The challenge of tunneling through Mediterranean karst aquifers: the case study of Trieste (Italy)

The planning of large-scale infrastructures in karst areas

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Abstract After the 1st May 2004, when new countries joined the European Union, the need was felt to link these states through an infrastructure network of motorway and railway links (high speed—HS/high capacity—HC) easily able to transport all possible goods throughout Europe. Within this framework, 14 different projects were developed with the aim of linking important cities. One of these links is the Corridor V connecting Lisbon (Portugal) to Kiev (Ukraine) and assigning a strategic role to Italy with respect to the integration process of these countries. In detail, part of the Corridor V is expected to start from Venice, reaching Trieste and from here on to Ljubljana (Slovenia) before proceeding to Budapest and finally reaching Kiev in Ukraine. The whole development (from Portugal to Ukraine) is approximately 4,000 km long of which, about 30 km (less than 1 % of the entire route), falls within the Italian Classical Karst area, a highly karstified zone, renowned worldwide as one of the best karst landscapes on the planet. The present paper regards the GIS statistical methodological approach used to identify the degree of karstification of the Italian Classical Karst providing the stakeholders all the necessary information while planning possible railway HS/HC solutions.

Keywords Classical karst · Hydrogeology · Tunnel · GIS · Karstification factor

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Introduction

When planning underground structures in karst areas it is necessary to carefully evaluate the extent of the karst landforms, including epigean and hypogean ones (Day 2004; Xeidakis et al. 2004; Casagrande and Zini 2005; Knez et al. 2008; Peila and Pelizza 2009; Ismail et al. 2010). In fact, if a hydrostructure contains carbonate rocks, these are most probably karstified. In this framework, it is critical for the success of the actions, to define the entity and the characteristics of the karstification with the dual purpose of minimizing the hydrogeological risks and quantifying the geomorphological ones. It is very important to analyze the possibility of encountering caves or other hypogean karst features and any interactions with percolating and underground flowing waters. The solution can certainly be found in the analysis of the speleogenetic framework, in its geological, geomorphological and hydrogeological characterization, at large and small scale, in shallow zones as well as at depth, using direct and indirect field investigations. All these data can be used later to obtain maps where certain field data allow the validation of the hypothesis built using statistical interpolations. The degree of karstification depends upon the jointed phases: (1) the duration of the rock's exposure to water; (2) to the quantity and type of the effective precipitation and (3) the hydraulic gradient between infiltration areas and any springs. In order to render a meaningful expression of karst features, the time required is usually much greater than the times scales within which people are accustomed to think (Furlani et al. 2009). It is important to remember that in the evolution of surface karst landforms, the karst (in the chemical sense of the word) generates meaningful shapes over a timescale with 10,000 years as the reference time unit. For the hypogean features, the time units are in the range of 50,000–100,000 years (Ford et al. 1988; Palmer 1991; Vigna 2002; White 2007). The karstification type depends on the geological and structural characteristics, from its geographical position, the geomorphology of the hydrostructure, the connections between the different zones including the epikarst and the vadose zone and the epiphreatic zone reaching the phreatic one. Even if the speleogenesis is "randomly distributed", the "randomness" is, in any case, driven by the discontinuities that force the path of infiltrating waters, the variable solubility driving the selective widening of the fractures and caves. The geometry of the Formation/Lithological Unit and the type and distribution of the discontinuities, guide the early stages of the speleogenesis forcefully and continue to guide their evolution over time, during and after the hierarchization of the hypogean groundwaters. Variations in the geological settings entail changes in the water hydrodynamics and in the chemical and physical processes and the karst itself is a chemical process and so its effectiveness depends mainly on three components. Apart from the "solid" part, (the rocks), the climatic characteristics are those that most affect the process, leaving subordinate role to the mixing phenomena (Ford and Williams 2007). It follows that the processes will have different effects in the different climatic zones, being sensitive to the presence of catalysts such as ions external to the system, temperature variations, etc. (soils, thermal waters, interactions with seawater, etc.). Time sees climate changes such as variations in the amount of rainfall, fluctuations in the base level with subsequent rejuvenation or aging of the hydrographic network, changes in the environmental and geological framework (vegetation cover, soils, landforms, tectonic, paleo-environmental and hydrogeological). All this means constantly evolving and interacting processes that, from time to time, lead the chemical developments to prevail over physical ones or vice versa. Dissolution (standard, accelerated or delayed), speleothems (localized or widespread), gravitational (falls and/or topplings) and hydrological processes (erosion, transport and sedimentation) always take place simultaneously.

As Xeidakis states (2004), from the engineering point of view a karst area can be considered one of the most difficult frameworks to study and to approach (Song et al. 2012). All the site-specific information that an expert can provide may represent only a good overview, but will never be exhaustive, and while faced with the construction of a new infrastructure, the unexpected can always occur, even in well-known areas. The development of caves and the directions they take are mainly controlled by the orientation of any joints and the directions taken by groundwater flow. But these skills are insufficient to predict the presence of voids, conduits and caves in the subsurface (Milanović 2000) as happened in the case of the Sol-an tunnel in South Korea where subsidences and sinkholes occurred during the tunnel excavation (Song et al. 2012). In addition, the comparison between geological structures and river patterns, as carried out by Zabidi and De Freitas (2011) helped in the evaluation of the rock quality mass classification. The preliminary results obtained were later verified, re-evaluating TCR, RQD and SCR values at the SMART tunnel construction site in Kuala Lumpur to reclassify and divide the rock mass in sectors with different qualities. According to Milanović (2000), "*the risk cannot be totally eliminated by increasing the investigative program, but perhaps it can be minimized to an acceptable level*". Marinos (2001) for example, introduces the importance of hydrogeological studies when addressing the issue of tunnels. Any tunnel constructed in a karstic environment offers experiences in groundwater problems associated with stability and safety issues, not only with the incoming water while tunneling, but also the sudden increase in the fluctuating water table. As a general consideration, Marinos (2005) asserts that it is essential to have an accurate preconstruction assessment of the groundwater conditions in order to avoid unforeseeable occurrences, or at least to constrain them. He also prepared a list of actions that might be included in the procedure of analysis with particular attention to karst environments where, at least in the early stages of investigations, it is fundamental to understand the karstic pattern around the tunnel and the hydrogeological conditions in detail. Marinos (2005), in fact, split up the assessable options into several possible hydrogeological models in a limestone environment, starting from Case 1 concerning non-karstic limestones and arriving at Case 2.2.2 where karstic limestones are involved and where the flow is guided by a homogeneous interconnected system of karst fractures and enlarged joints. For each one of these cases he specified the hydrogeological settings and the possible procedures to avoid any drawbacks. This author, also revised several case histories in limestone environments including the Giona (1973) and Dodoni (2000) tunnels in Greece, the experience in Ontario previously described by Ford and Williams in 2000, the case of Columbus in Ohio, USA (1992), of Montelungo in Italy (1997), the Steinbuhltunnel (2005) and Zuckerberg (2003) in Germany, the Karawanken tunnel in Austria/Slovenia (1989) and several other impressive cases around the world having all encountered difficulties due to the hydrogeological conditions. As he suggests, the Karst Commission of the International Association of Engineering Geology in the report drawn up by Calembert in (1975), presented a series of case studies in which fresh groundwaters engendered serious problems while boring the tunnels. Since then, the problems of karst features are still an open question while constructing such important infrastructures in extensive karstified areas. To date, researchers are not yet able to predict the presence of a subsurface cave or void. It is possible to reach a good degree of accuracy by estimation, but while going on with the construction, flexibility and ongoing investigation are required during the project.

