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KARST GEO-HAZARDS: CAUSAL FACTORS AND MANAGEMENT ISSUES

NARAVNE NESREČE NA KRASU: VZROČNI DEJAVNIKI IN VPRAŠANJA UPRAVLJANJA

Mario PARISE[1]

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Mario Parise: Karst geo-hazards: Causal factors and management issues

Karst terranes exhibit spectacular landforms that are often exploited as natural parks and show caves, and hosts very important natural resources. Further, karst terranes cover 20% of the Earth's surface and provides 20–25% of high-quality groundwater for drinking water. The fragility of karst environments makes it highly vulnerable to a variety of different geological hazards (or geo-hazards). This is due to its peculiar geological and hydrological features such as sinkholes and caves. In particular, the strict connection between surface and subsurface features emphasizes the fragile nature of karst. The occurrence of geo-hazards in karst terranes greatly differs from other natural settings. Natural and man-induced subsidence and sinkholes, slope movements favored by karst conduits and caves, flash floods related to inability of the system to manage water from heavy rainstorms, and pollution caused directly or indirectly by human actions are the main types of geo-hazards typical of karst terranes. Although mostly related to natural processes, their occurrence and consequent damage to both the natural and anthropogenic environment are often caused or exacerbated by man. As a consequence, management of karst terranes cannot be enacted without taking into account the peculiar features and behavior of karst terranes and aquifers, and the delicate balance with the different types of geo-hazards that may occur. Specific management actions should, therefore, be pursued in this fragile environment, with the intention of safeguarding the natural resources, biota, and population.

Key words: karst, hazard, human actions, management.

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Mario Parise: Naravne nesreče na Krasu: Vzročni dejavniki in vprašanja upravljanja

Kraška območja odlikujejo spektakularne reliefne oblike, ki so pogosto povod za ustanovitev naravnih parkov ali turističnih jam, ter pomembne naravne vire. Kras pokriva okoli 20% kopnega in zagotavlja okoli 20–25 % potreb po pitni vodi. Krhkost kraških okolij so razlog za njihovo visoko dovzetnost za različne geološke in druge naravne nesreče. Razlogi so v posebnih geoloških in hidroloških značilnostih, kot so vrtače in jame. Krhko naravo krasa zlasti poudarja tesna povezava med površinskimi in podzemnimi oblikami. Pojavljanje naravnih nesreč v krasu se močno razlikuje od tistih v drugih naravnih okoljih. Naravno in s strani človeka povzročeno pogrezanje, udori in plazenje so pod močnim vplivom kraških kanalov in jam. Poplave so povezane z nezmožnostjo sistema prevajati nalivne vode. Onesnaženje, ki ga človek povzroči posredno ali neposredno s svojimi aktivnostmi, so poglavitne nesreče v krasu. Čeprav so naravne nesreče večinoma povezane z naravnimi procesi, njihovo pojavljanje in posledično škodo tako za naravno kot antropogeno okolje pogosto povzroča ali pospeši človek. Upravljanje kraških območij zato ne more biti načrtovano brez upoštevanja specifičnih lastnosti in obnašanja kraških pokrajin, vodonosnikov in krhkega ravnotežja med različnimi vrstami nesreč, ki se lahko pojavijo. Zato bi bilo z namenom varovanja naravnih virov, živih bitij in prebivalstva treba uvesti posebne ukrepe upravljanja v tem občutljivem okolju.

Ključne besede: kras, nesreča, človeške aktivnosti, upravljanje.

[1] CNR-IRPI, Bari; e-mail: m.parise@ba.irpi.cnr.it

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INTRODUCTION

Geological hazards (or geo-hazards) are at the origin of a high number of victims and severe damage to society worldwide. They include, but are not limited to, landslides, earthquakes, floods, tsunamis, volcanic eruptions, etc. According to the Centre for Research on the Epidemiology of Disasters (2014), 337 disasters related to natural hazards were reported worldwide in 2013. Even though this number was the lowest of the last ten years, 22,452 deaths were registered as a consequence of the natural disasters in 2013, with floods being the most frequent.

