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Changes of the karst landscape and epikarst system in the area of the Tapolca karst terrains, North-West Balaton Highlands, Hungary

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Abstract

The caves in Hungary have been protected for a long time. The current national legislation on nature conservation states that all known and unknown caves are under ex lege protection but the karst areas above them are not. The territories above the caves can be owned by the state but also some of them belong to private owners, thus a great diversity of economic activities are conducted on them. Anthropogenic activities endanger both directly and indirectly the caves environment and the karst ground waters. The damages and pollution of caves take place through the epikarst systems which are in direct connection with the topographic ground surface. Therefore, it is of special significance to emphasize the natural processes taking place in epikarstic systems as well as to analyze the changes within epikarst terrains caused by human impacts. The effects of human impacts on epikarst system in the area of the Tapolca karst were analyzed both by field and laboratory methods. The historical evolution of land cover and land use was assessed related to the impact on the abiotic elements (soil and karstic cover-deposit, water) in Tapolca area. The intrinsic vulnerability was assessed using the semi-quantitative COP Method. The results show high resource vulnerability in all analyzed epikarstic sites.

Keywords: *karst system, land cover, intrinsic vulnerability, human impacts, epikarst, karst aquifer*

Schimbări în peisajul carstic și în sistemul epicarstului din zona carstică Tapolca, nord-vestul ținutului muntos Balaton, Ungaria

Rezumat. Protecția peșterilor are o lungă tradiție în Ungaria. Conform legislației naționale curente referitoare la conservarea naturii, toate peșterile din Ungaria sunt protejate de lege dar nu și terenurile carstice aflate deasupra lor. În cadrul teritoriilor carstice, deopotrivă aflate în proprietatea statului și în proprietate privată, au loc diferite activități economice care degradează și amenință direct și indirect calitatea mediului endocarstic și a depozitelor acvifere carstice. Degradarea și poluarea peșterilor are loc prin intermediul sistemului epicarstic, aflat în conexiune directă cu suprafața topografică. Din acest motiv este extrem de importantă cunoașterea proceselor naturale care au loc în sistemele epicarstice în relație cu schimbările cauzate de impactul antropic. Efectele impactului antropic asupra sistemului epicarstic Tapolca au fost analizate pe baza observațiilor de teren și a analizelor de laborator. Evoluția istorică a modului de acoperire a terenului a fost evaluată în relație cu impactul generat asupra mediului abiotic (sol și depozite carstice, apă) în zona Tapolca. Vulnerabilitatea intrinsecă a fost evaluată aplicând metoda semicantitativă COP. Rezultatele obținute arată că vulnerabilitatea resurselor carstice este extrem de ridicată în toate siturile epicarstice analizate.

Cuvinte-cheie: *sistem carstic, acoperirea terenurilor, vulnerabilitatea intrinsecă, impact antropic, epicarst, acvifer carstic.*

Introduction

Karst is a unique, non-renewable resource with significant biological, hydrological, mineralogical, scientific, cultural, recreational, and economic values (BC Ministry of Forests, 2003). On the other hand, karst terrains are very sensitive areas. Their sensitivity is attributed to the system of the three-dimensional effect area (Parise & Pascali, 2003; Ford & Williams, 2007; Parise, 2010). The human activities can produce intentionally or not severe impacts, often with irreparable damages in karst terrains. For example, land degradation caused by deforestation and overgrazing lead to soil erosion and destruction of the epikarst. Mining activities and limestone quarrying processes conduct to irreversible changes of landscape and karst features, and disturb karst groundwater resources. Whichever groundwater is vulnerable to human activity, because no groundwater is completely isolated from the above-ground environment. The degree of vulnerability depends on environmental and hydrogeological conditions, contaminant types and the time-scale of interest.

The distinctive hydrology and landforms of karst create a very special environment (Parise & Gunn, 2007) which distinguishes them from fissured and porous aquifers. Carbonate rocks that crop out and contain karst aquifers are extremely vulnerable to contamination (Ducci, 2007). Consequently, the transport of pollutants within karst aquifers may be

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extremely rapid and the attenuation is greatly limited (Marin, Andreo, & Mudarra, 2010).