In the present paper, the authors suggest an objective GIS-based methodological approach able to define a conceptual model of the karstified area under investigation in order, as far as possible, to avoid setbacks while undertaking the construction of infrastructure and to suggest the best solution during design. This is what took place during the Corridor V, high-speed railway line that should connect Lisbon and Kiev while passing through Italy and crossing the Classical Karst area (Fig. 1).

Methodological approach

When the aim, in the broadest sense of the term, is "to characterize" a karst area, the approach cannot be foregone. In fact, the methodological approach in an area affected by karst features implies the recognition, understanding and outlining of areas exhibiting different degrees of karstification. Joint geomorphological (on the surface and at depth) and hydrogeological (monitoring of springs, lakes, wells and caves) surveys are prerequisites for a successful outcome. It is not possible, in fact (Alija et al. 2013), to approach a karst area with a standard methodology (prospection and regular testing campaigns). The approach needs to be integrated with other techniques specifically adapted to the study site in order to locate and anticipate the problematic zones (Marinos 2005). Karstification has the peculiarity of not being homogeneous in space, either on the surface or at depth. For this reason, on occasion, investigations do not prove meaningful.

The present paper summarizes the methodological approach used to characterize the heterogeneity in terms of (1) the distribution of voids within the rock mass, and (2) groundwater circulation. It aims to objectively identify the karst features through a karst index (KF) that, in

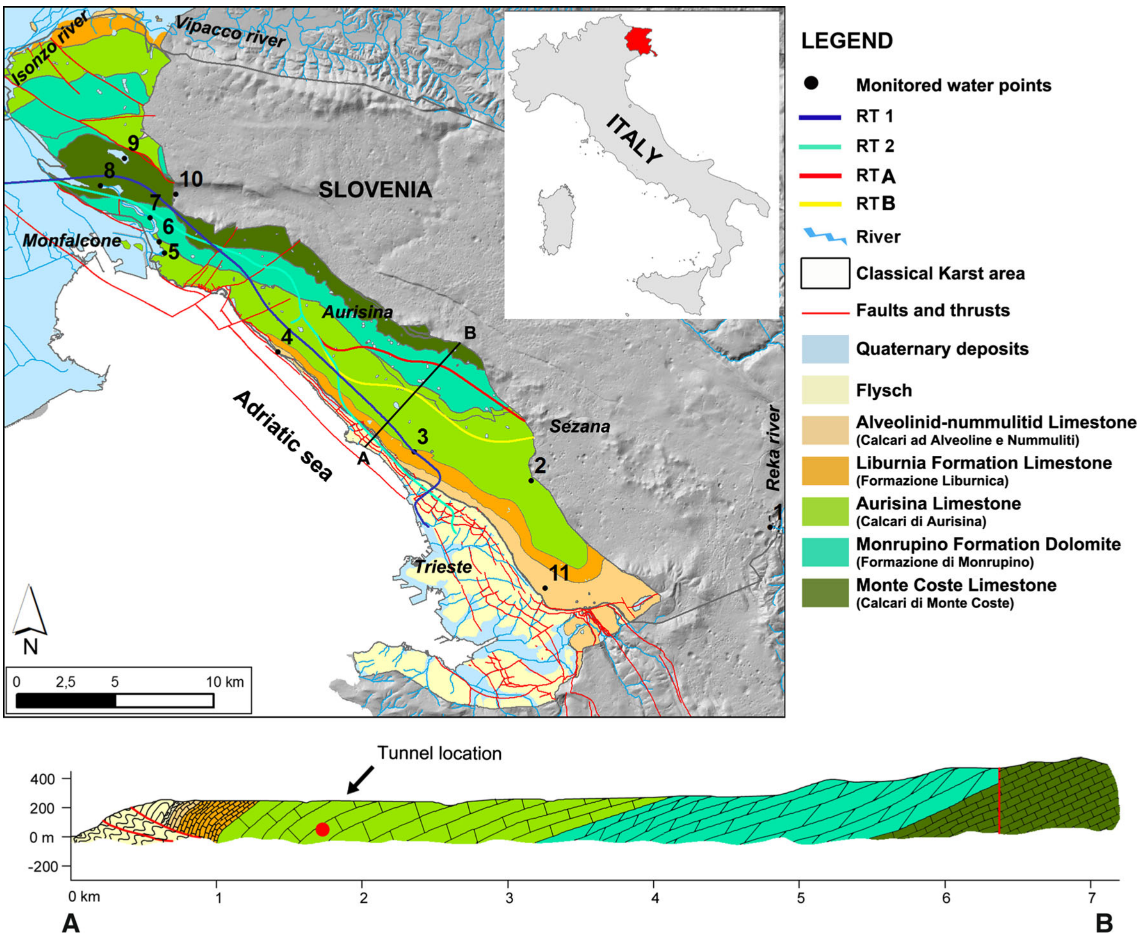

Fig. 1 Geological map of the study area and relative cross-section with the proposed railway tracks (RT), *1* Škocjan sinkhole, *2* Trebiciano Abyss, *3* Opicina piezometer, *4* Aurisina springs, *5* Timavo springs, *6* Sardos spring (Italian aqueduct), *7* Moschenizze Nord spring, *8* Pietrarossa lake, *9* Doberdò lake, *10* Klarici pumping station (Slovenian aqueduct), *11* Grotta Impossibile

conjunction with the lithological and the hydrogeological knowledge available, allows the area to be characterized. The approach starts with the identification of the main karst features such as the dolines and the caves and analyzes their density on the territory using GIS-based tools. Later on, the hydrogeological part is analyzed. The caves with waters and the springs can be used as study sites for measuring parameters such as discharges (Q), electrical conductivity (EC) and temperature (T) (Banzato et al. 2011; Mudry et al. 2008; Hershey et al. 2010; Galleani et al. 2011). The hydrographical and chemographical analyses allow an understanding of the system's response to rainfall events, allowing distinctions to be made between the main potential karst types: the dominant conduit system, any interconnected conduits and the dispersed circulation (Vigna 2002) each one exhibiting a well-defined and typical hydraulic behavior (Linan Baena et al. 2009; Fiorillo 2014). The characterization of the groundwaters in karst terrains at different water flow regimes is relevant in understanding the relationships between fractures and conduits, in order to define the water inflow, drainage effectiveness and the relationship with more vulnerable areas (Ford and Williams 2007; Galleani et al. 2011).

The Trieste case study

The idea of creating traffic corridors across Europe emerged after the end of the Cold War. Since then, modern infrastructure has been developed in order to facilitate the exchange of goods and commodities as well as passenger and road traffic between Europe and the Balkan States. The idea of Corridor V, the Trans-European high-speed rail network can be viewed in this context, connecting Lisbon to Kiev through Italy and running for over 4,000 km, crossing a wide range of environments and encountering virtually all the potential geological problems. Along the entire course, one of the most difficult areas to approach is the one linking Italy to Slovenia. Here, highly karstified rocks are widely distributed. Having crossed the French Alps and passing across the Po plain, the railway arrives at Monfalcone and from here, a tunnel is proposed that would cross the Trieste Classical Karst joining the two countries and connecting Trieste with Sežana (*c.* 350 m a.s.l.).