The response of the terranes to these events is highly dependent upon the geological, physical and morphological features of each specific setting. Further, the effects produced on the society are a function of good (or bad) practices in management of the terranes, their historical development, and the presence and distribution of the vulnerable elements at risk.

Some environments are more sensitive than others to occurrence of geo-hazards, due to their geological and hydrological peculiarities. Karst is recognized as one of the most fragile environment in the world: this statement is based upon a number of reasons, first and foremost the direct connection existing in karst between the surface and the subsurface (White 1988; Bakalowicz 2005; Ford & Williams 2007; Palmer 2007). This creates a unique system where any action performed at the ground, either natural or human-induced, will have rapid repercussions underground, affecting both the hypogean and epigean landscapes, the karst aquifers, and the whole ecosystem as well (White 2002; Palmer 2010). The delicate balance existing in the fragile karst environment is further testified by the fact that recovering the pristine conditions existing before a particularly strong event may require a very long time, and sometimes the recovery of the initial situation is actually not possible.

Karst terranes are among the world's most fragile settings, but, at the same time, they present spectacular surface and underground landforms, that are often exploited as natural parks and show caves, and host very important natural resources. At this latter regard, it must be reminded that karst covers 20 % of the Earth's surface and provides 20–25 % of the world's drinking water (Fig. 1), with high-quality groundwaters (Ford & Williams 2007). The Food and Agriculture Organization of the United Nations (FAO) forecasts that before 2025 at least 80% out of the demand of drinkable water in the Mediterranean Basin will be provided by karst aquifers. However, the direct connection between surface morphology and the underlying aquifer make underground karst waters extremely vulnerable to pollution.

Geo-hazards in karst have been dealt with in a number of recent papers (see, for instance, Gutierrez 2010; Parise 2010a; Gutierrez *et al.* 2014, and references therein). This article, after describing the main types of geo-hazards occurring in karst environments, focuses its attention on the role played by human actions in exacerbating the related effects, and on management of karst terranes.

In karst, discriminating among natural and anthropogenic hazards is not always straightforward. In many cases, the effects caused by hazards are favored, when not promoted, by human actions, which make particularly delicate the distinction between what is natural and what is not. Due to these reasons, even though clear

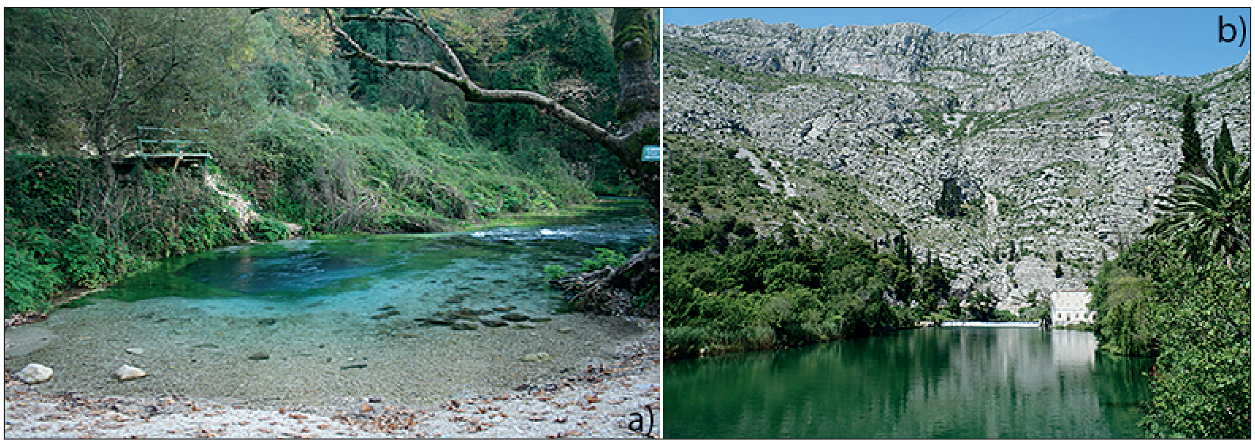

Fig. 1: Karst water resources: a) the beautiful scenery of the spring Syri i kalter (Blue Eye), an important high-quality karst spring of southern Albania (Photo: M. Parise); b) the Ombla spring, source of drinking water for the town of Dubrovnik, in Croatia (Photo: M. Parise).

anthropogenic hazards (i.e., those directly related to underground voids excavated by man; see Hermosilla 2012; Parise 2012; Parise *et al.* 2013), will not specifically dealt with, some reference to events where man has played a role will be presented in this paper.

