the memory effect, the latter being used as a reference.

FIGURE 21A, B and C show the relationships between CV, BFI and the regulation time with the memory effect.

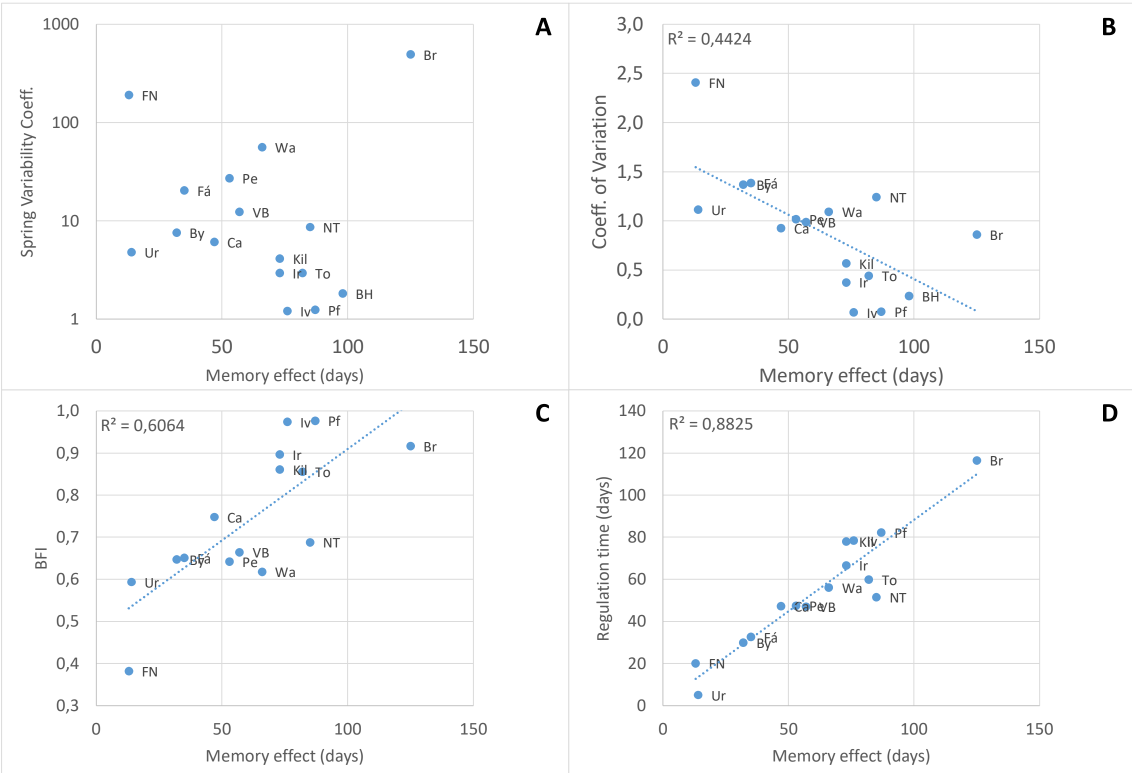


FIGURE 21: CORRELATION BETWEEN SOME STATISTICAL PARAMETERS GIVEN IN TABLE 2

4.3.4.2 Interpretation

FIGURE 21A does not show any clear relationship between the Spring flow Variability Coefficient (SVC) and the memory effect. This means that the SVC cannot be used alone if one is concerned by the characterization of the responsiveness of a karst spring. However, the SVC is able to capture long term variations that are not highlighted by the memory effect: For instance, The St Brigida Sp. (Br, NL) shows a high SVC, because the discharge can be very low for a long time as a response of low recharge during several years, while its memory effect is very high (>125 days). In that case, the SVC can bring another important information that is not covered by the memory effect. This low flow period is also a consequence of a very low mean discharge combining with a high memory effect, which means that several droughts will induce to dry up the karst system for a long time due to the resilience of the system. It is thus important to add another information to the memory effect, either the mean discharge or the SVC, the latter being used in Method 3.

FIGURE 21B shows a poor correlation between CV and the memory effect is poor (coeff. of determination R^2=0.4). For instance, CV given by the discharge time series of St Brigida Sp. (Br, CV=0.86) is close to the one from the Cardener Sp. (Ca, CV=0.93), while they give distinct memory effects (47 days and 125 days respectively, 125 days, the latter being underestimated for a maximum correlation length of 125 days). The corresponding time series are shown on FIGURE 22, where it is clear that the responsiveness of the Cardener Sp. is higher than the one of the St Brigida Sp. Thus, although its common use in karst hydrology, the CV can lead to misleading interpretations when most of the discharge variations are due to long term fluctuations (annual or higher period).

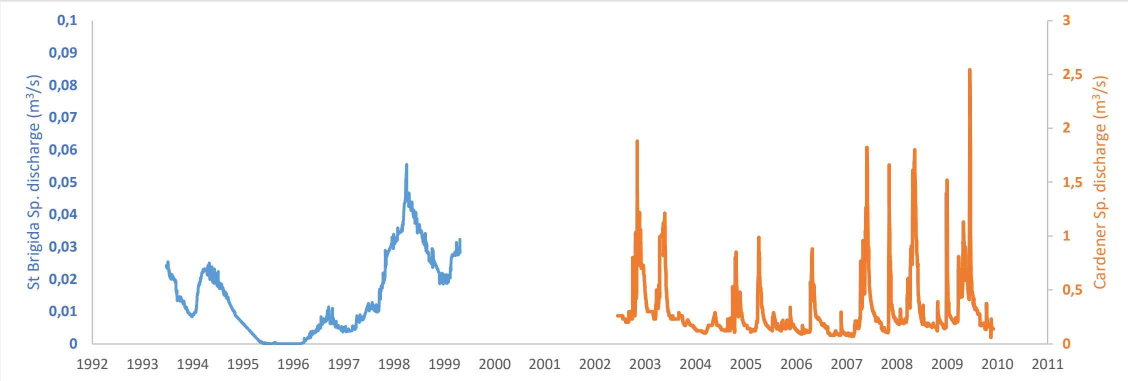


FIGURE 22: DISCHARGE TIME SERIES AT ST BRIGIDA SP. (BLUE LINE) AND CARDENER SP. (ORANGE LINE)

FIGURE 21C show that the BFI computed with a coefficient of 0.91 show a more significant and positive correlation with the memory effect (R^2=0.6), which means that the memory effect computed for various discharge time series also give some information on the relative importance of baseflow: The more the memory effect is and the more important is the relative contribution of baseflow to the spring discharge.

An example of baseflow separation method using the Lyne and Hollyck (1979) method is given in FIGURE 23. The use of such a baseflow separation method designed for surface stream is however questionable when applied to karst spring hydrograph separation. Karst groundwater flows can be conceptualized by quickflows through the larger karst conduits that drain smaller voids also called the matrix (Atkinson, 1977; Kovacs and Perrochet, 2014). The term matrix is used in this context for the fractures and fissures which supply the larger conduits, as in most carbonate aquifers there is little contribution from the bedrock matrix which generally has exceptionally low permeability. It is generally thought that it is groundwater flow from the fractures and smaller fissures which comprise the baseflow that sustains the spring flow. During recharge events, these matrix/conduit exchanges may reverse, and the baseflow should be considered negative (Kiraly, 2003; Bailly-Comte et al., 2010). Applied to karst spring discharge, it is thus assumed that the baseflow separation proposed by Lyne and Holllick (1979) gives the positive part of the karst spring baseflow, which may greatly overestimate the flow from matrix to conduits at the beginning of the flood event.

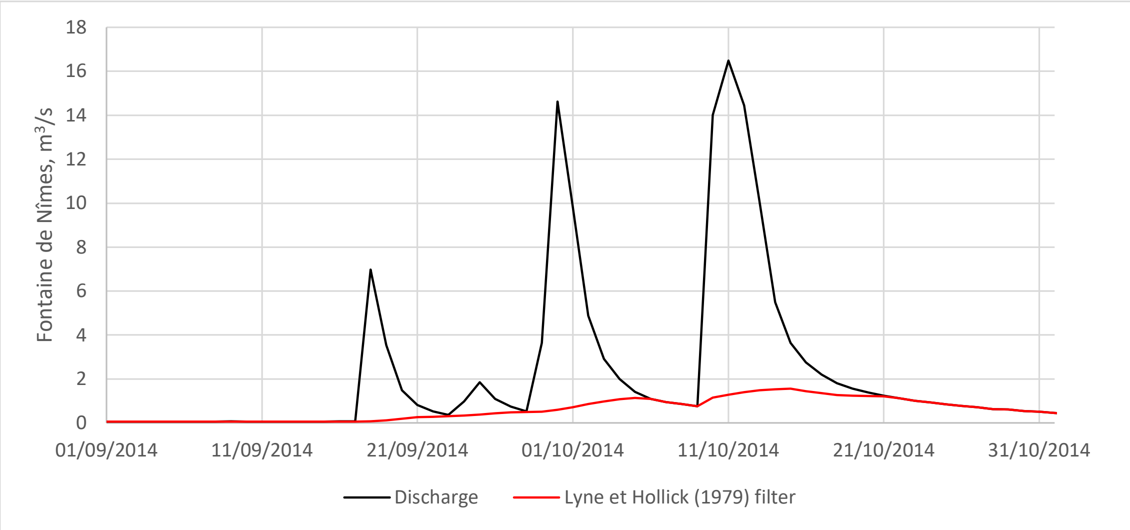


FIGURE 23: EXAMPLE OF BASEFLOW SEPARATION USING THE LYNE AND HOLLICK METHOD (1979) APPLIED TO THE FONTAINE DE NÎMES (FR) DISHARGE TIME SERIES

The BFI of the St Brigida Sp., for which the discharge time series is shown on FIGURE 22 is close to 1 (0.92), which means that most of the spring discharge should be considered as baseflow. This high BFI is interpreted as a consequence of the lithology (chalk). Other karst springs with relatively high BFI are the Tonkovic Sp. (To, HZ), Killeglan (Kil, IR) case study and the two karst systems developed in dolomitic limestones (Ivanscica, Iv, HZ and Ironselle, Ir, FR). High BFI for the Irish case study is probably a consequence of the indirect recharge through porous glaciofluvial deposits that cover the karstified limestones, while karst voids filled with porous dolomitic sands can explain the larger BFI found in dolomitic aquifers.

However, as shown by FIGURE 21D, the best correlation with the memory effect is given by the regulation time (R^2=0.88), which means that these two parameters can be used and interpreted in the same way. In addition, FIGURE 24 shows a very good fit (R^2=0.99) between the regulation time computed with spectral analysis of daily time series (Mangin, 1984) and the regulation time computed with Eq. 1 using a moving average filter. The relationship between the two regulation times is good for systems ranging from very low to very high regulation time (Grota Ursului, RO, and St Brigida Sp., NL, with regulation time of 5 and 116 days respectively). This means that the ratio σ250/σ can also be used be used to characterize the responsiveness of a karst spring when continuous data are not available at a daily time step.

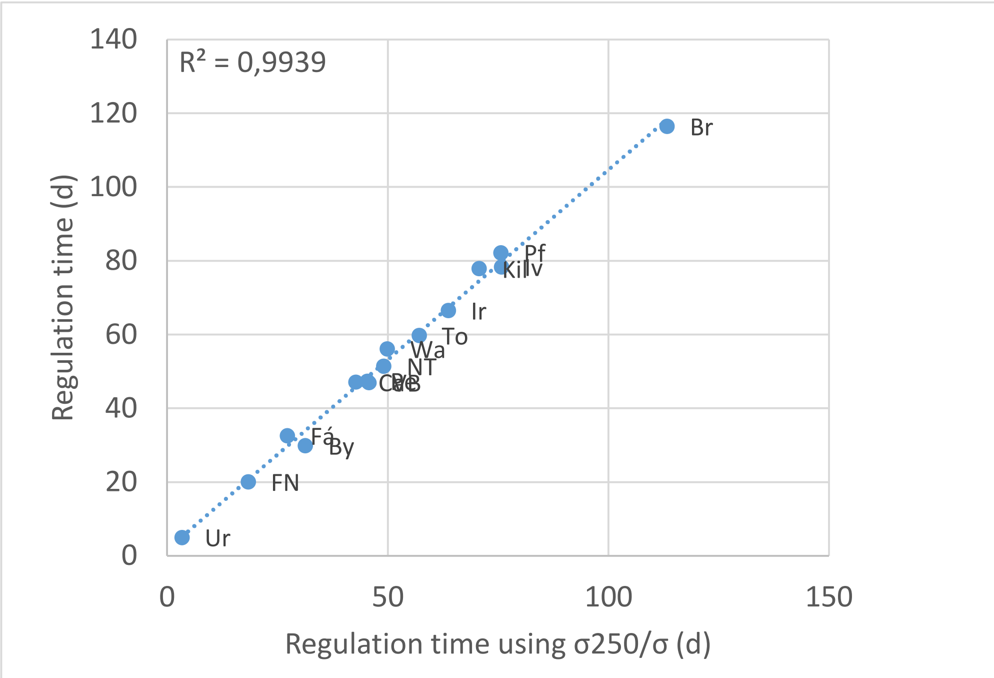


FIGURE 24: RELATIONSHIP BETWEEN THE REGULATION TIMES COMPUTED FROM SPECTRAL ANALYSIS AND THE ONE USING σ_{250}/σ (EQ.1)

4.3.4.3 Time step

It is often recommended to work with daily discharge time series, but in some cases exemplified by the Bedhampton Spring (BH, UK) case study, discharge is only available at a lower sampling rate. In that case, before computing statistical parameters, it is important to check if the sampling rate allows to characterize the responsiveness of the karst spring. This can be done using spectral analysis of the discharge time series. Power Spectral Densities (PSD) of discharge times series show how the variance of the discharge time series is distributed according to frequencies, ranging from 0 (long term trend) to 1/2Δt, with Δt the sampling rate of the discharge time series. The analysis of the slope of the spectrum is used to find the frequency beyond which the variance spectrum becomes flat (zero slope). In that case, the higher frequencies components can be described as a Gaussian noise, and the discharge time series is over-sampled. If the slope of the spectrum is always decreasing according to frequencies, then the spectrum is a function of the frequency. In that case, the discharge time series is probably under-sampled, and the results of the statistical treatments must be taken with caution.

For instance, FIGURE 25 shows two PSD computed with two discharge time series of the CHAKA project:

- The PSD of the FdN discharge time series (FIGURE 25A) show how the variance of the discharge time series is distributed according to frequencies, ranging from 0 (long term trends) to 0.5 cycles per day (cpd) for this daily time series. The spectrum becomes flat only for the highest frequencies, which means that the daily sampling rate may be too large for this system, hourly data should be used instead.
- The PSD of the BHS discharge time series (FIGURE 25A), which is a weekly time series is clearly different and shows a flat spectrum for frequencies higher than 0.06. This means that the discharge variations can be compared to a Gaussian white noise for frequencies

higher than 0.06, or a period lower than 16 days. Thus, the weekly time series is able to capture the flow dynamics of this spring.

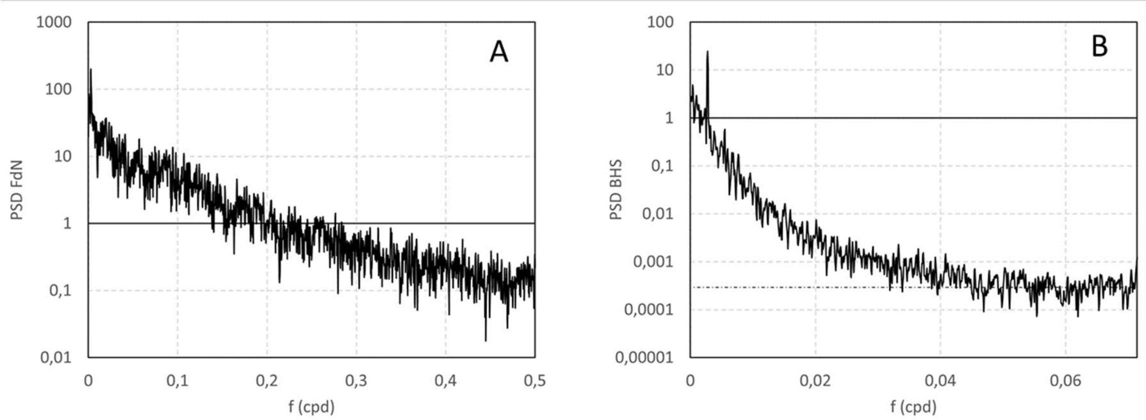


FIGURE 25: POWER SPECTRAL DENSITIES COMPUTED WITH DAILY (A, FDN CASE STUDY, FR) AND WEEKLY (B, BHS CASE STUDY, UK) DISCHARGE TIME SERIES

These two examples show that the time step of a discharge time series should be chosen taking into account the responsiveness of the karst spring. Spectral analysis can be used to check the consistency of this time step, which also means that methods used for the characterization of karst spring responsiveness should not be specific to a given time step.