The "Classical Karst" is a wide morpho-karstic unit that extends from the Isonzo River (ITA) as far as Postojna (SLO). It contains epigean and hypogean karst forms, whose concentration, dimension and type have made this area the worldwide symbol of karst phenomena. The Trieste Karst belongs to the "Karst-Friuli carbonate platform", the northern portion of the "Adria plate", formed by a thick sequence of carbonate rocks ranging from the Triassic to the Eocene (Cucchi and Zini 2007). In the area of interest the following outcrops occur: the "*Calcari di Monte Coste*", the "*Formazione di Monrupino*", the "*Calcari di Aurisina*", the "*Formazione liburnica*" and the "*Calcari ad Alveoline e Nummuliti*".

The *Calcari di Monte Coste* (Aptian–Albian) represent the most ancient part of the platform and are characterized by well-layered blackish-grey bedding mudstone typical of a shallow-water carbonate platform (shelf lagoon and tidal flats). At its base, the *Formazione di Monrupino* (Cenomanian), has monogenic breccias with dolomitic clasts. The prevailing lithologies are grey dolomite and blackish-grey calcareous dolomite. They are characteristic of shallow-water carbonate platforms (shelf lagoon and reefs). The *Calcari di Aurisina* (Late Cenomanian) are largely grey bioclastic limestones with very frequent radiolitids and hippuritids. They are typical of two slightly different shallow-water carbonate platform deposition environments: reef and open and inner platform and reef. The *Formazione liburnica* (Late Campanian–Thanetian) is largely characterized by two typical lithologies: a) light grey very fossiliferous (Rudist) limestones (a supertidal platform) and b) blackish-grey bedding mudstone (tidal flats). The *Calcari ad Alveoline e Nummuliti* limestones (Late Thanetian–Ypresian) are characterized by very light grey and very fossiliferous (Foraminifera and Gasteropoda) limestones initially deposited on a subtidal marine environment, and later on an open slope. At the top of the carbonatic sequence, the carbonates are overlain by Flysch (Lutetian) made up of marl and sandstone interbeddings, (Cucchi and Piano 2013).

From a structural point of view, the Karst Plateau is part of a wider geological unit known as the "Komen platform", characterized by a slightly asymmetrical anticline oriented NW–SE (passing approximately through Doberdò lake (ITA) and Sežana (SLO) and whose structure is complicated by a set of secondary folds and faults (Placer 1981). Along the edge of the plateau, in the coastal areas, the layers become subvertical and sometimes overturned. The anticline axis wheels slightly counterclockwise in the area close to the border with Slovenia, where a series of strike-slip faults with weak horizontal and vertical displacement are present. In the Italian part, the layers have a SW dip direction with a dip angle ranging between 10° and 30° (Cucchi and Piano 2013).

In a complex environment like the Trieste Karst the choice of the best railway route needs to respond to a range of requirements including engineering, socio-economic, environmental, geological and hydrogeological ones. Since early 2000, several different solutions have been studied in order to define this precarious equilibrium of allowing geological engineering and economic requirements to be satisfied. The projected tunnel is planned to cross the Classical Karst area between Monfalcone, Trieste and Sežana, entailing the excavation of two paired tunnels with a diameter of approximately 15 m and a distance between their centers of 25/30 m (excavation area approximately 350 m^2). The choice of the high-speed track heavily depends upon the environmental characteristics of the area of interest and this requires the prior definition of a detailed geological, geomorphological and hydrogeological conceptual model of the area. In order to draw this up, the first analysis to be done is the identification of the karst features and their degree of karstification, not only on the surface, but also below ground. The surface analyses contemplate the identification of the karst morphotypes at a small and medium scale. Beneath the surface, however, extensive cave systems can be recognized, an index of a mature karst where, in some specific places, the underground stream is visible. These karst windows reaching the phreatic zone are very useful points to monitor the waters flowing beneath (Fig. 1).

The evolution of the Classical Karst and the identification of the degree of karstification

The evolution and the construction of the conceptual model of the Classical Karst cannot be separated from the analysis of the available karst surface features, essential for the correct interpretation of the actual characteristics of the hypogean karstification. The karst hypogean hydrographic network that has evolved is conditioned by the structural settings and by the geodynamic stresses that have taken place. In the Authors' opinion, today the Classical Karst is at the early stage of phase 3 of the conceptual evolutive model already proposed by Ford back in 1989 where caves with a mixture of phreatic and water table-leveled components are present together with multiple loops.

The early stage of the speleogenesis, ongoing since the Late Paleogene, affects the thick Mesozoic carbonatic succession. During the early stages of the alpine oligo-miocene orogeny (25 Ma), the platform was moving towards the Cicerija Nappe, overlapping it. This crustal shortening, in our case involving the hinge area between the Alpine and Dinaric ranges, caused, and is still causing, a differential uplift that is higher in the southeastern sector (inland) than in the northwestern one (which became the spring area). The protocaves that evolved did so following the most favorable discontinuities giving rise to a low gradient hydraulic network oriented from SE towards NW. The high gradient generated by the Messinian salinity crisis (MSC, 5.96–5.33 Ma ago) led to the conduits deepening into gorges, to the voids widening due to collapses and to high *speleothem* accretion in the unsaturated zone. In the meantime, the vertical and subvertical caves widened and new features formed, sometimes intercepting large voids and chambers.

Therefore the Classical Karst's karstification has been evolving for more than 10 Ma and the original morphologies across the surface are today recognized only with difficulty. The old eroding surface initially evolved into a series of poljes orientated along the line of the Dinaric Alps, and, subsequently, after the lowering of the base level (MSC) developing into a plateau in which several solution dolines and sinkholes are set (Cucchi et al. 2001). The karst surface features, just as they appear today, are the result of the predominant lithological conditionings and only partially due to tectonic-structural ones. From the lithological point of view, the study area is characterized by the presence of widely outcropping limestones, dolomites and dolomitic limestones. It is well known from the literature (Cucchi et al. 1994; Ford and Williams 2007; Furlani et al. 2009) that a rock exposed to the surface undergoes weathering that leads to a progressive surface lowering that in the study area ranges from 0.009 mm/year on dolomites (*Formazione di Monrupino*), to 0.010–0.013 mm/year on sparitic limestones and 0.038 mm/year on micritic limestones. In simple terms this potentially different degree of karstification can also be identified in the field where its meaningful expression can be seen through the dolines and the caves (their dimensions and distribution). The evaluation of the doline aspect of the study began initially by outlining them according to their dimension and type (solution and collapse dolines) (Ford and Williams 2007). The cave aspect, however, was classified using cave entrances and their location was obtained by consulting the available cadaster (*Catasto regionale delle grotte del Friuli Venezia Giulia*, 2014).

