Advances in Karst Science

Catherine Bertrand
Sophie Denimal
Marc Steinmann
Philippe Renard *Editors*

Eurokarst 2018, Besançon

Advances in the Hydrogeology of Karst and Carbonate Reservoirs

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Advances in Karst Science

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Marc Steinmann · Philippe Renard
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Preface

The second edition of *Eurokarst* was held in Besançon, France, in July 2018 and involved about 180 participants from 23 countries from all over Europe and the world. All five continents were represented at this event. *Eurokarst* is the largest event on this theme in Europe.

The aim of the *Eurokarst* conference series is to continue promoting advances in research in the field of karst and carbonate reservoirs after more than 40 years of regular meetings.

Once again, the *Eurokarst* conference remains a platform where professionals, consultants, researchers and students can meet to learn about new technologies and methods but also about the practical challenges encountered in applications.

Knowing each other, sharing know-how and the latest scientific advances between the various national and international communities are the major strengths of *Eurokarst*. Among the current topics addressed during this event, and despite their recurrence, the understanding of flows in karst and carbonate formations, the protection and management of water resources are still relevant. In addition, some approaches are diversifying, particularly through the development of new sensors or methodologies applied more specifically to karst.

Eurokarst is a collaboration generator as demonstrated by the "Karst Modelling Challenge" (KMC) working group that was initiated by Pierre-Yves Jeannin at *Eurokarst 2016* in Neuchâtel (Switzerland) with the aim of identifying the most effective approach for modelling karst aquifers in different situations. Eight teams actually submitted models for the Phase 1 of the challenge, which was to model time series of spring flow. The special session dedicated to the KMC was a great success, and the discussions initiated during this session continued around poster communications (20% of the posters dedicated to this research group).

Eurokarst is also a training event, as demonstrated by the success of the workshops to familiarize participants with numerical fluid transfer modelling and new tools for protecting the resource. This day was dedicated to professionals in water resources management, as well as researchers and students. These workshops were initiated during *Eurokarst 2016* in Neuchâtel, and they met with great interest.

Finally, the frequency of this conference makes it possible to realize that the world of research in this very specific environment is progressing. It is satisfying to see that young researchers are as passionate as senior researchers. These young researchers were in the spotlight during this edition by their presence in large numbers and by their professionalism. Some of their works were highlighted by excellent presentations during the plenary sessions. As in *Eurokarst 2016*, the IAH Commission on Karst Hydrology presented awards to three of them. The choice was difficult and in no way detracts from the quality of the young researchers on the side of these awards.

In 2018, for the second edition, *Eurokarst* conference included around 160 communications covering a wide variety of topics in many fields related to karst. Among them, 27 are presented in this book. These articles provide an overview of recent progresses made in karst research. The articles are organized around five main topics:

- Karst landscape and geological control;
- Surface and groundwater interactions;
- Time series analysis;
- Karst modelling;
- Multidisciplinary regional studies.

As the organizers of the *Eurokarst* event and editors of this book, we are extremely thankful to a number of organizations and people who participated in the preparation of the event and without whom the book could not be published. First of all, we would like to thank the sponsors who contributed financially to support the conference:

- The French National Institute for Earth Sciences and Astronomy (CNRS-INSU);
- The Bourgogne-Franche-Comté region;
- The city of Besançon;
- The Communauté du savoir (CdS);
- The Laboratoire Chrono-environnement;
- Springer Verlag AG;
- The Rhone-Mediterranean Corsica Agency.

The partner organizations were the following:

- The University of Bourgogne - Franche-Comté, Besançon, France;
- The University of Neuchâtel, Switzerland;
- The University of Malaga, Spain;
- The Spanish Geological Survey (IGME);
- The SNO KARST;
- The Swiss Institute of Speleology and Karstology (SISKA);
- The International Association of Hydrology (IAH);
- The IAH Commission on Karst Hydrogeology.

We want also to thank very warmly the members of the Scientific Committee of the conference and some additional reviewers (see list on the following page) who have shared their expertise and knowledge with the authors in order to provide the best possible technical quality within the limited time frame available to publish the book. Finally, we want to thank Pierre Nevers who spent countless hours to polish the format of the papers as well as the persons in charge of the project for Springer: Jim LaMoreaux, Samuel Goodchild and Ramamoorthy Rajangam.

A special thanks to the members of the Laboratoire Chrono-environnement whose help was invaluable in organizing the conference. Thanks to Catherine Pagani, Christophe Loup and Nicolas Carry for their help throughout this organization. Thanks to postgraduate and students, especially Thibaut Garin, Justine Cagnant and Selwyna Mereatu and to the colleagues of Chrono-environment for their punctual but nonetheless valuable help.

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Part I

Karst Landscape and Geological Control

Detection and Characterization of Sinkholes Through Integration of Field Surveys and Semi-automated Techniques

M. Parise, L. Pisano, and V. Zumpano

Abstract

Sinkholes are among the most typical landforms of karst terrains. They may originate from a simple downward process, through dissolution of carbonate rocks, or through rapid, sometimes catastrophic, collapse, due to the presence of underground voids or cavities, from where the instability may eventually reach the ground surface. These two extremes imply a great variety in vulnerability of man-made structures, and damage to the population, which makes the analysis of sinkholes extremely important to society. In this contribution, we present an integrated workflow to detect, classify and analyze sinkholes. The ultimate aim is to evaluate the sinkhole susceptibility and hazard. The methodology used will be illustrated by means of an example from the karst of Apulia, south-eastern Italy.

