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

Deliverable 5.4

Groundwater management recommendations for karst and chalk aquifers

Authors and affiliation:

Maréchal JC. (BRGM), Hickey C. (GSI), Bailly-Comte V. (BRGM), Maurice, L (BGS), Stroj A. (HGI), Bunting, S.Y. (BGS), Charlier JB. (BRGM), Hakoun V. (BRGM), Herms I. (ICGC), Krystofova E. (CGS Pardo-Igúzquiza E. (IGME), Persa D. (IGR), Schubert G. (GBA), Skopljak F. (FZZG), Szucs A. (MBFSZ), Urbanc, J. (GeoSZ), Van Vliet M.E. (TNO), Vernes R.W. (TNO)

E-mail of lead author:
jc.marechal@brgm.fr

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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 aquifer 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 (including chalk) aquifers in order to improve their management. The objective of the GeoERA RESOURCE WP5 is to test and evaluate analytical and assessment methods and come up with an improved characterization framework and typology for karst 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.

In deliverable 5.3, karst classification methods were tested on the CHAKA case study springs to assess the water resource availability and the vulnerability of springs. Two methods were proposed which produce scatter plots that assess vulnerability on the Y axis and water resource availability on the X axis. In the current deliverable 5.4, the following management recommendations have been identified: sustainability assessment, source protection zones, vulnerability mapping, active and passive management, early warning systems and mitigation measures. These management measures are then recommended for springs on the basis of their position on the X-Y scatter plot classification diagrams. The more vulnerable and the less well regulated in terms of available water resources the aquifer is, as demonstrated by the classification methods, the more aquifer management recommendations there are.

As outlined in Deliverable 5.3, 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. The two vulnerability assessment methods 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 karst 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). The development of new methods for typology and classification and their application on karst/chalk aquifers case studies have been described in Deliverable 5.3 (Maréchal et al. 2021). Here we present the groundwater resources management recommendations associated with the outputs of the classification methodologies.

1.2 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 improve management practices of water operators, government, planners, engineers, scientists, farmers, land-owners and politicians in the context of karst hydrogeology.

This report constitutes the final Deliverable (D5.4.) of this work package. It contains the groundwater resources management recommendations adapted to each typology of karst/chalk aquifer.

1.3 Karst Aquifer Management Questions

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

1.3.1 Quantity: sustainability of supply

The sustainability of karst aquifers 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.

1.3.2 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 intrinsic 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 1).