The vulnerability assessment of inhabited karst terrains is extremely important for planning of a sustainable land use types, and also for sustainable use, protection and conservation of groundwater resources (Móga & Horváth, 2004; Keveiné-Bárány, 2005; Lóczy, 2006; Knáb et al., 2012; Móga et al., 2013).

The concept of the vulnerability of groundwater was created by Margat (1968) in the middle of the twentieth century and it is based on the assumption that the soil-rock-groundwater system may provide a degree of protection against contamination of groundwater by „self-purification" or „natural attenuation" (Zaporozec et al., 2002). Later, Albinet and Margat (1970), cited by Vrba & Zaporozec (1994), described aquifer vulnerability as being the possibility of percolation and diffusion of contaminants from the ground surface into natural water – table reservoirs, under natural conditions.

However, according to International Association of Hydrogeologists "vulnerability is an intrinsic property of a groundwater system that depends on the sensitivity of that system to human and/or natural impacts (Vrba & Zaporozec, 1994)". Thus, vulnerability is independent of whether or not contaminants are present and which focuses primarily on a description of natural environmental conditions is referred to as intrinsic vulnerability.

Vulnerability assessment consists in assembling of relevant information that characterizes groundwater vulnerability in order to produce a map that distinguishes areas of greater vulnerability from areas of lesser vulnerability. Over the last decades, numerous methods were developed for mapping intrinsic vulnerability of groundwater to contamination, and most of them use the advantages given by geographical information systems (Ducci, 2007). Review studies have discussed the vulnerability concepts and methods for porous and karst aquifers, published by Civita (1993), Vrba & Zaporozec (1994), Gogu & Dassargues (2000), Magiera (2000), Focazio (2002), Drew & Dunne (2004), Filippini et al. (2013), Foster et al. (2013), Iván & Mádl-Szőnyi (2017).

Due to the specific features of aquifers in carbonate rocks, methodologies have been created specially adapted for karst groundwater vulnerability assessments, which are quite different from those encountered in porous aquifers. As vulnerability maps are used as environmental management tools, it is essential to be able to estimate their reliability and ensure that the conceptual understanding of prevailing hydrogeological conditions is valid (Zwahlen, 2004; Vías et al., 2006; Polemio et al., 2009).

In European Union, concerns regarding management and vulnerability of aquifers in carbonate rocks have resulted in several programs, starting with COST 65 (Co-Operation in Science and Technology, 1995). Then, in 2003, the COST 620 task group, action "Vulnerability and Risk Mapping for the Protection of Carbonate- Karst- Aquifers", proposed the "European Approach" method. Subsequently, in the framework of the "European Approach" (Daly et al., 2002, Zwahlen, 2004), particular methods were especially designed for karst environment; some of them considering also the function of the epikarst and of the karst network (Doerfliger & Zwahlen, 1998). One of the karst-specific methods is the COP method. It was developed at the University of Malaga (Vías et al., 2002; Vías et al., 2006), and it is based on three factors that give the acronym of method: concentration of flow (C), overlying layers (O), and precipitation regime (P). Since COP method was proposed (Vías et al., 2002), it was applied and tested in different karst systems from Europe and other geographic regions (Vías et al., 2006; Ducci, 2007; Doummar et al., 2012; Andreo et al., 2006; Andreo Ravbar, & Vias, 2009; Marin, Andreo, & Mudarra, 2010; Bensaoula et al., 2016).

Due to geological and petrographic features of its territory, Hungary is relatively poor in caves compared with the surrounding countries (Dányi, 2011). This fact is one of the main reasons why all known and unknown caves are legally protected. Unfortunately, the law refers strictly to caves and does not take into consideration the karst terrains that are above the caves and where different human activities could have negative impact on epikarst and karst groundwater.

In Hungary, studies concerning human impacts on karst landscape and also on karst groundwater vulnerability were published by Keveiné-Bárány (1987), Mádlné Szőnyi (1997), Mádlné Szőnyi & Fule (1998), Bárány Keveiné et al. (2001), Mari (2003), Móga & Horváth (2004), Keveiné Bárány et al. (2007), Alföldi & Kapolyi (2007), Bárány Keveiné & Samu (2009), Mádlné Szőnyi (2009), Móga et al. (2010), Iván et al. (2011), Samu et al. (2012), Móga et al. (2013).

