A review on natural and human-induced geohazards and impacts in karst

F. Gutiérrez, M. Parise, J. De Waele, H. Jourde

Abstract

Karst environments are characterized by distinctive landforms related to dissolution and a dominant subsurface drainage. The direct connection between the surface and the underlying high permeability aquifers makes karst aquifers extremely vulnerable to pollution. A high percentage of the world population depends on these water resources. Moreover, karst terrains, frequently underlain by cavernous carbonate and/or evaporite rocks, may be affected by severe ground instability problems. Impacts and hazards associated with karst are rapidly increasing as development expands upon these areas without proper planning taking into account the peculiarities of these environments. This has led to an escalation of karst-related environmental and engineering problems such as sinkholes, floods involving highly transmissive aquifers, and landslides developed on rocks weakened by karstification. The environmental fragility of karst settings, together with their endemic hazardous processes, have received an increasing attention from the scientific community in the last decades. Concurrently, the interest of planners and decision-makers on a safe and sustainable management of karst lands is also growing. This work reviews the main natural and human-induced hazards characteristic of karst environments, with specific focus on sinkholes, floods and slope movements, and summarizes the main outcomes reached by karst scientists regarding the assessment of environmental impacts and their mitigation.

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1. Introduction

In the past two centuries the world’s population has increased exponentially, reaching over 7 billion people in 2011. The larger number of people has resulted in rapid urban expansion and increasing occupation of land, together with a rising demand of primary resources (water, building materials, food, electricity, etc.), with the consequent increasing anthropogenic impact on the environment (industries, wastes, pollution, traffic, etc.) (Goudie, 2013).

Humans are slowly learning how to deal with environmental issues, trying to find a sustainable balance between the use of resources and the need of preserving and recovering the natural assets (Middleton, 2013). Humans are also learning how to live in a changing environment, understanding the response of natural systems to both human and natural modifications (e.g. floods, landslides, and climate change), and building a societal resilience to natural disasters (Djalante, 2012).

Some areas in the world are intrinsically more vulnerable than others, depending on a series of factors like geology, geomorphology, hydrogeology, biodiversity, climate and so forth. If we only consider surface and subsurface geological factors, the most vulnerable areas are those with a direct relationship between surface morphology and subsurface hydrology, widely known as “karst”. The increase in population and resource demand is resulting in a progressive occupation of karst terrains. In order to minimize the impacts and hazards on these vulnerable and complex areas, man is head for learning how to “live with karst”.

This paper presents a review on hazards and impacts typical of karst, including sinkholes, floods, and slope failures, as well as anthropogenic impacts like pollution of karst aquifers. It deals with their genesis and controlling factors, their inventorying, investigation and assessment, as well as alternatives for their possible mitigation and remediation.

2. The karst environment

The shape of the Earth’s surface is the result of a wide set of physical and chemical processes that have acted over thousands or millions of years. The karst landscape takes its name from a region comprised between NE Italy and Slovenia dominated by outcrops of carbonate rocks. Karst refers to an ensemble of morphological and hydrological features and the dominant process responsible for them: dissolution of soluble rocks (mostly carbonates and evaporites). In karst landscapes (Fig. 1), surface and subsurface rock dissolution largely overrules mechanical erosion, leading to a distinctive morphology and hydrology (Ford and Williams, 2007). It may also occur in other carbonate rocks, such as dolostones. In less pure carbonate rocks or in limestone sequences with interbedded insoluble lithologies (Fig. 2), the typical karst features are less developed or even subordinate with respect to other types of landforms.

In most cases, carbonate rocks are dissolved by slightly acidic waters infiltrating into the rock. Acidity primarily derives from CO2 present in the air and in the soil, which slowly dissolves into the meteoric waters reducing their pH and increasing their corrosion capability. Other sources of acidity can be organic acids or oxidation processes occurring in aerate conditions. These aggressive waters percolate downwards and flow down-gradient in the phreatic (saturated) zone towards the discharge points (i.e. springs). In carbonate karst areas, most of the dissolution occurs in the epikarst, close to the surface (Williams, 2008), and rapidly decreases downwards as the saturation degree increases. A large number of papers address the problem of dissolution kinetics of carbonate systems interacting with meteoric waters (see for example Dreybrodt et al., 1996; Kaufmann and Dreybrodt, 2007; Palmer, 2007). Many factors influence the chemical reactions involved in the dissolution of carbonate rocks, which ultimately lead to a wide
variety of surface and underground features endemic of karst environments. At the interface between fresh and saline groundwater (Sáinz-García et al., 2011), or at the mixing zone between vadose and phreatic waters, different types of cavities may form (Dreybrodt et al., 2009). In young limestones close to the sea, enhanced dissolution at the interface between the freshwater body and the denser salt water gives rise to the so-called “flank margin caves” (Mylroie and Carew, 1990).

The acidity of dissolving waters not always derives from surface sources; it can also be produced locally (e.g. oxidation of sulfides such as pyrite; Tisato et al., 2012) or derived from CO$_2^-$ or H$_2$S-rich rising fluids. These highly aggressive rising waters sometimes lead to the formation of the so-called hypogenic cave systems (Klimchouk, 2009), some of which are created by fluids enriched in carbonic acid (e.g. Black Hills, South Dakota; Bakalowicz et al., 1987), or sulphuric acid (e.g. Guadalupe Mountains, New Mexico; Hill, 1987). In the case of hypogenic karstification, intensive dissolution may create extensive maze cave systems in areas lacking the typical surface karst morphology.

Karst also applies to other soluble rocks such as gypsum, halite, and even quartzite. Gypsum karst (Fig. 1) has been described in many countries and in a wide range of different climatic settings (Klimchouk et al., 1996; Calaforra, 1998). The deep-seated gypsum karst of western Ukraine, developed by artesian flows under confined hydrogeological conditions, has produced among the longest cave systems in the world, consisting of complex three-dimensional mazes over 200 km long (Klimchouk, 2000a). Gypsum is around 100 times more soluble than carbonate rocks. Consequently, karst in gypsum rocks evolves at a much faster rate and often causes severe problems to the built environment, frequently fostered by anthropogenic factors (Cooper and Gutiérrez, 2013). An even more soluble rock is halite, which only survives at the Earth’s surface in extremely arid regions or where salt diapirism continuously brings new salt to outcrop. The best studied salt karsts in the world are located along the Dead Sea (Frumkin, 2013), the Zagros Mountains, Iran (Bruthans et al., 2010; Zarei et al., 2011), and in the Atacama Desert, Chile (De Waele and Forti, 2010). Also quartz-sandstone terrains can display the typical karst features such as karren, caves and underground drainage (Wray, 1997; Piccini and Meccia, 2009). Although designated by some authors as “pseudokarst” (e.g. Aubrecht et al., 2011), there is clear evidence that dissolution is the prevailing morphogenetic process in these landscapes (Sauro et al., 2011).

The direct connection between the surface and the underlying aquifer makes underground karst waters extremely vulnerable to pollution. Moreover, the typical high secondary permeability of karst enables underground water to be transferred very rapidly (Goldscheider and Drew, 2007). This allows pollutants to be transported quickly and often without undergoing appreciable chemical and physical changes. The rapid transfer of water from the recharge areas to the discharge zone may also lead to abrupt changes in flow rate, which may vary by three orders of magnitude in a relative short time span (De Waele, 2008; Covington et al., 2009). Karst has also the ability of storing sediments and waters underground, including pollutants, which may be released during severe flow events (Mahler et al., 1999). Dissolution processes, together with mechanical erosion along underground pathways, may give rise to the formation of three-dimensional systems of conduits, and solutionally enlarged discontinuity planes (fractures, bedding planes), forming extremely complex three component permeability aquifer systems (Worthington, 1999; White, 2002). Still much research has to be carried out to comprehensively understand these aquifers for their appropriate management and protection (Palmer, 2010).

Finally, karst areas and aquifers are extremely valuable natural resources, hosting a wide variety of often unique ecological niches (Culver and Piper, 2005). Besides the often extremely rich variety of plants and animals, including species endemic of karst areas (e.g. troglobites, Proteus anguinus), the subterranean karst environments are also home to a variety of other life forms, including bacteria and fungi that play important roles in the biogeochemical cycles of these systems.
are also unique microbiological habitats. This biodiversity is worth protection and ongoing research on new cave dwelling species and microbiological communities might allow the discovery of new substances useful for medical purposes (Barton and Northup, 2007).

3. The different types of hazards in karst

3.1. Sinkholes

3.1.1. Genetic processes and resulting surface and subsurface features

Sinkholes or dolines are closed depressions with internal drainage, widely regarded as one of the main diagnostic landforms of karst (Ford and Williams, 2007). The term doline, derived from the Slavic word dolina, is used mainly by European geomorphologists (Gams, 2000; Sauro, 2003), whereas sinkhole is the most common term in North America and in the international literature dealing with engineering and environmental issues (Beck, 1984, 1988). Sinkholes display a wide range of morphologies (cylindrical, conical, bowl- or pan-shaped), varying in size up to hundreds of meters across and typically from a few to tens of meters deep. Compound depressions resulting from the coalescence of several sinkholes have been traditionally designated as uvalas (Sweeting, 1972). However, the term uvala, frequently applied with a loose meaning, is falling into disuse (Čalić, 2011 and references therein).

Sinkholes are often related to the dissolution of carbonate and/or evaporite rocks. There are some important differences between carbonate and evaporite karst systems with significant influence on sinkhole development and the associated hazards (Martínez et al., 1998; Gutiérrez et al., 2008a; Frumkin, 2013; Gutiérrez and Cooper, 2013): (1) Evaporites dissolve much more rapidly than carbonates (Dreybrodt, 2004). The equilibrium solubilities of gypsum (CaSO₄·2H₂O) and halite (NaCl), the most common evaporite minerals, in distilled water are 2.4 g L⁻¹ and 360 g L⁻¹, respectively. By comparison, the solubilities of calcite (CaCO₃) and dolomite (MgCa[CO₃]₂) in normal meteoric waters are generally lower than 0.1 g L⁻¹. This fact explains why in evaporite karst cavities form and develop much more rapidly, sinkholes generally show a higher probability of occurrence, and subsidence rates may reach much higher values. (2) Gypsum and halite have a significantly lower mechanical strength and a more ductile rheology than most carbonate rocks. Moreover, evaporite rock masses may weaken substantially at a human time-scale by rapid dissolution, frequently guided by discontinuity planes. These circumstances explain why sinkholes in evaporite karst areas may form by a broader diversity of subsidence mechanisms, including ductile sagging, and why collapse processes generally operate at higher rates. (3) Many evaporite sequences include hypersoluble facies (halite, glauberite, K-chlorides) rarely exposed at the surface. These contexts are particularly prone to the development of sinkholes and large subsidence depressions related to interstatal dissolution of salts, frequently misleadingly attributed to gypsum solution due to the lack of adequate subsurface data (e.g. Galve et al., 2009a; Guerrero et al., 2013).

