Mem. Descr. Carta Geol. D'It.
XCIX (2015), pp. 437 - 444
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Sinkhole monitoring to support landslide management

Il monitoraggio delle sinkhole a supporto della gestione dei fenomeni di dissesto

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ABSTRACT - The availability of geological and geomorphological data represents an important element to support local authorities in land management policies and the design of mitigation measures to reduce natural risk levels. These data allow to improve decision makers awareness during the process of design and construction of civil works both public and private. The authors, were appointed by the Verduno municipality (Cuneo Province, Italy), in order to provide the inventory and the classification of the geological and geomorphological elements of the Tanaro Valley sector falling within the municipal territory. In this area the geological setting is characterized by shallow and deep landslides connected to a karst system developed in the Vena del Gesso Formation (Upper Messinian), represented by gypsum, which exerts a relevant influence on groundwater and runoff behaviour. This study was accomplished in different and consequential steps which allowed i) to relate the field survey with the previous works and geological studies, ii) to realise the inventory with an appropriate and effective standard process for data field acquisition and iii) to develop and to implement a database to store field information. Information is organized in way to be read both on computer and on paper support. Thematic forms provides data related to specific aspects of the karsts shape such as the geographic location, morphology, evolution state, relationship to the anthropic activities, geologic and geomorphologic setting. The geographic features and the associated information are also available on a GIS. Specific command tools on database forms allow to easily read information and to perform specific queries. Finally, the study allowed i) to improve awareness on land processes, ii) the monitoring of the evolution of the karst phenomena and their relationship with runoff dynamics and iii) to develop an operative tool for checking and managing municipal territory data by local public managers.

KEY WORDS: karst, sinkholes, landslides, Verduno

RIASSUNTO - La disponibilità di dati geologici e geomorfologici rappresenta un elemento fondamentale a supporto delle autorità amministrative locali per la gestione del territorio e le politiche ambientali e per la definizione delle misure di mitigazione del rischio idrogeologico. Questo tipo di informazione permette di aumentare la qualità dei progetti di opera civili sia in ambito pubblico che privato. Gli autori sono stati incaricati dal Comune di Verduno (Cn) per realizzare un catalogo per la classificazione delle forme carsiche che caratterizzano il versante della Valle Tanaro che ricade nel territorio municipale. Questo settore è caratterizzato dalla presenza di dissesti superficiali e profondi connessi a un reticolo di cavità e condotti carsici sviluppato all'interno della Formazione della Vena del Gesso (Messiniano Sup.) costituito da livelli di gesso che esercitano il controllo del deflusso sotterraneo e superficiale. Lo studio è stato realizzato in fasi successive e consequenziali che hanno permesso i) di aggiornare i dati esistenti con quelli del nuovo rilievo geologico di superficie, ii) di realizzare il censimento delle forme carsiche utilizzando un sistema classificativo standardizzato e coerente ai dati rilevati sul terreno, iii) di sviluppare un catalogo digitale dei dati di terreno. Le informazioni sono state organizzate in modo da essere consultabili sia in formato digitale che cartaceo costruendo aree tematiche relative all'ubicazione delle forme carsiche, alla loro morfologia, al loro stato di evoluzione (maturità), alle relazioni con le attività antropiche e al contesto geologico e geomorfologico. I dati sono stati organizzati in ambiente GIS mentre specifici comandi permettono di consultare facilmente le informazioni disponibili e di eseguire ricerche per tematismi. In conclusione, lo studio ha permesso i) di aumentare le conoscenze dei processi naturali in corso, ii) di monitorare l'evoluzione dei fenomeni carsici e le implicazioni sul deflusso idrico di superficie e iii) i sviluppare uno strumento operativo di controllo e gestione del territorio comunale da parte dell'amministrazione municipale.