In this paper we present the results of investigations on changes in landscape karst system that has been induced by human activities in the last century within Tapolca town area. Abiotic and biotic ecological factors were investigated within area of epikarst system. In addition, the intrinsic vulnerability of groundwater Tapolca cave system was assessed and mapped using the COP method. A preliminary study regarding changes in the Tapolca karst landscape that have been induced by anthropic activities was published by Móga et al. (2013). In Hungary, the COP method was applied previously by

Székvölgyi et al. (2011 in the Bükk karst system, in North East Hungary.

Data and Methods

Study area

This study was conducted in the Tapolca karst system. It is a basin-like small region located between Keszthely Mountains and Balaton Highlands (Fig. 1 and 2) and covers an area of about 25 km^2. The Tapolca basin mainly consists of Sarmatian limestone, named Tinnye formation (Budai & Császár, 1999), and is surrounded by extinct alkaline basalt volcanoes truncated cone shape that were described as buttes (Gadányi, 2015).

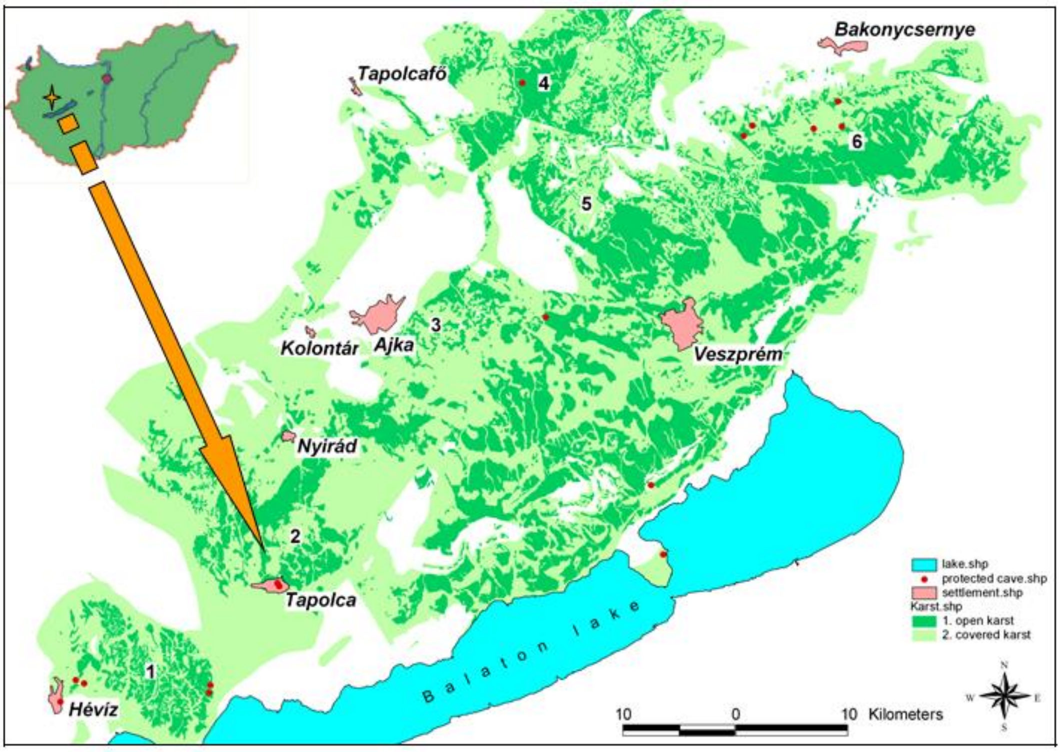

Fig. 1: Map of karst terrains in Hungary and location of the Tapolca study area

The largest residual cone Badacsony (438 m) rises on the southern margin of the Tapolca basin. The nearly horizontally Sarmatian limestone strata barely rise above the average surface of the Tapolca basin, which has altitudes ranging between 120-160 m above the sea level. These Sarmatian strata extend from north of Tapolca town to the Haláp basaltic cone. Overall, the shallow limestone beds do not stand out in a particularly way within the landscape. Therefore, the karst surfaces could be described as unspectacular. The common features that occur are shallow sink holes.