GEO-HAZARDS IN KARST

In karst, occurrence of geo-hazards strongly differs from the other geological, morphological and hydrological settings of the world (Gutierrez 2010; Parise 2010a; De Waele *et al.* 2011; Gutierrez *et al.* 2014). Subsidence and sinkholes originated by underground cavities, slope movements favoured by development of karst conduits and caves, flash floods related to heavy rainstorms, pollution events affecting the karst landscape and aquifers are the main types of geo-hazards observed. Even though mostly related to natural processes (Santo *et al.* 2007; Parise 2008; Festa *et al.* 2012), their occurrence and the consequent damage are often caused and/or exacerbated by human activities.

Fig. 2: Sinizzo Lake, a sinkhole reactivated by the 2009 L'Aquila earthquake in central Italy (see Parise et al. 2010): a) open cracks surveyed few days after the main seismic shock (Photo: M. Parise); b) the lake shore in the summer of 2010, with tourist lying exactly in the area where cracks are present, and the only evidence of the danger represented by the fences (Photo: M. Parise); c) general view of the lake in the summer of 2010, with in the background the scars left the rockfall triggered by the 2009 earthquake (Photo: M. Parise).

Sinkholes are by far the most common and typical geo-hazard, being karst typically characterized by caves, conduits and voids produced by solution of carbonates and evaporites. Sinkholes are related to processes that can be summarized in: dissolutional lowering of ground surface, rock roof failure into underlying cave, collapse of insoluble overburden into cave in soluble rock below, soil collapse into soil void formed over bedrock fissure, down-washing of soil into fissures in bedrock (Waltham *et al.* 2005; Gutierrez *et al.* 2008, 2014). Most of the aforementioned mechanisms of sinkhole formation occur in relation with gravity-related process, developing underground as a natural evolution of caves, once water moved at greater depths, thus leaving unsupported the cave walls. Breakdown deposits are very common in caves (Klimchouk & Andrejchuk 2002; Iovine *et al.* 2010), and their presence and distribution within underground systems should be properly faced when the development of karst caves interferes with the built-up environment, with possible consequences for the infrastructures above (Waltham & Lu 2007; Brinkmann *et al.* 2008; Bruno *et al.* 2008; Goldscheider & Bechtel 2009; Margiotta *et al.* 2012; Basso *et al.* 2013).

Further, sinkholes may be triggered, or re-activated, by other geo-hazards such as seismic shocks (Kawashima *et al.* 2010; Parise *et al.* 2010; Fig. 2), or by heavy, concentrated, rainstorms (Martinotti *et al.* 2015). At several sites, the distribution of sinkholes is so high that a general awareness about the problem is present in the local population, also thanks to road signs (Fig. 3) and leaflets dedicated to the wide public.

Sinkholes do occur with high frequency and rapid evolution in rocks other than carbonates, and in particular in evaporites (Closson *et al.* 2005; Jones & Cooper 2005; Frumkin *et al.* 2011; Cooper & Gutierrez 2013).

As concerns this type of geo-hazard, the most recent and promising directions of research seem to be the following: production of detailed databases and catalogues (Farrant & Cooper 2008; Parise & Vennari 2013); interferometric techniques applied to study of sinkholes, aimed at assessing premonitory signs of collapse (Closson *et al.* 2003); development of tools and procedures for the production of high-quality sinkhole inventory maps (Galve *et al.* 2011); geological and geotechnical modeling of the likely evolution of underground instabilities, up to development of sinkholes at the ground surface (Parise & Lollino 2011; Lollino *et al.* 2013).

Fig. 3: Road sign warning against possibility of sinkhole occurrence along the U.S. Route 285 in New Mexico, USA (Photo: M. Parise).