4.3.4.4 Choice of a statistical parameter

Results given by the discharge time series from the CHAKA project allows to select 2 parameters for the characterization of the karst spring responsiveness: the memory effect and the ratio σ250/σ. The BFI also gives interesting result when applied to karst spring hydrograph, but it requires a daily time series. Mangin (1984) introduced the memory effect in 1984, which means that there are a lot of case studies in scientific papers or engineering reports that provide memory effect for karst springs through the world. This parameter can be computed whatever the time step of the time series, and its value can be normalized with the value of 125 days that is used for short term correlation analysis of karst spring to avoid the influence of seasonal cycles.

It is thus proposed to use the memory effect for the characterization of the responsiveness of a karst spring.

4.3.5 *Results of classification method 2*

4.3.5.1 *First classification based on memory effect*

On FIGURE 26, the X axis represent the relative memory effect, which is the value of the memory effect expressed in days and divided by 125.

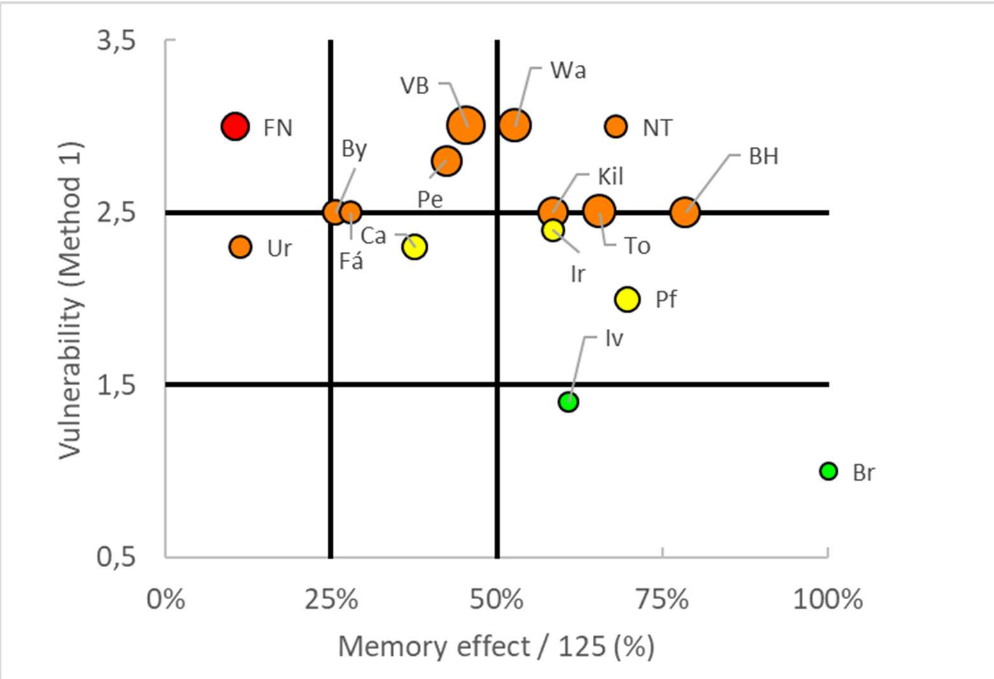


FIGURE 26: RESULTS OF THE FIRST CLASSIFICATION

This value of 125 days is high for karst spring with high regulation capacity, while a low value characterizes karst systems with low storage.

The value given by the method 1 (Y axis) are grouped in 3 classes (<1.5, >=1.5 and <2.5, >=2.5), which are shown by the two thick horizontal lines. In the same way, the values of the relative memory effect are grouped in 3 classes (<25%, >=25% and <50%, >=50%) to provide, at the end, 9 classes of results that can be used for recommendations for GW managements. These thresholds have been chosen to clearly distinguish the two karst systems that show a very high responsiveness (FN and Ur) with memory effect lower than 1 month (30 days divided by 125 gives 0.24 ~ 25%), and to classify karst systems with memory effect higher than 2 months as low responsiveness.

These 9 classes are grouped according to the following rules (FIGURE 27):

- Green points: Low vulnerability and high memory effect (>50%)
- Red points: High vulnerability and low memory effect (<25%)
- Orange points: Other cases with low memory effect or high vulnerability
- Yellow points: All the other cases

Responsiveness / Vulnerability	High (ME <25%)	Medium (ME>25% and <50%)	Low (ME>50%)
High			
Medium			
Low			

FIGURE 27 : GROUPINGS IN 4 CLASSES ACCORDING TO THE VALUES OBTAINED FOR THE Y-AXIS RELATED TO THE VULNERABILITY (METHOD 1) AND THE X-AXIS RELATED TO THE KARST RESPONSIVENESS.

The diameter of the circles is a function of the mean discharge (log scale) to better consider the availability of the GW resource, from 0.01 m^3/s to 25 m^3/s.

This is important information, without which can lead to misleading interpretation of FIGURE 26: The best result of this type of classification should be the case of low vulnerability / high relative memory effect (green points). This case is exemplified by the St Brigida karst system (NL) or the Ivanscica Sp. (HZ), which both deliver a very small groundwater flow (mean discharge: 0.014 m^3/s and 0.052 m^3/s respectively).

4.3.5.2 Second classification accounting for mean spring discharge

A second classification has thus been proposed to better account for the karst groundwater resource availability. It is assumed that the groundwater availability increases with both the mean discharge and the memory effect. As a result, a classification using discharge time series only is proposed in FIGURE 28 where the Y axis represent the mean discharge. In this framework, crossing the information given by the mean discharge and the memory effect is used to assess a karst groundwater resource availability index: This is done by subdivided the Y axis representing the mean discharge in 4 classes in a log scale from 0.01 m^3/s to 100 m^3/s. The log scale is used since it is of primary importance to distinguish karst systems that show various mean discharge in the range 0.01 to 1 m^3/s.

This new scale allows to compute an index linearly varying from 0 (0.01 m3/s) to 1 (100 m3/s), following a log scale and computed as follow, with Q the mean discharge in m^3/s : $Y=(2+\log(Q))/4$. For instance, a mean discharge of 1 m^3/s will give an index of $[2+\log(1)]/4=50\%$.

The product of this index with the value of the memory effect (divided by 125) is shown on FIGURE 28 with the different hyperbolas. Each hyperbola refers to the square roots of this product which ranges between 0 and 1. The result is used as a proxy for the assessment of the karst groundwater availability resource, which is called the Karst GW resource availability index (KGWRAI, see also the numerical values in FIGURE 20).

FIGURE 31 shows the results with varying color referring to the vulnerability classification from method 1, and varying size of square that refers to the ratio between the linearized mean discharge and the relative memory effect. Thus, along the same hyperbola, a larger square will refer to a karst system that has a higher mean discharge relative to its memory effect. In other words, the size of the square represents the relative importance of the mean discharge to quantify the karst GW resource availability index as compared to the memory effect.

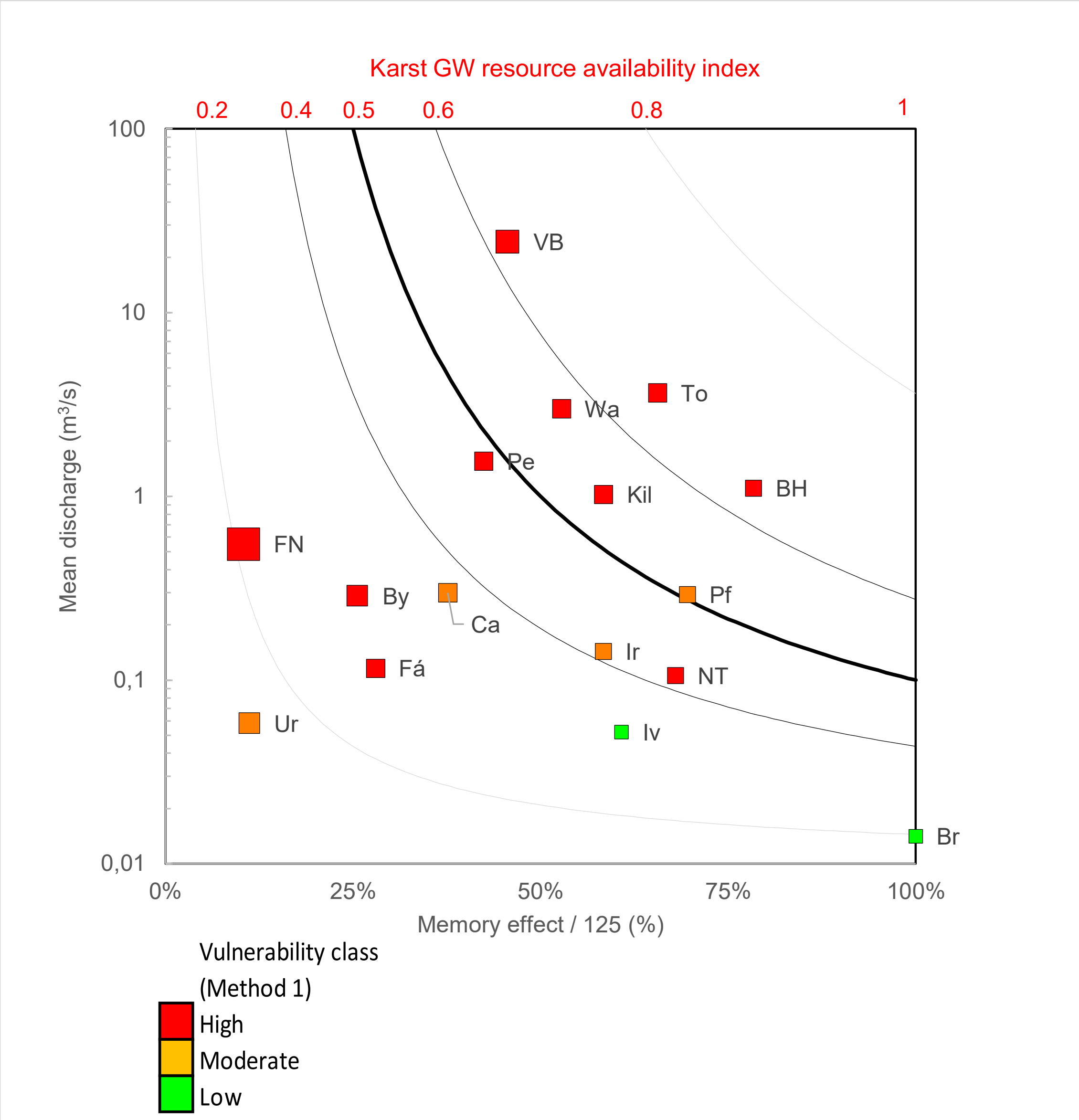


Figure 28: Classification of karst systems showing the computation of the karst GW resource availability index

This index is then used for a new classification combining the vulnerability assessment from the method 1 with the karst GW resource availability index (Figure 29), using the same color and sizes rules than the ones used for the first classification (Figure 26).

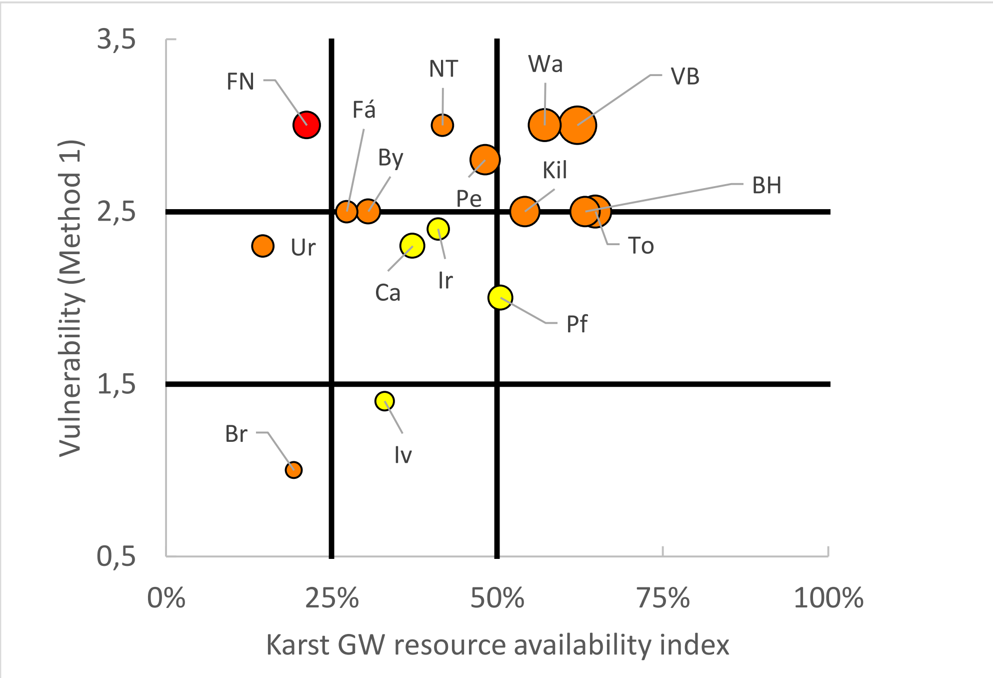


Figure 29: Classification of karst systems showing the computation of the karst GW resource availability index

This classification shows for instance that the Fontaine de Nîmes karst sp. is characterized by a high vulnerability with a low karst GW resource availability, which gives poor characteristics for water supply management. There is no karst system that shows low vulnerability with high karst GW resource, the best compromise between these two factors is exemplified by the Pfannbauernquelle case study (Pf, AU), which shows a high KGWRAI but a moderate vulnerability. The good results shown by the Figure 26 for the St Brigida Sp. are not validated by this second classification, reflecting its low discharge and thus its small size and the resulting poor GW resource.

As a result, this new classification shown by the Figure 29 is the classification proposed for the Method 2, combining the results of the Method 1 dedicated to vulnerability assessment with an easy to implement automatic procedure of discharge time series analysis, which leads to results without any user influence.

KGWRAI / Vulnerability	Low (KGWRAI <25%)	Medium (25%<KGWRAI <50%)	High (KGWRAI >50%)
High			
Medium			
Low			

Figure 30 : Groupings in 4 classes according to the values obtained for the Y-axis related to the vulnerability (Method 1) and the X-axis related to the karst GroundWater Resource Availability Index.

4.4 Method 3 (V-RC classification): quantitative classification based on monitoring data - discharge and other time series

4.4.1 Method description

4.4.1.1 Introduction

V-RC classification is aimed principally at aquifer and environmental management as a basis for effective drinking water source protection measures, flood and draught management, preliminary hydropower and water source potential estimations, etc. The classification separates two source characteristics that are most important for management: 1.) **regulation capacity** (RC, addressing spring discharge dynamics) and 2.) intrinsic **vulnerability** to pollution (V). Average discharge (Q_{av}) is also considered as an additional parameter, which serves as a basis for system size classification. RC in combination with Q_{av} effectively describes available water reserves, especially during draught periods when water shortages are typically present in many karst areas (e.g. Dinaric karst, Mediterranean karst).