On the outcrops surfaces there are root karren. The small sized and shallow dolines, which are the diagnostic landforms, are present mostly at the contact with the dolomite and Sarmatian limestone zone (Futó, 2003) in a relatively high density (Fig. 8). Some of them are arranged in rows, but others have coalesced into uvalas. In porous limestone beds, the level of karst water is close to the topographic surface during the whole year.

If the water level is high, the karst water rises and feeds temporary the karst springs. Near the vicinity of Zalahaláp village there are several temporary lakes that were formed in those karst pits where an impermeable layer material overlies at their bottoms. The Main Dolomite Formation, which forms the underlying structure of the basin, rises above ground on the eastern part of the Tapolca karst basin and occurs as blocks that are slightly higher than the average surface area of the karst region. This area consists of karst cones that hide remnants of the upper Cretaceous peneplain. However, from geomorphological point of view, this part of the Tapolca karst area is the most diverse due to both paleokarst and recent karst landforms that occur. On its surface more or less conical features alternate with shallow dolines. Just like in other areas of the Bakony Mountains, trace amounts of bauxite occur in sink holes.

The Tapolca karst system is located in the center of the Tapolca Basin, at the foot of the southwestern extensions of the Bakony Mountains, in the northern side of the Lake Balaton, but outside of the Balaton Upland National Park's borders.

Under Tapolca town, just 10-15 m below the topographic surface, there is a cave system, from which a line of about 9 km long include the Lake

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Cave, Hospital Cave, and Berger Károly Cave (Fig. 2, 3, 4).

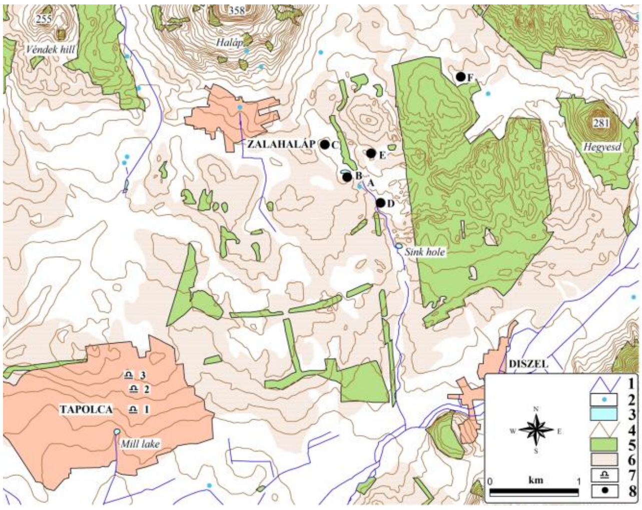

Fig. 2: Location of the Tapolca karst. Key: 1 – stream; 2 – spring; 3 - lake; 4 - contour lines (5m); 5 – forest; 6 - open karst; 7 - cave, 8 - sample areas. Sampled sites: A – Anonym spring; B – Lower Cser lake; C – Upper Cser lake; D – temporary stream; E – Anonym lake; F – Pokol (Hell) lake. Caves: 1. Lake cave, 2. Hospital cave, 3. Berger K. cave

They have hydrothermal origins (Futó, 2003). The labyrinth of passages running underneath the town was discovered in 1902, during the digging of a well. The passages are flooded with karst water, which can easily be contaminated by infiltrations that come from aboveground. The Lake Cave it was designated a protected area in 1942 and placed under strict protection since 1982. Many small collapses, sinkholes and shallow depressions, inside and outside of the town area, reveals that there is a larger and complicated cave system beneath the topographic surface.