Floods, and in particular flash floods related to very intense and clustered precipitation (White & White 1984; Currens *et al.* 1993), represent an important hazard in karst. Due to limited surface runoff, linked to the high solubility of carbonate rocks, and to rapid infiltration underground through the complex network of conduits and caves in the rock mass, rainfall is generally absorbed in the epikarst (Williams 2008), and released at depth to recharge the karst aquifers. On the occasion of heavy rainstorms, however, wide areas as poljes (Fig. 4), that appear dry for most of the years, may become flooded because the main swallow holes are clogged by soils, or simply not able to transfer great amount of water flowing at high velocity. This causes the occurrence of flash floods, and likely inundation of large areas, especially in lowlands (Fig. 5). At the same time, it has to be noted that the answer of karst settings to heavy rainstorms is highly dependent upon the correct management of the land: covering the natural swallow holes, or creating roads over the natural infiltration of water underground, may be at the origin of serious problems on the occasion of intense rainfall events (Fig. 6), with severe consequences and huge costs to society (Parise 2003; Delrieu *et al.* 2005; Delle Rose & Parise 2010; Kovačič & Ravbar 2010).

Slope movements in karst may have some features different from other non-karst settings: presence of conduits and passages created by solution adds further possible ways to flowing water, acting as possible planes of weakness in the rock mass. Evolution of slope movements in karst can thus be more rapid (Krautblatter *et al.* 2012; Palma *et al.* 2012), since the instability processes develop both at the surface and underground, through falls, localized failures and detachments from the cave walls and vault. Local, internal movements are also possible in those areas beneath which cave systems develop.

Fig. 5: Effects of the 2008 hurricanes in the Vinales area, Pinar del Rio province, Cuba (see Farfan Gonzalez et al. *2009) (Photo: H. Farfan Gonzalez).*

Fig. 4: Examples of poljes: a) mogotes bounding a polje in the Vinales National area, Cuba (Photo: R. Potenza); b) Popovo polje, in Bosnia Herzegovina (Photo: M. Parise); c) Grahovsko polje, in Montenegro (Photo: M. Parise).

Fig. 6 – Effects of 2003 floods in karst areas in the Taranto province, southern Italy: a) road earthfill destroyed by the passage of the flood (Photo: M. Parise), and b) occlusion of bridges by trees and vegetation (Photo: M. Parise).

In the last years, greater attention is being paid to the links between gravity-related movements and karst features. However, very few works so far have significantly treated this issue, that is of sure interest for both understanding of karst processes and land management (civil defense issues). In most cases, when describing landslides involving soluble rocks, karst is illustrated as a collateral factor, which does not appear to play an active role in predisposing or triggering the failures (see at this regard Gutierrez *et al.* 2014).

Development of karst processes, with the consequent weakening of the rock massif, may act as a predisposing factor for the onset of different types of slope movements. Notwithstanding the fact that some of the largest subaerial landslides in the world involved soluble rocks (Muller 1964, 1968; McGill & Stromquist 1979; Prager *et al.* 2008; Ivy-Ochs *et al.* 2009; Gutiérrez *et al.* 2012), the specific role played by dissolution and by the presence of karst features on slope stability and landslide kinematics have rarely been dealt with. For instance, large and catastrophic translational landslides in carbonate successions have been favored by laterally extensive planar bedding planes, but very few considerations about karst has been presented in the many articles published on these events: this is the case for both the 36.5 hm^3 Frank rockslide-avalanche in southwestern Alberta, Canada (Cruden & Krahn 1978; Jaboyedoff *et al.* 2009), and for the even more disastrous 1963 Vajont translational slide in northeastern Italy (Muller 1964, 1968; Hendron & Patton 1985; Semenza & Ghirotti 2000; Kilburn & Petley 2003).

