Int. J. Speleol., 31 (1/4) 2002: 181-199

KARST SUBSIDENCE IN SOUTH-CENTRAL APULIA, SOUTHERN ITALY

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ABSTRACT

Subsidence in the karst of Apulia (Southern Italy), one of the classical karst areas of Italy, is described in this paper. The carbonate rocks that make up the geological structure of the Apulia region are affected by subsidence, which is of different type and intensity depending upon geological, topographical, and hydrogeological conditions. In particular, we discriminate between inland subsidence and coastal subsidence. Inland subsidence is generally restricted to the presence of individual cavities, either empty or partly or totally filled with deposits produced by dissolution of soluble rocks underground. Locally, such subsidence can cause severe effects on anthropogenic structures above.

The coastal plains of Apulia, particularly the southernmost part (Salento Peninsula), show interesting karst subsidence. Here the main feature is the development of compound sinks extending for several thousands of square metres, or the formation of individual, mostly circular, dolines along the coastline. Occurrence of one or the other of the above features seems to depend upon topographical conditions, and also upon their relationship with sea level oscillations.

KEYWORDS: karst, subsidence, sinkholes, subsidence hazard, Southern Italy

1. Introduction

Subsidence is a geological hazard that affects many areas of the world. It can be related to several different processes, both natural and induced by Man. According to a widely accepted general definition, subsidence is: "*... the sudden sinking or gradual downward setting of the Earth's surface with little or no horizontal motion. The movement is not restricted in rate, magnitude, or area involved. Subsidence may be caused by natural geological processes, such as solution, thawing, compaction, slow crustal warping, or withdrawal of fluid lava from beneath a solid crust; or by man's activity, such as subsurface mining or the pumping of oil or ground water.*" (Bates and Jackson, 1987, p. 658).

The occurrence of subsidence events in various geological settings is an increasing hazard, as recently demonstrated by several papers dealing with this topic in different environments (e.g. Amin and Bankner, 1997; Carminati and Martinelli, 2002; Hu et al., 2002).

The complexity of subsidence phenomena is still greater in karst areas, which are characterized by very peculiar geological, morphological and hydrogeological features (Cvijic, 1918; Nicod, 1972; White, 1988; Palmer, 1990). The latter features, and particularly the presence of underground cavities produced by dissolution of soluble rocks, make karst a highly fragile and delicate environment, prone to subsidence caused by a variety of natural and anthropogenic processes (White, 1990; Tharp, 1999; Lamont-Black et al., 2002).

In some cases identification of landforms related to subsidence can be very difficult, since these may have been removed or had their effects partly cancelled out by past erosion, and remodelled or obscured by human activity.

The most common landforms produced as a consequence of subsidence in karst areas are sinkholes, whose dimensions (width, depth) depend upon local geological characteristics and also upon the rate of development and intensity of karst processes. In many cases, the sinkhole development may be preceded by the appearance of cracks in buildings and structures above, which might thus be considered as precursory features of a likely collapse.

Dolines are among the most widespread surficial landforms in karst environments, and not all of them are produced by subsidence. Thus, there can be a problem discriminating between dolines produced by karst subsidence and those related to other processes (e.g. simple dissolution of soluble rocks). Making this distinction can be particularly difficult in some cases because of the similarity of the morphologies produced. In an attempt to distinguish between different types of sinkhole, White and White (1987, p. 85), for example, define subsidence sinks as "*...those caused by upward stoping of a collapsing solution cavity through substantial thicknesses of bedrock, some of which may be non-carbonate*".

On the other hand, karst subsidence may also relate to the presence of heterogeneous fillings in subterranean cavities or in dolines. Settlement of these deposits, caused by the movement of water through them, with consequent physical erosion and chemical dissolution, may result in gradual downward settling of the ground above, with formation of a depression at the ground surface.

Sinkholes produced by karst subsidence can be isolated and localized, or may be more complex and ramify over a more or less wide area. In the latter case the morphologies produced have been described as compound sinks by White (1988). Their main characteristics are the development of many individual sinkholes that, with time and the evolution of karst processes, grow and coalesce to form large closed depressions. These are generally shallow, but may occupy areas of several square kilometres.

In the present paper, after a brief summary of past studies dealing with subsidence in karst areas, we describe some cases of karst subsidence in Apulia (Southern Italy), attempting to differentiate types of subsidence occurring within the different topographical, geological and morphological settings of the region, one of the classical karst areas of Italy.

2. Subsidence events and their effects on the natural and human environment

Dissolution and erosion in subterranean cavities may result in collapse and eventual breakthrough of the cavities to the ground surface, forming sinkholes. Whether natural or anthropogenically-induced, this process affects carbonate formations that are subject to karstification in many areas of the world (Jennings et al., 1965;

Calembert, 1975; Stringfield and Rapp, 1976; Cotecchia, 1980; Soriano and Simon, 2002). Such effects are commonly encountered during road construction or other engineering works in karstic areas (Pewe, 1990; Cavounidis et al., 1996; Roje-Bonacci, 1997; see also papers of Knez and Slabe, and Milanovic in this volume).

The karstic and engineering-geological literature offer details of many studies dealing, directly or indirectly, with such phenomena. They can be differentiated, according to the origin of the subsidence phenomena, as either natural or induced by human activities.

Considering the first category, it is worth quoting the case of East Tennessee, where, in a seven-year period, more than 250 karst subsidence incidents were registered, according to an inventory gathered by interviewing personnel of federal, state, and county agencies (Ketelle and Newton, 1987). Most of the sinkholes were twenty feet or less in maximum surface dimension.

Another example of a collapse feature formed by upward migration of an underground dissolution cavity by successive roof failures until it breached the land surface is the Wink Sink, in Texas. Here, natural dissolution of salt was in some way influenced by petroleum-production activity in the immediate area (Johnson, 1987).

Also in Texas, Kasting (1987) identifies two main forms of evidence for subsidence and collapse in carbonate rocks: 1) slumped units of stratigraphically younger Paleozoic beds within depressions formed in earlier carbonate rocks, and 2) "filled sinks" (i.e. dolines filled with horizontally deposited younger beds).

Piping extending from the limestone to the surface can be a further process leading to subsidence phenomena and sinkhole formation (Benson and Yuhr, 1987).

Alongside natural processes, several anthropogenic activities may induce sinkhole development and subsidence in karst environments. Among these, groundwater abstraction is one of the most common causes. For example, in 1977, when a spell of freezing weather was experienced in Florida State, strawberry growers in the Dover area applied large quantities of groundwater withdrawn from the Floridan aquifer to their crops (Hall and Metcalfe, 1984). This triggered development of at least 22 sinkholes, some of which resulted in property damage. Similarly, pumping of water from industrial wells in parts of Tennessee and Georgia has initiated active subsidence at several locations (Wilson, 1984).