PAROLE CHIAVE: carsismo, sinkhole, instabilità di versante, Verduno

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1. - INTRODUCTION

1.1. - Aim of activities

This study is part of the activities pursued by the Municipality of Verduno with the purpose of protecting the territory and the mitigation of landslide risk. This work allowed the understanding of a sector of the territory that is characterized by a specific geographical and geological setting and represents an historical element of economic and cultural development of the Verduno community for its agricultural activities: vineyard and hazelnuts.

The data collected during the inventory and the analysis that flow from it, in fact, are a useful tool for the administration and the population to implement the necessary actions to maintain and develop agriculture and human activities in equilibrium with natural processes. In particular, (Liguori *et alii*, 2004; Cooper *et alii*, 2009) the following objectives were pursued:

1 - Increase the knowledge about the territory natural phenomena;

2 - Check the status of conservation of natural forms useful for the management and disposal of surface water;

3 - Create an instrument of control and management of land through the creation of a database of karst surveyed.

These elements will help to establish the necessary actions to maintain their specific role in the surface and ground water system.

1.2. - Study area

The study area is entirely within the municipal area of Verduno, a little town of the south west area of Piemonte Region called Langhe. In particular, it includes the NW versant between the urban settlement and the Tanaro valley (fig. 1).

1.3. - Regional geological setting

The study area is part of the Tertiary Piedmont Basin (BTP) (fig. 2), a thick sequence deposited between the Middle-Upper. Eocene (about 40 million years ago) and the Messinian (about 6 million years ago) in a basin extended from the Alps, being formed, and the units deposited in a marine environment (Ligurian sedimentary units) which constitute the Apennines, which were also being formed (Sturani, 1973 ; Gelati & Gnaccolini, 1988,