An interesting issue to be investigated is the identification of slope movements in carbonate rock masses cropping out in morphological contexts where occurrence of landslides seems to be quite rare. Gringeri Pantano *et al.* (2002) and Nicoletti & Parise (2002) recognized previously unidentified landslide features in South-Eastern Sicily (Italy), and discussed the origin of these phenomena: they concluded that, given the local geological and morphological conditions, characterized by very low relief and quite strong limestone bedrock, such landslides could be explained only invoking a triggering factor represented by earthquakes. Even though this seems to be the more logical hypothesis, based upon a number of observations and considerations brought upon by the authors, a joint role played by karst processes cannot be entirely excluded, at least for some of the phenomena discussed. Similarly, Pánek *et al.* (2012) describe a mega-landslide in nearly horizontally inclined Miocene limestones of the northern Caucasus foredeep, showing a very gentle inclined slip surface: they, too, conclude that such a phenomenon could only had been triggered by an earthquake. Once again, the role of karst processes in favoring the development of instability features in almost horizontal limestone successions cannot be totally excluded.

Recently, a connection between caves and landslides has been pointed out in several papers in the Carpathians, covering the areas at the boundaries between the Czech Republic, Poland and Slovakia. Cavities produced by slope movements in flysch deposits, described in these works, are typically narrower than karst caves, and especially elongated in vertical directions; further, they are accompanied at the surface by gravity-related elements such as trenches and counterslope scarps. Generally described as crevice-type caves (Vitek 1983; Krejčí *et al.* 2002; Margielewski & Urban 2003; Baroň *et al.* 2004; Klimes *et al.* 2012; Lenart *et al.* 2014), they are mostly an effect of the gravitational movement. Pánek *et al.* (2010), in their study about landslides in the Polish Flysch Carpathians, identify three stages in the deformation of the slopes, based upon the observed surface and underground features: i) initial slope transformation with subsurface forms preceding the effective development of the landslide; ii) a rotational landslide, showing deeper propagation of the deformation effects; and iii) multi-stage landforms in large, complex slope movements. The case of Jaskinia Miecharska Cave (Margielewski 2006; Margielewski *et al.* 2007) is of particular interest, since the cave development strictly follows the strata bedding, and the ground surface as well, with its base actually coinciding with the landslide slip surface, or very close to it (see Fig. 4B in Pánek *et al.* 2010). This poses the question whether the cave was an element existing before the landslide, that could have played a role in its development and occurrence.

Even if not reported as crevice-type caves, similar features have been described in landslide contexts in Italy, from the Alps (Tognini & Bini 2001; Alberto *et al.* 2008), to the Titerno Valley (Budetta *et al.* 1994) and the Sorrento Peninsula (Santo *et al.* 2007), both in Campania, to the Scanno rock avalanche in Abruzzo (Nicoletti *et al.* 1993): long trenches, deep to a maximum of some tens of meters, are the main surface evidence of these large slope movements (Fig. 7).

Fig. 7: Several tens of meters-deep trench bounding the crown area of a deep slope movement in the limestones of the Sorrento Peninsula (Campania, southern Italy). Width of the trench at the surface is between 2 and 3.5 meters (Photos: M. Parise).

In rocks other than pure carbonates, such as clay-bonded quartz sandstones, development of conduits similar to those of karstic origin is at the origin of the landforms observed in the Strelec Quarry, in the northern Czech Republic (Bruthans *et al.* 2012). Headward development of the conduits (mostly along sub-vertical fractures in the rock mass) through piping processes resulted in increasing erosion, and in production of canyons and caves.

Pollution events may occur very easily in karst, with serious consequences in terms of loss of natural resources, with specific regard to water. They are typically induced by human activities, through direct injection of pollutants at the surface or directly within swallow sites, and can be highly exacerbated in particular conditions, such as post-war scenarios (Calò & Parise 2009). However, natural cases of pollution may also happen, for instance on the occasion of heavy floods, causing huge amount of water to infiltrate underground, possibly carrying great amount of pollutants, or simply causing a mixing between the water table and the surface waters produced by the flood. Quite often it is not possible to discriminate the actions of human origin from those that can be considered natural.

Given the peculiarities of the fragile karst setting, the planning and realization of engineering works (Milanovic 2002; Parise *et al.* 2015) is particularly delicate, and often result in environmental problems and/or damage to the natural landscape. Building dams, in particular, may require high costs, with results that often are not those expected, due to problems in filling the planned reservoirs because of leakage through karst conduits and fissures in the rock mass.