Keywords

Sinkholes • Karst • Susceptibility • Automatic mapping • Apulia

Introduction

Different mechanisms are at the origin of the formation of sinkholes, the most typical landforms of karst terrains (Waltham et al. 2005; Beck 2007; Gutierrez et al. 2014): some start at the ground surface, as the simple action of dissolution, slowly acting in downward direction; others originate from underground, which lead to instability and to the collapse of the cave roof (collapse sinkholes), or of the overburden (cover-collapse sinkholes). The variety of mechanisms implies also significant differences in terms of velocity processes, with important effects concerning civil protection issues and impacts on the built-up environment.

In regions as Apulia, the south-eastern sector of the Italian peninsula, almost entirely built of soluble rocks, karst is definitely the main morphogenetic agent. Along the coastlines landforms are produced by the interaction between karst and sea wave actions.

Identification of sinkholes, and full comprehension of the relationships between the observed karst landforms and the hydrogeological behavior of the carbonate rock mass, is a great challenge in Apulia (Del Prete et al. 2010; Festa et al. 2012; Margiotta et al. 2012; Parise 2015a, b). Especially when working over large areas, mapping sinkholes strongly depends on the scale of the final cartographic product, and the expertise of the operator as well. Changing the scale, some features may become impossible to map, while others can be shown in a quite different way. Subjectivity and karst knowledge of the operator is also a crucial point, as maps produced by several operators for a same area may be very different.

In the last decades, sinkhole occurrence in Apulia has become the main geological hazard, and many tens of sinkholes related to karst caves and with known time of occurrence have been documented (Parise and Vennari 2017). They represent only a small part of a high number of karst features which characterize the different karst sub-regions in Apulia.

In the attempt to find a semi-automatic methodology which might integrate, but not substitute, the classical mapping approach, we present in this contribution a comparison among three inventories produced for a sample area in the karst of Apulia. The first inventory was produced by the first author through intensive field mapping, while the other two were obtained by applying a semi-automated methodology.

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Dataset and Methods

Available Data

The study area was selected in the municipality of Ceglie Messapica (Brindisi province), in southern Apulia. It is an entirely karst area, showing some of the most typical landscape in the region, which covers a territory of 47 km^2. Choice of the area was dictated, beside the interesting karst features and the more than 50 natural caves registered in the municipality, by availability of some base data; namely, these consisted of the Regional Technical Map (topographic map, in scale 1:5000), aerial photographs from different years (nominal scale 1:32,000), 8-mt Digital Terrain Model (DTM) by Apulia Region, and 1-m resolution LiDAR DTM, produced by the local municipality.

Manual Mapping

The first inventory was obtained through intensive field mapping, by using the 1:5000 topographic map as base map; the field work was integrated by analogical stereoscopic analysis of the 1998 aerial photographs. As in many settings in Apulia, land morphology is generally flat, and the use of stereoscopic view is of great help to exaggerate the relief, in order to identify slight features created in the topography by karst processes. In the manual inventory, sinkholes were discriminated by endorheic basins, these latter being defined as terminal areas of confluence of two or more temporary water courses (named *lame*, in the local karst terminology; see Parise et al. 2003). Endorheic basins are generally of larger size with respect to sinkholes, but they show the same shape (mostly, circular to sub-elliptical), and often are located along the main *lame*. Morphologically, sinkholes produced by collapse processes are generally more well defined and recognizable, due to steeper margins and greater depth. The distinction becomes more difficult when dealing with sinkholes produced by solution processes and suffusion (Gutierrez et al. 2014), showing more subtle boundaries. Both sinkholes and endorheic basins may become partly or totally flooded after heavy rainstorms, with water remaining at the surface for hours or days, following the most significant rainfall events. This implies that from a hydrogeological standpoint the two features share the same behavior, acting as sites of concentrated infiltration of the waters underground, thus actively recharging the carbonate aquifer. However, given the different processes at the origin of sinkholes and endorheic basins, they were kept separated in the manual inventory.

Automated Mapping Using Lidar DTM and 8m-DTM

The sinkholes extraction through the semi-automatic mapping was performed by using the algorithm described by Zhu et al. (2014) and by Wall et al. (2017). This algorithm is based on the DTM exploitation in GIS environment and was successfully used to map sinkholes (dolines) in karst environment (Doctor and Young 2013; Wall et al. 2017).

We used the "Fill" tool available in ArcGIS software, that in karst topography is applied for the recognition of topographically depressed areas (Doctor and Young 2013; Jeanpert et al. 2016; Wall et al. 2017). This tool identifies the depressions in the input raster, so that it is possible to obtain a filled DTM that can be differentiated from the original to produce a depth raster. The tool can be reiterated multiple times in order to fill all the depressions with different depths in the raster. We decided to choose z-limits fills of 2-m intervals, starting from 2-m depth until we had redundancy in the number of filled depressions (Kobal et al. 2015). After obtaining the filled rasters for each z-limits, the difference with the initial raster was determined, and using the Boolean Logic the fill-differences were transformed into polygons representing the sinkholes.

Before moving to the calculation of the morphometric parameters, we decided to choose the shapefile polygons map with the z-limit better representing the real situation in the analyzed study area by using the expert opinion and field activity, but also through careful comparison with the manually mapped database (Fig. 1).

In order to make the process lighter and faster, we built a tool by using the Model Builder in ArcGis software. Once the model was set up, it required only the input DTM to perform the analysis and to provide the sinkholes polygon shapefile for the multiple z-limit.

In the case of automatic procedure, the identified features include both sinkholes and endorheic basins, regardless of the processes at the origin of these landforms. An overview of the number of features in each database can be found in Table 1.