In addition to those linked to natural karst caves, sinkholes may also occur above Anthropogenic cavities (Galeazzi, 2013; Parise et al., 2013) (Fig. 3). These cases, not directly linked to karst phenomena, although frequently found in soluble rocks, will not be treated in this review.

Several genetic classifications of sinkholes have been recently published, distinguishing two main groups of sinkholes (Williams, 2004; Beck, 2005; Waltham et al., 2005; Gutiérrez et al., 2008b) (Fig. 4). One of them corresponds to solution sinkholes, generated by differential corrosional lowering of the ground surface where karst rocks are exposed at the surface or merely soil mantled (bare karst). The development of these sinkholes is governed by centripetal flow towards higher permeability zones in the epikarst and the consequent focused dissolution (Williams, 1983, 1985; Ford and Williams, 2007). These depressions, although prone to flooding, do not pose ground stability problems unless they are underlain by dissolutional conduits or shafts of considerable size (Klimchouk, 2000b). The other group of sinkholes, which can be collectively designated as subsidence sinkholes, results from both subsurface dissolution and downward gravitational movement (internal erosion or deformation) of the undermined overlying material. These sinkholes, that cause the subsidence of the ground surface, are the most important from a hazard and engineering perspective. The sinkhole classification proposed by Gutiérrez et al. (2008b) integrates those proposed by Beck (2005) and Waltham et al. (2005) and covers the sinkhole types found in both carbonate and evaporite karst terrains (Fig. 4). This classification describes the end-members of the subsidence sinkholes using two terms. The first descriptor refers to the material affected by internal erosion and/or deformation processes (cover, bedrock or caprock), and the second descriptor indicates the main subsidence process (collapse, suffosion or sagging). Cover refers to unconsolidated alloigenic deposits or residual soil material, bedrock to karst rocks, and caprock to non-karst rocks. Collapse is the brittle deformation of soil or rock material either by the development of well-defined failure planes or brecciation, suffosion is the downward migration of cover deposits through voids and their progressive settling, and sagging is the ductile flexing (passive bending) of sediments caused by the lack of basal support. Frequently, more than one material type and several processes are involved in the generation of subsidence sinkholes. These complex sinkholes can be described using combinations of the proposed terms with the dominant material and/or process followed by the secondary one (e.g. cover and bedrock collapse sinkhole). A correct diagnosis of the sinkhole typology constitutes an essential step for a proper hazard assessment and the design of effective mitigation measures.

The cover material in mantled karst settings may be affected by any of the three subsidence mechanisms. The gradual lowering of the rockhead by differential dissolution may lead to progressive settlement of the overlying soil, producing cover sagging sinkholes. These processes result in a folded cover with basin structures (centripetal dips) that do not affect the underlying karst bedrock. Sinkholes thus produced do not require the formation of cavities, are typically shallow, vaguely-edged and can reach several hundred meters across.

Cover deposits may migrate downward into conduits and cutters associated with the rockhead, frequently showing a pinnacled geometry. Internal erosion of the cover may occur through a wide range of processes, collectively designated as suffosion or ravelling (Beck, 1988, 2005; White, 1988; Sowers, 1996; Waltham et al., 2005): down washing of fine particles by percolating waters, cohesionless granular flows, viscous sediment gravity flows (non-Newtonian) (e.g. Jancin and Clark, 1993), fall of particles, and sediment-laden water flows. Undermining of the cover by internal erosion may lead to the formation of two main types of sinkholes depending on the rheological behavior of the mantling deposits. Where the cover behaves as a ductile or loose granular material, it may settle gradually without the development of significant failure planes (continuous deformation) generating funnel- or bowl-shaped cover suffosion sinkholes, typically a few meters in diameter. When the cover behaves in a brittle way, subsurface erosion of the mantling deposits above a dissolutional pipe generally results in an arched cavity whose upward migration by successive soil failures eventually leads to the formation of a cover collapse sinkhole or a dropout sinkhole according to Williams (2004) and Walthams et al. (2005) classifications (Fig. 5). Cover collapse sinkholes, typically less than 10 m in diameter, commonly occur in a sudden way and have scarped or overhanging sides at the time of formation. Mass wasting processes acting at their margins may cause their rapid enlargement and transform them into funnel- or bowl-shaped depressions. Cover collapse and cover suffosion sinkholes cause the vast majority of the sinkhole damage (Beck, 2005; Waltham et al., 2005), since these are the sinkhole types most sensitive to human alterations and with the highest probability of occurrence.

Bedrocks and caprocks in carbonate karst areas underlain by cavities are typically affected by collapse processes. However, interstatal
Karstification in more ductile evaporitic sequences may lead to subsidence by collapse and/or sagging mechanisms.

Deflection of gravitational stresses around a cavity creates a tension zone over the roof that is overlain by an arched compression zone (voussoir arch) (White, 1988; Waltham et al., 2005). This tension zone controls the development of cupola-shaped failure planes, resulting in the generation of quite stable arched roofs. A peculiarity of karst rocks in terms of underground void stability is that their strength may be reduced substantially in a short period of time by dissolution and other weathering processes (i.e. crystal wedging), mainly acting along discontinuity planes (White and White, 2003; Parise and Lollino, 2011; Lollino et al., 2013). Collapse of the cavity roof typically produces a chaotic breakdown pile on the floor. As the cave migrates upward by successive collapses, the breakdown pile grows generating a breccia pipe, also called collapse chimney and breakdown column (Klimchouk and Andrejchuk, 2005). These trans-stratal structures may reach...
hundreds of meters in height when developed associated with thick evaporitic sequences (Warren, 2006; Gutiérrez and Cooper, 2013 and references therein). Whether a stoping void can reach the surface or not depends chiefly on the size of the opening, the overburden thickness and the bulking effect of the breakdown process (Ege, 1984; Andrejchuk and Klimchouk, 2002). The stoping process may cease if the cavity roof and the breakdown pile come into contact, thus choking the collapse pipe.

Collapse breccias can be classified considering the relative displacement of fragments (crack, mosaic and chaotic) and whether they have a clast-supported (packbreccia) or matrix-supported (floatbreccia) texture (Stanton, 1966; Kerans, 1988; Warren, 2006; Loucks, 2007). The highly pervious collapse breccias may act as zones of preferential groundwater flow and dissolution (Yin and Zhang, 2005). Karstification may transform chaotic packbreccias into a mass of corroded clasts embedded in karstic residue (floatbreccia). These dissolution processes involve a reduction in volume of the breccia that may lead to renewed subsidence. A less common collapse mode is the en bloc foundering of a cavity roof with limited internal deformation controlled by steep failure planes (ring faulting) (e.g. Pedley and Bennett, 1985; Gutiérrez et al., 2008b). These collapse processes typically lead to the sudden formation of steep-walled bedrock collapse sinkholes and caprock collapse sinkholes, both characterized by a low probability of occurrence. The main difference between these two types is that dissolution cannot affect breccia pipes made up of collapsed non-soluble rocks.

Sagging of bedrock or caprock is generally related to interstral dissolution of evaporites. Progressive dissolution within the bedrock may be accompanied by continuous flexure of the overlying strata, so that cavities do not necessarily develop beneath the sagging rocks. This subsidence process results in the development of disharmonic basin structures with centripetal dips restricted to the strata overlying the karstification zone. This subsidence mechanism produces bedrock sagging sinkholes and caprock sagging sinkholes that may reach hundreds of meters in length (Kirkham et al., 2003; Gutiérrez and Cooper, 2013 and references therein). Passive bending of the strata involves horizontal shortening that may be counterbalanced through the development of small-throw normal faults, fissures and grabens at the margins (e.g. Festa et al., 2012; Gutiérrez et al., 2012a). Secondary normal and reverse bending-moment faults may also develop at the margins and central sector of these sag basins (Ge and Jackson, 1998). The passive bending of rock strata may be accompanied by widespread fracturing (brecciation) and/or the development of superimposed collapse structures, preferentially in the more fractured central sector of the basins (Andrejchuk and Klimchouk, 2002; Guerrero et al., 2008a,b, 2013; Gutiérrez et al., 2008b).

3.1.2. Controlling and triggering natural and anthropogenic factors

When analyzing the factors involved in the development of sinkholes, it is important to take into account several issues. Subsidence sinkholes result from the concomitant or sequential activity of two types of processes: subsurface dissolution by groundwater flow, accompanied in some circumstances by abrasion (hydrogeological component), and downward gravitational movement of the overlying material (mechanical component). In carbonate karst areas, where dissolution processes operate at relatively slow rates, the effects of active corrosion over a human time-scale are of low relevance (Beck, 2005). In contrast, dissolution may be very rapid in evaporite karst settings, specially those with turbulent freshwater flows and those with highly soluble salts. Subsidence processes, particularly collapse and suffusion, can be very rapid in any karst environment and may be related to the presence of relict voids.

According to White (1984), the rates at which dissolution processes occur depend on a chemical and a hydrodynamic component. The chemical component relates to the dissolution reaction. The hydrodynamic component relates to the condition of the aqueous phase as a static or a moving medium. If the water is static, the solute flux takes place by diffusion across the diffusion boundary layer. If the water is moving, mass transfer in the moving water, termed convection, is added to diffusion with the consequent increase in the dissolution rate. Berner (1978) differentiated two extreme types of dissolution systems. The surface-reaction controlled system applies to low solubility minerals (e.g. calcite), in which the dissolution rate is essentially controlled by the dissolution reaction (chemical component). The transport-controlled system applies to high solubility minerals (e.g. halite), in which the dissolution rate depends largely on the flow velocity and regime (hydrodynamic component). Gypsum shows a mixed transport-controlled and a surface-reaction behavior (Raines and Dewers, 1997; Jeschke et al., 2001).

Natural and especially anthropogenic changes in the karst environment can activate or accelerate the processes (dissolution, subsidence) involved in the generation of subsidence sinkholes, triggering or favoring their occurrence or reactivation (e.g. Delle Rose et al., 2004). According to Waltham et al. (2005), human-induced sinkholes constitute the...
vast majority of new subsidence depressions. Table 1 presents the main natural or artificial changes that may induce the formation of sinkholes, together with their potential effects. This table, including key references of illustrative cases, is conceived as a checklist that can be used to elucidate and understand the factors that may have contributed to the generation of sinkholes. In agreement with several authors, our literature review reveals that increased water input to the ground and water table decline, either related to aquifer exploitation or mining-related dewatering, constitute the main sinkhole-inducing anthropogenic factors. The negative impact of these activities on sinkhole hazard is expected to increase in the future in many areas due to the growing demand in resources.