The classification is based only on quantitative water source monitoring data. The required data is typically available for majority of springs already used for water supply or other purposes. The method is primarily developed for springs, but it can be also applied to borehole data to quantify V only.

The main characteristics of the V-RC classification method are:

- RC estimation is based on discharge monitoring solely, while V estimation is based on available monitoring data of various (optional) physio-chemical parameters. In this way, RC and V estimations are mutually separated. Pumped wells can be classified for V only, and springs with only discharge data available for RC only.
- Input data (time series) can have various measuring frequencies and time-span: from occasional or monthly measurements to high frequency long-term continuous (i.e. hourly) measurements. However, resulting reliability level is specified, based on available input data.
- All incorporated methods are relatively simple to apply in order to be easily applicable in different countries, on various datasets (automated excel classification sheet and XLKarst tool for discharge analysis).
- Classification results are shown on two axis diagram: Y axis represents vulnerability, X axis regulation capacity, symbol size is related to system size and symbol color represents estimation reliability level. In that way proposed representation diagram provide complete information on the classified source and the basis (available data) on which the classification was made.

FIGURE 31 shows the representation diagram of the V-RC classification results. Results (circles) are separated in three categories in respect to vulnerability V and regulation capacity RC (9 possible combinations in total). Circles are placed based on their V-RC estimation scores (in decimal number) which allows distinction of different positions within the same category. Additionally, the size of the circles represents system sizes based on their average discharge (5 categories, figure 31), while the color of the circles represents reliability level of the final V score (red=low, yellow=medium, green=high). Wells (classified for V only) and springs lacking data for V estimation (classified for RC only) are not represented on the diagram.

Representation of the V-RC results

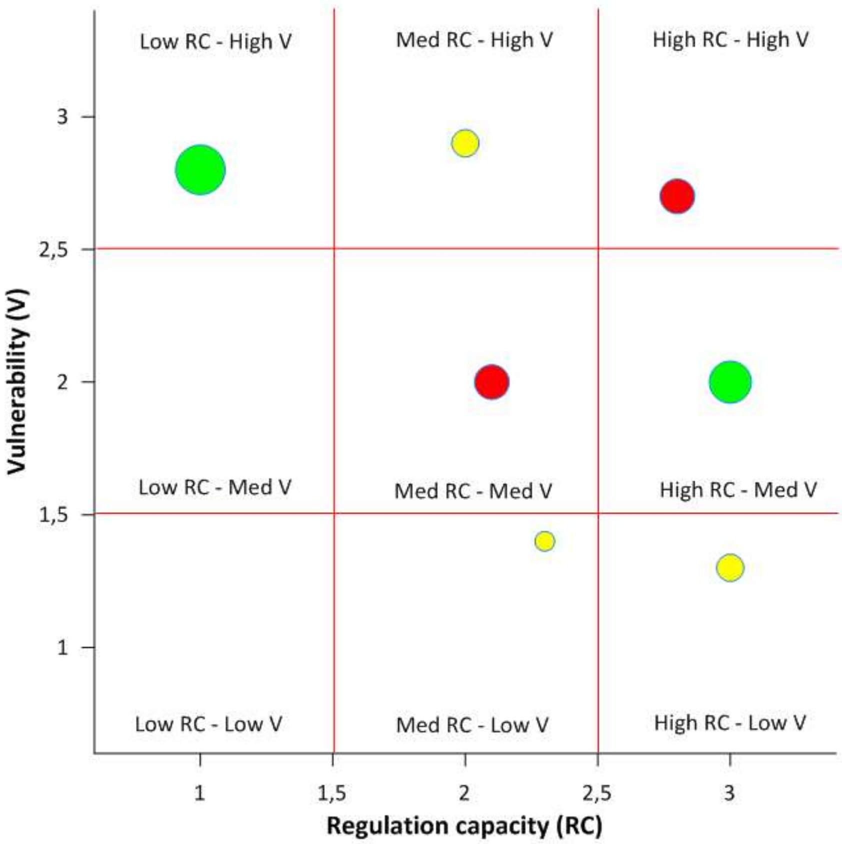


FIGURE 31: REPRESENTATION DIAGRAM OF THE V-RC CLASSIFICATION RESULTS.

4.4.1.2 Parameters and methods

REGULATION CAPACITY ASSESSMENT (RC)

Spring discharge

Spring discharge is the only parameter considered in a source RC estimation. Low RC of a spring is usually associated with its high intrinsic vulnerability (V) and historically spring discharge dynamic has often been used for estimation of karstification degree, which implies intrinsic vulnerability degree (Drogue, 1972; Mangin, 1975; Malik 2006). However, we believe that high RC is not always accompanied by low V, which is confirmed by some of the results of the included pilots in V-RC classification application (described in more detail in *Application to case studies: results* section). Therefore, we exclude spring discharge from V estimation, resulting in independence of V and RC estimation results.

Additionally, average spring discharge value is used for a categorization of a spring size (FIGURE 33). In that way a spring RC score supplemented by its size category provides complete information on expected water flow during various hydrological conditions (basis for estimation of flood risk and water reserves during draughts).

As tested and explained in section 3.3 of this report, no single statistical parameter can reliably characterize all important features of the discharge dynamics. *The memory effect* (ME) is identified as a most appropriate parameter for the characterization of the system inertia, i.e. the responsiveness of a karst spring (Section 4.3). However, the ME do not provide information on the amplitude of observed discharges occurring at large time scale (seasonal or multi-years), which is well described by the *spring variability coefficient* (SVC). Also, both methods are relatively simple for application and their results are unaffected by experts performing analysis. Therefore, we choose these two methods to be included in RC estimation, and the final RC score is calculated as a mean value of their results. In that way RC represents aggregate indicator of spring dynamics regarding both flow variability and system inertia. ME is mostly applicable for continuous (daily) time series data only (explained in more detail in Section 4.3.4), while SVC is applicable for both non-continuous (e.g. monthly) and continuous data. If continuous (daily) data is not available, SVC still can be used for preliminary RC estimation of the spring, but with low reliability level of the result.

Here are the more detailed descriptions of the methods:

Spring variability coefficient (SVC)

Netopil (1971) firstly proposed SVC for classification of springs. SVC is based on comparison of a ranked frequency of discharges measured at a spring:

$SVC=Q_{10}/Q_{90}$

where Q_{10} is the discharge exceeded 10% of the time, and Q90 is discharge exceeded 90% of the time (SVC>1). The method avoids using extreme values (linked to exaggerated variability of results and measurement uncertainties). SVC is a scaled indicator not dependent on absolute discharge values, allowing direct comparison of variable-sized springs.

As SVC can be applied on both continuous and discontinuous (monthly or irregularly distributed) discharge data, in the cases where continuous discharge time series are not available, only SVC is used for preliminary RC estimation (marked by low estimation reliability).

Threshold values for categorizing RC based on SVC are specified in **FIGURE 32**.

The memory effect (ME)

The autocorrelation function (acf) is an univariate time series analyses method described by Box & Jenkins (1976). Mangin (1984) used it for analysis of a karst spring discharge dynamics, and based on it proposed a term called the memory effect (ME). ME is defined as the time lag (in days) at the point where autocorrelation function value firstly falls below the 0.2. It roughly expresses the response duration of the karst system after a rain event, but it is also influenced by frequency and characteristics of recharge events (Jeannin & Sauter, 1998). ME is used as one of the indicators for RC assessments as it well describes responsiveness of the spring (described in detail in Section 3.3). The method can be applied to any time series that has a constant time step. For performing acf analysis XLKarst tool (Section 2.3) can be used. More detailed description of the acf method can be found within CHAKA Deliverable 5.1: Karst typology in Europe: state of the art (Hakoun et al. 2020).

Threshold values for categorizing RC based on memory effect are specified in FIGURE 32.

INTRINSIC VULNERABILITY ASSESSMENT (V)

V assessment is based on a number of physio-chemical indicators for presence of fast transport of water from the surface to a spring. Indicators are chosen according to how common is their monitoring at springs or wells, and to be dominantly indicators of intrinsic vulnerability and less influenced by land usage (anthropogenic influence). All available indicators are used for assessment, and final score is computed as average score of considered parameters, weighted by quality of their input data. However, if scores obtained from different indicators show significant disagreement (contrasting categories), additional attention should be paid to determine the possible causes of this. Oscillations of indicator values in ground water are typically within very narrow limits, so measurement accuracy is of prime importance. Therefore, available monitoring data should be carefully examined by experts before the assessment, and any suspicious measurements should be discarded. Recommendations and methodology for measurements of particular indicators are widely available in literature, so they will not be described here further. Observed presence of anthropogenic pollutants, which are not included in intrinsic vulnerability assessment, can be used to confirm or dispute the final assessment score.

Specific electrical conductivity (SEC)

SEC measurement data are used as one of the optional parameters for V assessment. Electrical conductivity (EC) of spring water is direct indicator of its total mineral load. As water conductivity is influenced by its temperature, measured conductivity values should be compensated for water temperature difference to 25°C. Temperature compensation mostly can be done automatically by measuring devices, and compensated measurements are called specific electrical conductivity (SEC). It is important to take care not to mix compensated and non-compensated measurements during SEC/EC analysis, so it should always be clearly stated if data represent SEC or EC.

Sudden drops in a spring water mineralization mark fast transport of freshly infiltrated water to the spring, which did not have sufficient time to chemically equilibrate within the hydrogeological system (Covington et al., 2012). Significant drops of SEC measurements during hydrograph flood events indicate high vulnerability of the system in respect to transport pollutants from the surface to the spring. On the other hand, much slower (yearly period) SEC oscillations in spring water can be present due to soil/epikarst organic carbon oscillations (Jeannin et al., 2017). This slow oscillation does not indicate fast transport of water through the system, and therefore variations connected to the single flood events generally present more reliable indicator than variability of the complete data series. One of two methods is used for V assessment, depending of available data frequency:

- *Determination of maximum observed SEC drop within 1-day period* is preferred method which is used if continuous (at least daily frequency) data are available;
- *Difference between minimum observed and modal SEC value* (determined on histogram of all measured data with 10 µS/cm bin width) is used only in the case of more rare and/or irregular measurement frequency.

As spring water chemograph typically show low amplitude yearly SEC oscillation, interrupted occasionally by short and more pronounced oscillations during hydrograph flood events, difference between minimum and most common value represents relative importance of fresh water share observed on a spring. However, this method is less reliable than direct determination of drop-magnitudes on continuously measured data, which is therefore preferred method.

As already stated, special care is required to detect and exclude all suspicious (potentially erroneous) measurements that can be caused by inadequate measuring procedures, or inadequate measuring location, or faulty devices.

Threshold values for categorizing V based on SEC data are specified in **FIGURE 32**.

Temperature

Temperature measurements are included as an indicator of fast transport through the system, similarly as SEC. Covington et al. (2012) examined in detail typical length scales required for freshly infiltrated water to equilibrate its temperature within the karst underground. Temperature is a highly reactive environmental tracer (Birk et al. 2006, Stroj et al. 2020), so even very small amplitude of oscillation during flood events signifies fast water transport from the surface to the spring. Therefore, high resolution temperature measurements are obligatory for spring V assessment. Also, measurement location should be immediately at the point of groundwater emergence, as temperature can sometimes change significantly within a few meters downstream (especially in combination of low spring flow and large temperature difference between air and spring water). Similarly, as a SEC, yearly oscillation period is frequently present in spring water temperature, which is not direct indicator of very fast transport of water from the surface.

Methods used for V assessment based on temperature monitoring data are almost the same as methods for SEC data:

- *Determination of maximum observed temperature difference within 1-day period* is preferred method used if continuous (at least daily frequency) data are available;
- *Difference between extreme and modal SEC value* (determined on histogram of all measured data with 0.1°C bin width) is used only in the case of more rare measurement frequency.

Similarly to SEC, both methods require special care for excluding all potentially erroneous measurements that can be caused by inadequate measuring procedures, or inadequate measuring location, or faulty devices. Threshold values for the V score based on temperature measurements are given in the **FIGURE 32**.

Total organic carbon (TOC)

Unlike nitrates, which are generally stable in karst groundwater, TOC is a short-lived tracer which marks very fast transport of water from soil to a spring (Emblanch et al., 1998; Mudarra et Andreo, 2010). Also, TOC is always present in soil regardless of land use. Consequently, TOC measurements are also included as an optional parameter for V assessment. As continuous (hourly or daily) TOC values aren't typically available, simply maximum observed TOC value in spring water (mg/l) is used for assessment. However, special expert care is required for excluding all suspicious measurements as extreme values can often be related to errors in measurement or sampling procedures. Threshold values of TOC for the V score calculation are given in the FIGURE 32.

Turbidity

Turbidity increases can be a tracer of fast water transport to springs, and are usually connected with increased bacteriological load (Mahler et al., 2000). In addition, this parameter is frequently continuously monitored and available on springs and boreholes used for water supply. Therefore, maximum observed turbidity (NTU) in a spring water is also used as an optional parameter for V assessment. Threshold values of turbidity for the V score calculation are given in the FIGURE 32.

Total coliforms

Coliforms in the spring water can also be viewed as an indicator of fast transport from the soil zone to the spring. Moreover, coliforms are present both in pristine and agricultural soils. As coliforms are usually monitored on water supply springs and boreholes, total coliform measurement data (cfu/100 ml) also can be used as one of optional parameters for V estimation. Threshold values for maximum observed total coliforms are given in FIGURE 32.

Isotope ^{18}O (‰)

Hydrogen and Oxygen stable isotope content in spring water (and precipitations) are more and more frequently measured as a standard part of karst system estimations. The smaller the amplitude of variation in spring water relative to precipitation variations, mean residence time of water within the hydrological system is longer (Maloszewski et al., 1983; McGuire et al. 2006). Therefore, ratio of variation amplitudes of ^{18}O content (‰) in spring water and local precipitations can also be used as one of the parameters used for V estimation. Threshold values of this ratio for calculating V score are given in FIGURE 32.

THRESHOLD VALUES

The threshold values for RC-V categorization, based on analysis of particular indicators, are specified in Figure 29. Values were determined initially by examination of large amount of karst spring monitoring data (some monitored on pilot sites included in the project, expanded by data available from other sites and previous monitoring projects, as well as data from comprehensive literature review), also considering prescribed standards for drinking water in EU countries, and finally based on expert knowledge and experience. Initial threshold values were further calibrated according to existing knowledge on included pilot sites (in order to minimize discrepancy between expected and calculated results), based on comparison of results obtained from different indicators, and to enable separation and identification of sources with different RC and V characteristics.

It should be emphasized that karst systems are generally characterized by high intrinsic vulnerability and low regulation capacity. However, RC-V classification is calibrated to be able to separate particular karst (and chalk) systems according to these two properties, although all of them can be characterized as high vulnerable/low regulated if we compare them to some other types of hydrogeological systems.

FIGURE 32: TABLE OF PARAMETERS, CORRESPONDING METHODS AND THEIR THRESHOLD VALUES FOR DETERMINATION OF RC AND V SCORE.

Parameter	Method	Low (1)	Med (2)	High (3)	
Discharge Q (m^3/s)	SVC (Q_{10}/Q_{90})	>10	3-10	<3	**RC**
	Memory effect (days)	<40	40-80	>80	
	Exp. rec. coef. (α, 1/day)	>0.01	0.005-0.01	<0.005	
	Q_{max}/Q_b	>6	3-6	<3	
SEC (µS/cm)	Min. to mod diff. (10 µS hist.)**	<20	20-50	>50	**V**
	Max. drop in 1 day**	<10	10-30	>30	
Temp. (°C)	Extreme to mod diff. (0.1 °C hist.)**	<0.5	0.5-1.5	>1.5	
	Max. diff. in 1 day**	<0.15	0.15-0.5	>0.5	
TOC (mg/l)	Max. observed value	<0.4	0.4-0.8	>0.8	
Turbidity (NTU)	Max. observed value	<4	4-10	>10	
Colif. (cfu/100 ml)	Max. observed value	<5	5-100	>100	
Isotope ^{18}O (‰)	Amplitude (spring)/amplitude (prec.)	<0.01	0.05-0.1	>0.1	

Final V & RC value = average based on all considered parameters, weighted by respective reliability levels (reliability levels are determined by available input data, Fig. 35).