At this point, we set up another model to smooth the polygons and calculate a series of morphometric parameters (Table 2) useful to characterize the obtained database: area; perimeter; CI (Circularity Index); nearest feature and its distance; length of the long and the short sinkhole axes (Kobal et al. 2015); azimuth of the sinkhole long axis, elongation ratio and shape (Basso et al. 2013). These parameters, well known in the literature (Basso et al. 2013; Pepe and Parise 2014; Kobal et al. 2015), are calculated for both the automatically and the manually obtained databases, and only two of them will be presented hereafter (Figs. 2 and 3).

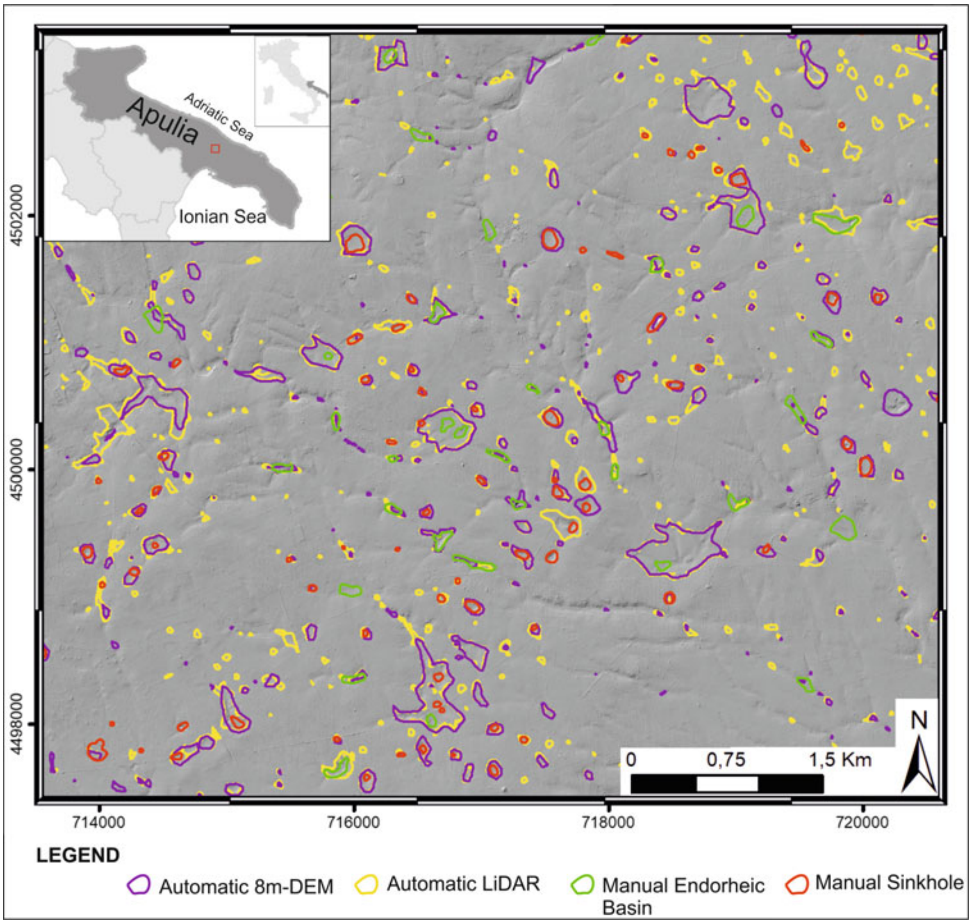


Fig. 1 Extract from the study area, showing the three datasets in different colors: green and red colors mark, respectively, the endorheic basins and the sinkholes mapped manually; yellow color indicates the sinkholes identified through the Lidar analysis, and purple color those identified through the 8m-DTM

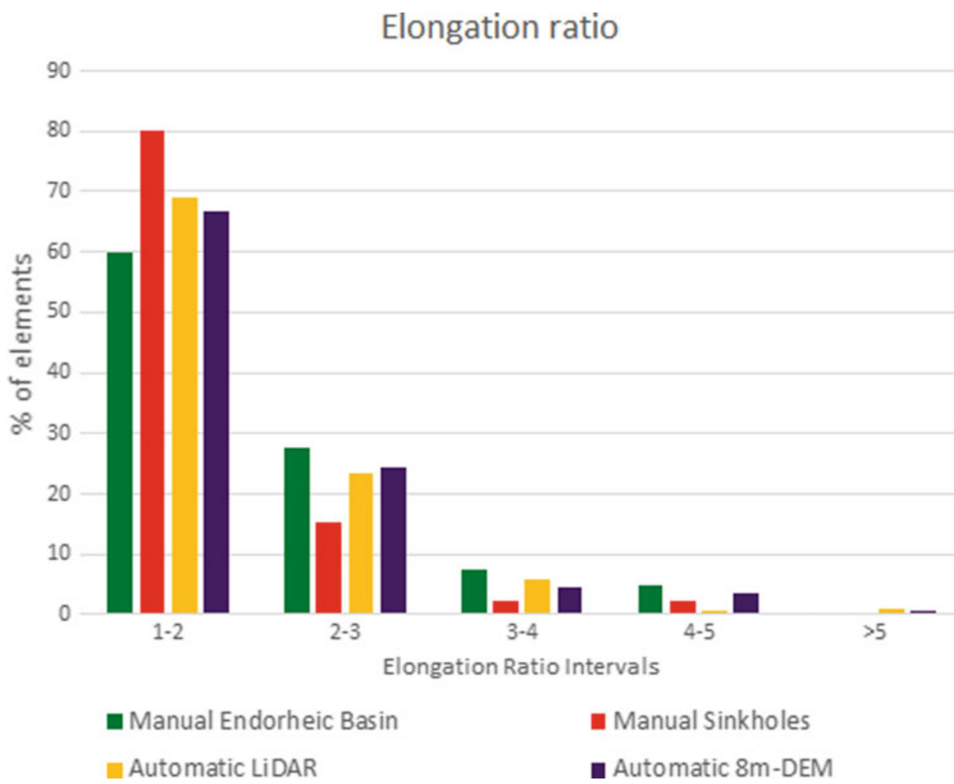
Table 1 Summary table of the mapped features, according to the different used techniques