3. The Apulia region

Apulia represented the geological foreland during the building up of the Southern Apennines of Italy. Most of the region is made of thick sequences of limestone and dolomite (Fig.1) formed within carbonate platforms during the Cretaceous (Richetti et al., 1988). Later on, these materials, having been faulted, deformed, and affected repeatedly by karst processes, were partly covered by recent deposits, mostly represented by calcarenites.

The landscape is generally flat, characterized essentially by landforms of karst origin, whose best morphological expressions are identifiable on the Murge Plateau of inland Apulia (Neboit, 1974; Sauro, 1991). There have been many active karst phases, producing an extensive network of underground cavities and conduits. Today the Apulia regional caves inventory, managed by the Apulian Speleological Federation,

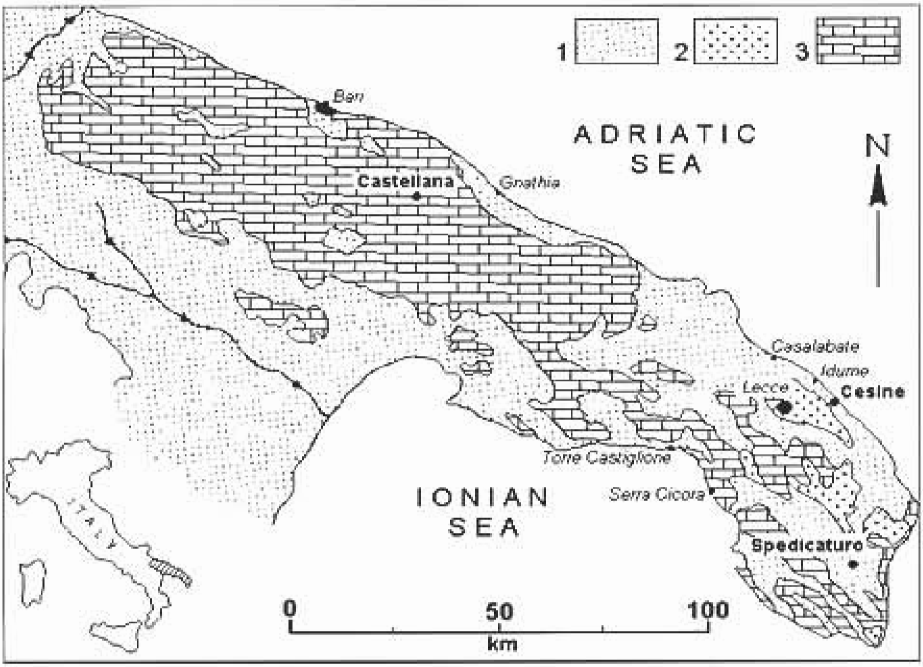

Fig.1 - Geological sketch of central and southern Apulia, and location of the case studies (in bold) discussed in the text. Explanation: 1) recent clastic cover (Pliocene – Pleistocene); 2) bioclastic carbonate rocks (Paleogene) and calcarenites (Miocene); 3) platform carbonate rocks (Cretaceous).Other localities cited in the text are also shown.

lists more than 2000 caves (Giuliani, 2000), including famous show caves such as the Grotte di Castellana and the Grotta Zinzulusa, as well as caves of great archaeological or palaeontological interest (e.g. Grotta Paglicci, Grotta dei Cervi at Porto Badisco and Grotta di Lamalunga).

Features characteristic of landscapes where karst is the main geomorphic agent, can be identified in Apulia, including the absence (or very limited presence) of surface runoff, outcrops of residual deposits from karst processes (the so-called *terra rossa*), and hydrological connectivity between surface and underground systems. The role of human activity must also be stressed, since the landscape has everywhere been modified markedly by anthropogenic intervention.

Most of this description will concentrate on the Salento Peninsula, which is the southernmost part of the Apulia region (Fig.1). It is formed of Jurassic to Cretaceous limestone and dolostone covered by Tertiary and Quaternary clastic carbonates and subordinate clays. Structurally, Salento is a wide horst, dissected into uplifted and lowered blocks by high-angle faults, striking NW–SE, (Doglioni et al., 1994), which locally show evidence of reactivation (Delle Rose, 2001). Reflecting the predominance of calcareous rocks, surface and underground landforms are characterized by karst features.

The present form of the Salento Peninsula began to develop during the Early Pleistocene, when tectonic uplift was accompanied by a relative lowering of the sea to its present level. Emergence took place discontinuously, leading to the formation of coastal plains on both the Adriatic (north-east) and Ionian (south-west) sides during the Late Pleistocene (Dai Pra, 1982; Palmentola, 1987). The elevation of the coastal plains is at most a few metres above sea level, and the partially swamp-covered plains extend inland for several kilometres.

4. Subsidence in the Apulian karst

This section considers only cases of subsidence produced by natural processes, not those caused directly by human activity. Nevertheless, some effects of subsidence on the anthropogenic environment also discussed. Subsidence in inland areas and that along the coastal plains are considered separately.

4.1. Inland subsidence

Subsidence in inland Apulia is generally related to the presence of individual underground cavities, whose upward stoping towards the ground surface may cause settlement and collapse of anthropogenic structures, where present. Such features, though numerous and widespread do not generally evolve to produce compound sinkholes (White, 1988), but instead they remain localized. Their presence is directly dependent upon the distribution and dimensions of subterranean cavities, and upon the local hydrogeological setting.

In the past several towns in Apulia have been affected by these phenomena, and in recent years many problems have had to be faced at some sites. The case at Castellana-Grotte (discussed below) is an example of such a situation.

Castellana-Grotte

The town of Castellana-Grotte lies some tens of kilometres south-east of Bari (Fig.1). It is famous worldwide due to its remarkable caves, first explored in 1938 and more than 3km long and 120m deep, which have become one of the most visited show caves in Europe.

The oldest part of Castellana-Grotte lies at the bottom of a karst basin, whose main morphological feature are flat valley floors filled with alluvial deposits, detritus and *terra rossa*. These valleys and drainage routes (locally called *lame*) are the remnants of the original hydrographic network (Parise, 1999). Most are directed toward the northern boundary of the Castellana catchment basin, where both its lowest-lying sector and the town itself are located. Largo Porta Grande, a broad square within the lowest part of the town, has repeatedly been the scene of flood events in the past. The origin of these floods must be sought within a combination of peculiarities of the karst environment and mismanaged human activity (Sgobba, 1896; Orofino, 1990; Pace and Savino, 1995; Parise, 2002).