Increased water input to the ground enhances internal erosion processes and may adversely modify the mechanical strength and weight of sediments. Moreover, water infiltration may reduce dramatically the strength and bearing capacity of sabkha deposits due to rapid dissolution of salts (Abdulali and Sobhi, 2002; Youssef et al., 2012).

The main potential effects of lowering the groundwater level include the loss of buoyant support of sediments, the increased groundwater velocity and the replacement of phreatic flows by downward vadose flows with a greater capability to induce suffusion. The latter effect is particularly important when the water table declines below the rockhead (Waltham et al., 2005). A peculiar and dramatic example of human-induced catastrophic subsidence related to water table lowering corresponds to the hundreds of sinkholes formed over the last 30 years in the Dead Sea shores inIsrael and Jordan (Yechiel et al., 2006; Closson et al., 2007; Frumkin et al., 2011) (Fig. 5).

The impoundment of water in reservoirs is a common cause of sinkhole generation. The infill of a reservoir involves imposing a load and creating unnaturally high hydraulic gradients that may lead to rapid

<table>
<thead>
<tr>
<th>Type of change</th>
<th>Effects</th>
<th>(1) Natural processes; (2) human activities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increased water input to the ground</td>
<td>Favors dissolution.</td>
<td>(1) Rainfall (Zhao et al., 2010; Youssef et al., 2012), floods (Hyatt and Jacobs, 1996), snow melting, thawing of frozen ground (Satkanas et al., 2006).</td>
</tr>
<tr>
<td>(cover and bedrock)</td>
<td>Increases the weight of sediments.</td>
<td>(2) Irrigation (Atapour and Aftabi, 2002; Kirkham et al., 2003; Gutiérrez et al., 2007), leakages from pipes (Shaqour, 1994; McDowell and Poulson, 1996; Jassin et al., 1997; Gutiérrez and Cooper, 2002, 2009; Dougherty, 2005; McDowell, 2005; Fleury, 2009; Buttrick et al., 2011), canals (Swan, 1978; Lucha et al., 2008b) or ditches (Gutiérrez et al., 2007), impoundment of water (Milanovic, 2000), runoff concentration (urbanization, soak-aways, drainage wells) or diversion (Knight, 1971; White et al., 1986), vegetation removal, drilling operations, unsealed wells and boreholes (Johnson et al., 2003; Johnson, 2005; Lambrecht and Miller, 2006; Liguori et al., 2008), injection of fluids, solution mining (Ege, 1984).</td>
</tr>
<tr>
<td></td>
<td>May reduce the mechanical strength and bearing capacity of sediments.</td>
<td></td>
</tr>
<tr>
<td>Water table decline</td>
<td>Favors dissolution.</td>
<td>(2) Water abstraction (Kemmerly, 1980; Newton, 1984; LaMoreaux and Newton, 1986; Chen, 1988; Waltham and Smart, 1988; Shaqour, 1994; Tihansky, 1999; Kaufmann and Quinif, 2002; He et al., 2003; Kejriwal et al., 2004; Waltham, 2008; Dogan and Yilmaz, 2011; García-Moreno and Mateos, 2011), de-watering for mining and excavation operations (Foose, 1953; LaMoreaux and Newton, 1986; Chen, 1988; Xu and Zhao, 1988; Zhou, 1997; Li and Zhou, 1999; De Bruyn and Bell, 2001; Klimochuk and Andrejchuk, 2005; Spyrsyksey et al., 2009; Pando et al., 2013), decline of water level in lakes (Yechiel et al., 2006; Frumkin et al., 2011), excavations acting as drainages (Fidelibus et al., 2011).</td>
</tr>
<tr>
<td>Impoundment of water</td>
<td>Reduces the thickness and mechanical strength of cavity roofs.</td>
<td>(1) Natural lakes.</td>
</tr>
<tr>
<td></td>
<td>May create an outlet for internally eroded deposits.</td>
<td>(2) Reservoirs (Milanovic, 2000 and references therein, Uromelivy, 2000; Dogan and Cicok, 2002; Romanov et al., 2003; Bonacci and Roje-Bonacci, 2008; Johnson, 2008; Bonacci and Rubinich, 2009; Cooper and Gutiérrez, 2013 and references therein), ponds (Calo and Parise, 2009), sewage lagoons (Davis and Rahn, 1997).</td>
</tr>
<tr>
<td>Erosion or excavation</td>
<td>Reduces the thickness and mechanical strength of cavity roofs.</td>
<td>(1) Erosion processes.</td>
</tr>
<tr>
<td></td>
<td>May concentrate runoff.</td>
<td>(2) Excavations (Walker and Mattat, 1999; Lolicama et al., 2002; Guerrero et al., 2008b; Fidelibus et al., 2011).</td>
</tr>
<tr>
<td>Static loads</td>
<td>Favors the failure of cavity roofs and compaction processes.</td>
<td>(1) Biogenic pipes.</td>
</tr>
<tr>
<td></td>
<td>Unloading favors the formation of fractures and dilation of pre-existing ones.</td>
<td>(2) Conventional and solution mining (Ege, 1984; Xu and Zhao, 1988; Gongyu and Wanfang, 1999; Li and Zhou, 1999; Andrejchuk, 2002; Autin, 2002; Sharpe, 2003; Yin and Zhang, 2005; Warren, 2006; Bonetto et al., 2008; Lucha et al., 2008a; Wang et al., 2008; He et al., 2009; Mesescu, 2011; Parise, 2012), tunneling (Milanovic, 2000; Song et al., 2012),</td>
</tr>
</tbody>
</table>
turbulent flows with a high capability to flush out sediments from conduits and enlarge them by dissolution (Milanovic, 2000; Romanov et al., 2003). On the other hand, continuous changes in the reservoir level are accompanied by flooding and drainage cycles in the karst system, which favor both mechanical and chemical subsurface erosion. Pre-existing and newly created sinkholes in reservoirs and in the foundation of dams may result in severe water leakages and stability problems, compromising the operation and safety of the hydraulic structure. Milanovic (2000) reviewed a number of dam projects severely impacted or abandoned due to water losses through sinkholes functioning as ponors.

The excavation of tunnels and mine galleries, apart from dewatering by pumping, may cause dramatic changes in the local hydrogeology, leading to the formation of sinkholes (Milanovic, 2000; Bonetto et al., 2008; Wang et al., 2008; Vigna et al., 2010b). The interception of conduits and cavernous rock by excavations performed below the water table may result in dangerous inrushes of water under pressure. The drainage of the aquifer towards underground artificial openings may lead to uncontrolled flooding of the excavation, rapid lowering of the water table, suspension of water supply from wells, enhanced internal erosion and development of sinkholes (Vigna et al., 2010a).

Sinkhole hazard may be particularly severe when fresh water flows into salt mines from an adjacent or overlying aquifer (Andrejchuk, 2002), or from a surface water body (Austin, 2002; Lucha et al., 2008a). The highly aggressive water may cause massive dissolution of salt and uncontrollable sinkhole occurrence, leading to the abandonment of the mine (e.g. Lucha et al., 2008a).

Sinkholes may also be caused by the formation of large cavities in salt formations by solution mining, which involves the injection of fresh water and the recovery of brine (Ege, 1984; Johnson, 1997; Andrejchuk, 2002; Warren, 2006; Mancini et al., 2009; Mesescu, 2011). These cavities may propagate upward several hundred meters through overlying formations in a few decades, eventually leading to the sudden occurrence of large sinkholes (Ege, 1984; Johnson, 1997).

Natural and human-induced static and dynamic loadings may trigger the collapse of pre-existing cavities under marginal stability conditions. The load imposed by heavy vehicles, drilling rigs, dumped material and engineered structures may cause dangerous sinkhole events. A similar effect may be expected from ground shaking related to explosions and earthquakes, as documented by several authors in Italy (Del Prete et al., 2010b; Kawashima et al., 2010; Parise et al., 2010; Santo et al., 2011).

3.1.3. Sinkhole inventory and investigation

Generally, the most important step in sinkhole hazard analysis is the construction of a comprehensive cartographic sinkhole inventory. The reliability of sinkhole susceptibility and hazard maps and the effectiveness of the mitigation measures largely rely on the completeness, accuracy and representativeness of the sinkhole inventories on which they are based. Sinkhole databases should preferably include information on the following aspects: (1) Precise location of the limits of the sinkholes and the underlying subsidence structures. This is essential to define accurately the unstable areas, including a setback distance around the sinkholes (Zhou and Beck, 2008). (2) Morphometric parameters. These data constitute the basis on which to analyze magnitude and frequency relationships of sinkholes. (3) Genetic type, that is subsidence mechanisms and material affected by subsidence (Williams, 2004; Beck, 2005; Waltham et al., 2005; Gutiérrez et al., 2008b). This is a crucial aspect, since the subsidence mechanisms determine the applicability and effectiveness of different mitigation measures and the capability of the sinkholes to cause damage. (4) Chronology, either relative or numerical ages. The latter is indispensable to calculate rates of sinkhole occurrence and hazard estimates in terms of spatial and temporal probability values (Galve et al., 2011; Parise and Vennari, 2013). (5) Activity, including subsidence rates, kinematical behavior (gradual, episodic or mixed), and age of the most recent deformation episode. (6) Relationship with conditioning and triggering factors. The analysis of the sinkhole hazard also requires as much information as possible on other karst features (e.g. caves, springs, ponors), the geology and hydrogeology of the area, and human activities that may influence dissolusion and subsidence processes (Parise et al., 2008). Since some pioneering initiatives like that of the Florida Sinkhole Research Institute, a number of institutions and associations have developed sinkhole and karst databases mostly integrated in a Geographical Information System (Florea, 2005; Cooper et al., 2011; Parise and Vennari, 2013). The sinkhole and karst databases together with the datasets and maps derived from them (e.g. sinkhole hazard models) are an extremely useful planning tool that may help decision-makers to manage karst areas minimizing environmental problems. It may also be a valuable source of information for private companies (insurance, geotechnical) and the general public, as well as an excellent platform for researchers.

The identification and precise mapping of sinkholes, subsidence structures and dissolution features is a difficult task. The geomorphic expression of sinkholes may be masked by anthropogenic activities (filling, construction) and natural processes (aggradation, erosion). Moreover, shallow cavities and active subsidence structures that may lead to the generation of sinkholes in the near future may not have any surface manifestation. For these reasons, it is highly advisable to apply as many surface and subsurface investigation methods as possible to identify and characterize sinkholes and potentially unstable ground (Fig. 6). Table 2 presents a list of investigation methods indicating the main type of data related to sinkhole hazard that may be obtained through their application. Additional information may be obtained in the quoted references and in publications dealing with the different techniques.