Mapping technique	Number
Manual mapping	131 (40 are endorheic basins)
Automated mapping (8m-DTM)	192
Automated mapping (Lidar)	523

Table 2 Summary table of the calculated morphometric parameters, the method used and the related reference

Parameter	Method	References
Area and perimeter	Calculate Geometry tool, ArcMap, ESRI ArcGIS®	–
Circularity Index (CI)	CI = 4πArea/Perimeter	De Carvalho et al. (2014)
Nearest feature	Near tool in Proximity Toolset, ArcMap, ESRI ArcGIS®	–
Distance nearest feature	Near tool in Proximity Toolset, ArcMap, ESRI ArcGIS®	–
Shortest and longest axes length	Minimum bounding Geometry in Feature Toolset, ArcMap, ESRI ArcGIS®	(Kobal et al. 2015)
Azimuth of the longest axis	Minimum Bounding Geometry in Feature Toolset, ArcMap, ESRI ArcGIS®	(Kobal et al. 2015)
Elongation Ratio (ER)	Ratio between the major and the minor axes	(Basso et al. 2013)
Shape	Circular: ER < 1.05; Sub-circular 1.05 < ER $\leq$ 1.21; Elliptical 1.21 < ER $\leq$ 1.65; Sub-elliptical 1.65 < ER $\leq$ 1.8; Elongated ER > 1.8	(Basso et al. 2013)

Fig. 2 Percentage of elements mapped with different elongation ratio



This procedure was applied to the 8 × 8 m resolution DTM and to 1 × 1 m Lidar DTM, giving different results in the number of mapped sinkholes (Table 1), but also in their shapes and the morphometric parameters (Figs. 2 and 3).

Finally we set up a last model to automatically clean the maps from possible artefacts attributable to errors in the DTM generation process, keeping only features significant as sinkholes. Following the published literature (de Carvalho et al. 2014; Bauer et al. 2015) the model was set up in order to operate a selection of the obtained polygons, on the basis of the diameter length and the CI. For the Lidar DTM, given its high resolution we decided to pick only the polygons with a diameter greater than, or equal to, 10 m, in order to eliminate small features probably not significant as karst forms (Kunaver 1983; Kobal et al. 2015). Furthermore, we eliminated the polygons with $CI < 0.1$ in order to have prevailing circular forms, and to decrease the number of elongated ones, which are typically attributable to water course segments.

For the 8m-DTM, we eliminated the polygons with a diameter smaller than 25 m, and with $CI < 0.1$.

The obtained databases were finally compared with the manually compiled inventory, and the differences were analyzed highlighting the strengths and weakness of each database.

Results

On the one hand, looking at the morphometric parameters considered, we evaluated that there is a certain degree of agreement in the elongation ratio (Fig. 2), showing the range 1–2 as the most common for all the considered techniques.

On the other hand, concerning the orientation (Fig. 3), there is a high heterogeneity in the data belonging to the different inventories. For the LiDAR- and the DTM-derived map, the highest count was found in the classes between 80° and 180°. In the manual inventory, the elements were almost homogeneously distributed in the entire 60–120° range (Fig. 3).

Other differences were also found in the shape of the sinkholes in the three inventories, and an example is reported in Fig. 4. In fact, it was observed that very often the accuracy of the sinkholes depicted with the automatic mapping is strictly connected with the DTM resolution, giving better results using LiDAR (the highest resolution). Further, during field observations the manual mapping was observed as the most accurate in the delineation of the correct sinkhole contouring.

Nevertheless, it is important to point out that some relevant sinkholes verified in the field were not detected by

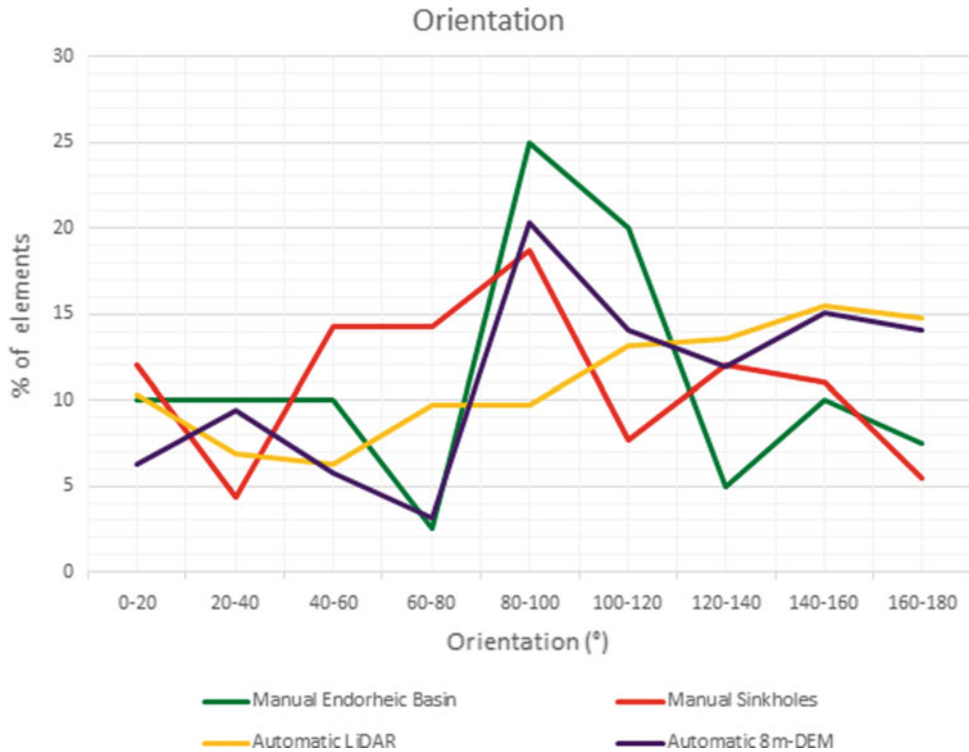


Fig. 3 Orientation of the major axis of sinkholes and endorheic basins, with respect to the North, for a range of 180°