Precisely the same site is also marked by subsidence phenomena related to the presence of underground cavities that are partly filled with colluvial deposits and *terra rossa*. In fact, on September 15 1968, a building on the west side of the square suffered serious damage due to differential settlement. It was evacuated temporarily, and some geological investigations were performed.

Local stratigraphy, as illustrated by boreholes drilled at the site, consists of a complex succession of detrital deposits and *terra rossa*, which fills a depression with a maximum depth of 55m. The bedrock is limestone, but large blocks of carbonate breccia were also encountered before the top of the carbonate rock mass was reached (Zezza, 1976). Eventually, to complicate the local geological situation further, a thin and laterally discontinuous layer of "*pozzolane*" (a deposit of volcanoclastic origin) was also recognized above the limestone at some locations. The origin of the latter deposits was not investigated fully; likewise, authors studying the site in the past did not explain the origin of the carbonate breccia. The blocks of breccia were probably related to repeated collapse from the original ceiling and from the walls of the cavity, and to successive re-cementation of the rocky debris.

In any case, the greater part of the ancient underground cavity was filled with *terra rossa*. Above that, a maximum thickness of 7m of detrital deposits was present; the latter deposits, originating from anthropogenic activity, were material used in historical times to level the old topography and allow construction at the site.

Following the 1968 event, other settlements occurred in 1969 (four months after the first one), and again in 1972, until the building had finally to be evacuated and abandoned (Fig.2). Only recently, the Municipality of Castellana-Grotte decided to recover the site, clearing away the debris and creating a garden area across the site previously occupied by the building.

Situations like that described at Castellana-Grotte, generally localized at a single site or distributed across an area of few tens of square metres, have been recorded during the last few centuries in many other towns of the Apulian karst, especially in the Murge Plateau.

Spedicaturo area

A second site of inland subsidence lies in the Salento Peninsula (Fig.1). The Spedicaturo area is part of an inland plateau delimited to the west and east by the low

Fig.2 - The site of Largo Porta Grande, at Castellana-Grotte, affected by repeated subsidence events since 1968 (photo taken in 2000).

relief areas of the Serre Salentine. It presents surface karst morphologies, including several dolines, partly or totally filled with residual deposits, as well as karren fields and many other micro-forms of karstic origin. Man has, over time, created a network of artificial channels across the area to control the flow of meteoric water, and to facilitate its infiltration into the underground karst system (Beccarisi et al., 1999).

Subsidence phenomena active in the area interfere with Man's activities and cause damage to structures and buildings. In March 1996, for example, collapse of the ceiling of a karst cavity resulted in the formation of a sinkhole in the vicinity of an important communication route that had to be closed temporarily (Carrozzo et al., 1996).

The local geological situation at Spedicaturo is characterised by the presence of Early Pleistocene calcarenites (the Salento Calcarenite Formation) that overlie Late Miocene marls, limestones and calcarenites (the Andrano Calcarenite). All of the stratigraphical sequence is sub-horizontally bedded. It is affected by SE–NW subvertical faults and several fracture systems, which appear to guide the development of subterranean karst landforms.

The difference in permeability between the two formations (very high in the Salento Calcarenites and low in the Andrano Calcarenites) determines the presence of a shallow aquifer in the Salento Calcarenites. Shallow phreatic speleogenesis operates close to the water table level, with formation of karst conduits and protocaves (*sensu* Ford, 1988), whose evolution occurs through successive ceiling collapse, formation of wide caverns and sinkhole development at the surface.

This mechanism can be identified readily in many more of the Salento caves, where the subsidence events, and the successive evolution of the forms so produced may result in the formation of compound sinks aligned along the main tectonic trends.

4.2. Coastal subsidence

In recent years the coastal plains of Salento have been affected by repeated episodes of land subsidence, some of which have damaged or destroyed roads and buildings. Consequently, understanding of these events and the processes causing them, and of their likely evolution in the future, is extremely important in helping to evaluate their incidence across large areas of southern Apulia, and to determining the most adequate measures for controlling and mitigating the related environmental hazards.

Sinkhole-like landforms in the coastal areas of Apulia have recently attracted great interest from researchers because of their possible archaeological significance, as evidenced for example at the archaeological site of Gnathia. A new interpretation has been proposed for the so-called "Amphitheatre", an elliptical depression within the ancient town of Gnathia, which was one of the most important harbours on the Adriatic coast during Roman times (Delle Rose et al., 2002).

Even though subsidence processes and the landforms they produce are present on both the Ionian and Adriatic side of Salento, the following section deals mainly with the situation on the Adriatic side. In addition, some details about the less well-developed karst subsidence on the Ionian side are provided.

Cesine area

For the purposes of this study, the Cesine area (Fig.3), with an extension of about $8km^2$ along the Adriatic coastal plain of Salento, has been analysed. Several events affecting the village of Casalabate during recent years illustrate ongoing karst subsidence processes within this coastal stretch. During the last decade there has been frequent development of sinkholes, which appear to be aligned along the main tectonic fractures (Delle Rose and Federico, 2002). In particular, formation of a sinkhole in 1993 caused collapse or severe damage of buildings (Fig.4). On that occasion, brackish water was found inside the dolines. This water comes from a coastal near-surface aquifer that contains salt water encroaching from the sea at lower level.

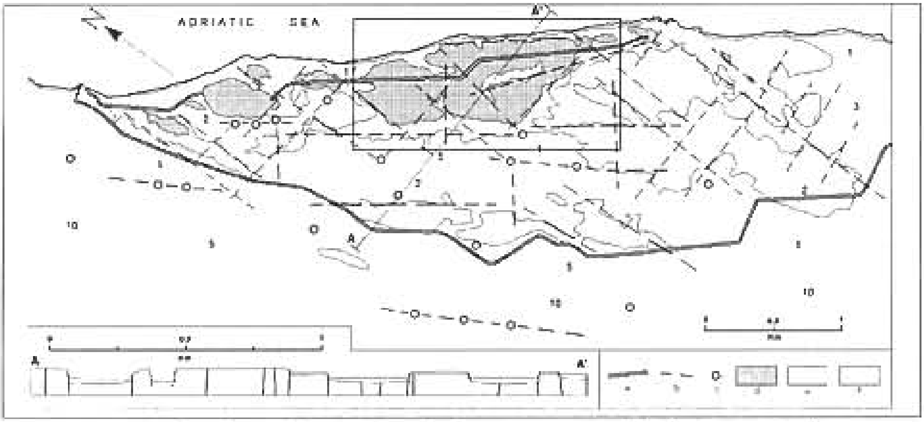

Fig.3 - Geological and morphological sketch of Cesine (see Fig. 1 for location). Explanation: a) reclamation channel; b) fractures of tectonic origin; c) doline; d) swamp; e) paludal deposits; f) Early Pleistocene calcarenites. Numbers indicate elevation above sea level (expressed in metres). The vertical scale is exaggerated in the section. The inset refers to the sector for which the evolution model of Fig.9 is discussed in the text.