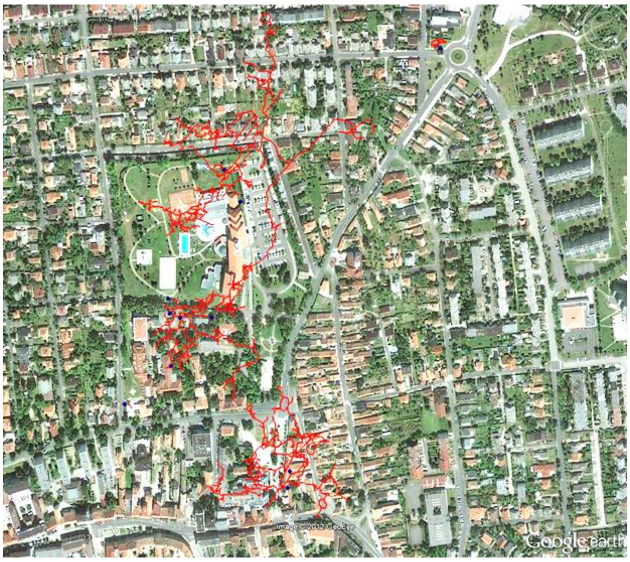

Fig. 3: Aerial view of Tapolca town showing the sketch of the Tapolca caves system (red line) that is developed beneath the town (http://www.termeszetvedelem.hu/_user/cave_images/4450-1_1355994454.jpg)

Most probably, such a collapse of the underground cave-system gave rise to the pit that is located right near to the Tapolca town hospital. Due to the flat surface of its bottom, the depression is used as a football field ever since it occurred. The karst water from the Tapolca caves system is thermal, with temperatures reaching 40°C. It is drained by the springs that emerge in the Mill Lake (Malom) (Fig. 4). In order to use the thermal water for curative reasons and wellness, a hotel was built above of the hollow that is connected to the cave system a few years ago.

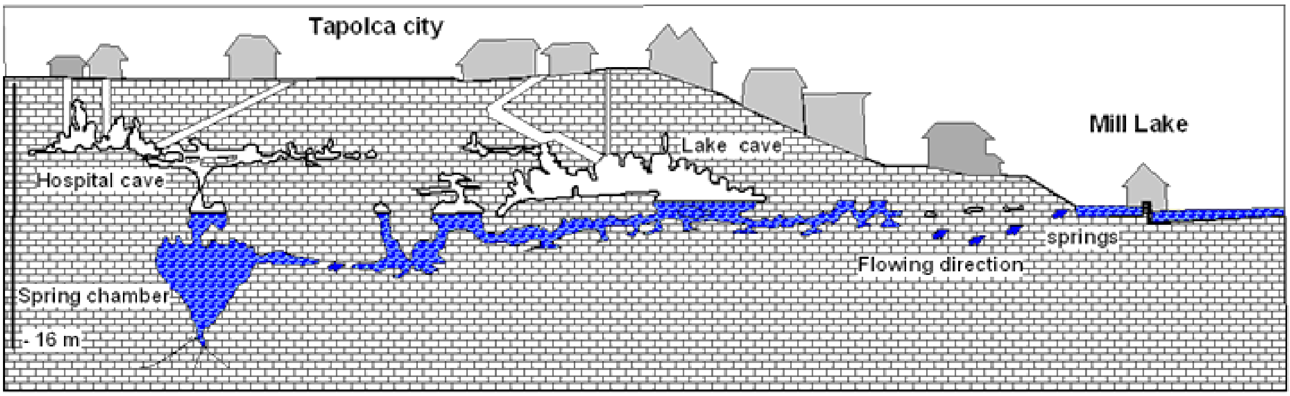

Fig. 4: Cross section through the karst system showing the development of the Lake Cave and Hospital Cave beneath Tapolca town, with chambers and galleries that are flooded by thermal waters flowing to the Mill Lake. Not drawn to scale (After Szabó, 2004)

The Tapolca karst area is one of the most vulnerable and impacted karst system from Hungary. The historical land use has undergone a significant change during the twentieth century. Limestone mining, both domestic and industrial, as well as bauxite mining, caused significant environmental damages: have changed natural landscape and produced particular antropogenic landforms, have altered and modified the natural vegetation, and disturbed the groundwater flows. Deep mining has produced surface collapses that changed the topographic surface. Even nowadays, regarding land use, in certain respects this is far from being environmentally friendly and sustainable. The human settlement that overlaps on Tapolca cave-system increases its vulnerability. Local authorities but also town `s people in general, hardly take into account the vulnerability of this special environment that is the karst system. These problems are connected with regulation flaws from recent decades, poor consideration of the privatization, and current spontaneous natural processes. Currently, the main source of pollution that threats the groundwater from the Tapolca cave systems are waste waters. Because of the reasons mentioned above, the Tapolca karst system deserves special attention and treatment.

Gathering data

The main goal was to assess the wide range of anthropogenic impact in the Tapolca karst area.