3.1.4. Sinkhole hazard and risk assessment

Once the pre-existing sinkholes and areas affected by subsidence have been mapped and characterized, the next step in the sinkhole hazard analysis is to predict the spatial and temporal distribution of future sinkholes and their characteristics. Ideally, it would be desirable to assess, with a reasonable level of reliability, the probability of occurrence of sinkholes of each type and with different diameters in every location. In areas with different sinkhole types, it is advisable to analyze them separately since they are most likely controlled by different factors and have different spatial and temporal distribution patterns (e.g. Galve et al., 2009b). Depending on the information available, two types of models can be produced to predict the occurrence of future sinkholes: susceptibility models and hazard models. The susceptibility models represent the likelihood of a sinkhole occurring in any specific place in terms of relative probability. These models do not provide quantitative probability values and consequently cannot be used as the basis for quantitative risk analyses. This is the type of model presented in most published works (e.g. Buttrick et al., 2001; Yilmaz, 2007). The hazard models provide an estimation of the spatial–temporal probability values of future sinkholes, that is, the probability for a given zone and time interval of being affected by a sinkhole event (Fig. 7A). Chronological information on the analyzed sinkholes, either a precise age or an age interval, is indispensable to calculate temporal frequency values (Galve et al., 2009c, 2011; Parise and Vennari, 2013). In most cases, the calculated spatial–temporal probability values correspond to minimum or optimistic hazard estimates, since they are commonly derived from incomplete sinkhole inventories. Preferably, hazard models should incorporate magnitude and frequency scaling relationships accounting for the probability of occurrence of sinkholes with different diameters (Galve et al., 2011). Quantitative hazard estimates are essential for risk assessments, cost–benefit analyses of mitigation strategies, evaluation of insurance policies or pre-purchase appraisal of land.

Several methodologies may be applied to construct sinkhole susceptibility maps. (1) Direct mapping of susceptibility zonations based on expert criteria (Edmonds et al., 1987; Ardaud et al., 2007). These maps have a significant subjective component related to the expert
judgements, are not reproducible, and may lack an objective basis for substantiating the distribution and boundaries of the susceptibility zones. (2) The deterministic models are based on stability analyses that take into account a number of parameters involved in the subsidence processes (Koutepov et al., 2008). These models considerably simplify the complexity of the subsidence processes, incorporate geometrical suppositions and require a large amount of geotechnical data difficult and expensive to obtain, especially when analyzing large and heterogeneous areas. (3) Susceptibility models may be derived from parameters related to the spatial distribution of the inventoried sinkholes, like sinkhole density, distance to the nearest sinkhole or preferred alignment and elongation directions. Generally, the underlying assumption of the susceptibility models based on sinkhole density, either number of sinkholes per unit area or percentage area affected by sinkholes, is that the likelihood of sinkhole occurrence is higher in the areas with higher sinkhole density (Angel et al., 2004; Galve et al., 2009b). The distance of each point to the nearest sinkhole may be used to assess susceptibility assuming that the likelihood of sinkhole occurrence increases with the proximity to existing sinkholes (Zhou et al., 2003; Gao et al., 2005; Kemmerly, 2006; Galve et al., 2009b,c). In areas where the sinkholes are structurally controlled, showing statistically significant preferred orientations and alignments, the belts of land defined by two or more aligned sinkholes following a prevalent trend may be classified as more susceptible. An alternative group of methods of susceptibility assessment incorporate data on variables that control sinkhole development. (4) The heuristic approach involves establishing susceptibility classes by judging the contribution of a number of variables on sinkhole formation. Some authors differentiate susceptibility classes establishing threshold values for specific variables and using decision tree models (Kauffmann and Quinif, 2002; Bruno et al., 2008). Another widely used approach is to apply a weighing or scoring system to a group of conditioning factors (Buttrick and van Schalkwyk, 1998; Zisman, 2001; Tolmachev and Leonenko, 2005). The main disadvantage of the heuristic methods is the subjective component of the susceptibility assessments. (5) The probabilistic methods allow the construction of susceptibility models analyzing the statistical relationships between the spatial distribution of known sinkholes and that of a set of controlling factors. Several papers present bivariate analyses quantifying the spatial relationships between sinkholes, or parameters derived from this data layer (e.g. sinkhole density, distance to the nearest sinkhole), and specific variables governing their distribution (Whitman et al., 1999; Orndorff et al., 2000). These analyses were aimed at assessing the contribution of variables to the development of sinkholes, rather than to produce susceptibility models. More recent publications present susceptibility models based on the statistical relationships between the sinkholes and groups of highly diverse controlling factors applying different mathematical frameworks; favorability functions (Galve et al., 2009b,c, 2011, 2012a), logistic regression (Lamelas et al., 2008), and frequency ratios (Yilmaz, 2007). The main advantages of these methods include their objective statistical basis, reproducibility, ability for analyzing quantitatively the contribution of factors to sinkhole development and potential for continuous updating. These statistical techniques have been applied satisfactorily to landslides because data on the main conditioning factors (e.g. slope, lithology, land use) can be easily gathered (Remondo et al., 2005). Conversely, in the case of sinkholes, the generation of sound probabilistic and heuristic models is more challenging due to the limited availability of information on the variables that control the subsidence phenomena, some of which are difficult and expensive to obtain due to their subsurface nature.

Regardless of the methodology used to construct sinkhole susceptibility models, the predictions on the future spatial distribution of sinkholes should be considered as un-tested hypotheses, however reasonable they might be. A susceptibility model developed through a complex and sophisticated methodology, but with a limited prognostic capability, may lead to inadequate planning, the application of ineffective mitigation measures and severe losses. Therefore, it is highly advisable to evaluate quantitatively and independently the prediction capability of the models. Few of the sinkhole susceptibility models published so far have been validated independently (Lamelas et al., 2008; Galve et al., 2009b,c, 2011; Buttrick et al., 2011). Model evaluation
implies comparing the distribution of susceptibility zones defined in a model, with that of an independent sinkhole population not used for the development of the model (cross-validation). Several statistical techniques may be applied to discriminate between the sinkhole sample used for modeling (training set) and that for evaluating (validation or testing set). The prediction capability of the models can be evaluated following practical information: (1) Quantitative assessment of the prediction capability of the model. For example, temporal evaluation of susceptibility models in a sector of the Ebro Valley, NE Spain, indicates that the best quality sinkhole susceptibility model is expected to predict more than 50% of the new cover collapse sinkholes within 20% of the highest susceptibility area (Galve et al., 2011). (2) Identifying the prediction approach or mathematical functions that yield better predictions (e.g. Galve et al., 2009b). (3) Assessing the ability of the model
to discriminate the most dangerous zones and, most importantly, the safest areas; lower and upper segments of the prediction–rate curve.

(4) Selecting the most significant variables and evaluating their contribution to the prediction/formation of sinkholes, providing clues on their genesis. This information may be highly valuable for the selection of mitigation measures.

(5) Analyzing the effect of the accuracy of input variables on the models, which helps to improve the quality/effort ratio in the commonly tedious and expensive data-gathering process.

In areas where there is chronological information available on the inventoried sinkholes, the susceptibility models, once independently validated, can be transformed into hazard models considering the frequency of sinkholes in each susceptibility class (Galve et al., 2009c, 2011; Fig. 7A). The resulting models generally provide minimum hazard estimates, since sinkhole inventories are rarely complete. Additionally, in case there is information on the size (diameter) of the sinkholes, there is also the possibility of incorporating an empirical magnitude and frequency relationship in the hazard model. Such hazard models provide estimates of the probability of occurrence of sinkholes with different diameters in each portion of the territory (Galve et al., 2011; Tolmachev and Leonenko, 2011). The ergodic assumption may be applied in case there is limited information on the frequency of rare large-magnitude sinkholes; that is, expanding virtually the length of the temporal record by enlarging the area, substituting time by space. Regardless of the methods used to develop and evaluate the sinkhole models, it is important to take into account that reliability of the predictions may decrease substantially through time, especially where sinkholes are largely controlled by changeable human factors.

Sinkhole risk assessments require obtaining quantitative data on sinkhole hazard and on the vulnerability of the exposed human elements. Vulnerability refers to the expected losses in case a human element is impinged by a sinkhole and the probability of injury or loss of life. Vulnerability, which is a function of sinkhole type and size, can be assessed on the basis of data about economic and human losses caused by sinkholes in the past. Sinkholes may cause direct and indirect losses.
For instance, in case a road is affected by a collapse, the direct risk corresponds to the cost of repairing or reconstructing the structure and the injuries or fatalities caused by the subsidence event. The impact on the economic productivity caused by the temporal loss in serviceability and the resulting delays in the transportation of people and goods accounts for the indirect risk. Indirect losses, although difficult to identify and estimate, are frequently higher than the direct damage. Risk models preferably should indicate the expected economic and human losses due to sinkhole activity in each portion of the territory (Fig. 7B, C). These models allow identifying the areas where sinkhole-related damage is expected to reach higher values and where the application of mitigation measures might yield higher benefit/effort ratios.

Cost–benefit analyses can be performed to identify the optimum mitigation strategies from the economic perspective and its expected cost-effectiveness (Galve et al., 2012a). Cost–benefit analyses involve comparing the sinkhole-related costs generated over the lifetime of the project for the “without mitigation” scenario and multiple “with mitigation” scenarios. Different mitigation strategies and engineering solutions may be considered in the latter. The costs computed in the “without mitigation” scenario correspond to the direct and indirect losses caused by sinkholes. The expenditures considered in the “with mitigation” scenarios are the extra investment on mitigation plus the direct and indirect damage caused by sinkholes that cannot be prevented with the applied measures (residual risk). For the estimation of the economic losses in future years a discount factor is applied considering the time value of the money. The cost-effectiveness of a particular mitigation measure can be assessed calculating the financial index called Net Present Value, which is the amount of money the investment on the mitigation measure is worth, taking into account its cost, losses saved, and the time value of the money. By means of a cost–benefit analysis, Galve et al. (2012a,b) identify the most profitable geosynthetic design for a road built in a sinkhole-prone area and assess its cost-effectiveness (Fig. 7D). This cost–benefit analysis considers: (1) the probability of occurrence of sinkholes with different diameters in each road section; (2) the stability of the road sections without geosynthetics and protected with geosynthetics of different resistances; (3) the expected direct and indirect economic losses for the different scenarios.