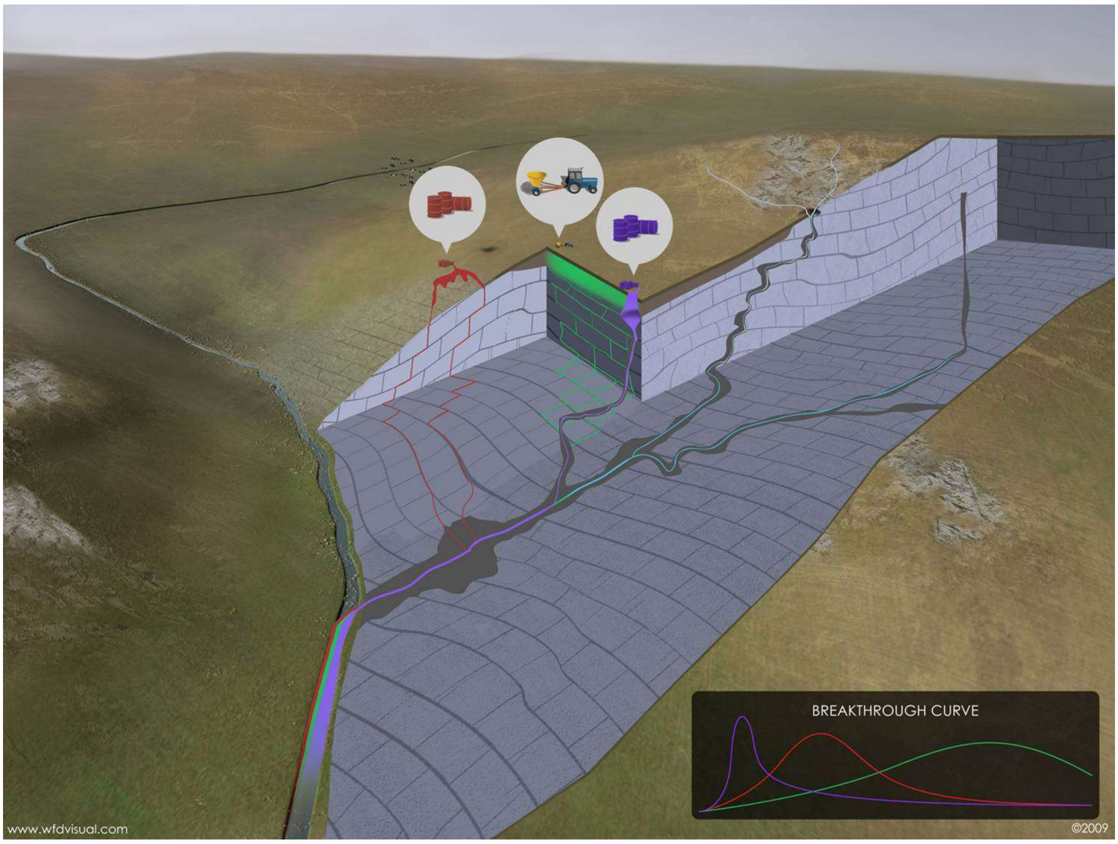

FIGURE 1: THE VARYING BREAKTHROUGH RATES AND CONCENTRATIONS FOR CONTAMINATION EVENTS ON DIFFERENT KARST ENVIRONMENTS, RED - LIMESTONE PAVEMENT, GREEN – COVERED KARST WITH THICK SUPERFICIAL DEPOSITS AND PURPLE – DIRECTLY INTO DOLINE BY PASSING THE OVERLYING DEPOSITS. (WWW.WFDVISUAL.COM/ GSI)

2 CLASSIFICATION OF KARST/CHALK AQUIFERS FOR GROUNDWATER RESOURCE MANAGEMENT

2.1 Introduction

From the perspective of water providers, the main interest in 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 summarize the three types of chalk/karst aquifers classification based on different kinds of data, which have been developed during this project (see Deliverable 5.3). They are illustrated on FIGURE 2. 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), without considering descriptive karst/catchment characteristics).