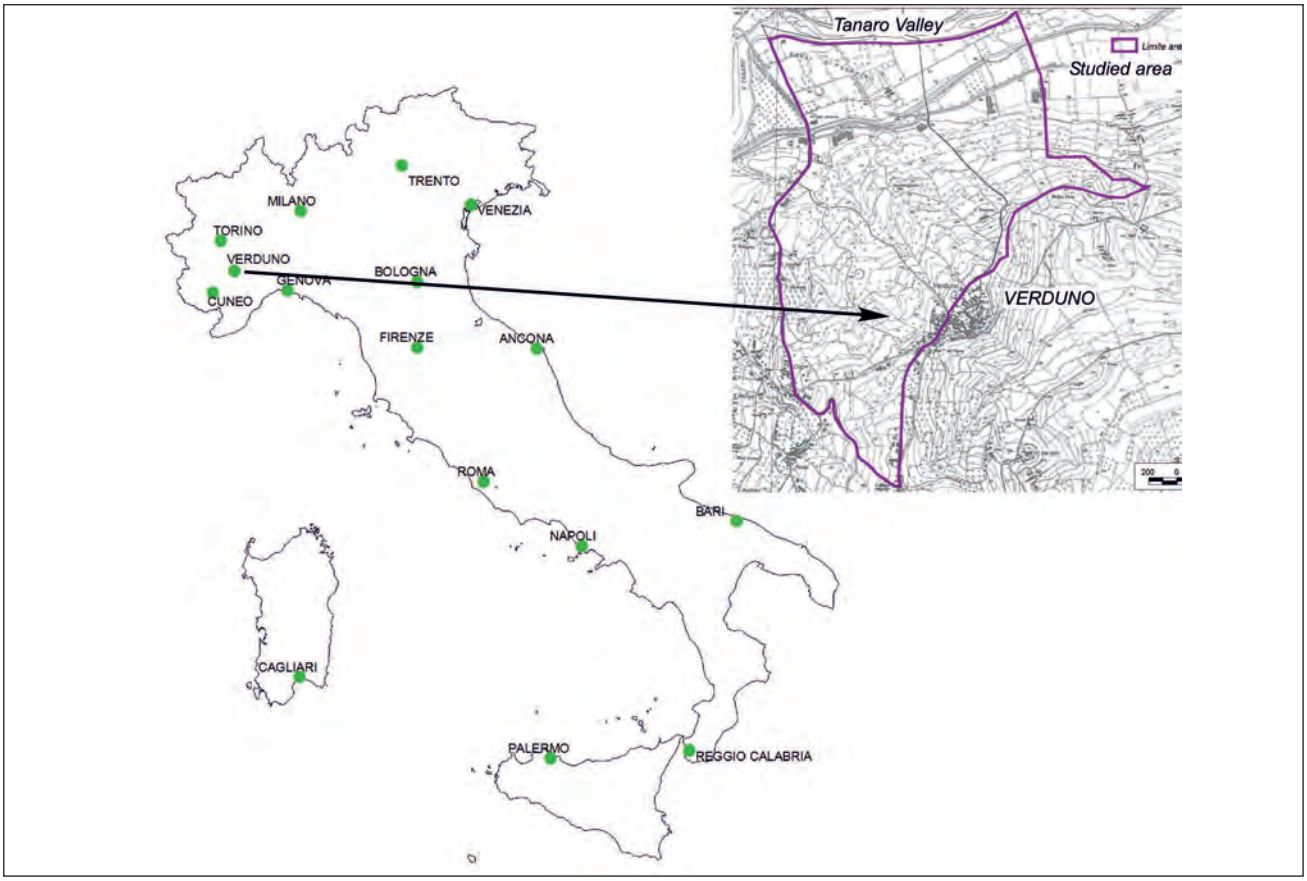

Fig. 1 - Studied area.
– Zona di studio.