Management of karst terranes cannot be carried out without taking into the due account the peculiar features and behaviour of karst landscapes and aquifers. The delicate and fragile equilibrium reached by nature in the course of millennia can be easily threatened by man, with catastrophic consequences to the society in terms of casualties and economic losses.

MANAGEMENT OF A FRAGILE ENVIRONMENT

Karst terranes present at the surface typical landforms such as closed depressions, dolines, ponor, and poljes (Fig. 4), and are characterized by a complex underground drainage system, which includes the aforementioned direct interaction between water flowing at the surface and groundwater (Nicod 1972; Ford & Williams 2007). The hydrological and hydrogeological features of karst terranes allows storage of great amount of high-quality water, a natural resource of high value that, however, may be easily threatened by anthropogenic actions (Parise & Pascali 2003). The latter point, in particular, poses high environmental problems, since a likely pollutant cannot be diluted by passing through different types of rocks in its downward movement, but it rather reaches the karst aquifer with all its potential of pollution, strongly impacting the water quality (Zwahlen 2004; Goldscheider 2005; Farfan *et al.* 2010). Differently than for the great majority of natural environments on Earth, in karst there is not necessarily correspondence between the surface watersheds, that are typically identified following the topographic divides, and the groundwater circulation (Dunne 1990; Gunn 2007). Water can infiltrate at a certain site (ponor, swallow holes, cave), and be transported in another, nearby watershed. Consequently, the only way to be sure of the course of water in karst is following it underground, when possible, or using dye tracers (Goldscheider & Drew 2007) to move along its path whenever man is not able to enter narrow or flooded passages.

Locating catchment boundaries in karst represents a highly complex goal, also because of the great variability that may be recorded in time. During floods, in fact, changes in the path followed by groundwater, with reactivations of generally fossil passages, have been repeatedly observed, originating overflow from one catchment to those nearby (Bonacci 1995; Bonacci *et al.* 2006; De Waele & Parise 2013).

All of this has direct consequences in terms of management of the hydric resources, and becomes an even more delicate issue when facing trans-boundary karst aquifers. Many country borders, that separate different states from the administrative standpoint, actually do not exist in karst; water management actions issued in a country, therefore, may have significant effects in the nearby areas, posing problems in terms of availability of good-quality waters, and triggering possible conflicts among populations. Lakes Ohrid and Prespa, shared by Macedonia, Albania, and Greece (Popovska & Bonacci 2007) are probably one of the best examples at this regard: hydrologically, the system of the two lakes should be ideally managed as a trans-boundary water resource (Amataj *et al.* 2007). However, so far no coordinated water resources management among the three countries has been established.

The hydrological peculiarities of karst cannot be ignored in both legislation and regulations about land use and planning. In the last centuries, with an increasing pace in the last decades, man has become one of the main agents shaping the landscapes, often causing heavy changes in the original environment (Goudie 2013). In the fragile karst setting, the transformations deriving from man's activities may have a great impact, and cause negative effects to the overall ecosystem (Parise & Gunn 2007), as well as inducing the loss of karst features and natural resources. To provide some examples, mining and quarrying produce severe impacts on the environment, causing loss of natural landscapes and frequently favoring events of degradation and pollution (Ryka & Werner 1985; Ekmekci 1993; Gunn 1993, 2004; Parise 2010b). Environmental degradation may occur both during the phase of work and after the end of the extraction. In karst, opening of quarries inevitably is in contrast with the presence of natural caves: finding a cave means typically trouble, because the working activity is delayed, if not stopped. Even where specific rules exist to safeguard karst caves (Quinlan 1986; Assad & Jordan 1994; LaMoreaux 1997; LaMoreaux *et al.* 1997; Fleury 2009), the common practice is to rapidly proceed to destroying the cave or filling it with waste materials (Formicola *et al.* 2010), without allowing cavers to explore, and document it. Further, abandoned mines and quarries, at the surface and underground, may easily become the sites where to illegally discharge wastes and pollutants (Delle Rose *et al.* 2007). This represents one of the highest negative impacts to the environment, and for this reason any mining and quarrying activity should necessarily include a final recovery plan of the site, aimed at avoiding such negative circumstances.