Fig.4 - Damage to buildings in the village of Casalabate, due to subsidence events that occurred in 1993 (photo taken in 1994).

Other events must be cited to emphasise the importance and frequency of subsidence phenomena in this area. Among these, during 2000, limited subsidence was observed on the beach at Casalabate, where elliptical dolines with a diameter of a few metres and depth in the order of 70-80cm, were produced (Fig.5). These dolines disappeared within two or three days due to the low resistance of the materials to erosion, and the small dimensions of the landforms.

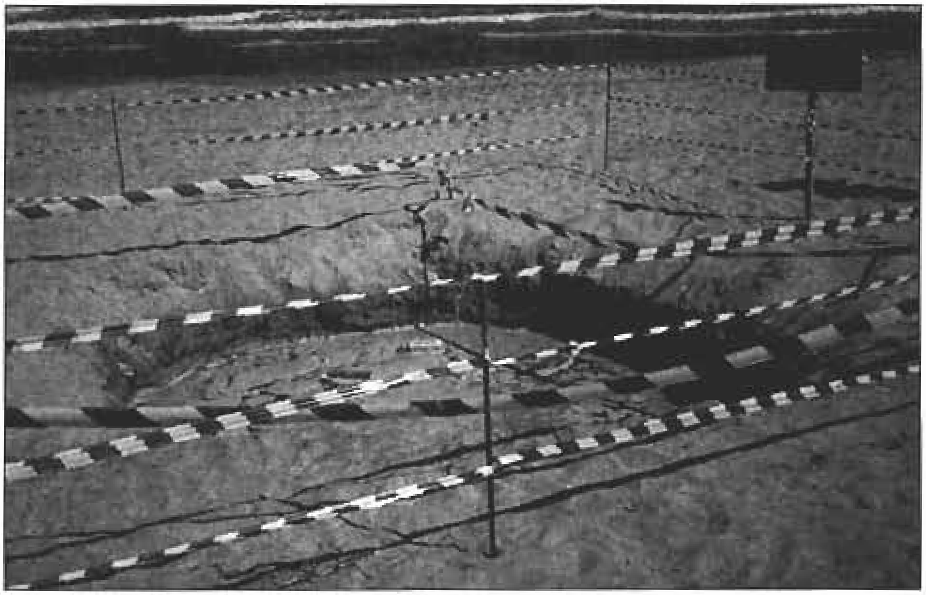

Fig.5 - Sinkhole on the beach of Casalabate (photo taken in 2000). The sinkhole disappeared a few days after the photo was taken.

More than one km^2 of the Cesine area is occupied by water, and swamp environments are present (Fig.6). Furthermore, marshland deposits, generally not greater than a metre thick, spread across an area of some $3km^2$. Cesine lies some 15km east of Lecce (Fig.1), and is elevated a few metres above sea level. Inland, the area becomes a slightly inclined plateau. The local bedrock comprises Early Pleistocene calcarenites, several tens of metres thick, lying with stratigraphical discontinuity over Pliocene calcarenites and calcilutites. The strata are affected by sub-vertical fracture systems. At the turn of the 20th century, reclamation works were performed in the area, and several reclamation channels were dug, of which the largest was 4m wide and 3m deep. This excavation exposed calcarenites cropping out in its floor and in its sides (Figs 3 and 7).

The shoreline is composed of beaches, bordered by sand dunes, alternating with small promontories of calcarenite rock. Inland, the calcarenites are covered by recent and active paludal deposits (clays and silts), and by residual (*terra rossa*) deposits that have been partially affected by pedogenesis. The shape and orientation of landforms such as shorelines, edges of escarpments and watershed divides depend largely upon the spatial arrangement of the tectonic fractures.

Fig.6 - Overall view of the Cesine area.

Fig. 8 - Swamp areas in the Cesine. Note, in the foreground, the recent development of a sub-circular doline.

Swamps and marshland developed by evolution from initial individual dolines, as described below. Sub-circular dolines are very common at Cesine (Fig.8). Their maximum area is some hundreds of square metres, with a maximum depth of several metres. Nowadays recognition of individual dolines in the marshlands is difficult. Moving inland, the dolines are generally covered by thin layers of *terra rossa*. However, in the latter case, the dolines can be still recognized by way of aerial photo interpretation. Even inland, most of the dolines appear to be aligned along the main tectonic lineations of the area (Fig.3).

The rate of evolution of karst features in this area can be appreciated even within the timescale of human life. Periodic surveying carried out in the last twenty years has shown, for example, the development of several dolines that were generally masked rapidly by fill deposits and vegetation cover. Enlargement of individual dolines due to rock falls around the perimeter, and a tendency for adjacent dolines to coalesce, with an overall widening of the area affected by karst subsidence, is common.

Underground water circulation is influenced in part by the tectonic fracture systems and is marked by submarine springs that lie along fractures running transverse to the coast. Underwater investigations, carried out after the sinking of part of submerged beach at Casalabate in 1997, revealed a spring with tubular conduits draining the aquifer and running parallel to one of the main fracture systems.

The swamp areas are flooded by brackish water produced by the mixing of salt water encroaching from the sea and fresh groundwater from the aquifers (Cotecchia et al., 1975; Tadolini et al., 1971; Delle Rose et al., 2000). Salinity of the brackish water, which is of the order of a few metres deep, increases towards the bottom.

The chemical and physical characteristics of the brackish water lead to enhanced dissolution of the carbonate rock, a phenomenon described as "hyperkarst" in the scientific literature (Cigna and Forti, 1986). Local speleogenesis can thus be traced to dissolution of carbonate deposits by brackish water. The brackish groundwater surface, the elevations of which relate to the average level of the sea, represents the karstic base level in the studied area.