The second step of the analysis is represented by the evaluation of the density of the cave entrances and the dolines carried out using the spatial analyst/density tool of the ArcMAP software, version 10.2. Each parameter was calculated using the Kernel Density tool where the search radius was 600 m both for the dolines and the cave entrances (Fig. 2). The Kernel distribution function used is a statistical method able to identify clustering in different scales (*K* function analysis), comparing the observed distribution of the study variable to the same number of randomly distributed points. This is a good method used for a non-homogeneous data pattern (Wong and Lee 2005). For both analyses, the density unit was the square kilometer. Raw data were later classified using the Jenks Natural Breaks classification method, partially manually reclassifying the classes in order to compare the maps. Breaks are typically uneven, but are ideal to separate values where large changes in values occur (Jenks 1967; de Smith et al. 2013). The two feature classes were later merged, obtaining a new density map that is the probability density function, corresponding to a karstification map or to a map indicating the areas most prone to the occurrence of karst

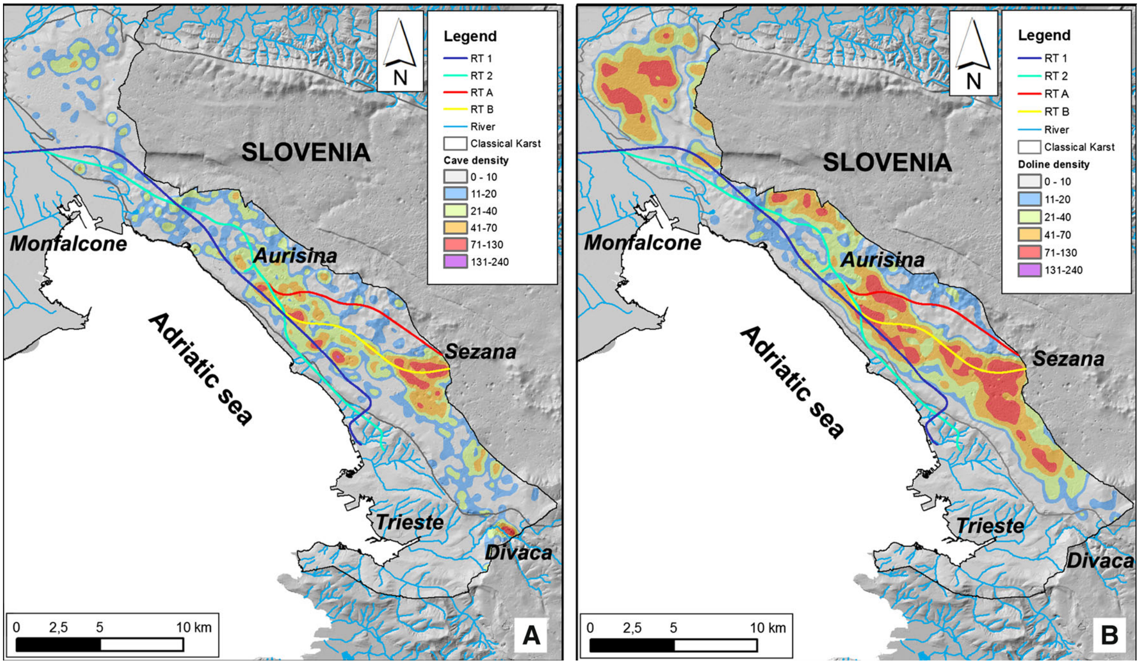

Fig. 2 Probability density function calculated through the Kernel density estimator (KDE) for the cave entrances (**a**) and the dolines (**b**) expressed as the No. of caves/km^2 or No. of dolines/km^2, respectively. A lower density of the karst features is encountered in correspondence to village centers or infrastructures is due to the indeterminacy encountered in these areas

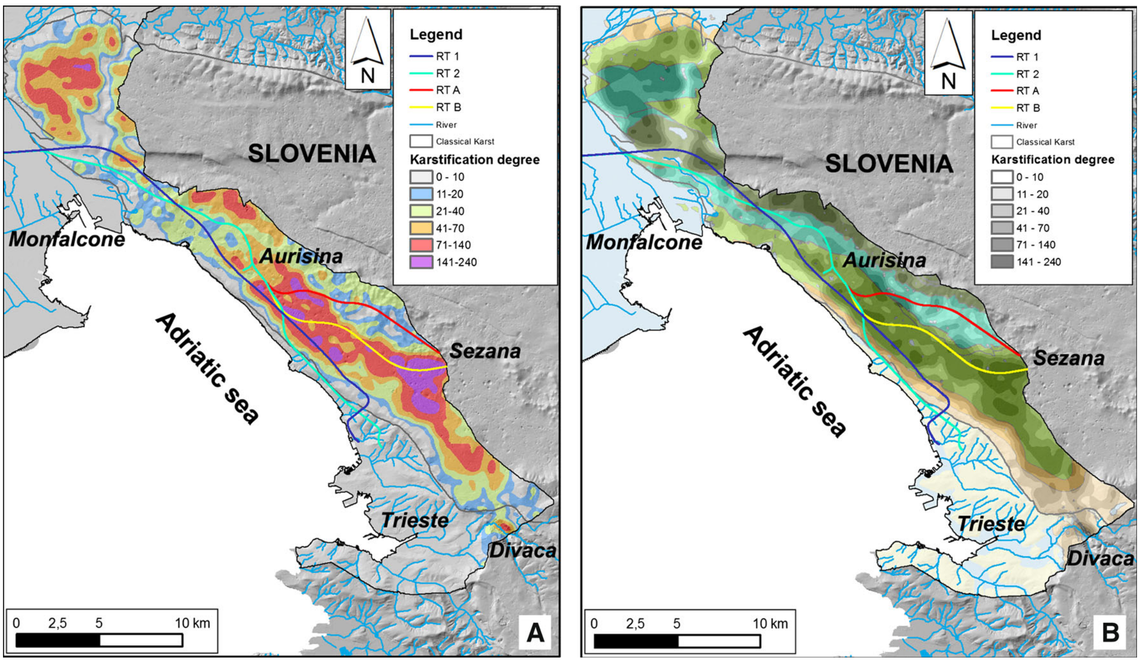

Fig. 3 Probability density function representing the karstification degree, calculated through the Kernel density estimator (KDE) for dolines and caves (**a**), karstification map overlaying the lithological one (**b**). The density the No. of caves/km^2 or No. of dolines/km^2 expresses the respective density

features. The density was calculated using the parameters previously defined (Fig. 3).

Having defined the density, the karstification intensity was compared with the lithology, identifying, for the study area, a karstification degree for each outcrop formation (Tables 1, 2, 3).

The cave entrance density was also calculated as well as its probability density function. Using the surveyed data,

Table 1 Cave entrances and spatial density in relation to lithological units

Units	Number of cave entrances (n)	Area (km^2)	Average density (n/km^2)
Total	2,860	157.76	14.08
Calcari ad Alveoline e Nummuliti	178	18.26	9.4
Formazione liburnica (a + b)	129 (43 + 86)	13.4 (2.6 + 10.8)	24.3 (16.4 and 7.9)
Calcari di Aurisina	1,915	63.3	30.2
Formazione di Monrupino	317	30.4	10.4
Calcari di Monte Coste	321	29.4	10.8

Table 2 Number of dolines and relative densities in relation to lithological units

Units	Number of dolines (n)	Area (km^2)	Average density (n/km^2)
Total	4,589	157.76	22.46
Calcari ad Alveoline e Nummuliti	107	18.26	5.8
Formazione liburnica (a + b)	232 (106 + 126)	13.4 (2.6 + 10.8)	17.3
Calcari di Aurisina	3,013	63.3	47.6
Formazione di Monrupino	426	30.4	14.0
Calcari di Monte Coste	811	29.4	27.6

Table 3 Karst feature density (dolines and cave entrances) in relation to lithological units

Units	Number of karst features (n)	Area (km^2)	Average density (n/km^2)
Total	7,439	157.76	36.58
Calcari ad Alveoline e Nummuliti	285	18.26	15.6
Formazione liburnica (a + b)	361 (149 + 212)	13.4 (2.6 + 10.8)	26.9
Calcari di Aurisina	4,924	63.3	77.7
Formazione di Monrupino	739	30.4	24.3
Calcari di Monte Coste	1,130	29.4	38.4

the average cave density was estimated to be about 15 caves/km^2 increasing up to 130 caves/km^2 in the area around Sežana, on the border with Slovenia (Fig. 2a). For the dolines, the average density was about 22.5 dolines/km^2 and a peak value of 130 dolines/km^2.