*average result of both methods is used,

**only one method is used based on available data.

FIGURE 33: SPRING SIZE CATEGORIES

$Q_{average}$	Categories
<0.01 m^3/s	v. small (1)
0.01-0.1 m^3/s	small (2)
0.1-0.5 m^3/s	medium (3)
0.5-1 m^3/s	large (4)
>1 m^3/s	v. large (5)

4.4.1.3 Classification procedure and computation of final scores

As already mentioned, final score for RC estimation is calculated as a mean value of scores based on both proposed methods. Final reliability level of RC score depends on the quantity of the input data. Corresponding reliability levels to available input data are specified in FIGURE 34.

Final V score is calculated as a mean of individual V scores of all available parameters, additionally weighted by their individual reliability levels (based on available data, FIGURE 34). Reliability level of final V score is based on sum of reliability levels of all applied parameters (threshold values are specified in FIGURE 32).
Complete process of computation of V and RC scores and their reliability levels can be done with automated excel sheet developed for performing the V-RC classification procedure (Fig. 32). Excel sheet is organized in a way that results of all applied methods and corresponding data reliability levels are filled in matching cells (yellow marked), while results are computed automatically.

FIGURE 34: RELIABILITY LEVELS CORRESPONDING TO AVAILABLE DATA FOR RC AND V ASSESSMENTS

<table>
<tr><th colspan="2">Discharge (Q)</th><th>Final RC rel.</th></tr>
<tr><td colspan="2">Irreg. or monthly 10-60; Weekly 1-3 y.; Daily 0.5-1 y.</td><td>Low (1)</td></tr>
<tr><td colspan="2">Daily 1-3y.; Weekly >3 y.; Monthly >5 y.;</td><td>Med (2)</td></tr>
<tr><td colspan="2">Daily >3 y.</td><td>High (3)</td></tr>
<tr><th>SEC; Temp.</th><th>V rel.</th><th>Final V rel.</th></tr>
<tr><td>Irreg. or monthly >10 in >12 months per.</td><td rowspan="2">Low (1)</td><td rowspan="9"></td></tr>
<tr><td>Daily 3-6 months; weekely 6-12 months</td></tr>
<tr><td>Daily 6-12 months; weekely ≥12 months</td><td>Med (2)</td></tr>
<tr><td>Daily ≥13 months</td><td>High (3)</td></tr>
<tr><th>TOC; Turb.; Colif.; ^{18}O</th><th></th></tr>
<tr><td>Irreg. or monthly >10 in >12 months per.</td><td>Low (1)</td></tr>
<tr><td>Monthly >36 months; weekly 12-24 months</td><td>Med (2)</td></tr>
<tr><td>Daily >12 months; weekly >24 months</td><td>High (3)</td></tr>
<tr><td rowspan="3">Summed V rel. (all available parameters)</td><td><4</td><td>Low (1)</td></tr>
<tr><td>4-7</td><td>Med (2)</td></tr>
<tr><td>≥7</td><td>High (3)</td></tr>
</table>

FIGURE 35: AUTOMATED EXCEL SHEET FOR V-RC SCORE CALCULATION. ONLY FIELDS MARKED WITH YELLOW CAN BE FILLED ACCORDING TO AVAILABLE DATA AND RESULTS OF THE APPLIED METHODS. FINAL SCORES ARE CALCULATED AUTOMATICALLY. EXAMPLE OF THE FILLED TABLE FOR PEĆINA SPRING OF THE GACKA RIVER IN THE DINARIC KARST OF CROATIA.

<table>
<tr><th colspan="10">Gacka - Pecina Croatia</th></tr>
<tr><th>PARAMETER</th><th>METHOD</th><th colspan="2"></th><th>RESULT</th><th>RC</th><th>V</th><th>RC reliability</th><th>V reliability</th><th>V weighting</th></tr>
<tr><td rowspan="6">Discharge (Q, m3/s)</td><td rowspan="2">SVC (Q10/Q90)</td><td>Q10</td><td>Q90</td><td rowspan="2">28.52</td><td rowspan="2">1</td><td rowspan="6"></td><td rowspan="6">3</td><td rowspan="6"></td><td rowspan="6"></td></tr>
<tr><td>3.85</td><td>0.135</td></tr>
<tr><td>Acf to 0.2 (days)</td><td colspan="2">Daily data</td><td>53</td><td>2</td></tr>
<tr><td></td><td colspan="2"></td><td></td><td></td></tr>
<tr><td rowspan="2"></td><td></td><td></td><td rowspan="2"></td><td rowspan="2"></td></tr>
<tr><td></td><td></td></tr>
<tr><td rowspan="2">SEC (µS/cm)</td><td>Min. to mod diff. (10 µS hist.)</td><td colspan="2">Irreg/monthly data</td><td></td><td rowspan="2"></td><td></td><td rowspan="2"></td><td rowspan="2">3</td><td rowspan="2">9</td></tr>
<tr><td>Max. drop in 1 day</td><td colspan="2">Daily/hourly data</td><td>33</td><td>3</td></tr>
<tr><td rowspan="2">T (°C)</td><td>Extreme to mod diff. (0.1 °C hist.)</td><td colspan="2">Irreg/monthly data</td><td></td><td rowspan="2"></td><td></td><td rowspan="2"></td><td rowspan="2">3</td><td rowspan="2">9</td></tr>
<tr><td>Max. diff. in 1 day</td><td colspan="2">Daily/hourly data</td><td>0.92</td><td>3</td></tr>
<tr><td>TOC (mg/l)</td><td>Max. value (mg/l)</td><td colspan="2"></td><td>0.88</td><td></td><td>3</td><td></td><td>1</td><td>3</td></tr>
<tr><td>Turb. (NTU)</td><td>Max. value (mg/l)</td><td colspan="2"></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Coliforms (cfu/100 ml)</td><td>Max. value (mg/l)</td><td colspan="2"></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td rowspan="2">Isotope ^{18}O (‰)</td><td rowspan="2">Max. diff. spring/prec.</td><td>dSpring (‰)</td><td>dPrec. (‰)</td><td rowspan="2">0.12</td><td rowspan="2"></td><td rowspan="2">3</td><td rowspan="2"></td><td rowspan="2">1</td><td rowspan="2">3</td></tr>
<tr><td>1.1</td><td>9</td></tr>
<tr><td colspan="5">Final Values:</td><td>1.5</td><td>3.0</td><td>3.0</td><td>3.0</td><td>3.0</td></tr>
<tr><td>$Q_{average}$ (m3/s)</td><td>1.55</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

4.4.2 *Application to case studies: results*

V-RC classification (Method 3) was applied on all CHAKA pilot sites, distributed in karst areas across the Europe (described in detail within Deliverable 5.2 of RESOURCE Project, CHAKA WP: Detailed conceptual hydrogeological models for pilot areas and case studies). Sufficient data was available for computing both V and RC scores for 16 out of 18 included spring sites. Remaining two spring sites has only discharge data available, so only their RC score was determined. There are also two sites with boreholes included in pilot sites, for which only V score was determined. Results of V-RC estimation with specified reliability levels and system (spring) sizes of all included pilot sites are specified in FIGURE 36. For easier comparison of the V-RC results, they are shown graphically on FIGURE 37. FIGURE 38 shows results for all sites with both V and RC estimations (16 sites) on proposed V-RC graphical representation scheme. Distribution of pilot sites based on the spring size (i.e. average discharge) is presented on FIGURE 39, and distribution of pilot RC and V estimation reliabilities (based on available input data) is shown on FIGURE 40.

FIGURE 36: RESULTS OF V-RC CLASSIFICATION (METHOD 3) FOR ALL CHAKA PILOT SITES (SPRINGS MARKED WITH BLUE, WELLS WITH YELLOW; RC AND V SCORE <1.5 IS LOW, 1.5-2.4 MEDIUM AND ≥2.5 HIGH; SPRING SIZES VARY FROM 1 = VERY SMALL TO 5 = VERY LARGE).

Site	Short name	RC	V	RC rel	V rel	Size
1	**Ton Cro**	3.0	1.1	3	3	5
2	**Pec Cro**	1.5	2.9	3	3	4
3	**BHS UK**	3.0	3.0	3	3	4
4	**Wald Au**	1.5	2.4	3	3	4
5	**Kill Ir**	2.0	3.0	3	3	4
6	**FdN Fr**	1.0	2.8	3	3	4
7	**LF Esp**	1.5	2.8	2	2	3
8	**BB Ro**	1.5	2.0	1	2	3
9	**Card Cat**	2.0	2.7	3	2	3
10	**StQ Cat**	2.0	2.7	1	1	3
11	**StB Neth**	2.0	1.5	3	1	2
12	**GU Ro**	1.5	2.4	1	2	2
13	**NT Hu**	2.5	2.0	3	1	2
14	**Iva Cro**	3.0	1.0	2	1	2
15	**Iron Fr**	2.5	1.6	3	3	3
16	**Pfann Au**	3.0	1.0	3	2	3
17	**VB BiH**	1.5		2	0	5
18	**BS Cz**	1.5		3	0	3
19	**Ess UK**		3.0	0	3	2
20	**B4 Slo**		2.0	0	2	2
21	**B9 Slo**		2.5	0	2	2

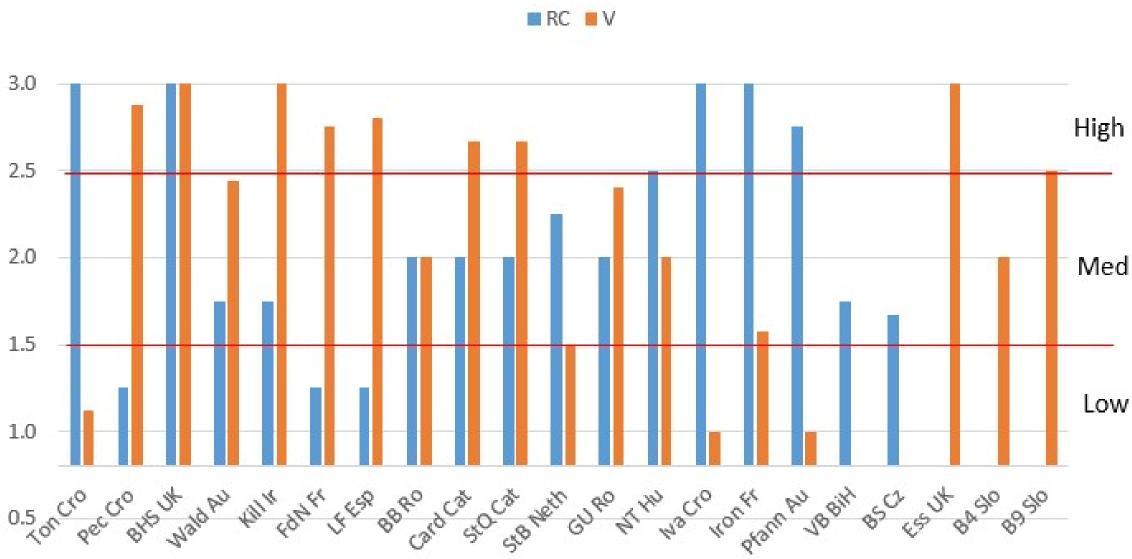


FIGURE 37: GRAPHICAL COMPARISON OF V AND RC FINAL SCORES FOR ALL CHAKA PILOT SITES.

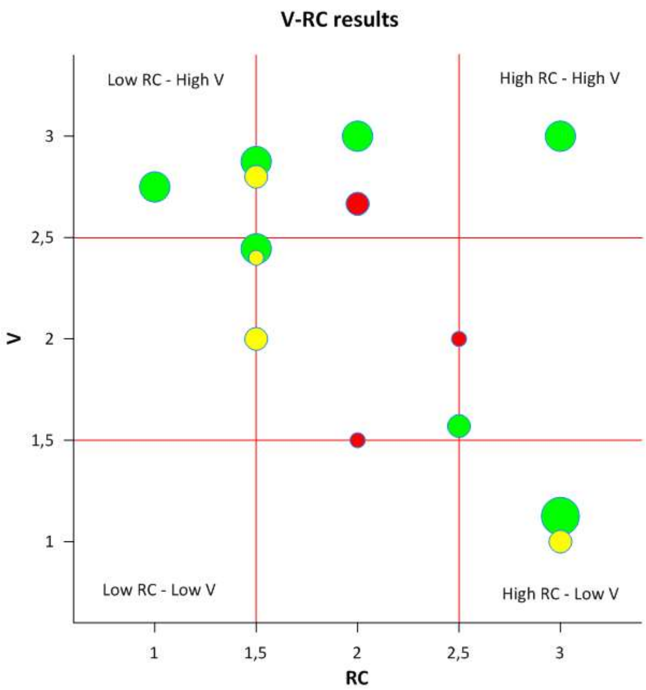


FIGURE 38: ALL CHAKA PILOT SITES (WHERE BOTH V AND RC ESTIMATION WAS POSSIBLE) ON PROPOSED V-RC REPRESENTATION DIAGRAM (CIRCLE POSITION ACCORDING TO FINAL V AND RC SCORES, CIRCLE COLOR BASED ON ESTIMATED V RELIABILITY AND CIRCLE RADIUS ON SPRING SIZE; SOME CIRCLES ARE OVERLAPPING DUE TO SIMILAR V-RC SCORES).

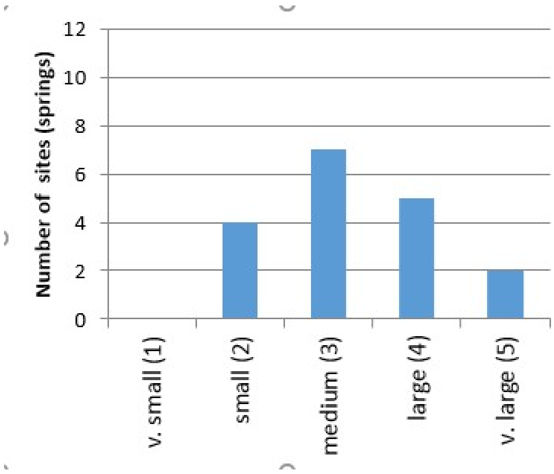


FIGURE 39: DISTRIBUTION OF CHAKA PILOT SITES (SPRINGS) BY THEIR SIZES (I.E. AVERAGE DISCHARGES)

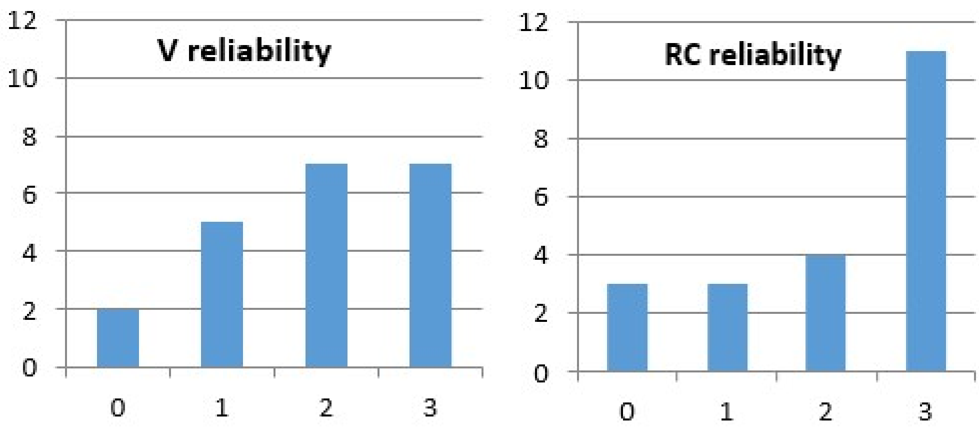


FIGURE 40: DISTRIBUTION OF CHAKA PILOT SITES BY RELIABILITY LEVELS OF THEIR FINAL V AND RC SCORES.