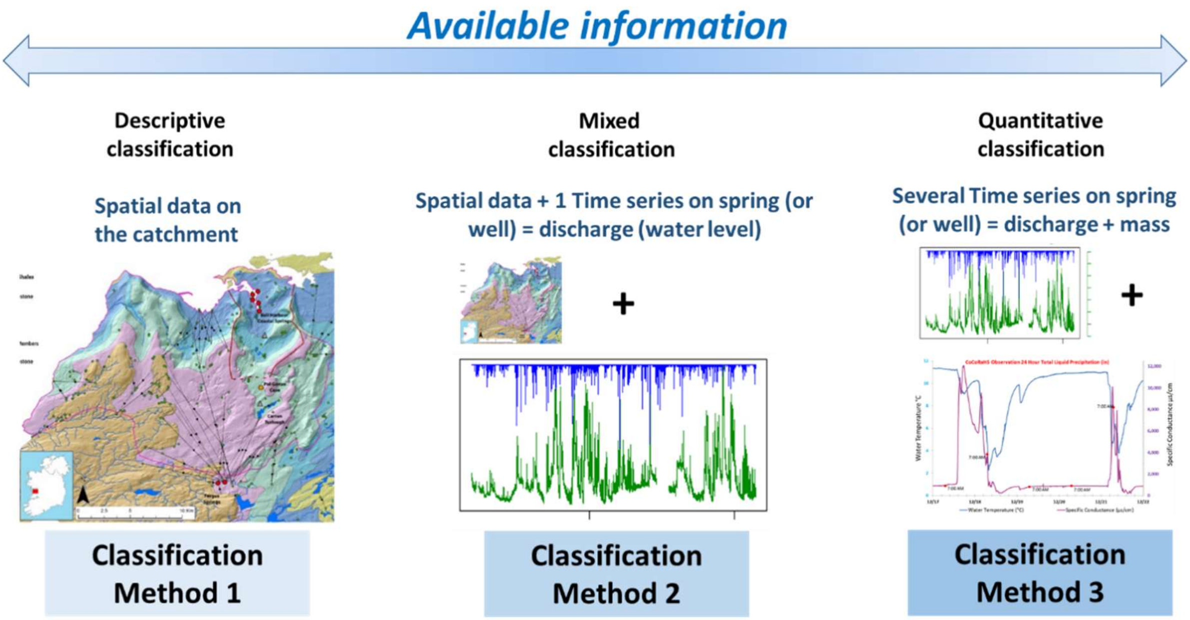

FIGURE 2: KARST/CHALK AQUIFERS CLASSIFICATION ACCORDING TO THE TYPE OF DATA USED

These three methods are briefly described here below.

2.2 Methods description

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. Their characteristics are summarized in the Table of FIGURE 3. More details can be found into Deliverable 5.3 (Maréchal et al. 2021).

Method 1 is a classification of vulnerability only, and is quick to apply. It combines the use of catchment data that are indicative of vulnerability and are generally always available (the degree of cave development; surface karst) and 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 are outlined in Maréchal et al. (2021), 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 Maréchal et al. 2021). 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. 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	Q + spatial data	Q + physio-chem. data
Method		Method 1	Method 2	Method 3
Result		Vulnerability	Vulnerability and GW availability	Vulnerability, Regulation Capacity and System size
Delivered information	Quantity	No information	KGWRAI = f(ME, Qmean)	RC = f(ME, SVC) + System size
	Quality	Potential vulnerability	Potential vulnerability (= Method 1)	Real vulnerability

FIGURE 3: COMPARISON TABLE OF THE THREE CLASSIFICATION METHODS CHARACTERISTICS (KGWRAI: KARST GROUNDWATER RESOURCE AVAILABILITY INDEX; ME: MEMORY EFFECT; RC: REGULATION CAPACITY; SVC: SPRING VARIABILITY COEFFICIENT).

3 GROUND WATER RESOURCE MANAGEMENT RECOMMENDATIONS

3.1 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.

3.2 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.

3.2.1 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 3.2.4).

3.2.2 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 4). Land use practices are normally controlled or prohibited in these source protection zones, with decreasing restrictions from 1 to zone 3 (Goldscheider 2010).

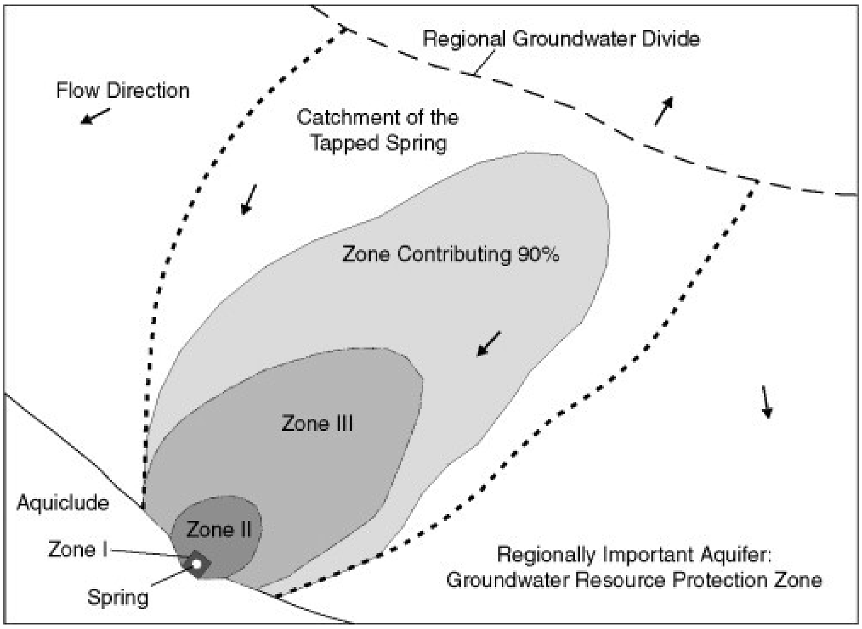

FIGURE 4: TYPICAL ARRANGEMENTS OF GROUNDWATER SOURCE PROTECTION ZONES FOR A SPRING (GOLDSCHEIDER 2010)

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 5

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 5).