In the whole study area, the highest concentration of epigean karst features can be identified in the *Calcari di Aurisina* with a number of features, in a single square kilometer estimated at almost double that found on the *Calcari di Monte Coste* and almost three times that encountered in the *Formazione di Monrupino*. The karst features (KF) recognized for the *Calcari di Aurisina* (63.3 km^2) have a density of 77.7 KF/km^2; 739 dolines are found in the *Formazione di Monrupino* (30.4 km^2) with a value of 24.3 KF/km^2 and 1,130 on the *Calcari di Monte Coste* (29.4 km^2) where the KF is equal to 38.4 KF/km^2. The *Calcari ad Alveoline e Nummuliti* are always the least karstified among the carbonatic rock outcrops, while the *Formazione liburnica* is comparable to the *Formazione di Monrupino* (Table 3).

Once the degree of surface karstification is understood, it is important to comprehend how this develops at depth. In all the areas where speleological knowledge is advanced, the analysis can be done combining data coming from speleological surveys with the ones from hydrogeological studies (spring, lake and cave hydrographs and chemographs).

Where speleological data is not available, the analysis can be done using only hydrogeological information. In the study area, 3,283 caves are known (*Catasto regionale delle grotte del Friuli Venezia Giulia*, 2014) for which the location, characteristics, plans and sections are available. More than 700 have been well enough surveyed to allow a reliable analysis of their geomorphological features. These caves were subdivided into homogeneous stretches and for each one of these, lengths, dips and directions were measured. A statistical analysis on the data collected allowed the identification of the joint sets on which any caves had developed. Vertical shafts are mainly set on subvertical discontinuity planes running N–S, the sub-horizontal or slightly tilted voids mainly following the dip in the strata (Cucchi et al. 2001). While analyzing the relationship between shafts and conduits, it was found that the shafts intersect the conduits, the former being younger (Cucchi et al. 2001). Not all the caves have the same depth and the same importance. Some are unusual because of their depth, others for their dimensions, others still for their length. In the Italian Classical Karst, 167 are sizeable caves (sub-horizontal length greater than 100 m), only 590 are shafts with a depth greater than 30 m. However, taking into account that the thickness of the limestone above sea level is not more than 350 m, some of the caves are very well developed. According to Zini et al. (2011), caves can be divided on the basis of the ratio between plan development (S) and depth (P). Using the index value (S/P), three types of caves can be recognized, HC type (caves with a prevailing sub-horizontal or slightly inclined development, $S/P \geq 1.3$), VC type (shaft with a prevailing vertical development, $S/P \leq 0.7$) and CC type (complex caves where horizontal passages, shafts and chambers form a diffuse network, $0.7 < S/P < 1.3$). The analysis carried out on the available dataset revealed that 1,123 caves have a $S/P > 1.3$, 1,483 have $S/P < 0.7$, 4 have $S/P = 1.3$, 4 have $S/P = 0.7$ and 635 have $0.7 < S/P < 1.3$.

Hydrogeological considerations

To understand the degree of karstification and the hydraulic interconnection between the subterranean voids, a monitoring survey was undertaken on the most meaningful water points available in the study area (springs, lakes, caves and wells). The study area is a wide karst transboundary hydrostructure where the Timavo Springs represent the forceful outflow of hypogean waters being fed not only by the precipitation, but also by the waters of the River Reka which plunge into the impressive Škocjan sinkhole.

From a hydrogeological perspective, the aquifer recharge is due to three different contributions: the autogenic recharge from precipitation on the karst surface, the allogenic one due to the entry of the River Reka into the sinkhole and the input coming from the Isonzo River alluvial aquifer.

The average rainfall contribution, in the karst area, is between 1,000 mm/year on the coast and 2,600 mm/year in the Reka watershed, with a mean effective infiltration of 20.6 m^3/s calculated on an annual basis (Civita et al. 1995).

The Reka River flows for about 43 km on impermeable rocks in Flysch facies; for the last 7 km, it is flowing on limestones developing an influent character. 50 km from the spring area, it disappears completely into the Škocjan sinkhole with a variable discharge ranging between 305 (at high flows) and 0.18 m^3/s (at low flows) with an average value of 8.26 m^3/s (Gabrovšek and Peric 2006).

The third important hydrological input is due to the influent character of Isonzo River in the northwestern sector of the area along a 5–6 km section. This contribution, already estimated at the beginning of last century (Timeus 1928), was later verified using natural tracers (Mosetti and D'Ambrosi 1963; Cancian 1987; Gemiti and Licciardello 1977; Doctor et al. 2000; Samez et al. 2005) and hydrogeological balance analysis and calculated to be of the order of 10 m^3/s (Zini et al. 2013).

All the infiltrated waters are later drained by the spring system covering a few square kilometers along the coast between the Aurisina spring and the town of Monfalcone. The main spring is the Timavo with an average discharge of 29.3 m^3/s, followed by the Sardos spring with 1.9 m^3/s, and then all the other smaller springs such as the Aurisina (0.3 m^3/s), the Moschenizze (0.5 m^3/s), the Pietrarossa and Sablici springs (1.2 m^3/s), Monfalcone 0.2 m^3/s, and Lisert (1.0 m^3/s) (Gemiti 1984, 1995), and lastly the coastal springs discharging below sea level and sited between Aurisina and Timavo, with an average estimated discharge of 0.5–1 m^3/s.

The meaningful water points were assessed using Schlumberger Water Services CTD DIVER data logger devices, continuously recording levels, temperature and EC with a sampling interval of 30–60 min (Fig. 1).

From the analyses of the hydrographs and chemographs, it emerges that the area is characterized by a very complex interconnected network of more or less karstified voids, giving an anisotropic character to the hydrostructure depending upon the matureness of the karst in question. During floods, the thickness of the epiphreatic zone may vary considerably, not only according to the scale of any rainfall events and the recharge type, but also as a result of the lateral transmission velocity of the impulses that arrive and whether these are diffuse via karstified joints or concentrated via stream-sinks. The voids seem to be continuous enough, interconnected and sufficiently wide to allow the hypogean volume to transmit the pressure almost simultaneously. This can be seen well when comparing the data of the Trebiciano Abyss and the Opicina piezometer (Fig. 4) located at 6 km one from one another.

The first figure represents the flow monitoring in a wide conduit system, the second on the other hand is typical of a fractured environment (while drilling the piezometer, no karst conduits were identified—300 m b.g.l.). In these two points, the water table fluctuations are comparable, the main pulses are almost coincident, but electrical conductivity and temperature behave in completely different fashions. In the Opicina piezometer temperature fluctuations are not recorded and EC is, on average, higher than the Trebiciano Abyss. Rough decreases in EC values due to neoinfiltration waters are not highlighted. On the contrary, during the main floods, in the piezometer, the EC increases are due to the piston flow effect reflecting the remobilization of resident waters.