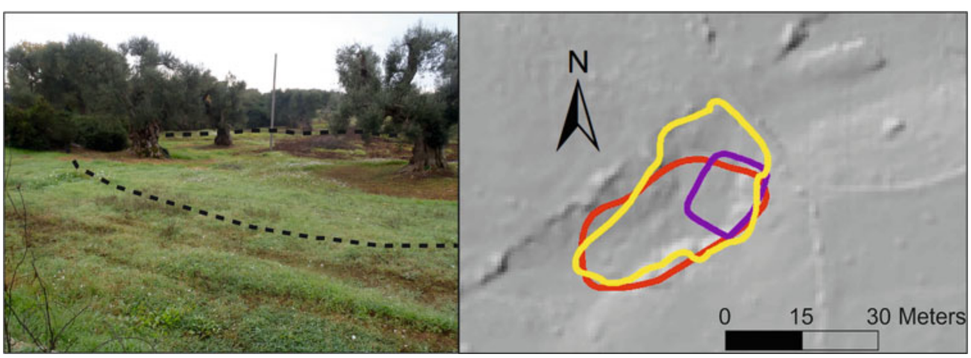


Fig. 4 Example of a sinkhole mapped by the different techniques. The "manual mapping" (through aerial photo interpretation) is shown in red, the automatic one obtained by using the Lidar DTM in yellow, and that by the DTM in purple. The dashed line in the picture to the left marks the boundary of the manual mapping

manual mapping but only by the automatic method. This indicates the understandable fallibility of the human eye in operating a complete scanning of the territory during mapping, especially in difficult conditions such as in areas with presence of a dense vegetational cover (Bauer 2015).

Conclusions

Overall the automated mapping can be considered an effective method, as demonstrated by multiple authors (i.e., Pardo-Igúzquiza et al. 2013, 2016; Wall et al. 2017), but on the basis of the evidences presented here, it cannot be considered self-sufficient to compile accurate and reliable sinkhole inventories. In fact, it was observed that automatic mapping can detect a much larger number of features with respect to the manual, this difference being commensurate with the resolution of the input topographic data.

However, considering the evidence collected during the field observations we can conclude that the automatic mapping cannot disregard the expert validation via visual interpretation and even better when it is carried out using digital stereoscopy. In some cases the automatic tool can overestimate the number of features counting morphological convergences or artifacts.

An advantage of the automatic procedure by using LiDAR is definitely the possibility to detect karst landforms in forested areas, where the vegetation covers might hinder, or completely mask, the presence of terrain features, making very difficult their identification in the field (Parise et al. 2018). In these situations, the possibility to have a look at the land without the canopy cover will certainly allow a better depiction of the landforms.

Generally, low-resolution DTMs are more easy to acquire as it is in our case study; moreover, one must take into account that the results are not fully satisfactory, especially in areas where depressions are of smaller dimensions.

On the other hand, applying the automatic mapping tool, especially over large areas, before starting the expert-based interpretation, could provide an important support in terms of time, precision and gaps reduction. In conclusion, we believe that integrating or better, anticipating, the manual mapping with the automatic one could be the right compromise for karst sinkhole interpretation and mapping.

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Karst and Vegetation: Biodiversity and Geobotany in the Sierra de las Nieves Karst Aquifer (Málaga, Spain)

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Abstract

The Sierra de las Nieves karst system is a high-relief Mediterranean karst that hosts important botanical diversity, including the unique Spanish fir *Abies pinsapo*. Vegetation is mainly controlled by the soil development and climatic conditions. In turn, the soil is controlled by lithology, fracturing, weathering and slope. There is also positive of soil and vegetation feedback in the epikarst development. This study focuses on the spatial variability of vegetation in a karst massif and its relationship with the main lithologies, karst depressions, fracturation density and slope. Contingency analysis shows degrees of association between the plant species studied and the other parameters. Thus, plant species preferences have been found for certain lithologies, degree of fracture development, karst depressions of ground slope.

Keywords

Karst • Biodiversity • Vegetation • Geology

Introduction

Only limited research has been carried out into the influence of karstic terrain lithology on vegetation (Williams 2008; Bakalowicz 2004, 2012). The spatial development of the epikarst is influenced by the interaction of different factors such as lithology, tectonic structure, density and orientation of faults and joints, degree of weathering, slope, vegetation and/or climatology (Klimchouk 2004). In addition, rainfall seeping through fractures and organic material increases the dissolution rate and fracture growth (Williams 1983; Ford and Williams 2007). Other characteristics or concentrations of different parameters related to chemical and microbial properties of soil or climate and their influence on vegetation have been analyzed by various authors (Bakalowicz 2004; Efe 2014; Liang et al. 2015; Tonga et al. 2017; Shen et al. 2013 among others). Results obtained show specifically that the chemical and microbial properties of the soil differed significantly depending on the vegetation types analyzed (Lu et al. 2014).