As can be seen in FIGURE 38 (V-RC diagram), the circles representing individual springs are generally clustered around a line which connects low RC/high V – medium RC/medium V – high RC/low V areas. However, some springs show significant deviations from that line towards the high RC/high V area, while no cases deviate towards low RC/low V. Large spring situated in chalk area of England (BHS UK) shows the most pronounced deviation due to multiple indicators of very fast transport from surface to the spring despite highly regulated discharge dynamics. Causes for such characteristics can be connected to high storage within the Chalk aquifer and significant soil cover on the surface, which can both buffer hydrological response of the spring. On the other hand the existance of well connected conduit systems with concentrated input points on the surface enable fast transport of a part of the infiltrated water, which can carry pollutatnts to the spring. There are also a few other examples with high V accompanied by medium RC, and with medium V and high RC (all deviating from the general trend). It can be concluded that although most typical karst springs are characterized by inverse RC-V relationship, there are also considerable deviations possible, which indicate the benefit of separation of V and RC estimations.

Regarding catchment lithology it can be also noticed that springs which drain dominantly dolomitic aquifers generally has high RC and medium to low V (Iron Fr, Pfann Au, Iva Cro), while springs with catchment composed of well karstified compact limestones medium to low RC and high V. However, deviations from this relation are also present (related to climate, soil cover, etc..), as the largest spring whithin high RC/low V category (Ton Cro) drain area dominantly composed of compact limestones. However, detailed explanation of various factors and processes influencing a spring V and RC characteristics is outside the scope of this classification. V-RC classification is rather focused on observed spring characteristics important for its efficient management, regardles of underlying hydro(geo)logical causes and processes.

4.5 Comparison of classification results

The three classification methods use different information to assess two main characteristics of karst springs and boreholes:

- Intrinsic Vulnerability: For methods 1 and 2 the same system (method 1) is used for assessing the intrinsic vulnerability. For these methods, the intrinsic vulnerability is assessed using a combination of the karstic characteristics of the catchment (surface karst and the extent of cave development) coupled with parameters measured at springs and boreholes which are indicative of vulnerability: rapid flow demonstrated by tracer tests, water quality indicators of rapid flow, maximum coliform counts, and timing of discharge response to precipitation. In method 3 intrinsic vulnerability is assessed from monitoring data of physio-chemical parameters: Temperature variability, SEC (maximum drop in one day or minimum to modal difference), TOC (maximum), Oxygen isotopes (ratios between site and precipitation), turbidity (maximum), coliforms (maximum). In both methods the average of the available parameters are used to produce an overall vulnerability score.
- Storage capacity/Regulation capacity: This is not considered in Method 1. Method 2 selected a single parameter – the memory effect. This was considered to best represent the storage of the system based on analysis of multiple time series analysis methods. This was combined with the mean discharge to provide a water resource availability index. Method 3 averages two criteria (the memory effect and SVC) from time series analysis.

In this section, we compare the results obtained using the three methods.

4.5.1 Vulnerability (M1-M2/M3) comparison

FIGURE 41 compares the vulnerability levels estimated using methods 1 and 3 for the case studies. First, we observe a lack of medium to low vulnerability case studies in order to explore the full range of possibilities. This is because most case study sites are from classically karstic aquifers which are inherently extremely vulnerable. Second, vulnerability scores are slightly different for some sites using the two different methods. For example To and IR have much higher scores with Method 1 than Method 3, and NT and Wa have slightly higher vulnerability with Method 1 than Method 3. In contrast BH, Kil and Br have slightly lower vulnerability with method 1 compared to Method 3. However, the general patterns in vulnerability appear fairly similar with both methods.

Method 1 and 3 in this report deal with karst aquifer vulnerability, and Method 2 incorporates the vulnerability output from Method 1. Method 1 uses the catchment characteristics and water quality indicators of rapid groundwater flow and the implications this has for ease with which potential pollutants may enter the aquifer and method 3 measures vulnerability using evidence of rapid flow from water quality parameters at the outlet of the karst system including time series data where available. Both methods have strengths and weakness for assessing the overall vulnerability of the system. For, and conversely. As discussed in Section 4.5.1

The differences may reflect the different data available at different sites and particularly the different data used in the two methods. For example Method 3 uses SEC, Temperature, Isotopes and TOC which are not used in method 1. Method 1 considers surface karst, the extent of cave development, and tracer tests, which are not considered in Method 3. Most of the case studies are in karst aquifers which have extensive surface karst and caves and so this brings the score up in Method 1, especially where other data are not available. For example the Tonkovic spring (To) has a higher vulnerability score with Method 1 compared to Method 3 (FIGURE 41). This is because at this spring there are stream sinks present in the catchment and the spring has a rapid response to rainfall, which together with medium scores for water quality and coliform counts results in a high intrinsic vulnerability using Method 1 compared to Method 3. Similarly, Ironselle spring (Ir) has extensive cave development in the catchment and rapid flow indicated by tracer tests, as well as moderate surface karst, moderate water quality indicators of rapid flow, and a discharge response to rainfall which results in a higher vulnerability score using Method 1 than Method 3. In contrast sites like BH, Kil and Br where surface karst and/or cave development is more limited, the Method 1 vulnerability score is lower than using Method 3. Surface karst, and the extent of cave development are included in Method 1 because it is useful to make the distinction for aquifers such as the Chalk which do not have much cave development and often lack surface karst and hence have lower intrinsic vulnerability. Tracer tests also provide an important additional line of evidence for vulnerability in these types of karst aquifer. The results for the Chalk boreholes (see Section 4.2.3 and Figure 17) suggest that the wide range in intrinsic vulnerability that occurs in the Chalk is relatively well captured with Method 1.

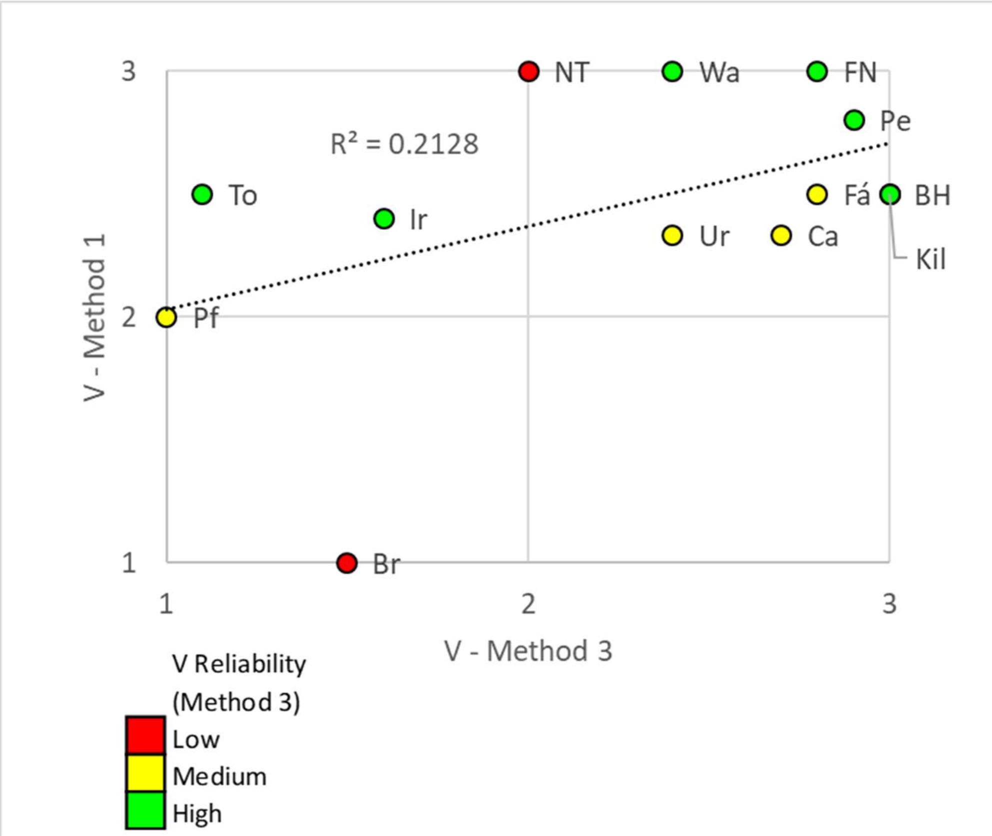


FIGURE 41: COMPARISON OF VULNERABILITY FACTOR ASSESSMENT ACCORDING TO METHOD 3 AND METHOD 1

Method 1 takes a fairly precautionary approach in that low vulnerability scores are only applied with sufficient data clearly indicating low vulnerability and where these are lacking the remaining parameters (often caves and surface karst which require less data) have more weight. Method 1 was also based on bringing together evidence for rapid flow and vulnerability so this may result in higher vulnerability scores. At some sites, Method 1 may indicate high groundwater vulnerability to pollution but the hidden properties within the aquifer itself may enable high levels of dilution and attenuation of pollutants that may mitigate against some of this vulnerability. However, karst aquifers are inherently vulnerable and the case study springs are mostly examples of more classically karstic aquifers which are likely to have high vulnerability, and the results from Method 1 appear to represent the range of karst aquifers tested quite well and produce results that might be expected (see Figure 18 and discussion in Section 4.1.4).

The vulnerability results for Method 3 are generally similar (FIGURE 41), suggesting that this method may also be characterizing intrinsic vulnerability quite well. However, the Chalk borehole sites could not be characterized using Method 3 and therefore the evidence for how well Method 3 works for less vulnerable karst aquifers like the Chalk is not as strong. In addition, Method 3 may suggest that no indicators of vulnerability exist at the outlet due to land use practices, distance and dilution but local vulnerable areas may exist. There are also some uncertainties in the thresholds and interpretation of some of the parameters in Method 3 that could result in some of the differences with the scores obtained with Method 1.

The temperature parameter of Method 3 assumes that a change in temperature is reflecting a component of rapid transfer of groundwater from surface to outlet and that the greater the amount of such transfer, the greater the temperature change, and therefore the higher the vulnerability. Whilst this can be the case, there are complications in the interpretation of this parameter in terms of vulnerability: There could potentially be an underestimation of vulnerability because there are uncertainties in how temperature signals are attenuated by distance travelled, dilution, size of conduit/rock surface area that the water is in contact with etc. On the other hand, the temperature parameter could overestimate vulnerability as there is only a very small difference in the threshold values for low, medium and high vulnerability and therefore factors such as air temperature changes at a spring, or changes in pumping regime at boreholes could result in temperature changes unrelated to direct transfer from the surface. Therefore, significant care must be taken in selecting a suitable measurement location and work should be conducted to demonstrate that the measurement is not influenced by these other factors. Groundwater temperature changes from human activities (ground source heat pumps, discharge of hot water for cooling etc.) could also complicate interpretation, and should be taken into account if present within the catchment. Further work might be useful to establish how best to use temperature as a measure of intrinsic vulnerability and what the best thresholds would be.

The TOC parameter of Method 3 assumes that the higher the TOC the more vulnerable the aquifer is. TOC can be a good indicator of aquifer connectivity with the surface and hence vulnerability, with some caveats. The time variance of TOC mean that a high sample frequency is required to capture the rapid flow component and insufficient sampling could lead to an underestimation of vulnerability. In addition, dilution of the rapid flow component with matrix water might lead to an underestimate of vulnerability. There is also some potential for some organic carbon that is not sourced from the surface which might lead to an overestimate of vulnerability. In the UK Chalk aquifer, TOC values from chalk borehole abstractions in an area with little other evidence of karst varied from 0.4 to 5.6 mg/l, with a mean of 1.6 mg/l from 76 samples (Ander et al., 2004). According to Method 3, these boreholes would all have high intrinsic vulnerability which is perhaps not consistent with our understanding of chalk karst. The Colne and Lee area of Chalk which is known to have many stream sinks and other indicators of karst had TOC ranging from 0.37 to 3.45 mg/l with a mean of 1.56 mg/l from 38 sites (Shand et al., 2003). Whilst these data are general, they do suggest that the thresholds used in Method 3 may be too low, and given the overall similarities between these two different chalk areas it also suggests that further work might be useful to establish the relationship between TOC and intrinsic vulnerability at individual sites with known differences in karstification. TOC clearly has very good potential as an indicator of vulnerability and needs to be tested on large key datasets comprising a range of karst aquifer types.

The oxygen isotope parameter assumes that the ratio between the ^{18}O content (‰) in spring water and local rainfall reflects the mean residence time of the groundwater (Section 4.4). Oxygen isotopes can be useful indicators of a surface water component to groundwater, and hence vulnerability. However, long and frequent measurement time series data are needed to characterize the isotopic composition of precipitation and groundwater. In addition, interpretation of oxygen isotope data can be complex and may be affected by the type of rainfall event, the height of clouds, where the rain fell, wind and weather systems etc. Finally, isotopes represent the average characteristics of the system, and some springs affected by a slower flowing component of water may still have highly vulnerability. Further research might be useful to determine how best this parameter can be used in assessment of intrinsic vulnerability.

SEC is a good parameter for assessing vulnerability where there is a large drop in SEC in a single day indicating a component of rapid transfer of water from the surface. There is some uncertainty in the best threshold values for relating the magnitude of the daily drop in SEC to low, medium and high intrinsic vulnerability, and it would be useful to investigate the relationship between SEC and vulnerability further, especially in karst aquifers with a high matrix/fracture porosity. Where non-continuous data are available, the difference in minimum to modal SEC value is used for the vulnerability assessment in Method 3 and it is not clear how well this method distinguishes between long term fluctuations in SEC which are not indicative of vulnerability and short term fluctuations that are.

There are some limitations in the use of coliforms and turbidity (and the use of other water quality indicators of rapid flow) as indicators of rapid groundwater flow, as discussed in Section 4.2 on Method 1.

For coliforms (used in both Method 1 and Method 3) the main limitation is the impact of the pollutant source term. This impacts the results from both methods and would not result in differences between them. However, there is a difference between the threshold values in the two methods. The greatest difference is in the threshold between the medium and high vulnerability class, which is 100 cfu/100 mls in Method 3 and 1000 cfu/100 mls in Method 1; and therefore means that more sites will be assigned high vulnerability with method 3 than method 1. The thresholds for Method 1 are based on the range of values observed in the chalk from quite a large number of boreholes, which includes some sites with > 10000 cfu/100mls, despite the chalk being generally less vulnerable than more classical karst. The highest coliform counts in the Chalk occurred at sites where there are other strong indicators of karst and rapid flow. High coliform counts of 10,000s cfu/100mls have also been reported in boreholes in a karst aquifer in Southern France (Mahler et la., 2000). The lower thresholds used in Method 3 reflect the low thresholds for coliforms used in drinking water standards. Defining thresholds for coliform counts is difficult because of the impact of the source term on the measured concentrations, but considering drinking water standards might be an approach which could link directly to groundwater protection strategies.

Overall, the two methods used for assessing vulnerability (Methods 1 and 3) show that the CHAKA case study sites have generally high vulnerability as would be expected from the conceptual understanding of the sites (Report Deliverable 5.2). Method 1 was also applied to 20 Chalk borehole sites demonstrating a range of vulnerabilities that appear to capture the inherent variability in sites in this non classical karst aquifer with limited cave development. Method 1 seems to be a useful first assessment of the vulnerability of a karst spring or borehole, that can also be applied in karst aquifers which have lower degrees of karstification, with some caveats. Factors such as surface karst features and the extent of cave development provide a quick method of assessing vulnerability using information that is generally readily available. Groundwater velocities from tracer tests provide unambiguous evidence of a component of rapid flow and hence high vulnerability at a site. However, the use of physico-chemical measurements from the spring or borehole (used in both Method 1 and Method 3) are more complex. The work in the CHAKA project has identified a range of parameters in methods 1 and 3 that can all be used to indicate high vulnerability. The presence of coliforms, short residence time compounds, turbidity due to rainfall, and TOC are all indicative of a rapid flow component and hence high vulnerability, although the concentrations present may be impacted by the source term. Drops in SEC, temperature variations and Oxygen Isotopes can all also be indicative of a rapid flow component, although the interpretation is more complex. With all these physico-chemical parameters there is an averaging effect with dilution between the rapid flow component and the longer residence time groundwater. Results from the Chalk aquifer which has high storage resulting in considerable dilution of the rapid flow component show that even when the proportion of rapid flow is relatively small, sites can be highly vulnerable to pollutants that happen to intersect those rapid flowpaths. The results of the CHAKA project show that these physico-chemical parameters are all useful for identifying high vulnerability, but some additional testing and analysis of these parameters using large key datasets from a range of karst aquifers would be useful to determine the necessary data requirements and the best threshold values to determine boundaries between high, medium and low vulnerability thresholds.