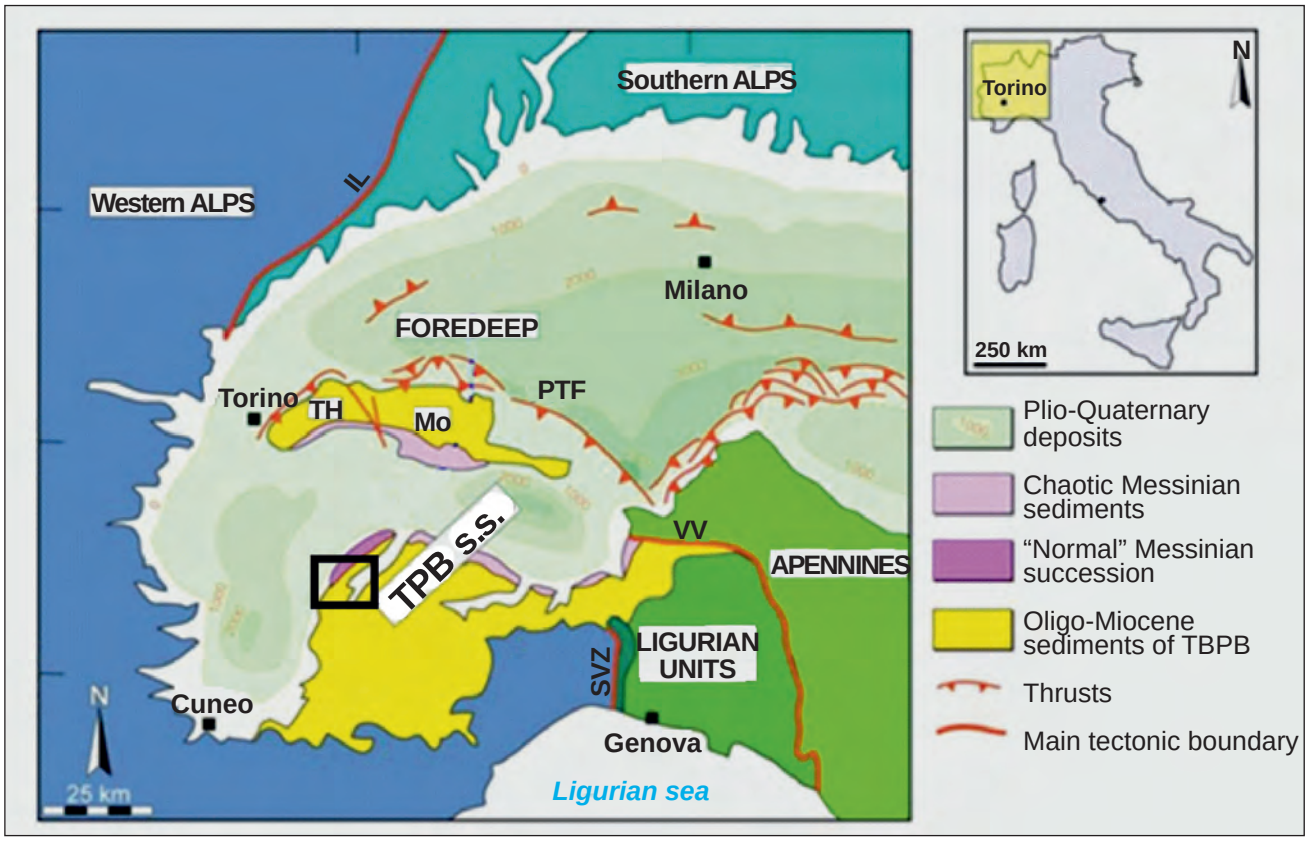

Fig. 2 - Geological setting of the study area (Bigi *et alii*, 1990).
– *Contesto geologico dell'area di studio (Bigi et alii, 1990).*

Bally & Snelson, 1980). The BTP is divided into several tectonic-stratigraphic domains or basins (Roure *et alii*, 1996): formation outcropping in the study area belong to the the basin of the Langhe.

The geological sequence of the study area is strictly related to the Messinian Salinity Crisis (MSC) characterized by the sudden drop of the sea level resulting in increased salinity of waters and the deposition of dissolved salts (such as carbonates, sulfates and chlorides) that originated mainly limestone and gypsum. Namely, the formations present in the area are the *Formation of Marne St. Agata Fossili* and the underlying *Formation of Gessoso – Solfifera* which recently was named *Formation of the Vena del Gesso* (Roveri & Manzi, 2007).

2. - METHODS: DATA COLLECTION AND DATA ORGANIZATION

The work was articulated into different stages which led i) to take into account the previous data and knowledge on geomorphology and land use , ii) to prepare the inventory having already established the necessary classification elements to describe karst forms during the field survey, iii) develop a database containing the data collected on the field that allows their storage, and overall their consultation and querying.

2.1. - Geomorphological setting and land use

The landscape of the area is strongly influenced by the lithostratigraphical setting of the Langhe which determines the formation of asymmetric valleys characterized by a "long gently slopes" corresponding to the direction of stratification, and a "short versant", with a steep slope opposite to the stratification (*cuestas* morphology).

The studied versant is affected by the presence of karst. It is characterized by a gentle slope typical of the "long versant" with the stratigraphic sequence formed by alternating layers of clay, sand and gypsum with the same average slope parallel to the versant and about 20 to 30 ° to the NW.

The landscape is strongly influenced by agricultural activities that are extremely developed throughout the area. This factor together with the alteration of natural surface layers, determines the overall reshaping of the slope and the restructuring of the shallow portion of the soil, severely limiting the retrieval on the surface of the primary stratigraphical structures.

Weathering processes are also observed along the outcrops of the banks of gypsum where the sinkholes and subsidence phenomena are developed (Cremonini *et alii*, 2009; Di Maggio *et alii*, 2009). In these areas the gypsum levels are altered by dissolution that determines the occurrence of karst (sinkholes) and micro-karst (cracking) and removes the original structure and decreases their consistency. This particular lithostratigraphical setting and the alternation of layers with different cohesion and consistency, leads to a general tendency to slope instability with the triggering of landslides.