The aggressiveness of the water tends to decrease with the increase in the degree of saturation. However, maintenance of hyperkarstic conditions is guaranteed by the continual "rejuvenation" of the brackish water. This phenomenon is caused both by salts contained in the encroaching sea water spreading into the groundwater (Tadolini and Tulipano, 1981), and by mixing of the water masses occurring as a result of tidal oscillations.

Chemical and biological karstic action at the surface, may also contribute to the collapse of cavity ceilings. Epigean features such as solution pans, in fact, make a significant contribution to the thinning (from above) of the ceilings, due to the frequent salinity variations in the solutions that produce hyperkarstic conditions.

The areas around the swamps, and in particular the many topographic depressions, host a paludal fauna and flora, whereas solution pans, grooves and wells are filled in part with soils and vegetation. In turn this leads to three different types of erosional action on the substrate: secretions of chemical substances, physical disintegration and chemical processes caused by the decay of organic matter (Schneider, 1977).

This type of phenomenon has also been observed in other karst areas. Norris and

Back (1990), for example, describe the geomorphic consequences of the groundwater mixing zones along the coast of Yucatan in Mexico. The formation of lagoons occurs through the development of subsurface dissolution channels, coalescing into cave systems (strongly guided by fracture patterns), collapse of the cave roof, formation of a lagoon, further erosion by biological activity, and final evolution through erosion by wave action.

Sinking occurs frequently at Cesine due to the limited thickness of the rock (from a few decimetres to a few metres at most), i.e. the cavity ceiling, between the surface of the brackish groundwater and the topographical surface.

The tectonic fracture systems affecting the carbonate units represent an important guiding factor in the geomorphological karst evolution of the coastal plains (Lin Hua, 1986). They have an effect not only on shorelines and watersheds, but also on shape and orientation of the areas subject to collapse, in a way similar to that relating to *uvala* development in the karsts of Slovenia and Triest (White, 1988).

In the Cesine area it was observed that sinkhole development normally takes place parallel to the shoreline, and tends to generate wide compound forms separated from the sea by narrow barriers of rocky substrate.

Even though marshland, commonly consisting of saturated peat or organic matter supported by weak soil, are subject to land subsidence when drained and used for anthropogenic purposes (Bozosuk and Penner, 1971), the case at Cesine is quite different. In fact, in the authors' opinion, the development of marsh and swamp areas is related directly to karst processes.

On the basis of field survey and geological, morphological and hydrogeological studies, the model of evolution shown in Fig.9 is proposed for the swamp area of Cesine. For the sake of simplicity, the model takes no account of variations of sea level and, consequently, of the karstic base level.

The model originates with the presence of individual dolines, whose distribution follows the main tectonic lines in the area (Fig.9a). Rock falls and spalling at the doline boundaries, guided by the main discontinuity systems in the rock mass, determine enlargement of the individual dolines (Fig.9b). Thus, the dolines acquire an elliptical plan, whereas an overall outline in the form of a broken line can be recognized.

The dolines tend to widen and coalesce along tectonic alignments, producing compound sinks extending for a few thousand square metres (Fig.9c). The compound sinks are separated from the sea by "barriers" of highly karstified and unstable rocky substrate (Fig.9d), the collapsing of which might lead to the formation of coastal channels.

The progress of these processes is relatively rapid, in geological terms. Considering the age of formation of the coastal plains (Late Pleistocene), and excluding from this very qualitative account the time during which sea level was much lower than today (due to the last episodes of glaciation), a maximum estimate in the order of several tens of thousands of years is obtained. The rapidity of the process is further evidenced, within human timescales, by repeated, though generally small-scale, events (local collapses, doline development, etc.) in the last few tens of years. This poses a problem in terms of assessing the geological hazards relating to this type of subsidence within the anthropogenic environment in Apulia.

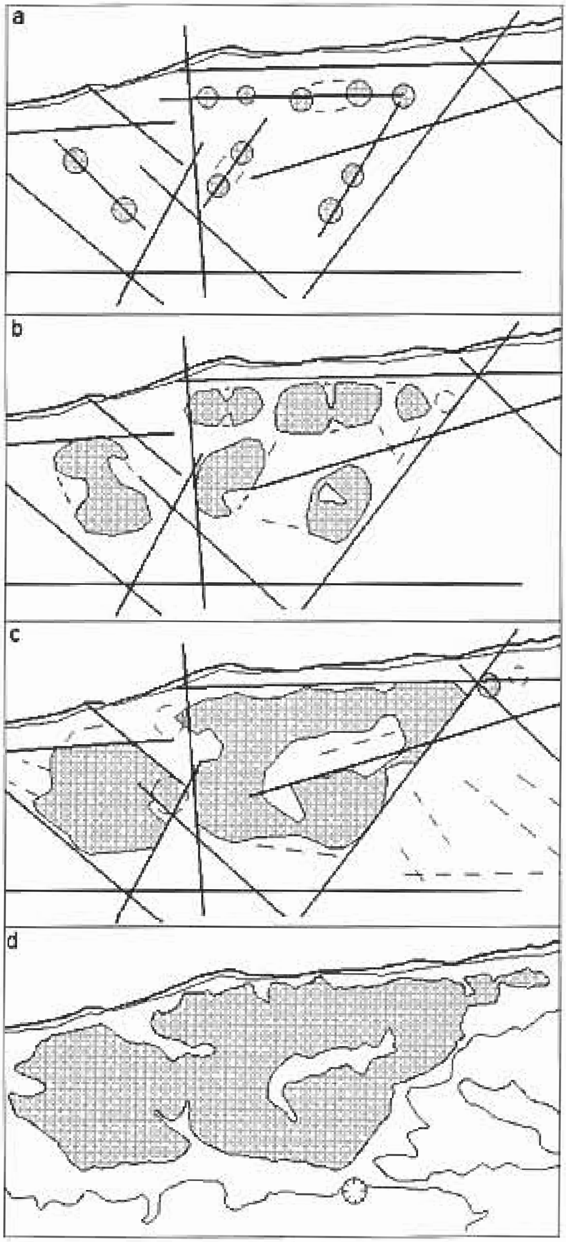

Fig. 9 - Model of evolution in the Cesine area: a) development of individual dolines; b) widening of dolines; c) coalescing of the individual dolines, with formation of compound sinks; d) present situation. For more details, see the text.

Ionian Coastal Plain

Between Torre Castiglione and Serra Cicora, on the Ionian side, the coastal plain joins inland with the low hills of an escarpment formed by a NW- to SE-striking fault. Toward the sea it is delimited by a low, jagged, rocky coast, with numerous inlets, mostly oriented sub-parallel or perpendicular to the coastline, and, less frequently, N–S or E–W.