Factors such as topography, soil formation and vegetation distribution have been studied by several authors (Atalay 1988, 1991, 1997; Barany-Kevei and Horváth 1996). The development of soils and the successional evolution and establishment of vegetation in karst terrains are primarily conditioned by the physical and chemical properties of limestones (Shen et al. 2013).

Liang et al. (2016) studied *Arbuscular mycorrhizal fungi* that form an important part of plant growth and restoration in degraded ecosystems. Thus, soil pH shows highest in the shrub and lowest in the tussock, and the clay content is lower and the silt and sand content is higher in the primary forest than in the other three vegetation types. Liu et al. (2016) study carbon sequestration potentials of karst vegetation.

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Both biotic and abiotic factors, such as climate, site condition, species composition, community structure and human disturbance, largely influence vegetation carbon stocks (Liu et al. 2016).

In this context, the availability of the above parameters together with plant species mapping would enable us to determine which factors influence the vegetation distribution.

This paper is a first comprehensive approach to identifying the relationship between vegetation and karst in Sierra de las Nieves. To do this, vegetation maps, lithologies, fracture density, karstic depressions and slope have been used. Geostatistical methods and ArcGIS tools have been used to process the information. Contingency analysis has been used to estimate the statistical significance between the plant species and other parameters available in the study area.

Case Study

Geological Setting

The Sierra de las Nieves karst system is a high-relief Mediterranean karst in Málaga province in southern Spain (Fig. 1) with a surface area of 125 km^2. The aquifer presents a wide range of altitudes from the system base level at the source of Río Grande Spring (359 m a.s.l.) to the maximum altitude on the Torrecilla peak (1919 m a.s.l.) as shown in the digital elevation model in Fig. 2. From a geological viewpoint, the Sierra de las Nieves aquifer is part of the Nieves Unit, formed by a Triassic to early Miocene succession mainly composed of carbonate formations (Fig. 1). From base to top, the Triassic series comprises dolostones, alternating marls, marly limestones and micritic limestones. The Jurassic–Paleogene sequence is dominated by cherty limestones, nodular limestone, marly limestones and marls (Martín-Algarra 1987).

The fractures and joints are taken from Pedrera et al. (2015) to estimate the fracture density by geostatistical methods (Fig. 3).

Previous Studies and Inventory of Vegetation

The vegetation database used is produced by of the Junta de Andalucía, Consejería de Medio Ambiente y Ordenación del Territorio (JA 2017).

Sierra de las Nieves displays a wide range of vegetation of significant biological interest including *Abies pinsapo, Quercus alpestris, Juniperus Sabina, Berberis hispanica, Ulex baeticus, Pinus halepensis, Pinus sylvestris* and *Quercus faginea* (Cabezudo-Artero et al. 1998). The main plant associations or species mapped by JA (2017) are *Abies pinsapo* (Figs. 4 and 8), *Juniperus sabina* (Figs. 5 and 8), garrigue (*Berberis hispanica, Ulex baeticus*) (Figs. 6 and 8), *Quercus faginea, Quercus alpestris* (Figs. 7 and 9), mixture

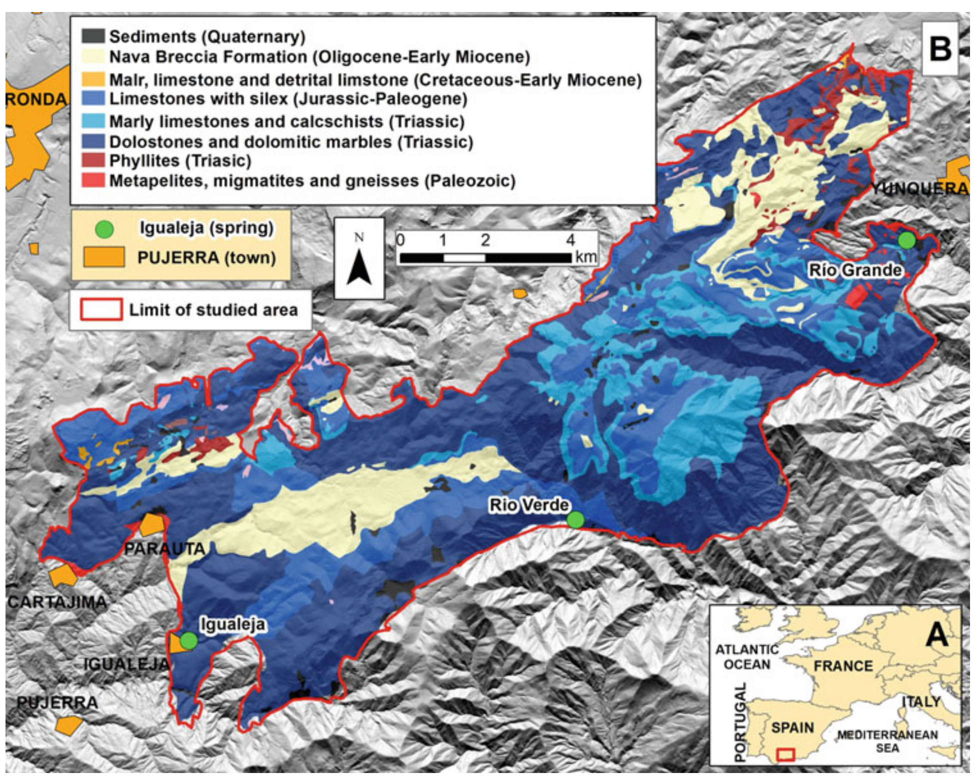

Fig. 1 Geological map of Sierra de las Nieves (modified from IGME 2015)