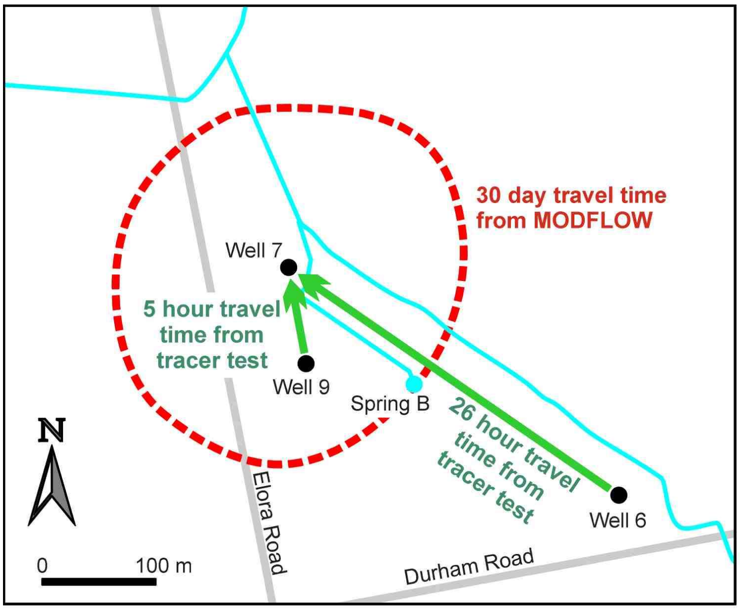

FIGURE 5: THE DANGER OF USING NON-KARST TECHNIQUES TO DELINEATE SOURCE PROTECTION ZONES IN KARST. WALKERTON TRAGEDY; TWO TRACES GAVE VELOCITIES ABOUT 70 TIMES FASTER THAN THE "CONSERVATIVE" MODFLOW SIMULATION INDICATED.

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.

3.2.3 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 that are outlined in Deliverable 5.3.

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.

3.2.4 *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.

3.2.5 *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 6** 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.