Firstly, our investigations were focused on the landscape changes caused by land use practices throughout the centuries. Thus, the karst landscape changes and alternations in coverage on multi-time planes were examined by integrated field surveys and GIS methods (Mari, 2003; Knáb et al., 2012; Móga et al., 2010). Topographic maps based on successive surveys (1774, 1856), EOTR (Unified National Map System 1985) 1: 100 000, and, SPOT IV images (2006) were used for mapping patches of different land uses in each year. The nomenclature of the Corine Land Cover Classes was used (http://land.copernicus.eu/pan-european/corine-land-cover).

Using the abundances of land uses, the relative frequencies of the different categories of each type of landscape element in each year were calculated and the proportion of each type of landscape element was graphed for the different years.

Secondly, the traceable changes that occur in the hydrosphere, biosphere, pedosphere, and epikarst system caused by anthropogenic processes were analyzed. The quality of surface waters was assessed using the biological assessment method and laboratory chemical tests. The water samples were taken from five sites – four lakes and one spring (Fig. 2). Measurements were done and assessed following the official Hungarian standard methods MSZ 12749 (1993).

The vegetation cover and soil microbial communities were investigated as biotic factors that control the intensity of the karst corrosion processes. In the end, for assessing and mapping of intrinsic vulnerability of the Tapolca karst system, it was applied the semi-quantitative COP Method (Vías et al., 2006).

The intrinsic vulnerability reveals the karst sensitivity to human activities that is assessed by mapping its geological, geomorphological, hydrogeological, climatological, vegetation and land use conditions. Intrinsic vulnerability depends exclusively on the natural proprieties of aquifer, which are linked to soil, lithology, hydraulic proprieties, recharge, and is independent of the nature of the contaminant (Ducci, 2007).

The vulnerability of the karst system is assessed according to the semi-quantitative COP method as the product of three factors (Fig. 5): the O factor refers to the capacity of the overlying layers, namely soil and unsaturated zone, to attenuate the contaminant, the C factor (concentration of flow) expresses the effect of the different infiltration processes, while the P factor incorporates the role of precipitation conditions in the definition of vulnerability (Vías et al., 2006). Finally, the COP index is assessed multiplicatively and refers to resource vulnerability. The assessment scheme of the C, O and P factors, according to the COP method (Vías et al., 2006), is presented in Fig. 5.

Geomorphological mapping of the study area was made using topographical maps of the Hungarian Army, 1: 10 000 scale. Geological information was provided by the 1: 100 000 geological series maps, published by the Hungarian State Geological Institute.

Results and Discussion

Landscape changes over time

Changes in the landscape of the Tapolca karst terrain over decades were studied according to changes in the land uses and land cover.

Changes in topographic features

In the study area, the degradation of the relief surface is primarily related to mining activities. These activities caused directly and indirectly substantial changes in the karst landscape on the surface and below the surface as well. The limestone quarrying for building materials has been shaped the landscape for centuries. Practically, at the outskirts of every village there is at least one limestone quarry in active operation. Also, in many places there are small abandoned open mining pits.

These indicate that small quarries have satisfied local needs. However, geomorphic impact of quarrying is revealed by typical montanogenic landforms, *sensu* Erdösi (1987).

A particular activity that caused significant changes on the surface was military training.