As for other sectors of the Langhe, the study area is affected by processes of instability that can be related to two types of phenomena: i) landslides and liquefaction of saturated soil (soil slip) and ii) planar and translational slip that may affect the deeper portions of the slope.

In the first case, landslide triggering is facilitated by the absence of vegetation cover (e.g. trees) and to lack of or insufficient management of water runoff due to wrong agricultural practices. The material mobilized is channelled assuming the kinematic characteristics of real "debris flow". Similar phenomena were observed at the base of the slope in the Verduno industrial area where, in conjunction with heavy rainfall, the concentration of solids and liquid flows led to critical conditions causing flooding and damage to industrial facilities and to the road along the Tanaro floodplain.

The conditions favouring planar and translational slips are strictly related to the disposition of the stratification parallel to the slope and the presence of rhythmic lithostratigraphic sequences with the alternance of marls, marly - sandstone and silty - sandy of the *Gessoso – Solfifera Formation* and the underlying *Formation of Marne St. Agata Fossili*. The sliding surfaces are localized along the contact between the layers (translation of type *layer by layer*).

2.2. - Field survey and sinkholes inventory

Field observations allowed to define specific features, geometric and geological evolution for the recognized karts forms also with regard to the human activity. In the latter case, we verified the degree of impact of human activities on natural process of evolution. The details were recorded on a standard sheet format useful on the field and organized following four main topics:

1 - Master Data: this section contains, in addition to the inventory date and the identification code of each karst form, its location and its condition; a photograph and a map showing the site;

2 - Morphometric elements: this section presents data on the size, shape and the presence of artificial reshaping. This refers to the possible covering and reprofiling and the presence of waste inside the cavities;

3 - Geological context: description of the local geological context observed directly on the site, it is also reported the presence of water within sinkholes;

4 - Type of sinkhole: the recognized shapes have been related to the types defined in the classification of karst phenomena such as the one conducted by ISPRA (Nisio, 2009) and describing, where possible, the following distinct genetic processes:

a. dissolution;
b. collapse;
c. subsidence;
d. Deep pipeline (deep collapse of a cavity).

A separate fifth section is dedicated to the data collected on the field for the monitoring of the chemical and physical characters of springs and water points observed in proximity of the dolines.

3. - ANALYSIS OF DATA COLLECTED AND OBSERVATIONS OF LAND

The karst forms of the inventory are all located throughout the municipality of Verduno in particular along the NW side of the Tanaro valley at an altitudes between 376 and 230 m asl. For this sector 28 karst forms we recognized (fig. 3).

Status of conservation of the forms observed, in most cases (about 57%), was defined as natural or defined as the result of natural dynamics of evolution of the cavity. However, the slope of the study presents a strong development of agricultural activities related to the cultivation of vineyard and hazelnut trees. It is therefore very likely that even in cases where the natural state is more evident, agricultural activities have played a role in the evolution of karst.

In the remaining cases, the depressions are masked and heavily altered by human activities. This case was reported as a "human-made condition". These forms present full or partial backfilling of soil or waste material (wood, brick and solid waste in general).

In some cases were backfilling was found, it was observed that the evolutionary process of the cavity, however, was still in place with the formation of concentric fractures and subsidence of the ground that evidence of the reactivation of the phenomenon of collapse. These forms are probably periodically backfilled by farmers.