Management of karst and related resources requires to perform analysis as concerns the social and economic effects in karst, broadening the usual approach and referring to concepts from other disciplines. To evaluate the ability of a system to absorb perturbation or disturbances, the term resilience, initially proposed in the field of ecology as a core concept within ecosystems (Holling 1973) is being widely used recently. As concerns natural disaster, resilience is the capacity to resist and recover from disaster losses (Kleina *et al.* 2003; Zhou *et al.* 2010). It includes the three components of i) response to disturbance, ii) capacity to self-organize, and iii) capacity to learn and adapt.

Since the social and environmental consequences of disasters (including pollution events) are strongly increasing, there is the need to involve stakeholders and population in strategies to manage the impacts (Djalante 2012; Lei *et al.* 2014). Such actions are especially required in heavily populated areas, or in those sectors in the proximity of big cities and metropolitan areas, where the intertwining among natural and anthropogenic factors may be very strong (Serre & Barroca 2013). This becomes particularly relevant in karst, due to the likely negative effects that human actions may produce to the natural landscape, the natural resources therein contained, and the karst ecosystems as well.

Repeated episodes of mismanagement in karst, with events of pollution, that have caused severe consequences, highlight how fragile this setting is and, once again, the necessity of a direct involvement of the population in order to create an environmental awareness, addressed to safeguard the delicate karst setting and the natural resources it contains. The concept of resilience in karst

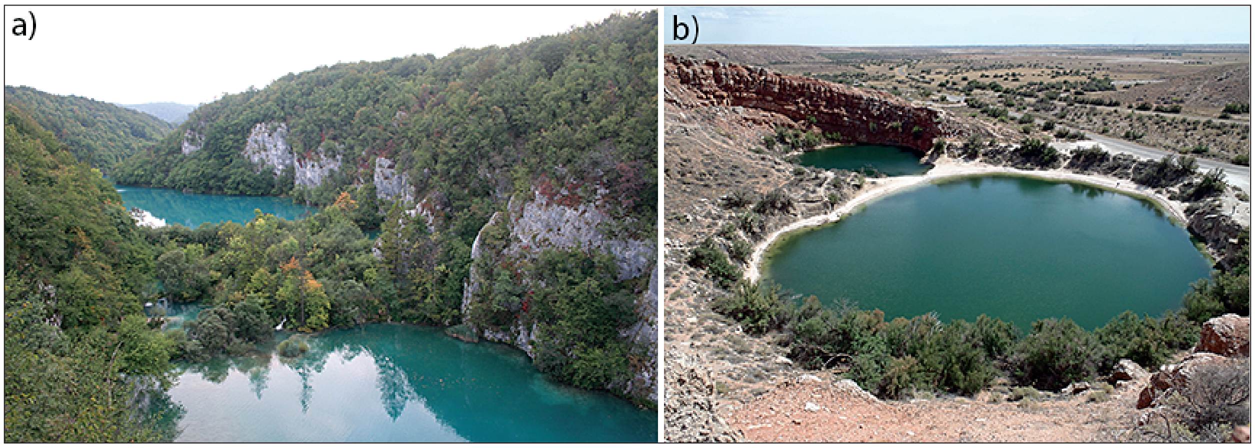

Fig. 8 –Natural karst park areas: a) Plitvice lakes, in Croatia (Photo: M. Parise); b) Mirror Lake at Bottomless Lakes State Park, New Mexico, USA (Photo: M. Parise).

should therefore be further object of analysis, involving all the three components above mentioned, and in particular performing an effort in adapting it to the peculiarity of karst environments.

In the light of likely future scenarios, linked with variations in the climatic conditions of the planet, this should even more properly faced. Derron & Jaboyedoff (2012), taking into consideration the climate change scenarios proposed by the Intergovernmental Panel on Climate Changes (IPCC 2007), present a sensitivity analysis to assess the impact that such changes may have on chemical weathering and the resulting rock mass weakening. Their results suggest that for carbonate rocks, atmospheric CO_2 doubling is the most impacting factor for both solubility (30% increase) and dissolution rate (20% increase). This could potentially result in higher weathering rates in the future and stronger predisposition of soluble rock masses to slope movements.