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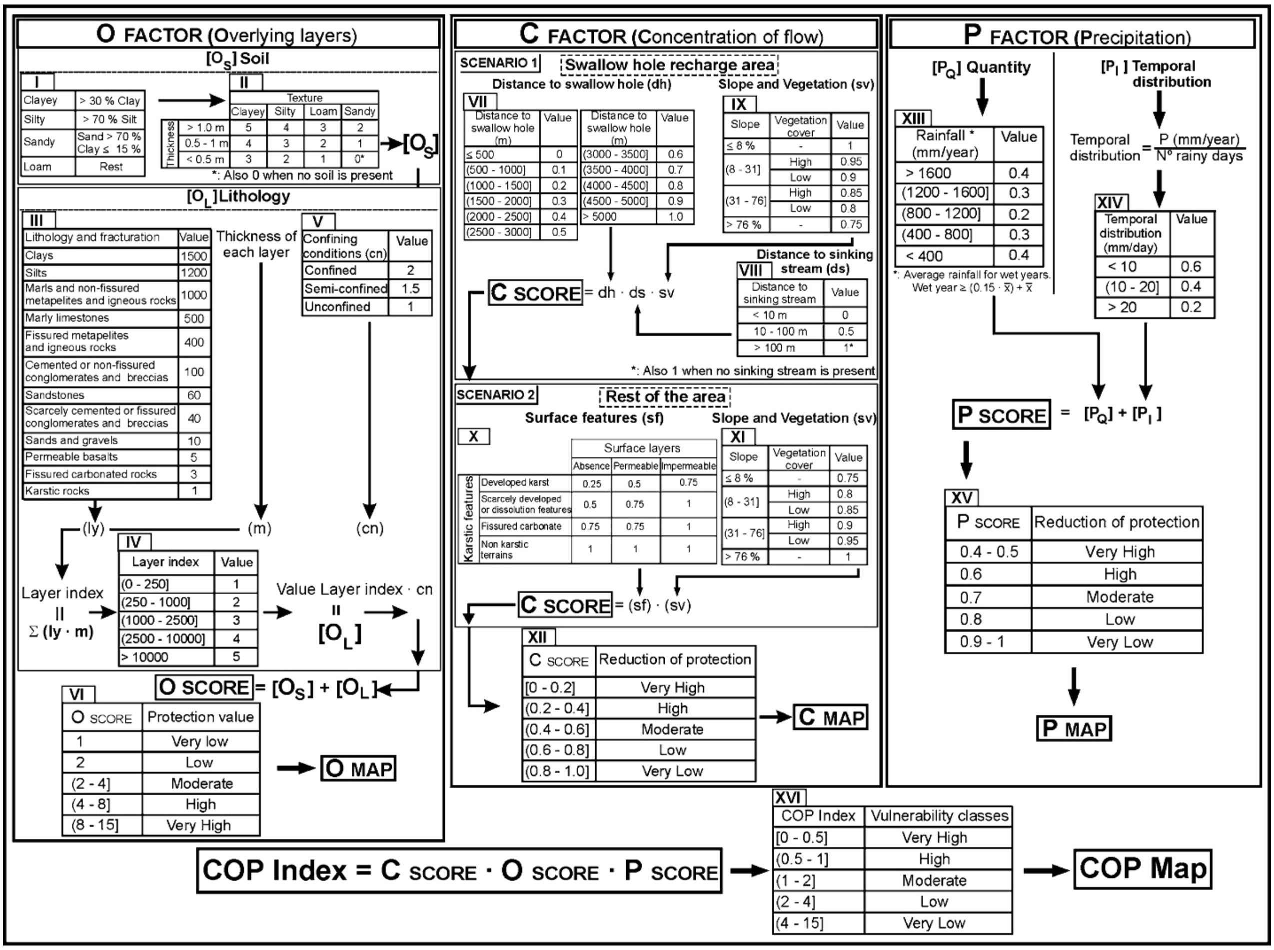

Fig. 5: The detailed assessment scheme of the COP method for intrinsic vulnerability mapping of karstic areas (University of Malaga, Vías et al., 2006)

In decades that followed the Second World War the area was used by Hungarian army for field training exercises of artillery and tanks.

Hundreds of meters of trenches and anti-tank positions that were made still exist (Fig. 6).

Fig. 6: The army "prints" on the abandoned training field is slowly invaded by spontaneous vegetation, but indubitably it will require a long time to be definitively removed from the landscape (Foto by Móga, 2010)

During the military training tasks, the wheel of the tanks drew an extensive network of dirt road. Pits developed from explosion of projectiles and tire tracks destroyed and removed the already thin patchy layer of soil that covers the limestone tablet. Overall, all these military trainings contributed to the increase of the open karst area surface. Even endokarst was used for military reasons. Thus, during the Cold War, in some rooms of the Hospital cave a nuclear bunker and military hospital were established.