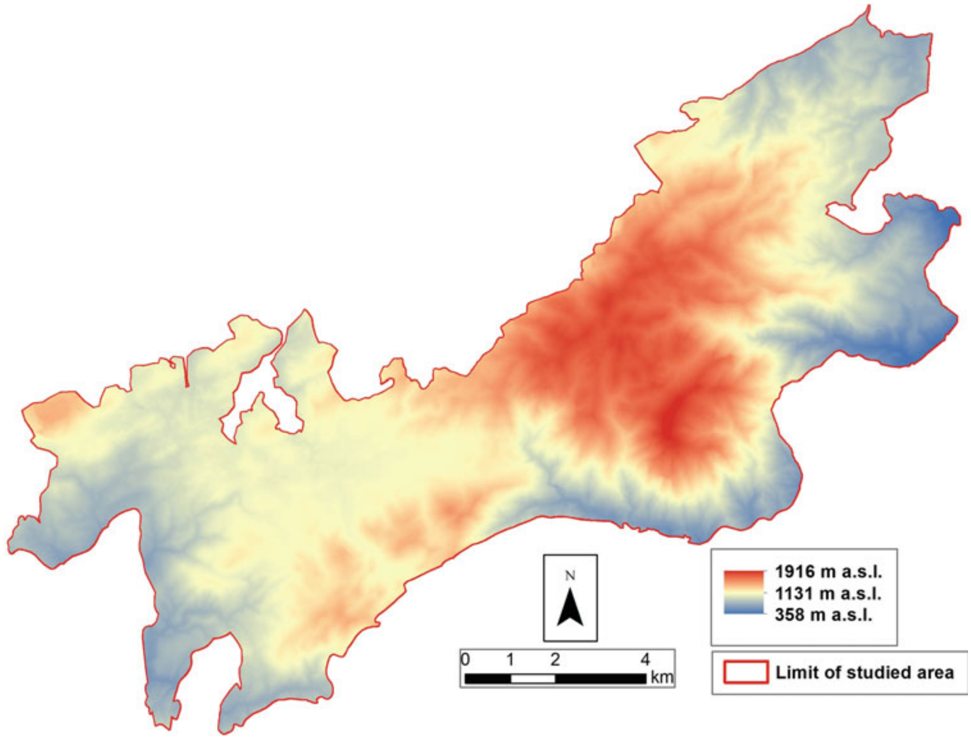

Fig. 2 Digital elevation model of the Sierra de las Nieves karst aquifer

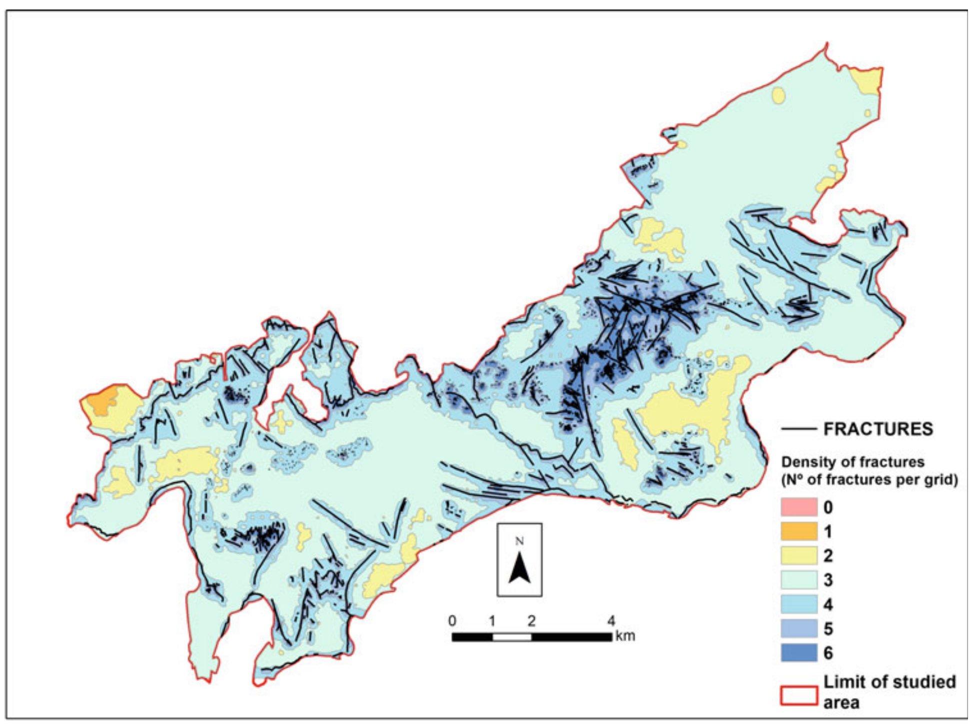

Fig. 3 Fractures and fracturing density estimated by Ordinary Kriging

of *Quercus ilex* and *Pinus genus* (Fig. 9), *Pinus genus* and high mountain scrub (*Cenista spartoides, Juniperus comunis* and *Berberis hispanica*) (Fig. 9) and *Quercus ilex* (Fig. 9).

Following observations in the study area, a four-stage conceptual model of spatial vegetation development is proposed (Fig. 10).