In order to face the very high pressure acting on karst environment and its natural resources, approaches dedicated to manage the delicate balance therein existing, with particular regards to the trans-boundary water resources and the precious habitats and species in karst, are necessary. These latter need to be dealt with through specific, dedicated actions of safeguard, aimed at not destroying the high-value biodiversity in karst (Brancelj & Culver 2005; Culver & Pipan 2009), and at mitigating as much as possible the occurrence of geo-hazards.

Safeguarding the unique groundwater ecosystems that are present in karst from natural hazards (Parise & Gunn 2007; Gutierrez 2010; Parise 2010a; De Waele *et al.* 2011; Gutierrez *et al.* 2014), including climate change at the global and local scale, and mitigating the related risks are the main priority actions to be followed in order to reach a sustainable management in this fragile setting. Analysis of geo-hazards in karst, and actions toward their prevention and/or mitigation of the related risks, requires to perform significant efforts addressed to a two-folds goal: i) a better comprehension of karst processes, and ii) development of specific approaches and procedures to face the most frequent typologies of geo-hazards (Veni 1999; Goldscheider *et al.* 2000; Vìas *et al.* 2006; Ravbar & Goldscheider 2009; Brinkmann & Parise 2012). These have necessarily to take into account the interrelationships between the surface and the underground worlds, as well as the time and space variability of many of the factors playing a role in karst ecosystems.

Analysis of geo-hazards in karst, as well as the choice of the prevention actions aimed at mitigating the risk, cannot be performed without carefully taking into account the specific features of this environment. Dedicated approaches should be encouraged, based upon the peculiarities of karst terranes, and the need to evaluate all the likely negative impacts. Adoption of procedures and indices such as the Karst Disturbance Index (KDI; Van Beynen & Townsend 2005; North *et al.* 2009), and the Sustainability Index for karst environments (SI; Van Beynen *et al.* 2012), are valid efforts in this direction. Even though not sufficient to a complete understanding of karst ecosystems, and to solve the related risks, these approaches are definitely a positive contribution to an increase awareness of the problems, especially in relation with the human activities, and may provide useful insights to calibrate future actions aimed at mitigating the negative effects of human actions in karst. From the first implementations of these indices (Calò & Parise 2006; De Waele 2009; North *et al.* 2009; Day *et al.* 2011; Angulo *et al.* 2013), it appears that knowledge of the main features of the karst environments, encompassing many different fields and disciplines of interest, is fundamental for a proper understanding of the changes occurring, and for linking such changes to specific actions by man or to variability of other factors (i.e., climate changes at the global or local scale).

It has to be kept in mind that karst has also a strong relationship with natural parks (Fig. 8): due to beauty of the scenery, and to richness of the natural heritage, in many karst areas there is the possibility of sustainable development and tourist activities, with opportunities of work for the local population, even in rural and/or semi-rural areas (Di Maggio *et al.* 2012; Angulo *et al.* 2013). Such opportunities should be encouraged with actions aimed at a correct land use in karst, that has to include also activities linked to the management of geo-hazards, to ensure safety to people and safeguard of the natural heritage (Fleury 2009; Nathwani *et al.* 2009).

CONCLUSIONS

More than in other environments, occurrence of geo-hazards in karst may cause serious damage and unrecoverable loss of the natural landscape and resources. Human actions, often overlooking the delicate and fragile karst setting, are frequently at the origin of natural disasters, or may act in exacerbating the effects of natural hazards. In order to mitigate the negative effects to the vulnerable elements in karst, and to reduce the related risk, land use planning and management should be performed in karst taking into the due account the intrinsic features of soluble rocks, and the related modality of groundwater flow and hydrology. At the same time, a priority to reach this goal is the growth of an environmental awareness, through which the communities living in karst terranes have to reach a sustainable approach in developing projects and actions addressed toward the most proper exploitation of these precious and invaluable environment.

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