### 3.1.5. Sinkhole risk mitigation

The subsidence of the ground related to the development of sinkholes may severely affect the integrity of any human structure including buildings, linear infrastructure (roads, railways, pipelines, canals), dams, and even nuclear power stations (e.g., Neckarwestheim, Germany, built upon karstified Triassic evaporites; Prof. Hermann Behmel, pers. comm.). Gutiérrez et al. (2009) present a compilation of building destruction cases related to sinkhole activity. Reviews on sinkhole-related accidents and damage in railways and roads can be found in Guerrerro et al. (2008b) and Galve et al. (2012a, Electronic Annex 1), respectively. Milanovic (2000) has produced an extensive compilation on karst-related problems on dams, including the development of sinkholes. Furthermore, collapse sinkholes occurring in a sudden way may cause the loss of human lives. In the Far West Rand of South Africa, karstic sinkholes induced by dewatering of dolomite aquifers for gold mining have caused a total of 38 fatalities (Buttrick et al., 2001; De Bruyn and Bell, 2001). A considerable number of people have died in road and railway accidents associated with sinkholes (Guerrero et al., 2008b; Galve et al., 2012a). Consequently, the design and application of effective risk mitigation measures, either of preventive or corrective nature, should be in many cases indispensable. Sinkhole risk management needs to be tackled through the synergic integration of multidisciplinary teams.

Several strategies may be adopted to eliminate or reduce the economic and social risk related to sinkhole activity. The safest option is the avoidance of the subsidence features and the areas susceptible to sinkholes (Fig. 8). Frequently, a setback distance is established around the sinkhole edges (Zhou and Beck, 2008). This preventive measure may be applied prohibiting or limiting development in the most hazardous areas through land use planning and regulations based on sinkhole susceptibility and hazard maps (Paukstys et al., 1999; Buttrick et al., 2001). However, in many cases hazard avoidance measures such as prohibiting development in potentially hazardous areas is not practically feasible. For instance, between 4 and 5 million South Africans currently reside or work on sinkhole-susceptible dolomite land (Buttrick et al., 2011). When subsidence-prone areas are occupied by people or engineering structures, the risk should be mitigated by reducing the activity of the processes (hazard), the vulnerability of the human elements, or both. Frequently, controlling subsurface dissolution and subsidence processes involved in the generation of sinkholes is a difficult and uncertain task, and consequently effective mitigation may require careful local planning and the application of subsidence-resistant engineering designs. Some countries and regions have developed regulations and guidelines related to unstable ground in karst areas establishing investigation requirements, recommendations or constraints on the type of development and indications related to engineering designs, precautionary measures and monitoring programs (van Schalkwyk, 1998; Paukstys et al., 1999; Buttrick et al., 2001; Cooper et al., 2011). Risk assessments and cost–benefit analyses based on sinkhole hazard models may be used for estimating the cost-effectiveness of different mitigation measures and selecting the most economically and socially adequate alternative.

Some corrective measures aimed at diminishing the activity of the processes include: (1) Preventing or controlling water withdrawal and the decline of the water table (magnitude and number of fluctuations), especially when situated close to or above the rockhead. (2) Controlling irrigation to reduce the extra input of water into the ground. (3) Installation of soak-aways and recharge wells cased below rockhead to prevent artificial water circulation through cover deposits and suffusion (Waltham and Fookes, 2003). (4) Lining of canals and ditches with impervious material. (5) Using flexible pipes with telescopic joints. (6) Using efficient drainage systems and diverting surface drainage (Zhou, 2007). (7) Reducing infiltration by blanket ing the surface and rock outcrops with geosynthetics or shotcrete. (8) Filling cavities in the rock or soil by grouting (Kannan, 1999) or seal ing the covered rockhead by cap grouting (Fig. 9). Large cavities may be filled with rock fills through shafts or large diameter boreholes (Milanovic, 2000) (Fig. 9). (9) Improving the ground by compaction grouting to increase the strength and bearing capacity of the soils (Fig. 9). (10) Preventing the inlet of water in swallow holes (pontos) and sinkholes by clogging them, constructing annular dikes or installing concrete plugs, which may be equipped with one-way valves in the case of estavelles (swallow holes that may function as springs during high water table periods). (11) Dynamic compaction in order to collapse shallow cavities and detect soft material associated with karst features (Fischer et al., 1993) (Fig. 9). (12) Remediating sinkholes. Zhou and Beck (2008, 2011) propose several sinkhole remediation methods. The alternatives for the treatment of the sinkhole throat in shallow sinkholes (<5 m; depth reachable by a backhoe or trackhoe) include: (a) Excavating the throat and plugging it with large blocks and concrete or grout, and (b) excavating and filling the fractures by dental filling with grout. The throat of sinkholes too deep for excavation equipment may be treated by: (a) compaction grouting, (b) jet grouting or (c) cap grouting. The next step is to fill the sinkhole depression. Initially, the bottom and walls may be lined with a geotextile filter fabric and a drainage structure is constructed if necessary. The sinkhole may be filled with compacted clay or granular material with layers forming a fining upward sequence following the inverted filter concept. The filled sinkhole is commonly capped by a layer of compacted clay or a rubber membrane, which may have a convex geometry with centrifugal slope.
Different types of engineering measures may be applied to protect structures from subsidence related to sinkhole activity. A critical design parameter is the maximum diameter of the sinkholes at the time of formation, as it determines the distance that has to be spanned to prevent deformation or collapse of the engineered structure. This parameter may be obtained from sinkhole inventories and the geological record. Special foundations for buildings include rafts, slabs, strips and ring beams of reinforced concrete (Fig. 9). These are strong foundations that distribute the load of the structures over large areas. Skin friction and end-bearing piles are commonly used to transfer the structural load to the soil cover or solid bedrock, respectively (Fig. 9). Another option is jackable foundations that allow leveling of light structures (Waltham et al., 2005; Cooper and Gutiérrez, 2013). Transportation structures like roads and railways can be reinforced by installing geosynthetics with high tensile resistance in the sub-base and embankments (Villard et al., 2000; Jones and Cooper, 2005; Briançon and Villard, 2008; Galve et al., 2012a). This technique prevents temporarily the formation of catastrophic sinkholes and accidents, serving as a warning system that allows the identification of subsurface cavities expressed as sags in the structure. In areas with thin unconsolidated cover, the mantling soil may be excavated in order to expose the rockhead irregularities (pinnacles and cutters) and the shallow cavities. The karst openings may be sealed with rock fills, concrete, or by slush grouting (dental grouting; Fig. 9). Subsequently the footings may be pinned to firm bedrock and the excavated area backfilled with engineered fills (Fischer et al., 1993; Knez and Slabe, 2004; Zhou and Beck, 2008). Sinkhole-resistant bridges can be built incorporating oversized foundation pads in the piers and a sacrificial pier design, so that the structure will withstand the loss of a supporting pier (Cooper and Saunders, 2002; Waltham et al., 2005).

Other non-structural measures aimed at reducing or ameliorating the financial losses and harm to people include: (1) Insurance policies to spread the cost generated by sinkholes among the people at risk. (2) The installation of monitoring and warning systems in critical locations (piezometers, strain gauges, geodetic devices, seismometers, laser and light transmitters and receptors). (3) Educational programs oriented to inform the public and decision makers about the objective likelihood of sinkhole occurrence, improving risk perception. (4) The fencing and provision of warning signposts of sinkholes and sinkhole-prone areas.

3.2. Floods

The frequency of disastrous flood events is increasing through time largely due to land use changes and the progressive development of hazardous areas. However, the investigations on the contribution of karst hydrology to surface flooding are still in their infancy. Karst terrains, due to the conduit permeability and high diffusivity of the aquifers, are particularly prone to groundwater flooding (Parise and Gunn, 2007 and references therein; De Waele et al., 2011). Moreover, infrastructure design and urban development in karst areas can affect runoff and the inflow of water at sinkholes, altering both the sinkhole-flooding response to storms and the behavior of springs, with shorter but higher magnitude flood hydrographs. Flooding may also occur after rapid recharge in the karst aquifer, inducing a quick rise of the groundwater level and a prompt discharge increase at permanent or temporary springs (López-Chicano et al., 2002; Bonacci et al., 2006; Jourde et al., 2007, 2014; Bailly-Comte et al., 2008a,b; Najib et al., 2008).

In karst environments, most of the surface flow tends to infiltrate rapidly and incorporate into underground flow paths. Consequently, the surface drainage network is poorly developed and runoff is generally inexistent except during exceptional rainfall events (Gunn, 2007; Bailly-Comte et al., 2009). Recharge associated with regular rainfall events may be either (i) diffuse, when rainfall infiltrates over extensive areas or (ii) concentrated, when channeled surface flow mostly infiltrates at specific sites, like swallow holes or sinkholes. Then, groundwater rapidly flows through fractures and conduits until it discharges through springs and/or gaining streams. High intensity storms and prolonged rainfall events may cause flooding due to: i) the limited capability of the meager surface drainage network to convey large volumes of water underground, and ii) the generally high permeability contrast between the epikarst and the underlying less karstified massif (Mijatovic, 1988). When the fracture and conduit network is insufficient to receive the effective drainage of infiltrating waters, backflooding and water table rise may occur, resulting in local flooding and the formation...
of temporary lakes (White and Reich, 1970; White and White, 1984; Mijatovic, 1988; Lopez et al., 2009). Damages are common in these situations, since man-made structures and human activities tend to be concentrated on the flat and fertile bottom of the depressions.

In karst environments the understanding of floods requires the consideration of a conceptual model accounting for different components (i.e., matrix, fracture and conduit) that exhibit distinct hydrodynamic response to rainfall events (Worthington, 1999; White, 2002) or pumping (Jazayeri et al., 2011). These components play different roles in the hydrology of karst systems due to their different size, distribution and associated flow kinematics (White and White, 2005). Primary porosity is associated with intragranular permeability of the bulk rock, as well as small solution voids and microfissures (Motyka, 1998). Secondary porosity is related to discontinuity planes, including joints, faults and bedding plane partings. Tertiary porosity consists of enlarged pipe- and fissure-like dissolution pathways, commonly related to solutionally enlarged discontinuity planes (Ford and Williams, 2007).

Floods in karst environments thus depend on the spatial distribution and characteristics of the aforementioned features, and can be attributed to one or both of two reasons: i) flow into the karst from allogenic...
sources exceeds the capacity of epikarst and ponors to absorb it; ii) the recharge of the aquifer exceeds its capacity to discharge through the springs, and water backs up underground to spill over and flood the surface. In both cases, water table rise may occur, in turn, in two different ways: fast and high groundwater level rise in zones of high hydraulic diffusivity, and slow water table rise in zones with low hydraulic diffusivity. Whatever the dominant processes involved in flooding, two different cases can be differentiated: 1) Karst terrain flooding and 2) river flooding in karst watersheds.