4.5.2 KGWRAI (M2) / Regulation capacity (M3) comparison

The relative memory effect expressed in % should theoretically address the same characteristic than the RC. **FIGURE 42** shows a comparison of the results given by the two methods. The correlation is relatively poor, even if a positive trend can be identified. This can partly be explained by the use of thresholds in the RC assessment. Two points stand out clearly in this relationship: The Grota Ursului (Ur, RO) has a medium RC while its memory effect is very low, and inversely for the St Brigida Sp. Going back to **FIGURE 21**A and B, one can see that these two points show inconsistent values of CV or SVC with the memory effect, while the relationships with the BFI or the Regulation time is consistent. Thus, the RC assessment using both the SVC and the memory effect ends up for these two cases study with a mean value that is different from the one given by the memory effect alone. Removing these two points rises the correlation to R^2=0.7.

As pointed out when describing the method 2, the Saint-Brigida Sp. should not be considered as a well regulated karst system since it can be sensitive to droughts at a multi-year scale. For the reason, adding the SVC parameter helps to reduce the RC in method 3, but it can also be noticed that the use of the mean discharge of this small karst system in the computation of the KWRAI (**FIGURE 28**) allows to classify this system as a system with low GW availability.

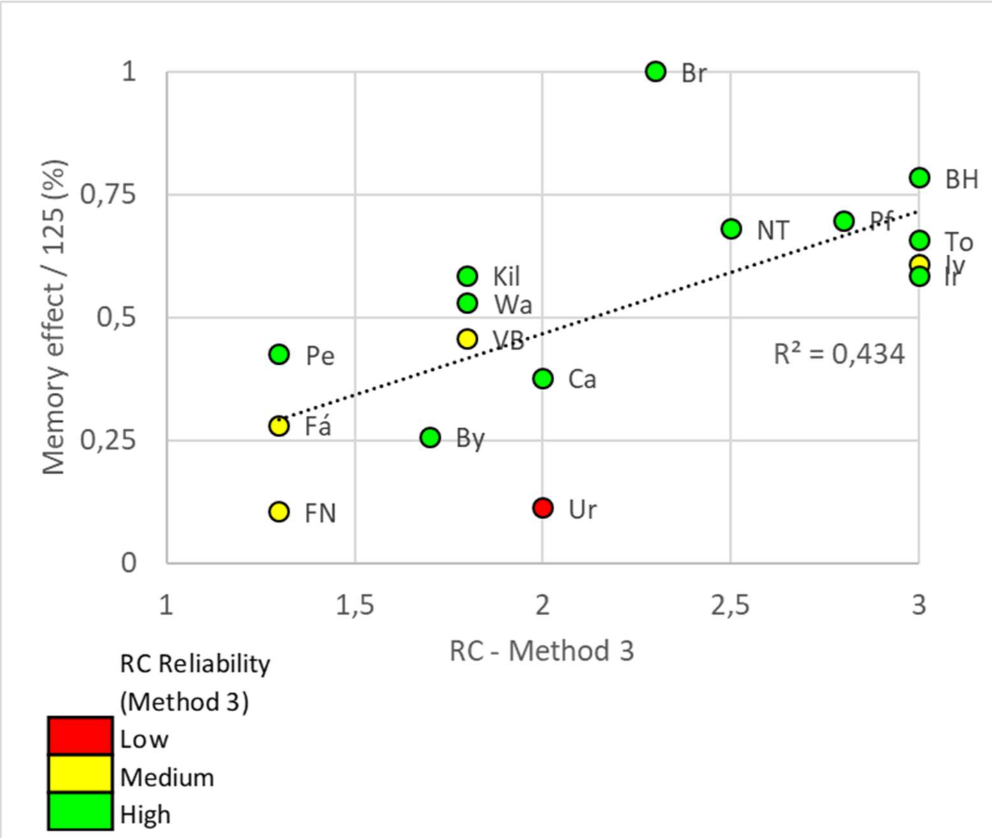


FIGURE 42: COMPARISON BETWEEN REGULATION CAPACITY FACTOR (METHOD 3) AND MEMORY EFFECT (METHOD 2)

The comparison between the KGWRAI and the regulation capacity is illustrated at FIGURE 43. The correlation is positive, with higher values of the KGWRAI for case studies with a higher mean discharge (larger circles). This is explained by the fact that the KGWRAI contains information on the mean discharge of the system.

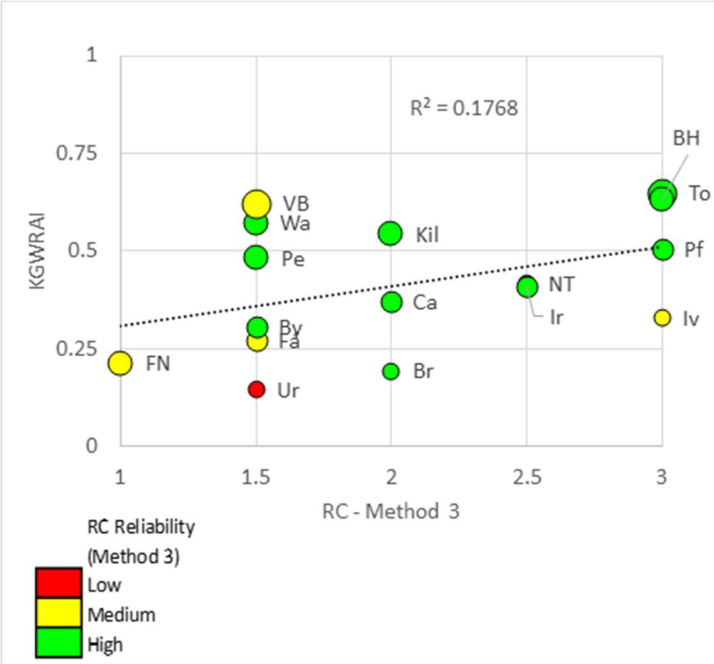


FIGURE 43: COMPARISON BETWEEN REGULATION CAPACITY FACTOR (METHOD 3) AND KGWRAI (METHOD 2)

4.5.3 Conclusion

In this section 3, we have proposed three new classifications methods of karst/chalk aquifers in order to help water operators and hydrogeologists to prioritize prospection and exploitation of well suited aquifers and propose adapted management recommendations (see following section 4). Their characteristics are summarized in the Table of FIGURE 44.

Method 1 is a classification of vulnerability only. It combines the use of catchment data that are indicative of vulnerability and are generally always available (the degree of cave development; surface karst) with indicators of rapid groundwater flow (tracer tests, water quality indicators of rapid flow, coliform counts, and a rapid discharge response to rainfall). A small modification enables application to borehole sites. Limitations and advantages of the method, together with recommended further work on parameters and thresholds are outlined in Section 4.2.4 and 4.5.1, but overall results from the CHAKA case studies and from 20 Chalk borehole sites suggest that Method 1 provides results that are consistent with our understanding of the sites that have been used.

Method 2 provides an assessment of the water resource availability based on discharge time series analysis which is combined with the vulnerability assessment of Method 1 to enable consideration of both these factors that are important for water resource management. In Method 2 a groundwater resource availability index is proposed which is based upon the memory effect time series analysis method combined with the mean spring discharge. These parameters were selected following the application of several time series analysis methods to the CHAKA case studies (see sections 3.2 and 4.3). The memory effect provides an evaluation of the proportion of rapid groundwater flow, and the amount of storage in the system thereby providing useful information on the resilience of the system to precipitation variability, which when combined with the mean spring discharge gives an indication of the overall resource availability.

Method 3 provides an alternative to method 2 for combining an evaluation of intrinsic vulnerability with an evaluation of the regulation capacity of a spring. For the vulnerability assessment, it uses mostly different parameters to Method 1 and is focused entirely on physico-chemical parameters measured at the spring that can be indicative of vulnerability (SEC, TOC, Turbidity, Coliforms, Oxygen Isotopes, Temperature). The method highlights these parameters as useful indicators of high vulnerability in karst aquifers, but requires some further validation of thresholds and data interpretation as outlined in Section 4.5.1. For the regulation capacity assessment, Method 3 uses two times series analysis methods: It combines the memory effect (also used in Method 2) to characterize the response time, with the SVC parameter which characterizes the discharge variation at different time scales. The assessment of groundwater availability, which is important information for potential end users for a sustainable management of the resource, requires consideration of average flow, which is used as a third piece of information to set point sizes in the output graph.

Required (minimum) data		Spatial data and indicators of rapid flow	Method 1 + Q/H time series	Q/H + physico-chem data
Method		Method 1	Method 2	Method 3
Result		Vulnerability	Vulnerability and GW availability	Vulnerability and Regulation Capacity and system size
Delivered information	Quantity	No information	KGWRAI = f(ME, Qmean)	RC = f(ME, SVC) + system size
	Quality	Vulnerability	Vulnerability (fromMethod 1)	Vulnerability

FIGURE 44: COMPARISON TABLE OF THE THREE CLASSIFICATION METHODS CHARACTERISTICS (KGWRAI: KARST GROUNDWATER RESOURCE AVAILABILITY INDEX; ME: MEMORY EFFECT; RC: REGULATION CAPACITY; SVC: SPRING VARIABILITY COEFFICIENT).).

5 GROUND WATER RESOURCE MANAGEMENT RECOMMENDATIONS

5.1 Introduction

The EU developed the Water Framework Directive (WFD) (2000/60/EC) recognises the delicate balance between all aquatic ecosystems and requires all member states to implement plans to maintain and improve all our water environments. This Directive is unique in that, for the first time, it establishes a framework for the protection of all waters including rivers, lakes, estuaries, coastal waters and groundwater, and their dependent wildlife/habitats under one piece of environmental legislation. The directive recognises the need for an integrated approach for the sustainable management of our water bodies and the interdependency of our water bodies on each other. The need for community-based action and improvement s is also a key component of the WFD approach.

Integrated catchment management (ICM) is now seen as the best overarching framework for the philosophy for water management, including drinking water source protection (NFGWS 2019). This **multiple-barrier approach**, which is an integrated system of procedures, processes and tools that collectively prevent or reduce the contamination of water, must involve a multi-disciplinary team such as government, planners, engineers, scientists, farmers, land-owners and politicians (NFGWS 2019, Bakalowicz 2011). However, national efforts are very variable and sometimes there is little integration into national policy and planning.

5.2 Karst aquifer management recommendations

Karst aquifer recommendations are outlined in the following sections. The recommendations outlined are considered those that must be applied in order to protect and effectively manage karst resources. They are necessary to enable planning and licensing authorities to carry out their functions, and to provide a framework to assist in decision-making on the location, nature and control of developments and activities in order to protect groundwater.

5.2.1 Sustainability assessment (SA)

As karst systems are characterized by fast and intense hydraulic reactions to hydrologic events, temporal variations of the groundwater table can be tens of meters. This can give rise to periods of droughts and periods of flooding. Sustainable management of karst groundwater and surface water resources must include an assessment of the resource in terms of changing land-use, growing population and climate change. This will give an idea of future floods and droughts and predicted impacts on dependent water users to a change in the hydrological regime. This will help in adjusting the abstraction pumping rate for an optimal management of the resource.

It is recommended that water and resource managers carry out a sustainability assessment of the resource in terms of its current usage, predicted future usage and water demands. The entire ecosystem services must also be considered in these calculations. These predictions must include an assessment of global population change, changes in land usages and climate change impacting baseflow and overall karst resources.

It is recommended that a plan is put in place to mitigate against any issues with demand and supply such as flooding and drought by active and passive karst management (see section 5.2.4).

5.2.2 Source Protection Zones (SZ)

There are a number of ways of preventing contamination, such as improved well siting, design and construction and better design and management of potential contamination sources. However, one of the most effective ways is utilising groundwater protection schemes as part of the planning process.

Groundwater protection is addressed by most countries by a set of different rules and regulations at national or local level that aim to prevent contamination of the aquifer. Maximum allowable concentrations for pollutants have been established and monitoring programmes are usually performed in order to check and establish good land use management practices. In the EU there are various Directives established to protect groundwater, such as the Nitrates Directive 91/676/EEC, the Integrated Pollution Prevention and Control (IPPC) Directive 96/61/EC, the protection of groundwater against pollution and deterioration Directive 2006/118/EC and the Water Framework Directive (WFD, 2000/60/EC). The WFD calls on all Member States for the characterisation of aquifers and the establishment of safeguard zones to protect groundwater used for abstraction of drinking water. Many countries characterise their aquifers into differing flow regimes and by resource value. Many countries policy and planning guidelines and regulations then recognise the resource value of these aquifers.

One of the most fundamental ways to protect our valuable groundwater drinking water sources is through source protection zones and the implementation of proper land-use practices in these zones. Many national groundwater protection schemes differentiate at least three types of source protection zones. Zone 1 can often be the *well or spring head protection zone,* and is usually the area immediately surrounding the source. Zone 2 is often referred to as the *inner protection zone*, and is usually delineated to protect the supply from microbial contamination. Therefore, time of travel (TOT) is often a criteria used to delineate this zone. Different countries use different time of travel as a cut off, depending on local conditions. For example, the inner protection zone (zone 2) in Croatia is 24 hours with zone 3 defined by 1-10 days TOT (if known), Switzerland uses 10 days TOT, The UK uses 50 (SPZ 1) and 300 (SPZ 2) TOT and 100 days in Ireland. However, often the entire ZOC is within 100 TOT (Daly and Drew 1999). Zone 3 is often called the *outer protection zone* and may be part of the catchment, a certain percent of the catchment or the total rest of the catchment (FIGURE 45). Land use practices are normally controlled or prohibited in these source protection zones, with decreasing restrictions from 1 to zone 3 (Goldscheider 2010).

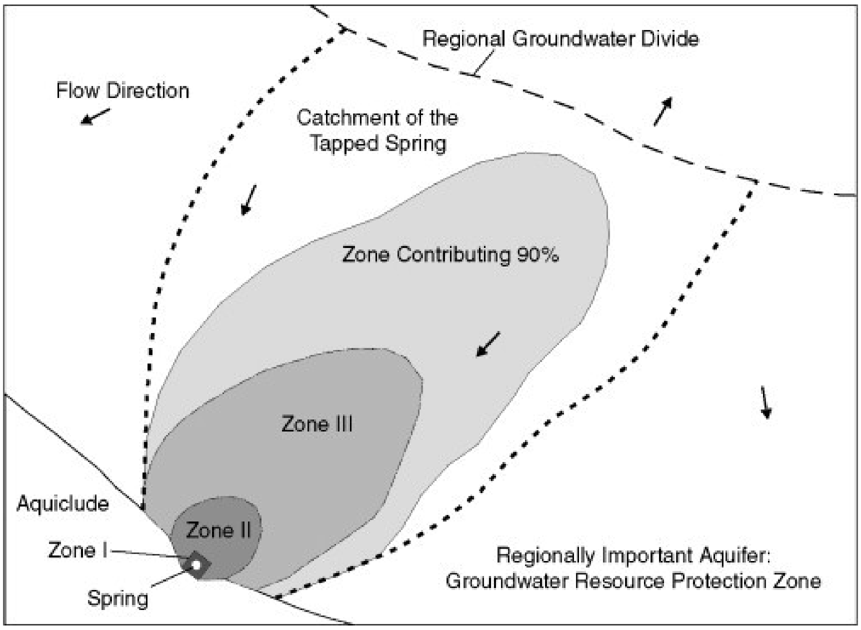


FIGURE 45: TYPICAL ARRANGEMENTS OF GROUNDWATER SOURCE PROTECTION ZONES FOR A SPRING (GOLDSCHEIDER 2010)

In karst groundwater aquifers, the delineation of these zones is more complicated. The nature of karst means that groundwater can travel great distances very quickly. This can mean that groundwater can travel from the outer areas of the catchment to the source within a matter of days (or even hours). This can mean that the whole catchment should be considered as the Inner protection zone. Indeed, this is the approach used in Ireland in karst catchments. As this area can be very large, is useful to then further subdivide the karst spring catchment on the basis of a vulnerability to obtain source protection zones. These source protection zones then have different restrictions on land use practices, and are used to off-set the large socio-economic implications of having such a large inner protection zone in karst areas.