3.1. - Morphometry of the inventoried cavities

The most common form is elliptical, representing 68% of cases, whereas the remaining 32% is characterized by a circular shape. The elliptical

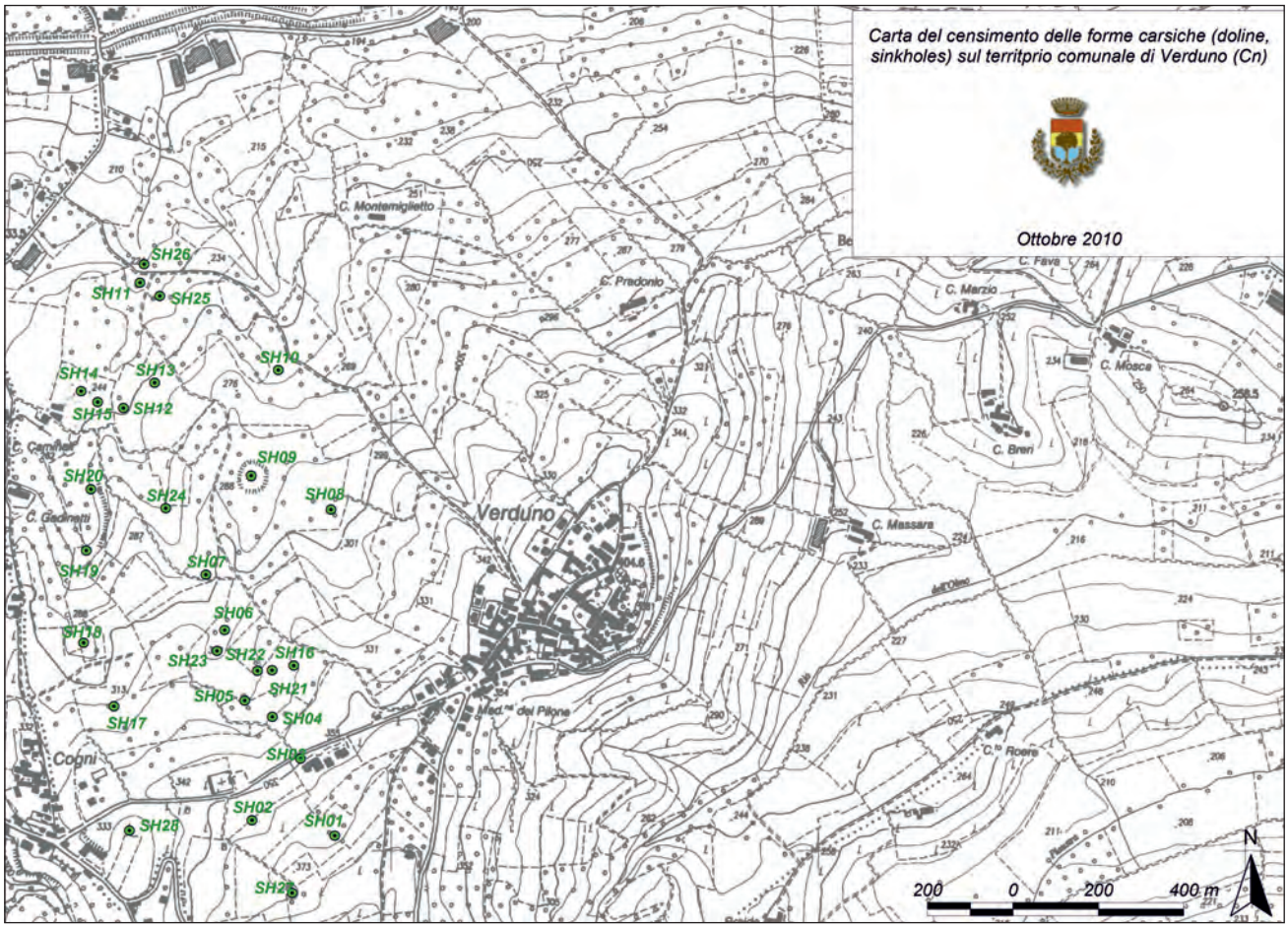

Fig. 3 - Location of all karst forms identified on the territory of the Verduno municipality.
- *Localizzaizone delle forme carsiche identificate nel territorio comunale di Verduno.*

shape is more common with the major axis parallel to the slope and is connected to the action of upstream erosion of the runoff and stream waters flowing into the same cavity.