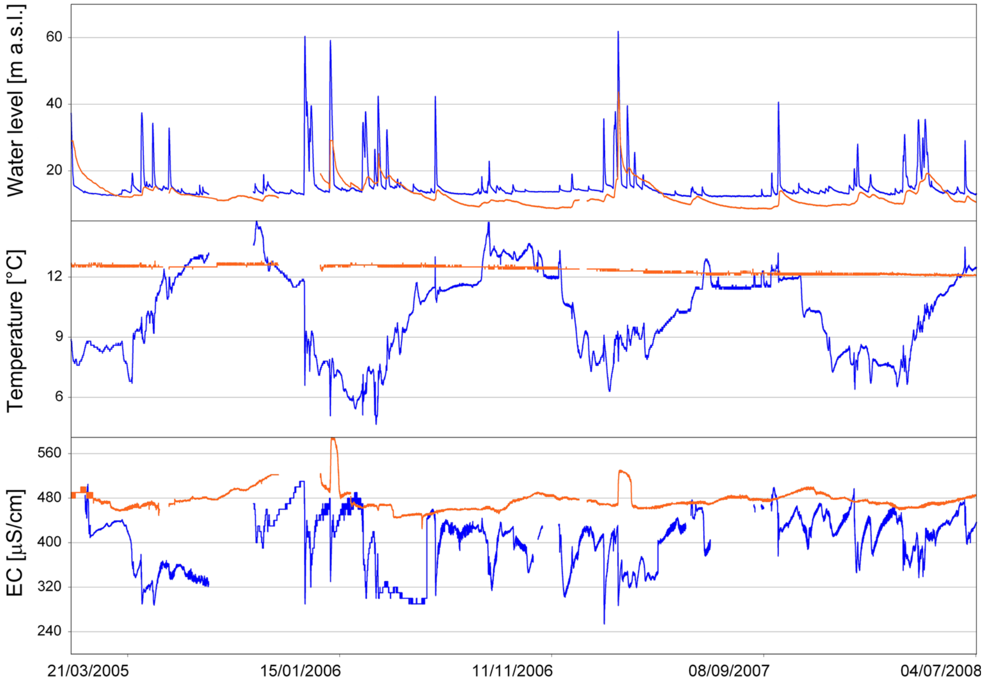

Fig. 4 Water level (m a.s.l.), temperature (°C) and electrical conductivity (µS/cm) comparison between the Trebiciano Abyss (*blue*) and the Opicina piezometer (*orange*)

The main springs are all located in a narrow area (about 12 km^2) where it is possible to identify more than 80 outflow points having a total mean discharge of about 35 m^3/s. At different flow regimes, in the different springs, different contributions (Isonzo, Reka, effective infiltration) prevail. In the southeastern sector of the Classical Karst, during floods, the influence of the River Reka is dominant where a rapidly increasing discharge corresponds to an early small piston effect followed by a large decrease in EC values. At the same time a variation in temperature due to seasonality, is observable (increase in summertime, decrease in wintertime). The circuit connecting the Škocjan cave with the Timavo springs is characterized by flood impulses transferring waters within 1–3 days. In all the other flow regimes, the Isonzo River aquifer contribution prevails. As proposed by Vigna (2002) and Galleani et al. (2011) this southern sector mainly exhibits a highly effective drainage system with a fast replacement of the waters (Fig. 5) characteristic of an aquifer having a high degree of karstification.

In the northwestern sector, however, the degree of karstification is lower. In Fig. 6 two springs are compared: the main spring in the western sector (Moschenizze Nord—MoN) and the Timavo Spring. In the chemograph, the behavior of the whole northwestern sector is highlighted which, during floods, shows a piston effect due to the pushing of freshly infiltrated waters, thus tending to mobilize the resident groundwaters. In the MoN spring the Reka contribution has never been recorded. The behavior of this sector is closer to the moderate effective drainage system described by Galleani et al. (2011). The linking point between the two systems are the springs of the Sardos and the Timavo. These hypotheses are also supported by the tracer test carried out by Timeus on 20th May 1910. The injection of LiCl at Vrtece on the Vipacco river bed, was detected 9 days later at both springs (Timavo and Sardos) passing through Doberdò and Pietrarossa 4 days earlier.

During the low water regime, all the springs are mainly draining waters coming from the Isonzo River system. In high water regimes the Timavo Springs are mainly draining River Reka waters, while the Sardos spring is draining mixed waters (from both the Reka and Isonzo River systems). During normal flow, the Timavo Springs are draining mainly Reka River waters and the Sardos spring is draining primarily Isonzo River waters (Zini et al. 2014).

Discussion and conclusions

Karst areas are so variable, that, while analyzing them, each single situation needs to be considered as unique. The degree of karstification as well as the type of karst need to be clearly identified prior to approaching any feasibility plan.

The study area has been analyzed since the early 1800s and since then, researchers have tried to understand its geological, structural and hydrogeological settings together with the genesis and evolution of the area. Since then, speleological research activity has also increased, giving hydrogeologists the possibility to use the caves discovered as natural laboratories. Over the years all this allowed an

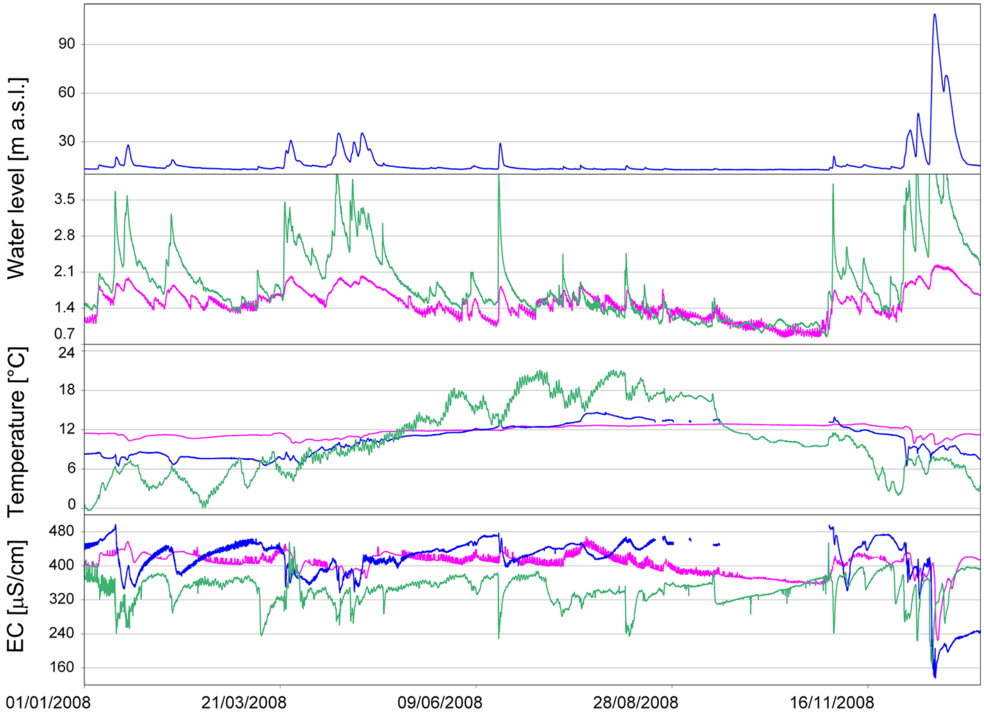

Fig. 5 Water level (m a.s.l.), temperature (°C) and electrical conductivity (μS/cm)—a comparison between the Škocjan cave (*green*), the Trebicano Abyss (*blue*) and the Timavo Springs (*pink*) between January and November 2008