3.2.1. Karst terrain flooding

Although references to flooding from groundwater are rather limited, this special kind of phenomenon has recently been described in several karst areas (e.g., López-Chicano et al., 2002; Pinault et al., 2005; Bonacci et al., 2006; Najib et al., 2008). When groundwater levels rise significantly due to extreme rainfall events, the water table can reach the topographic surface generating floods (Price et al., 2000; Négrèl and Petelet-Giraud, 2005). Water table changes can affect the whole aquifer or part of it, particularly in karst reservoirs that are partitioned into compartments with distinct hydrodynamic properties. In these contexts, water table changes can be spatially and temporarily heterogeneous and the rise of groundwater levels can cause the activation of numerous temporary springs at unexpected sites, resulting in significant damage.

Groundwater level fluctuations are linked to the recharge potential and the hydrodynamic response of the underground reservoir. The recharge potential largely depends on factors like the precipitation attributes and the surface infiltration capacity, which in turn is conditioned by antecedent conditions. The hydrodynamic response depends on the hydraulic diffusivity parameter which controls the pressure transfer processes. Rapid and significant water table rises occur in karst aquifers with high diffusivity coefficient, with rates as high as 30 m h⁻¹ (Bonacci, 1987, 1995) and magnitudes higher than 100 m.

The catastrophic flood of February 1986 in Cetinje Polje, with no precedent over the 500-year long written history of the old Montenegrin capital, offered an excellent opportunity to examine some features of the complex hydrogeologic behavior of karst (Mitrovic, 1988). The flood was caused by the exceptional coincidence of three hydro-meteorological factors: severe precipitation, warm winds, and snow melting. A total rainfall of around 670 mm fell in the polje drainage area between 16 and 20 February 1986, with destructive effects on the town of Cetinje, where tens of houses were flooded. The simultaneous sudden temperature rise, caused by warm southerly wind, transformed the snowfall into rainfall, which in turn caused the fast melting of a 0.7–1 m thick snow cover. This superseded water input, almost instantly percolating through the epikarst, could not be conveyed by the deeper endokarst drainage system. Moreover, rapid recharge in the aquifer led to an almost simultaneous rise of more than 20 m in the water table, showing (i) the limited storage capacity and high diffusivity of the endokarst drainage system and (ii) the higher hydraulic conductivity of the epikarst than that of the underlying underground drainage system. After this catastrophic flood event, a tunnel was excavated for the diversion of runoff towards an adjacent valley to prevent flooding.

Similar phenomena involving engineering works to prevent flooding were reported by Parisé (2003) at Castellana-Grotte, southern Italy. The town is located at the lowest part of a catchment, where surface runoff accumulated on the occasion of the major rainstorms, following the network of slightly-incised karst valleys, locally called “lame”. After repeatedly damaging floods, including the severe 9 November 1896 event, engineering works were performed to enhance water infiltration. Four deep natural shafts were connected through tunnels to create an underground system able to absorb large amounts of infiltration to prevent surface flooding during heavy rainstorms. After completion of these engineering works in 1911, only minor floods were recorded.

At scales smaller than the single catchment, water table rises can also result in local groundwater ponding, particularly in low-lying areas such as closed karst depressions and blind valleys. There, temporary ponds may appear due to water table rises above the topographic surface, or be formed because of changes in the behavior of swallow holes when surface water flow exceeds their absorption capacity (Fig. 10). As a result, the water level increases abruptly giving rise to a lake and backflooding with only surface water contribution. This behavior is common in blind valleys and closed depressions, such as poljes of the Classical Karst (Kovačič and Ravbar, 2010) or turloughs, mainly known in the Republic of Ireland. Turloughs are transient karst lakes recurrently affected by floods that result from high groundwater levels in topographic depressions, plus, in some cases, lateral inflow from adjacent catchments (Naughton et al., 2012). They are intermittently inundated on an annual basis, mainly from groundwater, and have a substrate and/or ecological communities characteristic of wetlands. When excess recharge cannot be accommodated by the karst aquifer due to insufficient aquifer storage or flow capacity, groundwater levels rise and surface runoff inundate poljes or turlough basins.

The hydrological functioning of turloughs can be described as a function of two general conceptual models (Naughton et al., 2012): the flow-through system and the surcharged tank (Fig. 11), both potentially receiving inflows from proximal and distal catchment areas. The principal difference between the two models is the timing and interaction between inflow and outflow. In the flow-through model (Fig. 11A) both inflow and outflow occur simultaneously and largely independently within the turlough basin. In the surcharged tank model (Fig. 11B), the turlough acts as an overflow storage for the underlying karst flow network, essentially accumulating excess groundwater that cannot be accommodated by the karst due to insufficient capacity. In this case, there is no outflow during filling periods, while during recession periods only inflow derived from the proximal catchment still enters the turlough.

Depressions with hydrological behavior similar to turloughs have been reported in Wales, Slovenia, Spain and Canada (Blackstock et al., 1993; Goodwillie and Reynolds, 2003; Sheehy-Skeffington and Scott, 2008). From a hydrogeological standpoint, turloughs have been compared to poljes, as both display periodic inundation and lacustrine deposition, with the same difficulty of measuring inflows and outflows, and the associated water budget (Bonacci, 1987). However, they differ geomorphologically: turloughs are small basins with gentle sides, whereas poljes are characterized by extremely flat floors and structurally-controlled margins (Gunn, 2006; Ford and Williams, 2007).

3.2.2. River flooding in karst watersheds

The hydrological behavior of lowland karst areas is largely controlled by complex interactions between underground and surface waters (White and White, 1984; Gunn, 2007). Water is lost to and gained from groundwater sources via diffuse infiltration, swallow holes, estavelles and springs, depending on the prevailing hydrological conditions. Underground and surface processes must be considered as a whole to better assess the dynamics of floods at the scale of a karst system traversed by a river that may feed the aquifer with allogenic recharge. Such hydrologic systems are particularly prone to groundwater/surface water (GW/SW) interactions during floods.

Due to the variable interconnections between streams and the different permeability components of karst aquifers, GW/SW interactions are particularly complex. In order to explain these hydrodynamic interactions at different spatial scales, various classifications of GW/SW exchanges have been proposed (Dahl et al., 2007; Bailly-Comte et al., 2009). In these classifications river reaches are described according to (i) the type of hydraulic connection and (ii) the flow direction of the surface water and the groundwater (Fig. 12). In theory, perched-losing and connected-losing reaches of a river occur in the upstream part of the watershed, and are separated by a hypothetical hinge line from the downstream connected-gaining reaches (Sophocleous, 2002). In practice, river reaches gain or lose water according to the variable
hydrological conditions, and are thus described as gaining/losing reaches with a possible predominant flow direction.

At the scale of a small karst watershed, like the Coulazou watershed in southern France, various types of hydraulic connections and flow directions have been described revealing that karst/river hydrodynamic interactions are strongly time-variant; it is shown that initial groundwater level may be used to forecast the type of hydraulic connection between the river and the aquifer, and that flow direction (gaining or losing reaches, e.g. Fig. 12) can be inferred from temperature and electrical conductivity measured in a cave located beneath the riverbed. Note that flow direction is controlled by the limited discharge capacity of the karst drainage network, so that losing river reaches, either perched or connected, can change into gaining (Fig. 12) when the intensity of precipitation and recharge increases. Such conceptual model can be used to design a semi-distributed numerical model accounting for both transfers of surface and underground water along the riverbed (Bailly Comte et al., 2012). Considering peak discharge as the main indicator of flash flood hazard, modeling results have shown that: i) the aggravating effect of the karst system may be higher than 80% with respect to expected values from surface runoff only, and ii) the karst system has a relatively limited regulation effect even for low water table conditions prior to the flood.

In a study on Flumineddu Canyon (Sardinia, Italy), De Waele et al. (2010) estimated peak flows of a flash flood in a karst catchment; very high values were found, ranging between 200 m$^3$/s and over 1200 m$^3$/s upstream and downstream of the carbonate area, respectively. The comparison between modeled and empirical peak flows measured in eight transects allowed the calculation of river losses ranging 1200 m$^3$/s upstream and downstream of the carbonate area, respectively. During these events, groundwater levels rise suddenly and cause the appearance of numerous temporary springs contributing to the surface runoff. This combination of both groundwater and surface water can increase the peak discharge of floods by a factor of two, if compared to the discharge predicted by hydrological modeling only considering surface runoff (Jourde et al., 2007). In small catchments, fast groundwater contribution to the surface drainage may lead to floods with discharges higher than 5 m$^3$/s/km$^2$ (Camarasa-Belmonte and Segura-Beltrán, 2001). In watersheds smaller than 100 km$^2$ of the Gard region, southern France, specific peak flood discharges have exceeded 20 m$^3$/s/km$^2$ during the 2002 floods (Delrieu et al., 2005; Gaume et al., 2009).

Discharge from karst can sometimes generate prolonged groundwater flooding that implies great volumes, particularly following long wet periods, which can be particularly harmful in the case of large karst catchments. In 2001, the Somme chalk watershed, France, was affected by an unusual catastrophic flood (Négrel and Petelet-Giraud, 2005). During this flood, groundwater contribution to stream flow was estimated to be over 80% (Pinault et al., 2005). This special kind of flooding can last for months depending on the amount of water stored in the aquifer, and may cause particularly severe damage.

To better quantify flooding hazard and assess the relative importance of surface and underground processes, Jourde et al. (2014) analyzed the role of karst aquifers in the development of floods in the Lez watershed, southern France, where active management of the groundwater resource is performed. This active management consists in pumping water directly from the drain at a depth below the level of the spring outlet, extracting only part of the naturally renewable storage water. During low-flow conditions, when pumping rates exceed the natural discharge of the karst aquifer, it causes an important drawdown and the spring dries up. During autumn and winter rainfall events, the karst aquifer is recharged and its reserves are renewed; the water level in the drain then rises above that of the pool. Understanding flash floods in this Mediterranean river is very important for the urban areas situated downstream (i.e. Montpellier), where recurrent inundations have caused severe damage in recent years (December 2002 and 2003, September 2005).