In these cases we observed a generally symmetrical profile transversal to the slope, whereas the longitudinal profile is asymmetric: the upstream side is less steeper than the downstream and in general the swallow hole is localized at the foot of the downstream side (fig. 4).

The following table shows frequency classes related to the size of the cavities observed on the field.

About half of the recognized forms (43%) has a diameter ranging between 5 and 20 metres. This dimension corresponds, in the studied cases, to a mature stage of evolution with a formed swallow hole and no longer subject to increase in size. Only in four cases backfilled cavity was observed. Given the estimated size of the hole, these forms were attributed a mature stage of development. This condition of growth is also marked by the fact that, despite the backfill, the process of collapse is evident by the presence of failures and fractures that line the perimeter of the depression (tab.1).

Tab. 1 - *Size classes used for the description of the forms observed on the field and their distribution.*
– Classi di dimensione utilizzate per la descrizione delle forme osservate sul terreno e loro distribuzione percentuale.

Dimensions (m)	Nr	Freq.%
< 5	7	25
5 - 20	12	43
20 - 50	6	21
> 50	2	7
ND	1	4

The observed shapes with a diameter of less than 5 meters, corresponding to 25% of the total, are those for which the evolutionary stage is just estimated because influenced by human activity (remodelling and backfill), which have severely altered or obliterated the morphology of the cavities. Only in one case among these was possible to

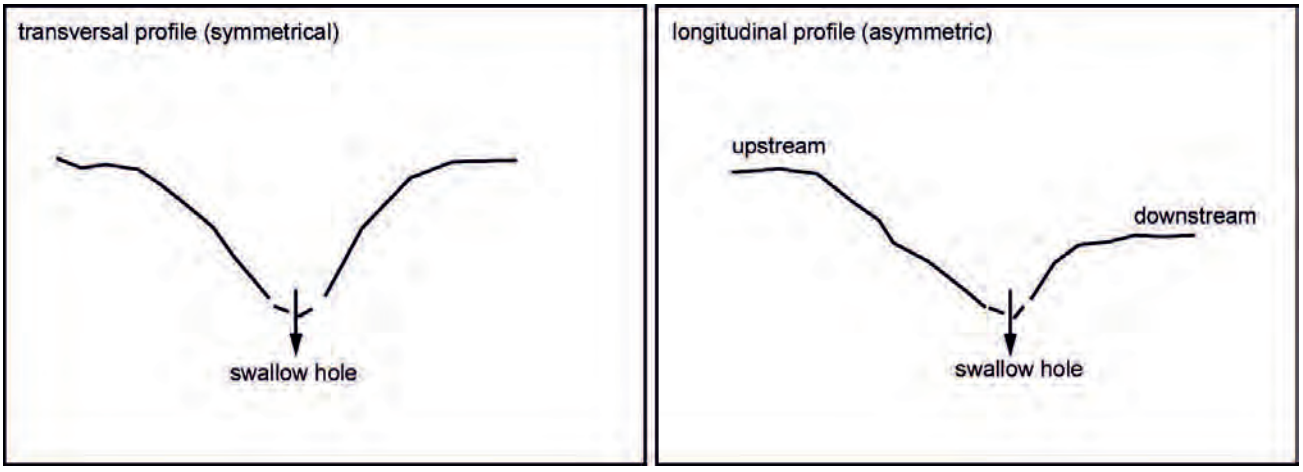

Fig. 4 - Transverse and longitudinal profiles of typical elliptical cavities.
- Profili trasversali e longitudinali di una cavità tipica di forma ellitticsa.

recognize a mature stage of development. This cavity has a cylindrical shape, a diameter of about 1 m and a depth of about 2 m.

The cavities with diameters between 20 and 50 m represent 21% of the cases, also are characterised by depth ranging between 5 and 20 m. In one case the depth observed on the field has been estimated being more than 20 m. This spectacular cavity is characterized by particularly steep lateral slopes which do not permit a safely access; the inflow water from upstream feeds a small lake formed at the base of the cavity. Along the downstream slope there are signs of instability processes probably due to erosion of the feet on the swallow hole.