Fig. 4 *Abies pinsapo* forest

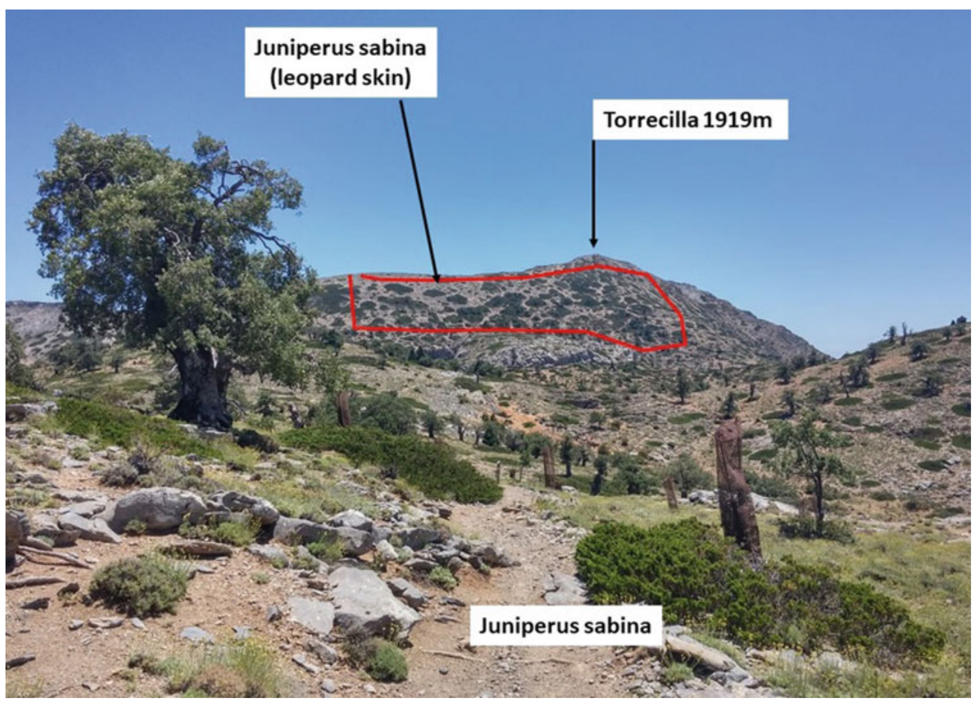

Fig. 5 *Quercus faginea* and Juniperus Sabina

Vegetation Mapping by Remote Sensing

Sierra de las Nieves shows a wide range of vegetation types: needleleaved evergreen trees (*Abies pinsapo*, *Pinus halepensis* or *Pinus sylvestris*), broadleaved deciduous trees (*Quercus alpestris, Quercus faginea* and *Quercus ilex*) and shrubland (*Juniperus Sabina*, *Berberis hispanica*, *Ulex baeticus, Cenista spartoides and Juniperus comunis*) (Cabezudo-Artero et al. 1998).

This study used spring and summer images for land-cover classification. Two Level 1C Sentinel-2 scenes of the same area in southeast Spain were downloaded (tile T30SUF). The

Fig. 6 Garrigue (*Berberis hispanica*, *Ulex baeticus*)

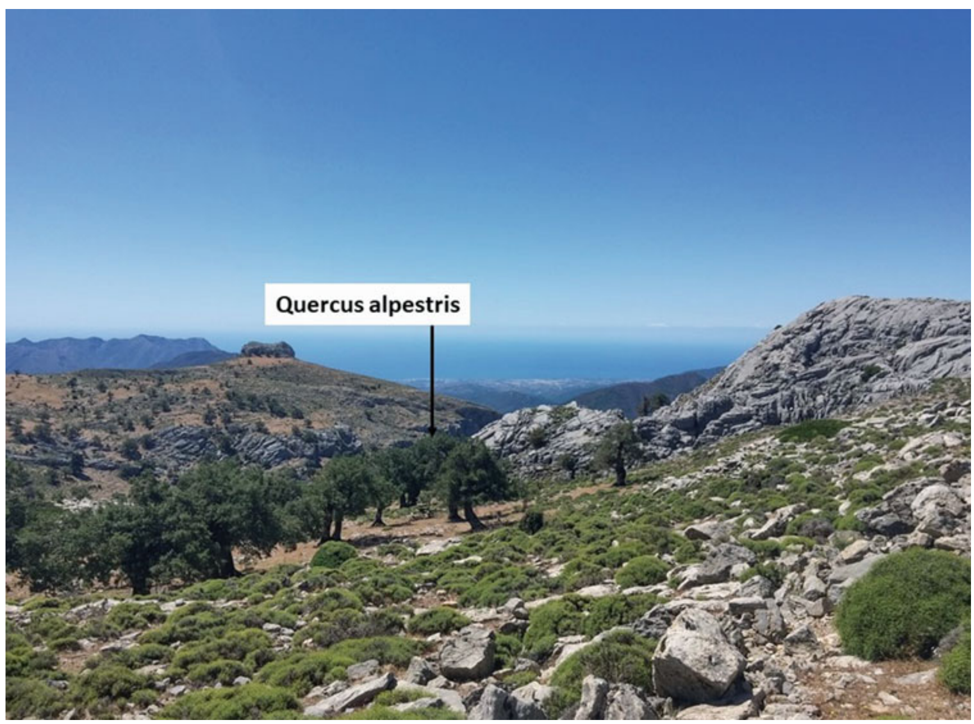

Fig. 7 *Quercus alpestris*

images were acquired on July 23 and March 20, 2017, and downloaded from the ESA Sentinels data hub. Both Sentinel-2 scenes were cloud-free and were processed from Top-Of-Atmosphere (TOA) Level 1C to Bottom-Of-Atmosphere (BOA) Level 2A reflectance using Sentinel-2 Toolbox (Sen2Cor). The spatial resolution of the red-edge and short-wave infrared (SWIR) bands was resampled to 10 m using the nearest-neighbor method to ensure integration with the 10-m visible and near-infrared (NIR) bands. Normalized difference vegetation index (NDVI) (Rouse