Along the coast, Late Pleistocene calcarenites and fossiliferous limestones crop out (Dai Pra, 1982), with an overall thickness of several metres. The strata are characterised by several sub-vertical fracture systems with average directions approximately coincident with the main coastline directions. The Pleistocene deposits lie unconformably over Cretaceous limestones and dolostones, which in turn show sub-vertical fracture systems with varying orientations. Clays and marsh silts, dune and shore sands and residual deposits (*terra rossa*), partially affected by pedogenic processes, form the recent superficial cover.

The area is characterized by various karst morphologies, including numerous collapse dolines, known locally as "*spunnulate*", a dialect term that can be translated literally as "sunken". Other epigean karst features, filled in part with soil and vegetation, are also widespread. The dolines and compound sinks are easily

Table 1. Summary of different situations of karst subsidence in central-southern Apulia, and their main features

Location	Local bedrock	Phase of evolution of hypogean karst systems	Karst dissolution	Sinkhole development
Murge, Serre Salentine	Limestones and dolomitic limestones (Cretaceous)	Old age of karst systems; the active karst level is present at greater depth	Absent, or limited to condensation from moist draughts	Related to the presence of individual cavities
Inland plateaux	Calcarenites (Tertiary and Quaternary)	Active speleogenesis (shallow phreatic type)	Present along karst conduits	Localized along the main tectonic lines, with formation of aligned compound sinks
Coastal plains	Calcarenites (Quaternary)	Active speleogenesis, with formation of caves at the water table	Hyperkarstic conditions within brackish water of the coastal aquifer	Widespread over the coastal plain, with formation of wide compound sinks. The recognition of their alignment along the main tectonic lines is more difficult

observed where fill deposits are thin or lacking and near the shoreline, where a bare lithic substrate is present because of the erosional action of the waves. Inland, the dolines are filled either naturally or by farmers, who tend to use them for agricultural purposes.

As observed on the Adriatic side, some dolines are separated from the coast by narrow barriers of highly karstified and unstable rocky substrate, the collapsing of which may lead to formation of coastal inlets (Delle Rose and Federico, 2002).

5. Discussion and conclusion

Subsidence phenomena in the karst of Apulia, described in this paper, can be considered as a relatively widespread hazard, as is also the case in many other karst areas. Geohazards such as flooding and subsidence are, for example, present in the Mediterranean karst. This is the case at many sites in Spain, where subsidence phenomena occurring in the evaporite rocks create serious damage to buildings in urban areas (Gutierrez and Cooper, 2002; Soriano and Simon, 2002).

The hazards related to these types of phenomena can be very difficult to evaluate, and this poses a serious problem in the management of those parts of karst areas that are selected for constructional activities. In such geological conditions it is very important to perform detailed studies aimed at the identification of possible underground cavities and their secondary fill deposits.

Analysis and mapping of geological hazards related to karst require an interdisciplinary approach devoted to examination of the specific problems presented in the karst environment (Forth et al., 1999). The peculiarities of karst make it a unique setting from many different points of view (geological, morphological, hydrogeological, not to mention its high vulnerability in terms of land degradation, pollution and human impact). Again it must be stressed that study of areas affected by karst subsidence cannot be restricted to examination of their geological characteristics. As evidenced by Cooley (2002), to understand the hazard related to subsidence phenomena fully in areas where carbonate rocks are overlain by clay materials, it is fundamental to study the geotechnical characteristics of the clay mantle. These relate closely to the occurrence of collapse features, and are in turn tied directly to the underlying water flow routes and their development through time. Also, in areas where only carbonate rocks crop out, the contributions of experts in speleology, karst morphology, geotechnics, hydraulics, etc., may be crucial.

Karst exerts a very strong influence on the general geological environment and specifically on the engineering-geological one, in relation to land-use activities and regional planning (Liszkowsi, 1975). The specific character of karst environments puts several restraints on many types of human activity and land-use. Subsidence events, extremely difficult to forecast because they are commonly related to site-specific conditions and still more to local stratigraphy, may result in serious economic and social damage to the anthropogenic environment.

On the other hand, the interest of studying the characteristics and evolution of areas such as Cesine, with a high natural environment value, should not be overlooked. Besides helping to reach a better understanding of the processes causing land subsidence and the development of sinkholes in karst areas, such study can help support correct management of the territory, and for its sensible exploitation for nature- and landscape-oriented tourism. In this context it would be interesting to establish karst management guidelines, following the good examples already available from some land management authorities, such as the Tasmania Forestry Practices Code (Forestry Commission, 1987).

The great importance of karst environments and aquifers is further evidenced by the estimate that water supplies for one-quarter of the world's population are gained from karst, either from discrete springs or from karst groundwater (Gillieson, 1986). As a direct consequence, there is an urgent need to maintain high water quality in karst. This is not an easy task, due to the high to very high vulnerability of karst environments and groundwater. Nevertheless, protection of karst catchment areas, including non-karst areas that contribute drainage to the karst, represents the first priority of appropriate karst management.

The Apulian karst case studies illustrated in this paper provide a preliminary description of the various types of subsidence phenomena that can be observed in the area. A tentative classification of the phenomena described is shown in Table I, where the subsidence cases are described in terms of local geological conditions, karst processes and resultant morphological landforms. This scheme needs to be more fully validated, through its extension and application in other areas. Nevertheless, in the authors' opinion, it represents, a good starting point for analysis of the cases of karst subsidence in the Apulia region.

The Salento Peninsula is of particular interest for the analysis of such phenomena, since it appears to present two different phases of karst subsidence evolution. On the Adriatic side, the development of wide and distributed subsidence is observed. The Cesine represents the best example, with swamps and lagoons of brackish water, enclosing remnants of the old calcarenite topography within the flooded areas. Moving inland, similar landforms (sinkholes, depressions) can be recognized, but with greater difficulty, due to the presence of vegetation and, in some cases, to the effects of anthropogenic activity that have strongly modified, if not obliterated, the original landforms. To date the farthest inland that the emergent water table has been identified in a sinkhole is more than 2km from the coast.

On the Ionian side, on the other hand, the slightly different topography (plains at higher elevation, adjoining the sea at a rocky cliff line a few metres high) evidences a younger stage of evolution of the same type of phenomena. In this case, the dolines are individual rather than ramifying over wide areas as compound sinks. This distribution strongly favours continuous evolution of the dolines through perimeter rock falls and spalling that cause their enlargement and widening. Recognition of compound sinks derived from the coalescing of two or more individual dolines is very rare along the Ionian coastline.