**Fig. 10.** Plan de Estan, a closed depression in the floor of the Benasque glacier valley (Spanish Pyrenees), drained by swallow holes. The depression is affected by flooding when the inflow of surface runoff exceeds the outflow capacity of the ponors. Arrows point at the high-water mark (strand line) corresponding to the 17 June 2013 flood, well above the road. Image taken on 26 June 2013, during the recession of the water level. Note the flooded section of the road on the right. (Photo: José María García-Ruiz.)
In this watershed, calcareous terrains are located in the headwaters of the basin, so that the river flow largely derives from a karst system. The analysis of different flood events showed that the volume available for water storage in the epiphreatic zone (before the flood) controls the occurrence of large flash floods. When the karst aquifer is depleted (late summer), the epiphreatic zone of the aquifer can store part of the precipitation, thus mitigating surface flooding (Fig. 14A). On the contrary, when the karst aquifer is saturated, no storage is available in the epiphreatic zone and rainfall generates a general groundwater level rise above the overflow surface, thus contributing to surface flooding (Fig. 14B). In such a situation with groundwater pumping from a karst aquifer that significantly influences flooding, the knowledge on the karstification degree and depth is of major importance to assess whether it is practical to pump larger amounts of water and thus generate larger drawdowns, as a flooding hazard mitigation measure. If water supply is secure, the larger depletion of the aquifer is able to reduce flash flood hazard downstream, regardless of the period of the year. As the resource (groundwater supply) and the hazard (flooding) are linked to each other, an integrated management of the karst watershed can be performed to mitigate flood risk without jeopardizing water supply.

3.3. Slope movements

The role played by karst in predisposing and/or favoring landslides and slope instability has been barely explored, largely due to the difficulty of its investigation and assessment. Slope movements in soluble rocks such as carbonates and evaporites are generally studied and described without paying much attention to the voids produced by karst processes and their detrimental influence on the mechanical properties of the rock masses. Nevertheless, the presence, distribution and frequency of voids of different sizes, from inaccessible small conduits to caves accessible by man, may have a significant impact on the overall stability of a slope and its hydrology, acting as preferential pathways for the groundwater flow (Dunne, 1990). Moreover, active weathering processes, especially in highly soluble evaporites, is an additional factor that promotes lack of basal support, breakdown processes in the underground environment, progressive rock mass weakening, and instability at the surface.

Fig. 11. Schematic representation of a turlough functioning either as (A) a flow-through system or as (B) a surcharged tank. (After Naughton et al., 2012.)
Landslides affecting karstified rock masses cover all known typologies, as described in the classification of slope movements proposed by Cruden and Varnes (1996). The link with karst features such as solutionally-enlarged joints is clear for rockfalls and toppling failures, while it appears to be more obscure for other types of instabilities.

In karst settings, dissolution widens discontinuities in the rock mass, especially near the surface before water reaches saturation. The impact on the rock mass strength of this process may be very significant when combined with frost weathering, which produces high pressures on the walls of clefts and joints, and their dilation and propagation. In the case of rock masses with a high density of stress release cracks in the outer zone, rockfalls and toppling failures are the most common categories of slope movements (Santo et al., 2007; Krautblatter et al., 2012; Palma et al., 2012). The rockfall at the Catiello Mt., near Positano, near Positano...

**Fig. 12.** Diagrams illustrating gaining/loosing connected/perched reaches in relation to an underlying karst aquifer (modified after Bailly-Conne et al., 2009). Perched gaining reaches occur when high intensity rainfall induces perched groundwater flow due to limited capability of epiphreatic zone to convey large volumes of water towards the underlying less karstified massif. Conversely, connected loosing reaches are observed when the rainfall intensity is low.

**Fig. 13.** Groundwater/surface water interactions in the case of incised river channels within a karst watershed. Concentrated recharge activating intermittent springs, sinking and rising of water in reaches with flow along shallow subsurface paths, generate discharge variations.
southern Italy, occurred on January 4, 2002, along an open crack with evidence of long sustained karstification, recorded by speleothems and the infill of the crack including pyroclastic deposits (Santo et al., 2007). With the likely contribution of freezing and thawing, karst in this case played an instrumental role in instability, involving a 100 m-high dihedron of carbonate rock.

The dissolution-related weakening of the rock mass may have a significant impact at a human-time scale on slopes underlain by evaporite rocks (Fig. 15), favoring the occurrence of different failure types (Parise and Trocino, 2005; Gutiérrez et al., 2008d; Iovine et al., 2010). A number of papers document large failures in slopes underlain by evaporites largely related to deep-seated dissolution (Tsui and Cruden, 1984; Guglielmi et al., 2000; Seijmonsbergen and de Graaff, 2006; Alberto et al., 2008; Jaboyedoff et al., 2011; Gutiérrez et al., 2012a,b; Carbonel et al., 2014; Mège et al., 2013).

In addition to enlargement of discontinuities by dissolution, water circulation in karst conduits may also favor instability inducing high fluid pressures with the consequent decrease in the normal effective stress and shear strength on failure planes. In peculiar situations, when the water table rises, a fire-hose effect may be produced by the rapid flow in karst conduits. Calcaterra et al. (2003) discuss the possible influence of such effect on the May 1998 mudflows in Campania, Italy, based upon observation of several karst conduits exposed in the carbonate bedrock by the sliding of the overlying volcaniclastic materials.

One of the few documented cases in which a natural cave has been involved in the formation of a slope movement is the 1899 rockslide at Amalfi, Southern Italy, which affected a large cave recorded by historical photographs (see Fig. 11 in Santo et al. (2007)). The presence of the cave was probably an instrumental factor for the development of the landslide that killed several people.

Using speleothem dating from caves brought to the surface by gravitational movements, Pánek et al. (2009) reconstruct the evolution of the Foros landslide, a rock failure in the Crimean Mountains (Ukraine). These authors point out the need to take into account karst processes when analyzing the factors involved in the development of large landslides and deep-seated gravitational slope deformations (DSGSD). They illustrate how speleogenesis and crack propagation accompanied
by dissolution may create favorable conditions for the development of large rock slope failures in carbonate masses.

In long-lasting landslides like DGSDS, karstification and the consequent weakening of the rock massif may act as a predisposing factor since the onset of the slope movement. As Pánek et al. (2009, p. 180) propose, the role played by “karstification as a preparatory factor of the development of catastrophic slope failures in mountainous settings should be the objective of future studies”. In fact, some of the largest subaerial landslides in the world affected carbonate and/or evaporite bedrock (Muller, 1964, 1968; McGill and Stromquist, 1979; Prager et al., 2008; Ivy-Ochs et al., 2009; Gutiérrez et al., 2012b). The development of large and catastrophic translational landslides in carbonate successions is typically favored by the presence of laterally extensive and extremely planar bedding planes. One of the most famous examples is the 36.5 hm³ Frank rockslide-avalanche, which destroyed the southern end of the town of Frank in southwestern Alberta, Canada (Cruden and Krahn, 1978; Jaboyedoff et al., 2009). Even more disastrous was the 1963 Vajont transational slide in northeastern Italy, that fell into a reservoir generating a huge impulse water wave. The tsunami overtopped the concrete dam leading to a sudden catastrophic flood that completely destroyed some villages in the Piave Valley killing over 2000 people (Muller, 1964, 1968; Hendron and Patton, 1985; Semenza and Ghirotti, 2000; Kilburn and Petley, 2003). In both cases, karstified limestones were involved in the movement, but the role played by dissolution processes and karst features on slope stability and the kinematics of the landslides remains unresolved.

In cases where deep-seated dissolution involves large rock masses, the effects are felt at the slope scale, as shown in several Alpine orogens (Tognini and Bini, 2001; Alberto et al., 2008; Gutiérrez et al., 2012b; Carbonel et al., 2014). These instability phenomena typically show a particularly high vertical displacement component related to subsidence above the karstified zone, in addition to the outward displacement typical of landslides.

Another situation in which karst features are described or at least hypothesized as likely factors predisposing to slope movements is rock failures in coastal cliffs, due to deepening of coastal caves and/or notches (Vallejo, 2012).

4. Assessing human impacts on the karst environment

Earth’s landscapes are the result of a series of processes that may act continuously or during discrete events occurring with different temporal frequencies. Landscapes have been shaped, destroyed, and rebuilt again over geological times, in a natural cycle. In recent times, besides the complex suite of natural processes, the human factor has started playing an important role interfering directly (e.g. urban development) and indirectly (e.g. global warming) with the environment. The assessment of natural and anthropogenic impacts on the environment is of crucial importance for reducing the negative effects and promoting sustainable development. These assessments are common practice and are generally based on a set of biological and physical-chemical indicators (Bain et al., 2000).

In the past, notwithstanding the rugged topography and the paucity of surface water, humans tended to live close to karst areas, where the majority of springs are located. The increase in human population has progressively led people to occupy more karst areas and build new settlements and infrastructures (Parise et al., 2009).

Karst environments and the water resources associated with them are highly vulnerable and sensitive to human alterations. The FAO (Food and Agriculture Organization of the United Nations) forecasts that before 2025 at least 80% of the demand of drinkable water in the Mediterranean Basin will be derived from karst aquifers. This highlights the urgent need of adequately protecting this resource from actions that may have adverse effects on its quality and availability (White, 1988, 2002; Bakalowicz, 2005). Protection of karst environments is a mandatory step to maintain, safeguard and transmit its extreme richness and biodiversity to future generations. This is a challenging task due to the increasing impact posed by human activities on the karst environments (Table 3).

Especially in lowland karst, due to the scarce relief and the subdued features, many landforms may be lost due to anthropogenic activities such as intense quarrying, stone clearing and crushing practices (Gunn, 1993; Parise and Pastaci, 2003; Delle Rose et al., 2007; Canora et al., 2008). Land use changes also results in degradation of the epikarst (Williams, 1983, 2008), which, even in areas where it has a reduced thickness, provides a vital function for karst ecosystems (Pipan and Culver, 2013), controlling runoff infiltration.

Further, the expansion of urban areas (including communication routes and industrial facilities) in karst is leading to an increasing number of pollution events, with severe consequences on the karst ecosystems and the quality of groundwater (De Waele and Follesa, 2004). The situation is even more exacerbated in post-conflict scenarios, as experienced for instance in karst areas in the Balkans (Caló and Parise, 2009). Actions must therefore be undertaken to assess the negative impacts of the increasing pressure on the fragile karst environment and minimize them.

Tourist exploitation in karst may have high impact if not reached through a careful evaluation of the deriving effects. Opening of show caves, for instance, must consider and respect the “visitor capacity”, that is “that flow of visitors into a defined cave that confines the changes in its main environmental parameters within the natural ranges of their fluctuation” (Cigna and Forti, 1988).

Environmental Impact Assessments (EIA) of anthropogenic activities have become a mandatory requisite during the pre-approval stage of projects not only in Europe and America, but also in many other developed countries. These EIAs are often based on general indices that take into account the environmental, social and economic impacts, without taking into consideration the peculiarities of specific landscapes like those of karst terrains.

The protection of the karst environments, due to their intrinsic vulnerability, unique hydrological behavior, and exceptional subterranean ecosystems, requires specific approaches and measures (Veni, 1999). In karst, it is preferable to undertake vulnerability assessments starting with a hydrogeological EIA, given the direct relationships between the surface and subsurface environments and the peculiar hydrologic regime. Subsequently, other fields of research should be investigated, depending on the study area.