Karst can also mean that areas of influent karst landforms, such as sinking streams, that may be further away from the source, can be classified as the inner zone, while the non karst or influent zone, closer to the source, can be classified as the outer zone. In a non-karst area, the inner protection zone is usually established through standard hydraulic methods and modelling. However, standard hydraulic methods cannot be applied in karst aquifers and can lead to disastrous consequences FIGURE 46

In 2000, in a small town called Walkerton in Canada, the use of non-karst specific methods for delineation of source protection zones, led to a preventable tragedy where over 2,500 were poisoned with E. Coli and other gastrointestinal diseases and 7 people died. A pollution incident had occurred well outside what was delineated as the 30 day TOT, using Modflow. However, subsequent dye tracing investigations demonstrated that this area was inside the catchment and water and contaminants from here could get to the source (a well) in one day (FIGURE 46).

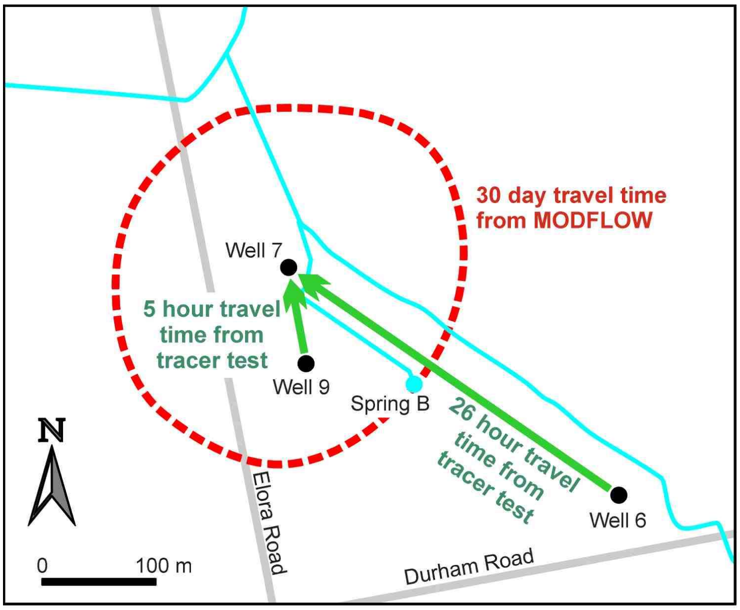


FIGURE 46: THE DANGER OF USING NON-KARST TECHNIQUES TO DELINEATE SOURCE PROTECTION ZONES IN KARST. WALKERTON TRAGEDY; TWO TRACES GAVE VELOCITIES ABOUT 70 TIMES FASTER THAN THE "CONSERVATIVE" MODFLOW SIMULATION INDICATED.

Consequently, source protection zone delineation in karst must include karst specific methods such as water tracing experiments and other karst specific methods of investigation. Similar to vulnerability assessment in karst terrains, source protection zone delineation in karst must include detailed hydrogeological investigations of a karst system as a precondition. Some countries (such as Ireland) include parts of the catchment that would otherwise be outside the source catchment, for example, the allogenic (non-karst) catchment to a sinking stream that is connected to the source. It is also recommended that the whole catchment area to influent karst landform be designated as extremely vulnerable. Of the participating countries surveyed for this project, 92% of the study area sources had a zone of contribution defined. Half of the case studies had source protection zones defined, however, most to these are not used as a drinking water source. It is recommended that all sources have a zone of contribution defined using karst specific methodologies and all drinking water sources have source protection zones defined using karst specific methodologies.

5.2.3 Vulnerability mapping (VM)

This section considers catchment vulnerability mapping with is focused on the pollutant risks within the catchment rather than the intrinsic vulnerability of the spring or borehole which is considered in the vulnerability assessments of Methods 1 and 3 (Section 4).

Karst groundwater vulnerability maps are critical tools for the development of groundwater management and protection strategies. They are a fundamental layer in any land use planning and are usually easy to use and understand.

As many karst systems are large, from several tens or hundreds of km^2, it is often impossible to impose strict conditions in terms of planning and control of human activities over such an area. However, assigning different vulnerability categories within the catchment means different land use practices and controls can occur within the catchment zone, making it more practical to manage overall.

The distinct nature of karst and the specific problems posed in terms of protecting karst groundwater was recognised in the Co-operation in Science and Technology programme COST65 (COST Action 65 1995). This was established to share ideas and information of karst water protection practices on a pan-European basis. Its successor COST Action 620, was established to develop karst specific protection strategies (Daly and Drew 1999). European Commission, COST Action 620, Vulnerability and risk mapping for the protection of carbonate (karst) aquifers was set up to develop an improved and consistent European approach for the protection of karst groundwater.

COST ACTION established a European method for karst specific vulnerability, but this method can also be applied in non-karst areas. There are many different vulnerability methods for use in karst terrains, such as COP, LEA, VULK, PI, EPIK, The German method, the Time-Input method and the Irish Method. Many of these methods were developed during the framework of COST 620 and are based on a modification of the European approach. Most of these methods involve some sort of assessment of the overlying layers plus and additional assessment of the catchment and concentration of flow at influent karst features. There are some recent papers assessing the different karst specific vulnerability methods (Moreno-Gómez et al 2019, Hamdan et al 2016, Ivan et al 2017) as well as GeoERA HOVER WP7.

However, standard methods do not always apply to specific regional situations and parameter adaptations are often necessary (Moreno-Gomez et al, 2019). As Karst systems are so individual detailed hydrogeological investigation of a karst system is a precondition for vulnerability mapping. This must include an inventory of karst landforms and their function. Remote sensing techniques, such as LiDAR, make remotely mapping large areas possible, though the best results are always obtained from detailed field mapping programmes.

A survey of the participating countries and their landuse management practices for the case studies was conducted for this project. Of the countries that responded (12 in total), exactly half did not have vulnerability zones defined in their case study sites. It is recommended that all sources in karst aquifers delineate zones of vulnerability within their zones of contribution (ZOCs). This must be carried out using karst specific methods, such as karst landform mapping. This will enable more vulnerable areas to be identified and prioritised in terms of land use management restrictions.

5.2.4 Active and passive management of karst aquifer resources (AM and PM)

Method 2 and 3 of this report consider the source discharge and hydrograph as a way of classifying the karst aquifers, and combine this with an assessment of vulnerabilty. The discharge component of these methods enables an assessment of the water resource availability and its likely resilience to variations in precipitation and drought (regulation capacity). Assessing the sustainability of the source in terms of climate change and growing populations has already been discussed (4.2.11). Passive management of karst aquifers involves exploiting the supply without changing the hydrodynamic properties of the aquifer itself or just collect water flowing naturally at a spring by gravity.

However some additional measures could be put in place to mitigate against the effects of extremes on a water supply. In karst aquifers that are considered to have extremely low regulation capacity (under method 3) these measures may be essential in order to effectively manage the water supply.

This type of management of karst systems is called active management (Baudement et al, 2017, Bakalowicz 2011). Active aquifer management usually involves using the transmissive zone below the base level of the system (by drawing down the water level below the spring) to increase supply during drought and mitigates the flood discharge at the source during high water levels and proportionally increases the groundwater storage available for use as a drinking water supply (Baudement et al, 2017). Essentially pumping aims at emptying more storage space, which will be recharged during the next rainy season.

In other highly karstified aquifers, such as those found in part of China, the storage may be so low relative to the flood pulses making the resourse almost unusable without some intervention. Milanovic (2000) provides several examples of underground dams partially or completely sealing karst conduits in China. Sometimes these dams are also developed for producing electricity via an underground waterfall (Bakalowicz 2011). Other techniques such as managed aquifer recharge (MAR) are being used in areas more frequently in emerging developments and are especially common in arid and semi-arid regions.

5.2.5 Mitigation Measures (MM)

All sources require source protection strategies. In some cases, this may not be enough and some sources may still have persistent water quality issues due to land use conflicts within the catchment. These sources will require more robust mitigation strategies as a means of ensuring effective achievement of safe and secure water supplies. A mitigation strategy will involve further investigation in order to target the main sources of the contamination at the source. The mitigation measures must be efficient and effective and usually require some cost benefit analysis and acceptability amoung stakeholders before choosing the most suitable measures (NFGWS 2019).

Mitigation measures can be grouped into categories such as source control (this can be point or diffuse), mobilisation control, pathway interception and receptor and instream works (such as riparian or buffer zones around a stream or in karst environments, a sinking stream). **FIGURE 47** shows a sample flow chart for deciding on appropriate mitigation measures in a landscape setting. It is not specific to karst areas but many karst areas would give rise to a point source pollution source at entry to the karst system and so the ‘point’ pathway can be followed.

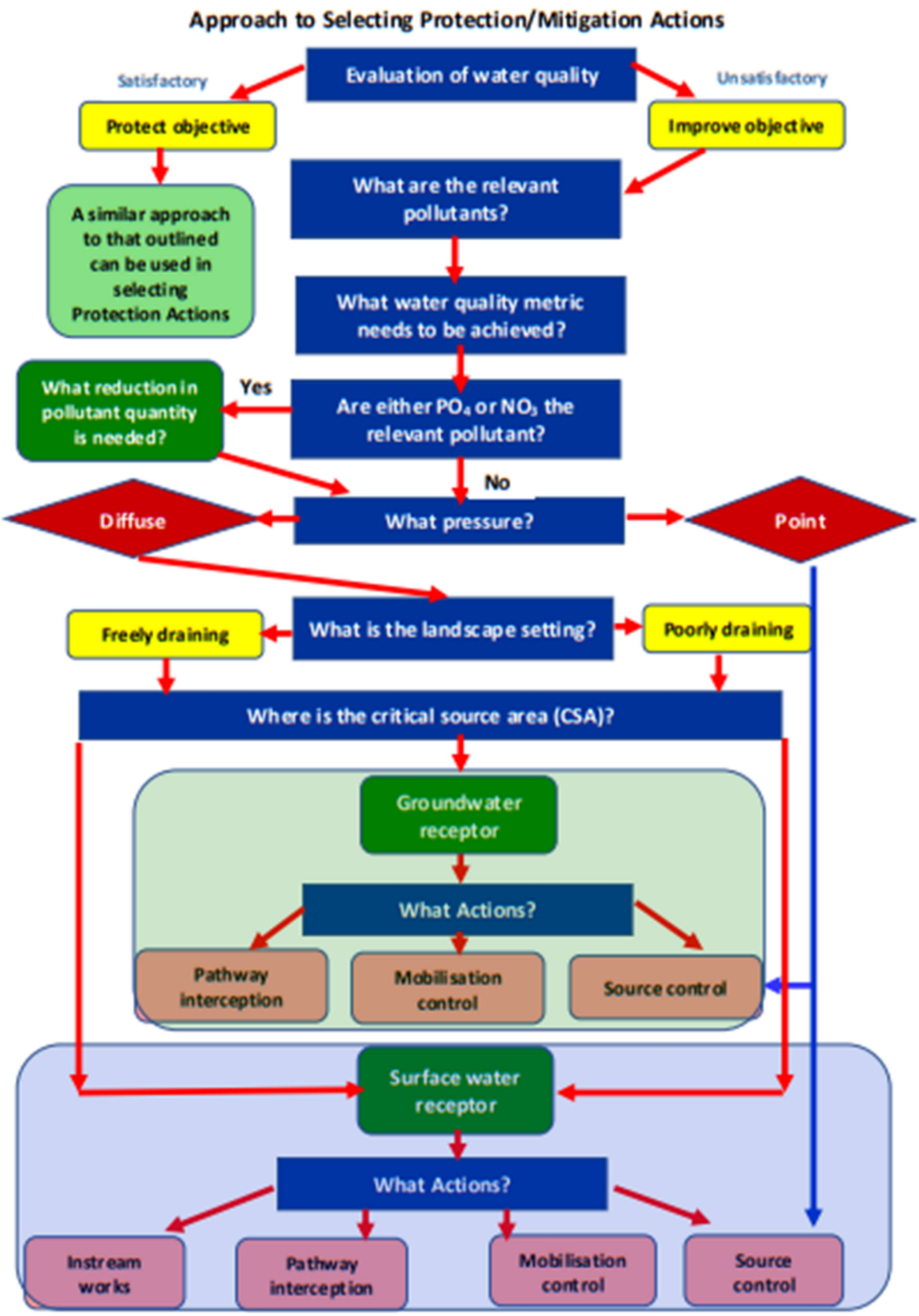


FIGURE 47: PROCESS FLOWCHART ILLUSTRATING A RECOMMENDED APPROACH TO DECIDING ON APPROPRIATE MITIGATION ACTIONS (NFGWS 2020)

FIGURE 48 show some sample mitigation options in a typical agricultural setting to give an idea of some of the mitigation options available.

Location in landscape	Category of action	Action	Protection/mitigation options
All farmland	Discussion with farmers	1	Farmer engagement and collaboration
At the source of the pollution pressure	Pollutant reduction, or elimination	2 3 4 5 6 7 8 9 10 11 12 13 14	Farmyard management to prevent runoff to watercourses and/or infiltration to groundwater Appropriate application of N fertiliser Appropriate application of P fertiliser Use of precision technology Management of farm roadways, drinking troughs, supplementary feeders and gateways Using low crude protein animal feeds Integrated weed management Proper storing, handling and disposal of chemicals Use of boom sprayers Weed-wiping applicator Petrol/diesel & waste oil management Management of land reclamation Organic farming
	Reducing mobilisation of pollutants on land	15 16 17 18 19 20 21 22 23 24	Liming of soils (Timing of fertiliser applications Low emission slurry spreading Use of protected urea Multi-species grassland swards Red and white clover Cover/catch crops Reducing soil compaction Land preparation for tillage and grassland Rewetting peat soils areas
Along the pollution pathway	Pathway interception	25 26 27 28 29 30 31 32 33	Riparian buffers In-field grass buffers Hedgerows Wild bird cover crops planted alongside watercourses Agro-forestry Woodlands Drainage ditch management and sediment traps Low earthen mounds/bunds Farm ponds and wetlands
At the polluted watercourse	Receptor/instream works	34 35 36	Livestock exclusion from watercourses (Bank stabilisation Removal of riparian invasive species

FIGURE 48: MITIGATION MEASURES AND ACTIONS GROUPED BY LANDSCAPE LOCATION IN AN AGRICULTURAL SETTING (NFGWS 2020)

In addition to meeting water quality objectives, mitigation measures have huge potential co-benefits to biodiversity, reduced ammonia emissions, flood mitigation and others such as sources of fuel (such as willow plantations for treating wastewater effluent), as well as scenic and aesthetic values. Consideration of the additional benefits from mitigation options for related environmental objectives is a good way of achieving optimal outcomes for the environment and, perhaps, public acceptance for the activities. These additional benefits emphasise the connectedness of nature and are, therefore, a means of delivering genuine environmental and economic sustainability for communities (NFGWS 2019).
As FIGURE 50 shows mitigation measures are considered optional in a moderate vulnerability setting where there are some water quality indicators of contamination at the spring and are deemed necessary where there are persistent water quality indicators of contamination at the spring (high vulnerability settings) as indicated by water quality parameters. The mitigation measures must first be targeted in the ZOC and focused on areas of extreme and high vulnerability within the ZOC.