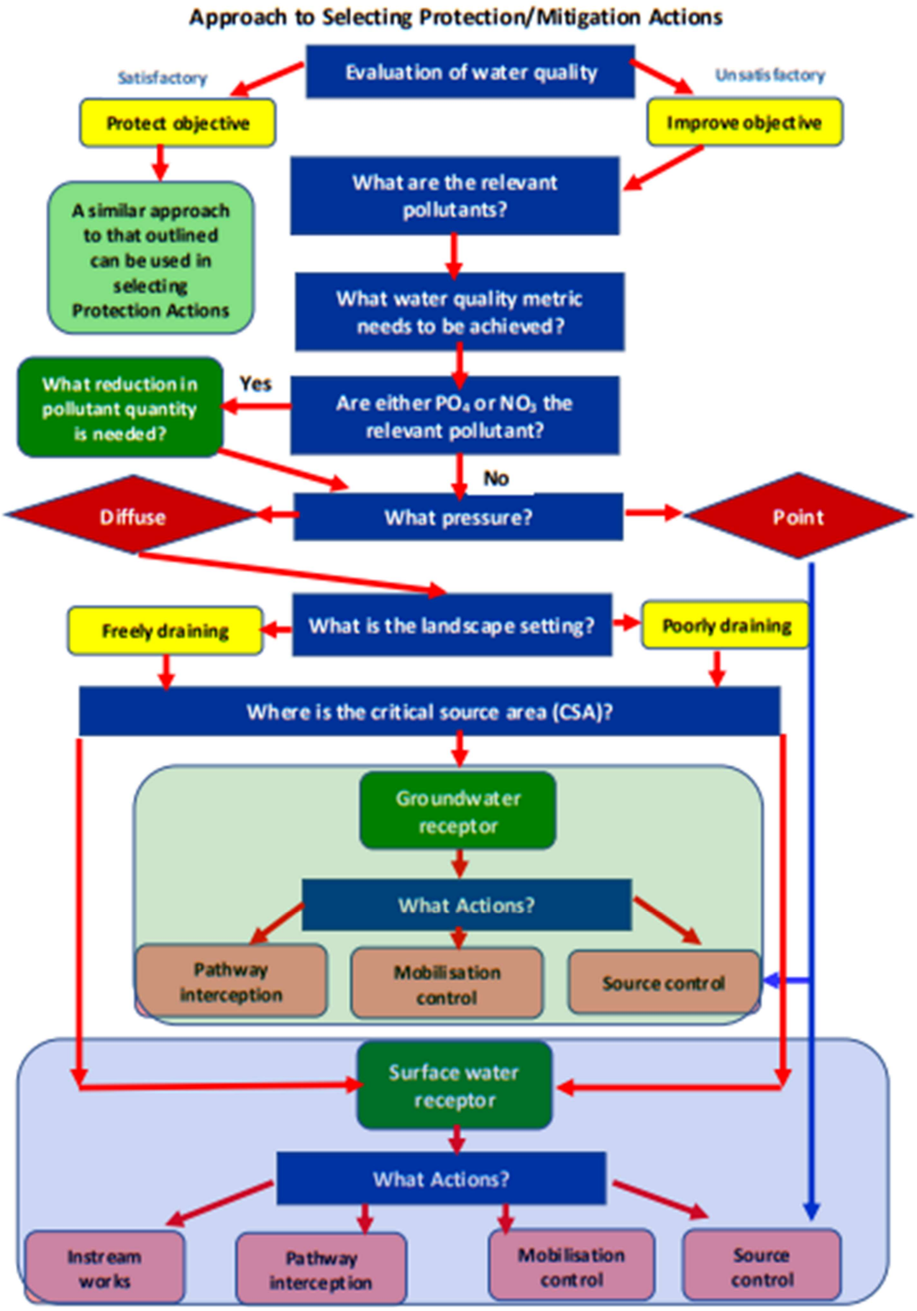

Figure 6: Process flowchart illustrating a recommended approach to deciding on appropriate mitigation Actions (NFGWS 2020)

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

FIGURE 7: 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 9 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 persistant 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.

3.2.6 *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 9), 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).

3.3 Karst Aquifer Recommendations and Classification Methods

The karst classification methods have been outlined and described in Deliverable 5.3. 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 8 shows the data reliability categories in relation to data availability, for method 3. Method 1 ranks springs 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 may suggest that the assessment score 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 8 is suggested.

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

FIGURE 8: 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 9). 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 9, 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 9: 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

3.4 Conclusions

Management of karst aquifer must continue to protect our invaluable karst environments. Karst aquifers are 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 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 9, recommendations that are considered for all karst sources (especially if used as a water supply) are: sustainability assessment, source protection zones and vulnerability mapping. Sustainability 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 as a flashy spring with 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.

4 CONCLUSIONS

In this report, we have considered the two main parameters for the sustainable use of karst groundwater resources: quantity and quality. We have identified and outlined the key management tools which are available to ensure the sustainable use of karst groundwater resources in relation to quantity and quality: sustainability assessments, source protection zone delineation, catchment vulnerability mapping, active and passive management, early warning systems, and mitigation measures. Previous work (outlined in Deliverable 5.3) produced two karst classification systems that enable quantity (or resource availability/regulation capacity) to be plotted on the X axis and intrinsic vulnerability to be plotted on the Y axis to produce an overall spring classification. In this report we relate the outputs from these classifications to the management tools available and recommend which tools should be applied to karst springs according to their position in the classification diagrams. The more vulnerable and the less well regulated in terms of available water resources the aquifer is, as demonstrated by the classification methods, the more aquifer management recommendations there are.

This report provides a framework for assessing the management requirements of karst springs on the basis of a matrix comprising three classes of vulnerability and three classes of water resource availability/regulation capacity.

We have high confidence in the importance of applying the management tools outlined in this report in karst aquifers, and the classification methods proposed in Deliverable 5.3 provide a promising first attempt at karst classification aimed at water management issues. However, these classification methods have only been applied to a limited set of case study sites. As noted in deliverable 5.3, 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 vulnerability classification to boreholes also needs further investigation. Deliverable 5.3 also highlighted the need for further research using large datasets from a wide range of karst aquifers to improve the vulnerability classifications which feed into the management recommendations outlined in this report.

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