The intrinsic vulnerability of karst aquifers to pollution may be assessed through the hydrogeological and geological parameters that determine the sensitivity of groundwater to contamination by human activities (Molerio-León and Parise, 2009; Farfán-González et al., 2010), and is independent of the nature of the contaminants and how these are introduced into the system (Dörfliger et al., 1999; Zwahlen, 2004). A number of methods have been proposed to evaluate the vulnerability of karst aquifers, mostly based on GIS methodologies. Some of these methods have been developed for porous and fissured aquifers, such as DRASTIC (Aller et al., 1987), AVI (van Stempoort et al., 1993), SINTACS (Civita and De Maio, 1997), and PI (Goldscheider et al., 2000). Other methods were specifically designed for karst aquifer vulnerability mapping: EPIK (Dörfliger et al., 1999), COP (Vlas et al., 2006), the Slovene approach (Ravbar and Goldscheider, 2007), and PaPRIKa (Kavouri et al., 2011). The use of multiple methods in a specific karst area commonly results in different vulnerability maps (Gogu and Dassargues, 2000; Neukum et al., 2008; Ravbar and Goldscheider, 2009), in which reliability is strongly dependent upon quantity, quality, and interpretation of the available data. Despite these differences, these maps should be used as a basis for protection zoning and land-use planning, searching for an acceptable compromise between water protection and economic interests.

Alongside the specific vulnerability assessments, the complexity of karst environments requires a more holistic approach to
comprehensively assess the multiple impacts on these fragile ecosystems. For this purpose, van Beynen and Townsend (2005) proposed the Karst Disturbance Index (KDI), aimed at appraising the impact of multiple human activities and natural processes on the karst environment (Fig. 16). The original KDI covers five categories (geomorphology, atmosphere, hydrology, biota, and cultural factors), each one composed of several attributes, in turn subdivided into a number of indicators. This method has satisfactorily been applied in Apulia, Italy (Calò and Parise, 2006), Florida (North et al., 2009), and Jamaica (Day et al., 2011). In the original KDI the evaluator gives numerical scores to each indicator (0 for no disturbance, 3 for almost complete destruction or catastrophic impact). For some indicators, the lack of historical data makes scoring impossible and the assessor has to introduce a “lack of data” (LD), identifying areas in which further research is needed to be able to assign a score. The final value of KDI comprised between 0 and 1, is obtained by dividing the summatory of the scores of the indicators by the highest possible score. This normalization of the KDI reduces the subjective nature of the assessor’s evaluation. A feasible way of simplifying the KDI is to evaluate the disturbances instead of the indicators. Disturbances are similar to indicators, but less specific and thus more readily quantifiable. This modified KDI, which also makes use of normalized values, has successfully been applied in Sardinia, Italy (De Waele, 2009).

A further development of the KDI is the creation of the Karst Sustainability Index (KSI) (van Beynen et al., 2012) that takes into account 25 indicators related to the environment, economy, and society.

5. Final considerations and future prospects

Karst environments are affected by specific hazards and impacts, largely related to their endemic geomorphological and hydrological peculiarities determined by the soluble nature of the bedrock: (1) Poorly developed surface drainage network and presence of enclosed depressions; (2) prompt water infiltration and prevalence of underground drainage; (3) fast circulation of groundwater through conduit networks towards springs and discharge areas, with consequent high susceptibility to pollution; (4) ground surface typically underlain by irregular rockhead, voids, weak sediments, and active dissolution zones that may eventually lead to subsidence and unstable areas. (5) Karst areas typically include highly valuable resources, outstanding ecosystems with endemic or rare species, and remarkable sites from the cultural and esthetic perspective (e.g. archeological and/paleontological sites, show caves). All these assets are highly vulnerable to many human activities, which may lead to significant local and far-field impacts and irreplaceable heritage losses.

Areas underlain by evaporites may pose even more difficult conditions for engineering projects due to the singular properties of these rocks: (1) They are much more soluble than limestones, and karstification acting on evaporites may create substantial voids, enhance considerably the permeability, and cause a significant reduction in the mechanical strength of the rocks at a human time scale. (2) Dissolution-induced subsidence processes associated with evaporites may display higher rates and frequencies, as well as a wider range of mechanisms, due to their lower mechanical strength and more ductile rheology. (3) In evaporites, especially salts, deep-seated dissolution may affect vast areas through the progression of dissolution fronts, creating extensive active subsidence depressions and a wide variety of surface deformation features. These frequently undetected gravitational ground displacements may adversely affect multiple engineering projects.

The most common hazards associated with karst include sinkholes, flooding, and slope movements. Other relevant hazards include water leakage at dam sites and other hydraulic structures, and flooding of underground excavations, occasionally involving dangerous sudden inrushes of pressurized groundwater. Human activities may lead, intentionally or unintentionally, to a great variety of impacts, including degradation of the karst landscape, destruction of the epikarst, loss of karst landforms, occurrence of sinkholes, and exacerbation of the effects produced by floods. The identification, assessment and mitigation of these environmental problems commonly require the application of specific methods adapted to the singularities of the karst systems. Investigations in karst areas frequently require higher efforts than in other terrains due to the following circumstances: (1) Active processes, mainly governed by water, mostly operate beneath the ground surface, and in most cases are not directly observable. (2) Karst massifs are highly anisotropic and heterogeneous, and consequently subsurface investigations need to be performed through expensive and spatially-dense data-collection programs. (3) The spatial and temporal distribution patterns of some karst features and processes are highly unpredictable. (4) Environmental impact assessments require the evaluation of many factors with complex interrelations that commonly require additional investigations.

Environmental problems associated with karst have a notorious impact in many regions of the world. Carbonate and evaporite rocks occur over 20% of the Earth’s ice-free continental area, and around a quarter of the global population depends on karst water supply. The true significance of these problems is commonly greater than those perceived, largely due to the hidden and sometimes disperse character of the negative effects. Despite the fact that the scientific community has substantially improved the understanding of the karst systems and our ability to prevent and mitigate the associated hazards and impacts, the amount of problems can be expected to rise in the future due to multiple reasons: (1) the number of people and human structures exposed to hazardous processes will keep on increasing; (2) human pressure on karst systems will be progressively higher, augmenting the frequency and intensity of environmental impacts and induced hazards; (3) the growing demand of water and energy will determine the development of large hydrological projects in karst areas, in spite of their typically difficult conditions and unpredictable behavior; (4) technical and political decisions are frequently taken without an adequate and comprehensive understanding of the complex karst systems.

The different types of subsidence sinkholes, involving downward ground displacement, are the most relevant from the hazard and
A common misconception is that a requisite for the development of subsidence sinkholes is the presence of cavities. However, some processes leading to subsidence sinkholes may form by progressive dissolution and the concomitant passive bending of the overlying sediments, without developing a significant void. Further, subsidence in evaporite karst is frequently ascribed to gypsum dissolution, the rock commonly exposed at the surface. However, many evaporitic formations also include beds of more soluble salts (halite, sylvite, glauberite) rarely exposed at the surface, but that may play a significant role in the development of subsidence phenomena. Specifically, investigation methods, like boreholes drilled with saline water and expert core logging are needed to confidently characterize this critical aspect of the karst bedrock. The most severe and potentially harmful sinkholes are bedrock and caprock collapse sinkholes, due to their large size and catastrophic kinematics. However, the damage associated with these sinkholes is commonly low due to their low probability of occurrence. Conversely, a significant proportion of the subsidence damage in karst areas is related to relatively small cover collapse and cover suffusion sinkholes, with a much higher spatial and temporal frequency. There is commonly a good spatial and temporal correlation between the frequency of sinkholes and the degree of interference between human activities and the functioning of karst systems, clearly indicating that a great proportion of the damaging sinkholes are human-induced. These risk situations often lead to troublesome litigations, in which the parties affected may not be able to get any compensation, due to the difficulty in demonstrating with certainty the direct cause-effect relationship between the inductive or triggering human action (e.g., water input to the ground, water table decline) and the subsidence activity.

Although efforts devoted to sinkhole investigation have considerably increased in the last decade, there is still large room for improving the conceptual and methodological basis of sinkhole risk investigation and management. In the near future, it would be desirable to make progress on several practical issues: (1) Investigate large subsidence structures related to deep-seated evaporite dissolution identifying the areas affected by active deformation and assessing its kinematics. (2) Construct and update comprehensive sinkhole inventories including chronological data, particularly in the areas where dissolution-induced subsidence has higher economic and societal impact. (3) Evaluate independently and quantitatively the prediction capability of sinkhole susceptibility models produced in the past, especially those that are being used for land-use planning purposes. This can be effectively achieved by comparing the spatial distribution of the susceptibility zonation
and the sinkholes formed after development of the models. It may come out that in some areas relevant decisions are being taken on the basis of unreliable predictions. (4) Produce hazard models providing estimates on the spatial–temporal probability of occurrence of sinkholes with different diameters, incorporating magnitude and frequency scaling relationships. (6) Assess quantitatively indirect losses related to sinkholes, in addition to direct damage, in order to weight the true economic dimension of these hazardous processes. (5) Investigate different types of sinkholes in diverse contexts applying multiple geophysical techniques. (6) Expand our experience on active sinkhole monitoring, by using techniques as high spatial and temporal resolution InSAR data, photogrammetry, air- and ground-based LIDAR, leveling, extensometers, fiber optic strain sensors, and microseismicity. Effective monitoring systems might be used to anticipate catastrophic collapse sinkholes through precursory deformation as the basis for early warning systems. (7) Appraise the performance of mitigation measures applied in the past, to check whether they have fulfilled the expectations related to the design parameters, and refine the calculation methods.

Slope movements in soluble rocks have been rarely studied with a specific focus on karst processes, and their likely influence on the development of instabilities. The main reasons are the logistic difficulties and temporal constraints for assessing the effective role played by dissolution and the presence of natural caves in the degradation of the mechanical properties of the rocks. Karst caves may decisively control the occurrence of slope instabilities, since they represent weakness zones in the rock mass, further acting as preferential pathways for the groundwater flow, and favoring weathering processes. This issue should merit greater attention by the scientific community, in the attempt to understand the main karst-related factors controlling both the development and triggering of different types of slope instabilities.

Among the hazards dealt with in this review, floods are probably those for which greater mitigation efforts may be performed. Once the surface and groundwater circulation is understood, such information and the potential hazardous situations should be considered for land-use planning and development, as well as in the design and implementation of engineering projects and works. If such actions are carried out without producing significant alterations in the karst system maintaining the main absorption points to allow water to find its way underground, and avoiding it to occupy the flood-prone areas, the impacts from flooding events may be managed without causing frequent and severe losses to society. These efforts should be accompanied by educational activities involving population residing in karst in order to encourage good practices.

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