5.2.6 Early warning systems

As karst systems can be very responsive to recharge inputs, contamination events can also be quite short lived and intense. Thus, karst springs are characterised by long periods of sufficient water quality, interrupted by short but severe contamination events. Managing these events and identifying them on time to respond, is a major challenge in karst aquifer management. It is a major challenge of karst water managers to identify these events in time and respond accordingly (Pronk et al. 2007).

Under conditions of climate and land-use change, long-term trends in karst water quality are also a concern for many water suppliers, e.g. with respect to nitrate, organic carbon or dissolved oxygen. (The European Union (Drinking Water) Regulations 2014 (S.I. 122 of 2014).

One of the most common problems with karst springs is the contamination by microbial pathogens. The presence of faecal bacteria and Enterococci, in particular is a cause for alarm. While not all faecal bacteria will be harmful, their detection may indicate the presence of additional bacteria, viruses and parasites that can cause serious illness, such as Cryptosporidium. These are bacteria found in large numbers in the faeces of humans and other warm-blooded animals and their presence in a water supply usually originate from agricultural activities in the catchment. However, it can also indicate where wastewater treatment facilities are inadequate (e.g. poorly operating septic tanks/municipal wastewater treatment systems) (NFGWS 2017).

The dynamics of a karst system (shallow soils, point recharge via dolines and swallow holes and rapid conduit flow) combined with source factors (such as land spreading at certain times, spillages and unplanned contamination events) and other climatic factors such as heavy rainfall, may results in intense spikes of these microbial pathogens, which may overwhelm the treatment system causing risk to human health. Microbial monitoring at springs requires sampling and subsequent testing of the sampling and so it is an inefficient and effectively useless as a warning system as to when an event it about to occur.

However, we have seen that many hydro-dynamical and hydro-chemical properties can be continuously monitored and so can serve as a useful indicator of an imminent pollution event. Method 3 outlined in this report describes some of these indicators such as sudden fluctuations in temperature and EC recorded at the spring. While these parameters do not necessarily indicate contamination at a source, they do demonstrate a sudden change in the rapid pathways between the surface and the source. Other indicators such as a sudden increase in Total Organic Carbon (TOC) and turbidity can also be a good proxy for indicating an increase in microbial pathogens. A study by Pronk et al, 2006, showed that TOC appears to be a better indicator for bacterial contamination than turbidity. Another emerging technique is the use of Tryptophan-like fluorescence (TLF) sensor to measure Biological Oxygen Demand (BOD) and organic pollution. Where the risk of faecal contamination of the source is deemed moderate to high (FIGURE 50), an early warning system, such as a turbidity alarm and/or automatic shutdown of the intake should be considered. This should be part of a wider treatment system including filtration, duty and stand-by disinfection with automatic switch-over and other barrier treatments such as UV treatment, which should be standard in all water treatment facilities. This should be put in place in the context of the wider source protection plans that aim to limit (and prevent, if possible) the entry of faecal matter into the raw water supply (NFGWS, 2017).

5.3 Karst Aquifer Recommendations and Classification Methods

The three different classification methods have been outlined and described previously.

Availability and reliability of data is a big issue when assessing the correct karst aquifer recommendations. For example, if there are no data available on sinking streams in the catchment, then they will not be assigned the correct groundwater vulnerability category or no mitigation measures can take place at them. Similarly, if water tracing experiments have not been carried out in the catchment it is very hard to calculate the inner protection zone (or zone to protect against microbial pollution) as conventional aquifer methods will give misleading and sometimes risky results.

Similarly if using the spring (or source) hydrograph/chemograph to calculate vulnerability (and resource availability and regulation capacity of the system) then the more data the better. It is unsafe to presume a set of aquifer recommendations based on a vulnerability assessment made with very little data. Figure 19 shows the data reliability categories in relation to data availability, for method 3. Method 1 ranks catchments in relation to 6 groups of characteristics: surface karst, caves, water quality, coliforms, tracer tests and discharge. Lack of data in any one of these categories indicates the method is less reliable. Therefore, the following data reliability categories are assigned: High reliability – all 6 categories have a score (no data gaps), moderate reliability – 4-5 categories have a score (1-2 data gaps) and low reliability – less than 4 categories (3 or more data gaps).

In order to apply a conservative approach in the absence of reliable data the system shown in FIGURE 49 is suggested.

	High Vulnerability	Moderate Vulnerability	Low Vulnerability
High reliability	High	Moderate	Low
Moderate reliability	High	High	Moderate
Low reliability	High	High	High

FIGURE 49: CONSERVATIVE VULNERABILITY ASSUMPTIONS IN RELATION TO DATA RELIABILITY

The karst aquifer recommendations can be used with either Method 2 (which uses Method 1 for vulnerability) or Method 3 (Figure 46). The recommendations are shown in all categories, such as sustainability assessment, source protection zones and karst landform mapping, while the desirable recommendations are only shown the categories where they are most appropriate but they can be applied elsewhere. For example, mitigation methods are suggested as desirable in all moderate vulnerability settings but are only considered essential in high vulnerability settings. Another example is the active aquifer management recommendation, which is only recommended in aquifer with low regulation capacity or high responsiveness at the source but it can be applied elsewhere.

As can be seen in FIGURE 50, the amount of karst aquifer management recommendations increases with increasing vulnerability and decreasing regulation capacity or increasing responsiveness of the source.

	Regulation Capacity (M3)	RC < 1.5	1.5 < RC < 2.5	RC > 2.5
Vulnerability (M3)	KGWRAI (M2) Vulnerability (M1 & M2)	Low <25%	Medium >25% and <50%	High >50%
V > 2.5	High	SA SZ VM AM MM EW	SA SZ VM PM/AM MM EW	SA SZ VM PM MM EW
1.5 < V < 2.5	Medium	SA SZ VM AM (MM)	SA SZ VM PM/AM (MM)	SA SZ VM PM (MM)
V < 1.5	Low	SA SZ VM AM	SA SZ VM PM/AM	SA SZ VM PM

FIGURE 50: KARST AQUIFER RECOMMENDATIONS IN RELATION TO THE 3 CLASSIFICATION METHODS. MANAGEMENT RECOMMENDATIONS ARE: SA: SUSTAINABILITY ASSESSMENT – SZ: SOURCE PROTECTION ZONE – VM: VULNERABILITY MAPPING – AM: ACTIVE MANAGEMENT – PM: PASSIVE MANAGEMENT – MM: MITIGATION MEASURES – EW: EARLY WARNING

5.4 Conclusions

Management of karst aquifer must continue to protect our invaluable karst environments. Karst aquifers must be considered in terms of water quantity and quality, and so their protection and sustainable management is of utmost importance to sustain water supply as well as the rivers and ecosystems which are dependent on the karst aquifer. Exploitation of groundwater resources must also take into consideration the impact of groundwater - surface water exchanges and aquatic ecosystems in downstream rivers and other dependent ecosystems. Although groundwater from karst aquifers is an important drinking water resource, it must be remembered it is particularly vulnerable to contamination. The particular nature of karst aquifers means that they need special and karst specific protection and management strategies. Their management should be part of an integrated water resource management strategy involving multiple stakeholders. This should be an iterative process involvement monitoring and making adjustments. Karst aquifer management strategies must be incorporated into regional and national planning and policy.

The recommendations outlined in this section encompass some of the key karst aquifer management strategies. As previously stated and shown in FIGURE 50, recommendations that are considered to all karst sources (especially if used as a water supply) are: sustainability assessment, source protection zones and vulnerability mapping. Sustainabiity assessment future proofs the supply and source protection zones and vulnerability mapping are essential for improving and maintaining the quality of the source and for protecting the human health and the health of its dependent ecosystems. Karst specific methods must be used in a karst setting so karst landform mapping must be carried out before source protection zones and vulnerability mapping can be performed. Additional recommendations such as active and passive management, early warning systems and mitigation measures are desirable recommendations that may be necessary in certain systems, such a flashy spring with very low regulation capacity or a source that is prone to intense sporadic spikes of contamination.

Integrated catchment management (ICM) is now seen as the best overarching framework for the philosophy for water management, including drinking water source protection (NFGWS 2019). This **multiple-barrier approach**, which is an integrated system of procedures, processes and tools that collectively prevent or reduce the contamination of water, must involve a multi-disciplinary team such as government, planners, engineers, scientists, farmers, land-owners and politicians (NFGWS 2019, Bakalowicz 2011). However, national efforts are very variable and sometimes there is little integration into national policy and planning.

6 CONCLUSIONS

Karst aquifers provide important and vulnerable resources which large global populations depend on and which also sustain rivers and important ecosystems. In this report, we have proposed methods to classify karst systems according to their capacity to be sustainably exploited for drinking water and other water usage purposes. It is thus the availability of the groundwater resource that we want to classify, combined with ensuring that the water is of good quality. Therefore, classifications on scatter plots with two axes are proposed: one axis relating to vulnerability (Y axis in our approach) and the second to the availability of the resource (X axis).

In order to quantify the vulnerability (Y axis), we have proposed two methods that attribute an index between 1 (low vulnerability) and 3 (high vulnerability). Method 1 combines the use of catchment data that are indicative of vulnerability and are generally always available (the degree of cave development; surface karst) with indicators of rapid groundwater flow (tracer tests, water quality indicators of rapid flow, coliform counts, and a rapid discharge response to rainfall). The vulnerability assessment from Method 1 is used for the Y axis in Method 2. A small modification enables application of Method 1 to assess the intrinsic vulnerability of borehole sites. The vulnerability component of Method 3 uses mostly different parameters to Method 1 and is focused entirely on physico-chemical parameters measured at the spring that can be indicative of vulnerability (SEC, TOC, Turbidity, Coliforms, Oxygen Isotopes, Temperature).

Methods of quantifying the availability of the water resources (X axis) are proposed in Methods 2 and 3. In Method 2, following consideration and comparison of different times series analytical methods, two indicators were considered most appropriate for the X axis: the memory effect and the KGWAI (Karst GroundWater resource Availability Index). The first combines the memory effect with additional information on the average discharge rate at the spring (indicated by the size of the point on the scatter plot) while the second one integrates both the memory effect and the average discharge. In Method 3 a regulation capacity assessment is made for the Y axis which uses two times series analysis methods: It combines the memory effect (also used in Method 2) to characterize the response time, with the SVC parameter which characterizes the discharge variation at different time scales. The assessment of groundwater availability, which is important information for potential end users for a sustainable management of the resource, requires consideration of average flow, which is used as a third piece of information to set point sizes in the output graph.

The following management recommendations have been identified: sustainability assessment, source protection zones, vulnerability mapping, active and passive management, early warning systems and mitigation measures. The need for these different management measures are linked to the outputs of the classification systems (for vulnerability and water resource availability), according to their position in the classification diagrams.

These methods are a promising first attempt at karst classification aimed at water management issues based on the case studies available for the CHAKA project. Most of the case studies are within more classically karstic aquifers, and therefore further work is needed to assess the applicability of the methods to karst aquifers such as the Chalk with lower levels of karstification. Most of the case studies are spring sites rather than boreholes and therefore the application of the methods to boreholes also needs further investigation. Methods 1 and 3 identify a number of important physico-chemical parameters measured at spring and borehole sites that can indicate high vulnerability of karst sites. However, there remain some uncertainties about the thresholds and interpretation of these physico-chemical parameters, and further research using large datasets from a wide range of karst aquifers is recommended to improve the vulnerability classifications.

Overall this CHAKA project workpackage has identified the key parameters that are important for assessing water resource availability and vulnerability in karst aquifers; produced classifications that show promising results for the 17 CHAKA case study sites (and 3 additional dolomite sites), as well as applying a vulnerability method to 20 Chalk boreholes; developed a means of associating the classification results with management recommendations; and identified the areas where further data analysis could enable improved classification.

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8 APPENDIX

8.1 Appendix 1: Notes on Method 1 score assignments for 20 Chalk boreholes from Southern England

Site	Surface karst	Conduits	Water quality	Coliforms max (cfu/100mls)	Tracer tests	Transmissivity (m2/day) Or pumping rate (l/s)
1	Many Stream sinks	Size unclear	Coliforms, turbidity, metaldehyde	38700	2.3 km/day over 6.8 km	Modelled T up to 2500, pumping up to 155 l/s
2	Many stream sinks	Insufficient data	Coliforms, turbidity, freshwater species	241900	2.9 km/day over 2.9 km	Modelled T is 2500
3	Stream sinks present	Insufficient data	Coliforms, Metaldehyde, some turbidity	1010	Rapid flow in tests in catchment, no detection at site in one test, but insufficient tests	Modelled T is 5000
4	Stream sinks present	"large fracture" reported	Coliforms, Metaldehyde, some turbidity	1733	Velocity 120 m/day but only one tracer test	Modelled T is 5000
5	Stream sinks and river losses	Insufficient data	Insufficient data	1180	Rapid flow in tests in catchment, no detection at site in one test, but insufficient tests	Modelled T is 5000
6	Stream sinks present	No data	insufficient data	201 (based on 440 samples)	Rapid flow in tests in catchment, no detection at site in one test, but insufficient tests	Modelled T is 2500
7	Stream sinks present	No data	Insufficient data	52 (based on 320 samples)	No data	Modelled T is 2500
8	Stream sinks present	No data	Insufficient data	1414	No data	Modelled T is 10000
9	River leakage	No data	Turbidity, metaldehyde, coliforms	15 (based on ~720 samples)	No data	Pumping rate 46 l/s
10	River leakage	No data	Turbidity, metaldehyde, coliforms?	1 (in 3 out of on 1300 samples)	No data	Pumping rate is 104 l/s

11	Closed depressions, dissolution pipes, possible small stream sinks	No data	Coliforms?, low turbidity, no short residence time pesticides	1 (in 6 out of 748 samples	no data	modelled T is 845-1005
12	Clay with flints and dissolution pipes, no stream sinks	"Significant conduits/ cavities" Score 2 or 3?	Coliforms; no short residence time pesticides; occasional turbidity max 5 NTU not clear if this is karst related.	4 (coliforms in 3 out of 720 samples)	No data	Modelled T is 1000
13	No stream sinks or dolines but dissolution pipes present	"solutional Fissures"	Coliforms; no short residence time pesticides; occasional turbidity max 6.4 NTU not clear if this is karst related.	25 (based on ~760 samples)	No data	Pumping rate ~ 27 l/s
14	No stream sinks or dolines but dissolution pipes present	No data	Coliforms, turbidity max 1 NTU, no short residence time pesticides	100 (based on ~680 samples)	No data	Pumping rate ~ 36 l/s
15	River losses, possible small stream sinks	Limited data, "solutional fissures"	Only one of ~820 samples with coliforms; turbidity up to 7 NTU (unclear if due to karst); no short residence time pesticides	6 (only 1 sample out of ~820 had coliforms	No data	Pumping rate ~ 35 l/s
16	Possible solution features, possible river losses, possible small stream sinks. Not enough evidence to score 3	Limited data "fissures"	No coliforms, no short residence time pesticides, turbidity generally < 0.6 NTU, max 1.2 NTU	No coliforms (~765 samples	No data	Pumping rate ~15 l/s

17	dissolution pipes, clay with flints, Possible small stream sinks	Limited data "fissures"	Occasional coliforms, low turbidity, no short residence time pesticides	4 (10 samples with coliforms out of ~680 samples)	No data	Modelled T is 1000
18	Dissolution pipes, possible small stream sinks	Limited data "fissures" and "cavities"	Coliforms, occasional turbidity (unclear if related to karst), no short residence time pesticides	122 (based on ~750 samples)	No data	Modelled T is 500
19	No evidence of surface karst	No data	Occasional coliforms; little turbidity (2 samples > 5 NTU), nitrate fluctuations in response to rainfall. Could score 3?	201 (based on ~350 samples)	No data	Modelled T is 500; pumping 75 l/s
20	Springs, closed depressions, dissolution pipes, possible small stream sinks, not enough evidence for 3	No data	Occasional coliforms; low turbidity, no short residence time pesticides	19 (based on ~ 600 samples)	No data	Modelled T 845-1005