Taking into account conditions encouraging hyperkarst collapse the relative risk for buildings, infrastructures and, above all, the safety of people, the length of the coastal plains exposed to karst subsidence hazard in the Salento Peninsula is estimated to be several dozen kilometres. Subsidence phenomena have already made a significant contribution to the development of large swamp areas along other stretches of the Salento coastline, such as at Idume, and have caused considerable shoreline recession, with formation of large inlets, such as east of Torre Castiglione, on the Ionian side.

REFERENCES

AMIN A. and BANKHER K. 1997. *Causes of land subsidence in the Kingdom of Saudi Arabia*. Natural Hazards 16 (1): 57-63.

BATES R.L. and JACKSON J.A. 1987. *Glossary of geology*. American Geological Institute, 3rd edition, 788 pp.

BECCARISI L., CHIRIACO' L. and DELLE ROSE M. 1999. *Il sistema carsico Vore – Spedicaturo*. Itinerari speleologici 8: 31-36.

BENSON R.C. and YUHR L.B. 1987. *Assessment and long term monitoring of localized subsidence using ground penetrating radar*. Proc. 2nd Multidisciplinary Conference on Sinkholes and the Environmental Impact of Karst, Orlando, 9-11 February 1987: 161-169.

BOZOZUK M. and PENNER E. 1971. *Land subsidence in built-up marshland*. Canadian Geotechnical Journal 8: 592-596.

CALEMBERT L. 1975. *Problemes de geologie de l'ingenieur en regions karstiques*. Bull. Int. Ass. Eng. Geology 12: 93-132.

CARMINATI E. and MARTINELLI G. 2002. *Subsidence rates in the Po Plain, northern Italy: the relative impact of natural and anthropogenic causation*. Engineering Geology 66 (3-4): 241-255.

CARROZZO M.T., DELLE ROSE M., FEDERICO A., NEGRI S. and QUARTA T. 1996. *Individuazione con georadar di cavità carsiche nella zona di Nociglia (Lecce)*. Proc. 15th Conf. Gruppo Nazionale di Geofisica della Terra Solida, CNR: 35-40.

CAVOUNIDIS S., MARINOS P. and PAPADOPULOS T. 1996. *Subsidence investigation for reservoir*. Proc. 7th Int. Symp. on Landslides, Trondheim (Norway) 2: 675-681.

CIGNA A.A. and FORTI P. 1986. *The speleogenetic role of the air flow caused by convection*. 1st contribution. International Journal of Speleology 15: 41-52.

COOLEY T. 2002. *Geological and geotechnical context of cover collapse and subsidence in mid-continent US clay-mantled karst*. Environmental Geology 42: 469-475.

COTECCHIA V. 1980. *Review of subsidence phenomena in Italy and the world*. In Hommage a Leon Calembert. Liège, Editions Georges Thone: 72 pp.

COTECCHIA V., TAZIOLI G.S. and TITTOZZI P. 1975. *Geochimica delle acque della penisola Salentina in relazione ai rapporti tra le acque di falda, le acque marine sotterranee e il mare*. Geol. Appl. Idrogeol. 10: 205-224.

CVIJIC J. 1918. *Hydrographie souterraine et évolution morphologique du karst.* Rev. Trav. Inst. Géogr. Alpine, t. VI: 375-426.

DAI PRA G. 1982. *The late pleistocene marine deposits of Torre Castiglione* (southern Italy). Geogr. Fis. Dinam. Quat. 5: 115-119.

DELLE ROSE M. 2001. *Salento Miocene: a preliminary paleoenvironmental reconstruction.* Thalassia Salentina 25: 159-197.

DELLE ROSE M. and FEDERICO A. 2002. *Karstic phenomena and environmental hazard in Salento coastal plains.* Proc. IAEG Congress, Durban (South Africa), september 2002.

DELLE ROSE M., FEDERICO A. and FIDELIBUS C. 2000. *A computer simulation of groundwater salinization risk in Salento peninsula* (Italy). Proc. 2nd Int. Conf. on Computer Simulation in Risk Analysis and Hazard Mitigation, Bologna (Italy): 465- 475.

DELLE ROSE M., PAGLIARULO R. and PARISE M. 2002. *Some insights for the evolution of the Adriatic coast line as inferred from research at the archeological site of Gnathia* (Apulia, southern Italy). Proc. Workshop "Late Quaternary sea level changes and coastal zone evolution", Ostuni (Italy), 30-31 May 2002, vol. Abstracts: 69-72.

DOGLIONI C., MONGELLI F. and PIERI P. 1994. *The Puglia uplift (SE Italy): an anomaly in the foreland of the Apenninic subduction due to buckling of a thick continental lithosphere.* Tectonics 13: 1309-1321.

FORD D.C. 1988. *Characteristics of dissolutional cave system in carbonate rocks*: 25-27. In: James N.P. and Choquette P.W. (Eds.) – Paleokarst. Springer-Verlag.

FORESTRY COMISSION OF TASMANIA 1987. *Forest Practices Code.* Hobart, Government Printer: 46 pp.

FORTH R.A., BUTCHER D. and SENIOR R. 1999. *Hazard mapping of karst along the coast of the Algarve, Portugal.* Engineering Geology 52 (1-2): 67-74.

GILLIESON D. 1996. *Caves.* Blackwell Publishers, Oxford: 324 pp.

GIULIANI P. 2000. *Elenco delle grotte pugliesi catastale al 31 ottobre 1999.* Itinerari Speleologici 9: 5-41.

GUTIERREZ F. and COOPER A.H. 2002. *Evaporite dissolution subsidence in the historical city of Calatayud, Spain: damage appraisal and prevention.* Natural Hazards 25 (3): 259-288.

HALL L.A. and METCALFE S.J. 19984. *Sinkhole collapse due to groundwater pumpage for freeze protection irrigation near Dover,* Florida, January 1977: 248-251. In: Burger A. and Dubertret L. (Eds.) - Hydrogeology of karst terrains, vol. 1.

HU R.L., WANG S.J., LEE C.F. and LI M.L. 2002. *Characteristics and trends of land subsidence in Tanggu, Tianjin, China.* Bull. Eng. Geol. Environ. 61: 213-225.

JENNINGS J.E., BRINK A.B., LOUW A. and GOWAN G.D. 1965. *Sinkholes and subsidence in the Transvaal dolomites of South Africa.* Proc. 6th Int. Conf. Soil Mechanics.

JOHNSON K.S. 1987. *Development of the Wink Sink in west Texas due to salt dissolution and collapse.* Proc. 2nd Multidisciplinary Conference on Sinkholes and the Environmental Impact of Karst, Orlando, 9-11 February 1987: 127-136.