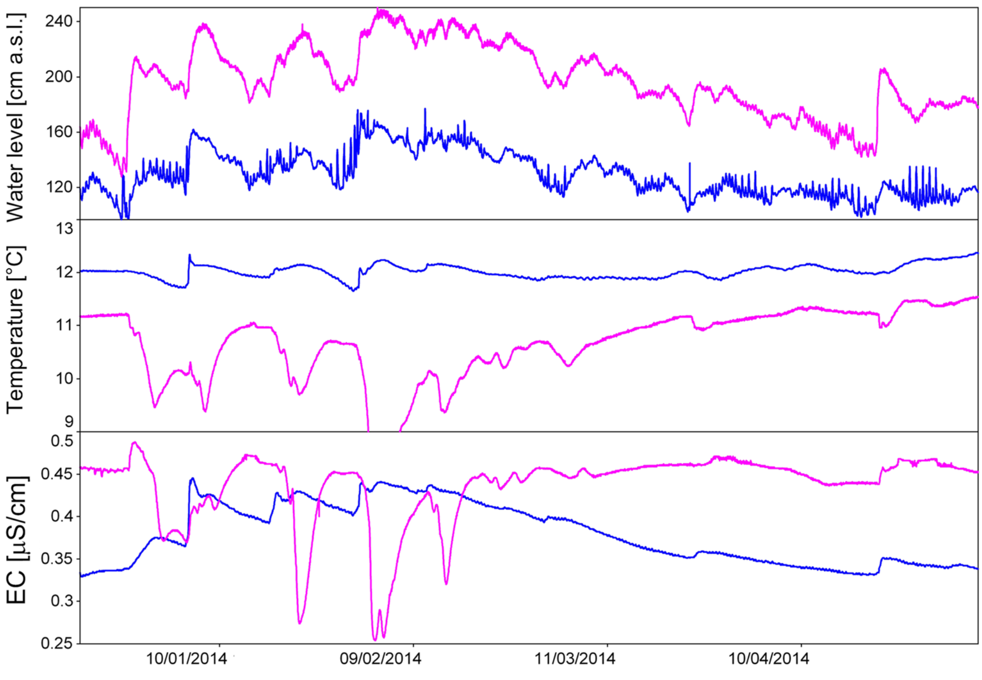

Fig. 6 Water level (cm a.s.l.), temperature (°C) and electrical conductivity (μS/cm)—a comparison between the Timavo Springs (*pink*) and the Moschenizze Nord spring (MoN) (*blue*) between January and April 2014

ever greater detailed idea of the setting of the Italian Classical Karst area, but faced with challenging new projects such as the Corridor V all this knowledge and much more is needed to support the decision-makers with objective information in producing a geohazard assessment of the occurrence and probability of the karst features.

The Italian Classical Karst, from a lithological/geotechnical point of view, is not a highly differentiated area, but what emerges from the objective approach adopted is that it presents large differences in the degree of karstification; differences that need to be taken into account while planning important infrastructures.

Even if the *Calcari di Aurisina* represent the most karstified in lithology terms, within them, the spatial heterogeneity is quite high. This is especially noticeable in the area between Aurisina and Sežana where the density of caves and dolines reaches peaks of 130 dolines/km^2 and 134 caves/km^2. The situation completely changes while approaching from the north east and to the south of this area with outcrops of the *Formazione di Monrupino* and the *Calcari ad Alveoline e Nummuliti*, respectively. Here the cave (max value of 45 cave/km^2) and doline (max value of 50 cave/km^2) density decreases drastically with wide areas having less than 10 KF/km^2. Although always being, in absolute terms, a high value, when compared to the *Calcari di Aurisina*, the density of the karst features can be considered barely a third of those of the *Formazione di Monrupino* and a fifth of that of the *Calcari ad Alveoline e Nummuliti*.

From a speleological point of view, the study area has been widely surveyed and explored. The number of known caves is huge, but, of course, certainly represents only a part of the voids present within the rock mass. In any case, these are a representative and meaningful sample on which a statistical analysis can be carried out (Table 4). 46 % of the known caves are simple shafts (VC), more recent features with a prevalently vertical behavior, developing in a prevailing NS direction (Cucchi et al. 2001). They have an average depth ranging between 20 and 150 m and a diameter of about 3–6 m. Only a few shafts reach diameters of 20–30 m.

19 % of the known caves are complex (CC). They are the expression of a highly karstified area where several shafts (usually developed along a discontinuity) become linked together by sub-horizontal stretches.

35 % of the known caves are sub-horizontal or slightly inclined galleries (HC). Usually they are not larger than 20 m in diameter, but they can reach up to 50 m and a length of up to one hundred meters. They are slightly inclined, following the dip of the strata (10°–30°) or the vertical discontinuity systems and may sometimes evolve into canyons (Cucchi et al. 2001). In the investigated sector, between the Timavo Springs and Sežana, the hypogean sub-horizontal features have a prevailing SW direction. Southeast of Sežana; however, two different trends are present: one following the veering of the stratification, dips to SE, the other one NW (Visintin 2007). Among the different geological units there is no predominance of one cave type over the others, but the distribution is almost uniform (CC is higher and VC and HC are similar). Densities are similar for all the units with a clear increase in the *Calcari di Aurisina* as highlighted in the KF factor.

While drilling a tunnel, caves always represent a problem. But while shafts usually have a small cross-section and could easily be bypassed, the sub-horizontal caves could have such dimensions (stretches range between 300 and 500 m length, 60 m wide and 80–90 m high) that require huge engineering approaches that are usually very expensive. In the Trieste Classical Karst area, the sub-horizontal caves mainly develop in a SW direction and this direction is the most difficult to approach while drilling in the case of this project.

Most of the available and analyzed data refers to the unsaturated zone, but the characterization of the saturated zone has been carried out through the analysis of the data logged by the continuous recording devices.

Highly karstified volumes connect the sinkhole to the springs implying the presence of wide conduits in the phreatic and epiphreatic zones and high fluctuations in the water table (Fig. 5).

The situation is different in the northwestern sector between the Isonzo River and the spring area where a less hierarchized and more diffuse circulation system prevails, confirmed by lower water table fluctuations.

Summarizing, the phreatic zone, or better still, the water table during the low water regime, is at about 2–5 m a.s.l between Pietrarossa and Aurisina and rises until it is about 12–13 m a.s.l. in correspondence with the area of the Trebiciano Abyss. The water table fluctuations during floods are completely variable in the different zones with smaller excursions in the northwestern sector (3–10 m) and larger ones in the southeastern sector where the River Reka sinks into the Škocjan caves.

From the spring area where fluctuations are of few meters, the levels increase up to 28 m close to Aurisina (Casagrande and Zini 2005) exceeding 70 m at the Opicina piezometer and reaching up to 110 m in correspondence with the Trebiciano Abyss.