Two cases are characterized by a diameter larger of 50 meters. They are located in the centre of large depressions visible even on the aerial photos (aerial photographs, flight of the year 2006) and on topographical maps of the Piedmont Region (CTR).

3.2. - Local geological setting

The study area, due to the inclination of geological strata arranged according to the steepness of the slope, has a very weak percentage of the geological units outcropping. These outcrop only along the roads cut and along the rivers and canals where surface water erosion exposes the terrains beneath the soil; within the sinkholes, where the processes of evolution of the cavity is very stringent (mature state of evolution), the collapse of the walls has revealed the Messinian gypsum banks which are alternated to the marl levels.

The gypsum banks have morphologies typical of karst and micro-karst. Gypsum levels within the cavities are often disjointed, fractured and weakened by the dissolution phenomena.

Moreover, depending on the type of gypsum crystalline form, the dissolution process produces different effects. In the case of selenitic gypsum, the action of dissolution tends to shatter the crystal structure of the rock. In the case of the microcrystalline gypsum, the dissolution generates a more continuous karst with the development, in a first phase, of an epi-karst morphology and then of well developed channels and sinkholes.

3.3. - Types of sinkholes recognized on the field

The classification of the forms observed on the field has not been completed yet because it was not always possible to trace with certainty the genetic process of each cavity. The classification proposed is rather a qualitative assessment made on the basis of the following elements:

- thickness of soil cover above the levels of gypsum;
- outcrop of the banks of gypsum outside and near the cavities;
- direct observation of the swallow hole or well-developed karst shapes;
- presence of concentric fractures along the edges of the cavity.

According to the field observations, the karst shapes were distinguished following the types of cavities described above. Those cases for which it was not possible to recognize the genetic process, a generic class was given. These are mainly the cases in which human activity almost completely obliterated the morphology of the cavities (for example, by backfilling).

In table 2 karst forms distribution is shown distinguished based on the genetic process to which they are linked.

Tab. 2 - *Distribution of inventory forms according to the classification adopted that distinguishes the genetic processes of a cavity.*
– Distribuzione delle forme censite in accordo con la classificazione utilizzata per la definizione dei processi genetici delle cavità.

Type	Nr	%
Dissolution	4	14
Collapse	10	36
Subsidence	12	43
Deep pipeline	0	0
ND	2	7

3.4. - Measurements on site

Where waters were observed within or near the cavity, their main physical and chemical parameters (electrical conductivity, temperature and pH) were measured.

In general, the measurements were realized on waters that flow into the cavity (surface water) and on the waters present within the cavity (underground water). For these two types of water circuits, the following values were measured (tab. 3):

Tab. 3 - *Values of physical and chemical parameters measured in the cavity or near them.*
– Valori dei parametri fisici e chimici misurati in sito.

	Surface water	Groundwater
Electrical conductivity (µS/cm)	830	2450
Water temperature (°C)	18:07	13:05
pH	8:06	8:09

3.5. - Final considerations

The most obvious result of this study, in fact, is the mapping and inventory of karst elements: this data is useful especially in view of efforts to ascertain the natural potential of the territory of Verduno and put them in a integrated system for the management of surface and underground waters.

Another important result obtained in this phase is the creation of a dynamic database that represents the operational tool available to address the next steps towards the definition of solutions to problems found on the field. In fact, by consulting the database it is possible to relate the development of a phenomenon of instability of the slope with the presence of karst formations, their conservation status and their role in the organization of runoff water.

In order to carry out works to manage water runoff, it will be useful to test their integration with the natural drainage forms in order to minimize the environmental impact, exploiting the natural ability of these forms in the disposal of water runoff.

Acknowledgments

The authors thank the Municipality of Verduno for the support during the field activities.

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