KASTNING E.H. 1987. *Solution-subsidence-collapse in central Texas: Ordovician to Quaternary.* Proc. 2nd Multidisciplinary Conference on Sinkholes and the Environmental Impact of Karst, Orlando, 9-11 February 1987: 41-45.

KETELLE R.H. and NEWTON J.G. 1987. *Inventory of karst subsidence in the Valley and Ridge Province of East Tennessee.* Proc. 2nd Multidisciplinary Conference on Sinkholes and the Environmental Impact of Karst, Orlando, 9-11 February 1987: 25-29.

LAMONT-BLACK J., YOUNGER P.L., FORTH R.A., COOPER A.H. and BONNIFACE J.P. 2002. *A decision-logic framework for investigating subsidence problems potentially attributable to gypsum karstification.* Engineering Geology 65 (2-3): 205-215.

LIN HUA S. 1986. *Geological structure: an important factor controlling karst development.* Proc. of the Anglo-French Symp. "New directions in karst", september 1983: 165-174.

LISZKOWSKI J. 1975. *The influence of karst on geological environment in regional and urban planning.* Bull. Int. Ass. Eng. Geology, 12: 49-51.

NEBOIT R. 1974. *Plateaux et collines de Lucanie orientale et des Pouilles.* Etude morphologique. Libr. Honore Champion, Paris.

NICOD J. 1972. *Pays et paysages du calcaire.* Presses Universitaires de France, Paris, 242 pp.

NORRIS R.M. and BACK W. 1990. *Erosion of seacliffs by groundwater*: 283-290. In: Higgins C.G. and Coates D.R. (Eds.) - Groundwater geomorphology: the role of subsurface water in earth-surface processes and landforms. Geol. Soc. Am., spec. paper 252.

OROFINO F. 1990. *Castellana-Grotte: le vicende storiche di Largo Porta Grande.* Itinerari Speleologici 4: 39-46.

PACE P. and SAVINO G. 1995. *Largo Porta Grande e la conca carsica di Castellana-Grotte.* Umanesimo della Pietra-Verde 10: 35-44.

PALMENTOLA G. 1987. *Lineamenti geologici e morfologici del Salento leccese.* Quad. Ric. Centro Studi Geot. Ing., Lecce 11: 7-30.

PALMER A.N. 1990. *Groundwater processes in karst terrains*: 177-209. In: Higins C.G. and Coates D.R. (Eds.) - Groundwater geomorphology: the role of subsurface water in earth-surface processes and landforms. Geol. Soc. Am., spec. paper 252.

PARISE M. 1999. *Morfologia carsica epigea nel territorio di Castellana-Grotte.* Itinerari Speleologici 8: 53-68.

PARISE M. 2002. *Flood history in the karst environment of Castellana-Grotte* (Apulia, southern Italy). Geophysical Research Abstracts 4 (full paper submitted to Natural Hazards and Earth System Sciences).

PEWE T.L. 1990. *Land subsidence and earth-fissure formation caused by groundwater withdrawal in Arizona*; a review: 219-233. In: Higgins C.G. and Coates D.R. (Eds.) - Groundwater geomorphology: the role of subsurface water in earth-surface processes and landforms. Geol. Soc. Am., spec. paper 252.

RICCHETTI G., CIARANFI N., LUPERTO SINNI E., MONGELLI F. and PIERI P. 1988. *Geodinamica ed evoluzione sedimentaria e tettonica dell'Avampaese Apulo.* Mem. Soc. Geol. It. 41: 57-82.

ROJE-BONACCI T. 1997. *Influence of the fluctuation of groundwater levels upon the formation of sinkholes.* Proc. Int. Conf. "Engineering Geology and the Environment", Athens, 1: 997-1002.

SAURO U. 1991. *A polygonal karst in Alte Murge* (Puglia, Southern Italy). Zeitschrift für Geomorphologie 35 (2): 207-223.

SCHNEIDER J. 1977. *Carbonate construction and decomposition by epilitic and endolitic micro-organisms in salt- and freshwater*: 248-260. In: FLÜGEL E. (Ed.) – Fossil algae. Springer-Verlag, Berlin.

SGOBBA A. 1896. *Della inondazione avvenuta in Castellana il 9 novembre 1896.* Stabilimento Tipografico N. Ghezzi, Monopoli: 15 pp.

SORIANO M.A. and SIMON J.L. 2002. *Subsidence rates and urban damages in alluvial dolines of the Central Ebro basin* (NE Spain). Environmental Geology 42 (5): 476-484.

STRINGFIELD V.T. and RAPP J.R. 1976. *Land subsidence resulting from withdrawal of groundwater in carbonate rocks.* Proc. 2nd Int. Symp. on Land Subsidence, Anaheim (USA).

TADOLINI T. and TULIPANO L. 1981. *The evolution of fresh-water/salt-water equilibrium in connection with withdrawals from the coastal carbonate and carstic aquifer of the Salentine Peninsula* (Southern Italy). Geol. Jb. C 29: 69-85.

TADOLINI T., TAZIOLI G.S. and TULIPANO L. 1971. *Idrogeologia della zona delle sorgenti Idume* (Lecce). Geol. Appl. Idrogeol. 6: 41-64.

THARP T.M. 1999. *Mechanics of upward propagation of cover-collapse sinkholes.* Engineering Geology 52 (1-2): 23-33.

WHITE W.B. 1988. *Geomorphology and hydrology of karst terrains*, Oxford University Press: 464 pp.

WHITE W.B. 1990. *Surface and near-surface karst landforms*: 157-175. In: Higgins C.G. and Coates D.R. (Eds.) - Groundwater geomorphology: the role of subsurface water in earth-surface processes and landforms. Geol. Soc. Am., spec. paper 252.

WHITE W.B. and WHITE E.L. 1987. *Ordered and stochastic arrangements within regional sinkhole populations.* Proc. 2nd Multidisciplinary Conference on Sinkholes and the Environmental Impact of Karst, Orlando, 9-11 February 1987: 85-90.

WILSON R.L. 19984. *Karst induced subsidence in the Chattanooga-Rossville area, Hamilton County, Tennessee and Walker County, Georgia*: 258-260. In: Burger A. and Dubertret L. (Eds.) - Hydrogeology of karst terrains, vol. 1.

ZEZZA F. 1976. *Significance of the subsidence collapse phenomena in the carbonatic areas of southern Italy.* Geol. Appl. e Idrogeol. 11 (1): 123-132.