The high flow thickness is highly variable with an average value of 20–30 m. If we focus on the hydrographs, while flooding, the rising limb in the hydrograph is very sharp indicating a very fast rise of the water table level

Table 4 Cave type distribution vs. geolithological units. Cave types are subdivided into: simple shafts (VC), sub-horizontal or slightly inclined galleries (HC) and complex ones (CC)

	VC	VC density	CC	CC density	HC	HC density
Calcari ad Alveoline e Nummuliti	65	3.6	169	9.3	72	3.9
Formazione Liburnica	37	2.8	137	10.2	62	4.6
Calcari di Aurisina	899	14.2	1,895	29.9	618	9.8
Formazione di Monrupino	124	4.1	310	10.2	116	3.8
Calcari di Monte Coste	138	4.7	316	10.7	121	4.1

Table 5 Summary of the investigated parameters analyzed for each proposed railway track

	Solution RT1		Solution RT2		Solution RTB		Solution RTA	
	km	%	km	%	km	%	km	%
Geology								
Total length in carbonate rock	26.348	100	21.671	100	13.505	100	12.308	100
Calcari di Monte Coste	8.826	33	7.435	34				
Formazione di Monrupino	2.427	9	6.900	32			8.725	71
Calcari di Aurisina	12.115	46	5.926	27	13.505	100	3.583	29
Formazione Liburnica	1.720	7	1.160	5				
Calcare ad Alveoline e Nummuliti	1.260	5	0.250	1				
Doline density								
Very low	7.034	27	8.917	41			5.425	44
Low	4.343	16	5.135	24	0.135	1	2.154	18
Medium	6.410	24	4.959	23	0.876	6	2.115	17
High	5.431	21	1.641	8	5.854	43	1.477	12
Very high	3.130	12	1.020	5	6.640	49	1.137	9
Karstification								
Very low	4.887	19	4.583	21			1.009	8
Low	2.961	11	5.376	25			4.661	38
Medium	5.996	23	4.756	22			1.964	16
High	5.386	20	4.218	19	1.484	11	1.496	12
Very high	5.924	22	2.333	11	7.187	53	2.581	21
Extremely high	1.193	5	0.404	2	4.834	36	0.597	5
Groundwater								
Vadose zone	20.948	80	21.671	100	13.505	100	12.308	100
Epiphreatic zone <50 m	2.460	9						
Epiphreatic zone >50 m	2.480	9						
Phreatic zone	0.460	2						

with important discharges. The lag time is very short, with ranges of a few hours, the transmission is fast and peak discharges recorded in the Trebiciano Abyss can be detected at the spring area within 24 h.

Summarizing, what emerges is a conceptual model where the area is, on average, highly karstified with heterogeneities, mainly linked to the lithological and geomorphological variations. The distribution and density of the karst features is such that rainfall waters quickly transfer to the phreatic zone as well as to the spring area. The phreatic zone, characterized by the presence of wide conduits, is particularly well developed in the SE zone where higher gradients are present allowing rapid flows and quick rises in the water table. The northwestern sector exhibits lower gradients and more diffuse network conduits. In any case the study area can be considered a mature karst according to the classification proposed by Ford and Williams (2007).

The geoenvironmental characterization of an area permits the suggestion of more conscious choices to the decision-makers. The more the analysis is objective and repeatable and the more the decisions are scientifically based and any uncertainties or at least the knowledge of the possible drawbacks are acceptable and predictable. This is what is happening in the Classical Karst area, where different possible tracks (RT) for the High Speed Railway Corridor V connecting Venice to Ljubljana were proposed and analyzed. Two different tracks are compared here in order to identify the best possible choices taking into account not only the geological and hydrogeological characteristics, but also the socio-economic ones. The tracks RT1 and RT2 link Monfalcone to Trieste, while RTA and RTB would connect Aurisina to Slovenia crossing the border at Sežana.

RT1 is the deeper track, ideal considering the slopes and the curvature radii for a track having characteristics of High Speed and High Capacity (HS/HC). It connects Monfalcone to Trieste passing through all the karst area with a long tunnel emerging in correspondence to a wide doline close to Aurisina. It leaves Monfalcone at 9 m a.s.l. arriving at the bottom of the doline at 91 m a.s.l. before descending towards Trieste at 11 m a.s.l. where it intercepts the contact between carbonate rocks and Flysch. The total length of the section in carbonate rock is of 26.348 km.

The alternative to this solution is the RT2 where slopes are higher and curvature radii are smaller. This solution allowing the track to remain higher in elevation than RT1, more easily reaching the actual Aurisina station, losing the HS option in favor of only a HC link. It leaves Monfalcone at 10 m a.s.l., reaching 170 m a.s.l. at Aurisina station and going down towards Trieste where it intersects the contact between carbonate and Flysch at 103 m a.s.l.

To reach the border with Slovenia at Sežana, from Aurisina station, RTA and RTB were the proposed solutions. Both are shallower with respect to the RT1 solution, they reach the border at, respectively, 304 m a.s.l. (RTA) and 289 m a.s.l. (RTB).

To compare the feasibility and the possible drawbacks of each individual track, Table 5 was constructed taking in the analyzed geological, geomorphological and hydrogeological parameters.

From a geotechnical point of view, the ideal course is the one that intersects fewest karst features and that has fewest interactions with the phreatic and epiphreatic zones.

In this sense, from the analysis carried out, it emerges that the *Calcari di Aurisina* are the most karstified unit in which the highest density of dolines and caves are present and in which the probability of identifying other karst features is the highest. It follows that the best solution is the one that intersects it least, and, especially its eastern sector, close to Sežana, where the karstification density reaches values of 140 KF/km^2. Between the two proposed tracks, the RT1, with 46 % of its length passing through the *Calcari di Aurisina* unit is disadvantaged with respect to RT2, having only 27 % of its length in the same lithology. On the basis of the different path elevations, RT1 and RT2 may be differently affected by hydrogeological problems. Both courses run for the main part of their length in the vadose zone and the drawbacks may be created by inrushes caused by the rainfall regime, by the characteristics of the epikarst and by the variability in the frequency of the discontinuities encountered.

20 % of the RT1 path may be affected by groundwaters. In this particularly vulnerable area, several difficulties could occur, not only during construction, but also during the operational phase. While drilling, sudden inflows could occur with high hydrostatic pressures especially during floods when the water table can reach levels up to 100 m above the railway track. These inflows may also be associated with the washing in of loose filling material. Moreover, the risk of groundwater contamination is always high, as is the possibility of spring yield decline. From the entire study it emerges that the less problematic track is the RT2 one crossing the less karstified units and being unaffected by the phreatic and epiphreatic zone. This solution is the most convenient not only from a geotechnical point of view, but also from the economic one (less karst features intersected means lower costs for the tunnel creation) but this choice also means sacrificing HS, and this is a socio-political decision.

Equally clear is the choice between the two proposed tracks connecting Aurisina to Sežana. The best solution is the RTA track, having 70 % of its course running through the *Formazione di Monrupino*. The RTB option, however, plans to cross the worst sector of the entire study area.

The proposed methodological approach permits the identification, from a geotechnical point of view, of the areas where the probability of encountering karst features while drilling is lowest, representing a good tool in approaching a feasibility project. This approach is a probabilistic one and not deterministic, useful in a karst environment but unsatisfactory when it comes to identifying single realities. As reported by all the authors (Milanović 2000; Day 2004; Xeidakis et al. 2004; Casagrande et al. 2005; Waltham et al. 2005; Ford and Williams 2007; Knez et al. 2008; Peila and Pelizza 2009; Ismail et al. 2010), karst territories are extremely heterogeneous and difficult to approach. An example is given by the *Grotta Impossibile*, one of the broadest caves of the Classical Karst, discovered in November 2004, while drilling the highway tunnel connecting Trieste to Venice. The cave, still under exploration, is more than 2 km long and 160 m deep. A part of it is a gallery about 200 m long, 50 m wide and more than 80 m in height. This cave, linked to an old phreatic level, develops in an area with a very low degree of karstification (Fig. 1) where nobody (neither researchers nor speleologists) could have hypothesized encountering it. Luckily, the building tunnel intersected only a marginal part of the cave system and not the wider section, therefore not compromising the whole drilling progress. Moreover, in the rest of the drilled tunnel (2,850 m), the intersected karst features were not significant (only a few small shafts and little voids).

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