Changes in land uses/land cover

Figure 7 shows the profile of the land uses and their cover proportion within the study area for each analyzed year. In the eighteen century the most abundant uses were the pastures. The proportion of arable land was small and natural forests covered around one third of the area. In next century, the surface area of arable land increased to the detriment of pastures. Land use has become more diverse in the next two centuries. These changes in land use lead to a more diverse landscape, but with effects in natural vegetation. In the study area, the natural vegetation related to the climate condition consists of pure oak forests, which are prevalent, mixed forest of oaks with hornbeam, and dry circum-pannonian grasslands (Fekete et al., 2014; Zólyomi, 1967).

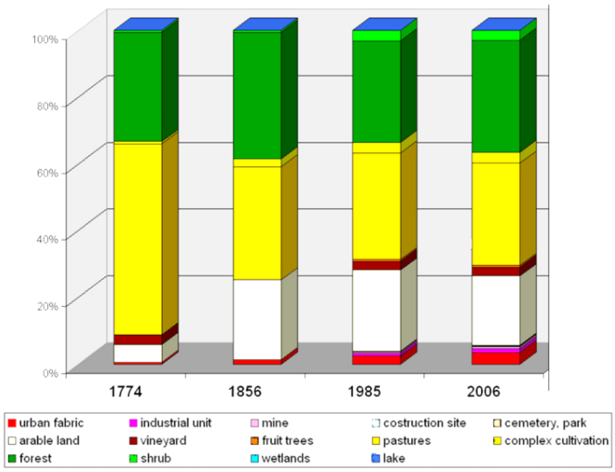

Fig. 7: Changes of the land cover in the study area between 1774 and 2006

Around the springs, temporary small running waters and lakes, there are typical wetland vegetation and marsh meadows that provide valuable wildlife habitats. Due to anthropogenic activities, the natural vegetation has been heavily transformed during the past centuries. The surface area of natural forests has been decreased, and scrublands increased in the last two centuries due to both deforestation and to the continuous abandonment of the traditional agricultural and livestock farming activities on grasslands (fig. 8).

Fig. 8: Typical landscape in the Tapolca basin - dry grasslands and shrubs that grow in shallow dolines. In the background, the slope hills are vegetated by forest plantations and semi natural forests. The hills are volcanic cones (Foto by Móga, 2010)

However, in order to achieve an enhanced comparability, several categories of land cover maps should be combined for 1985 and 2006. The percentage values concealed many changes that occurred naturally since there was not even 1% difference between the forest cover in 1784 (32.7 %) and 2006 year (33.6%). While the forest area increased slightly, tree species composition has changed greatly between the two years. The proportion of the natural deciduous forests decreased significantly, and the planted forests have replaced them, in particular with those consisting of alien pine species (Móga et al., 2010).

In terms of appearance, the tree species composition and functions of the newly planted forests are certainly different of the natural ones and far from ideal. For example, the largest planted forest is located between Diszel and Zalahaláp villages and it is dominated by monospecific stands of alien black pine (*Pinus nigra*). The structure and species composition is changed by the occurrence of *Quercus* sp. and *Fagus* sp. in some areas of this forest. There should be mentioned that on the map of 1856, the vineyards and orchards were not clearly marked. For this reason, the area covered by forest is older than 1784. Alien aggressive invasive black locust trees are dominant along roads and canals in spontaneous woody shrubs. Bauxite mining deeply changed water shortage having as a consequence the degradation and threat of the habitats of rare plant species, especially the rare wetland orchid plant species. Due to agriculture practices, the water level regulation and peat extraction, the typical plant communities have been irredeemably destroyed and drying wet meadows, hayfields and drought-tolerant plant communities have taken over their place.

Changes in the karst's ground cover due to natural and anthropogenic effects

The Pannonian sandy deposits that overlay on the Sarmatian limestone were largely eroded by external forces (the wind and the water). As a result, the Sarmatian limestone bedrock, which slightly slopes from north to south, has outcrops or is close to the ground surface. Because patches of open karst alternate with covered karst, the Tapolca karst terrain has a mosaic like pattern.

Soil and sediments were sampled for analyses along a transect between Zalahaláp village and the Cser lake (Fig. 2). During the field surveys, we found that the non-karstic cover sediments - marine Pannonian sands, lacustrine gravels and sands - were poorly affected by soil development processes. Paleokarstic pits are filled with red clayey sediments. Open karst areas are completely unsuitable for agricultural purposes. We found only small patches of karst lithomorphic soils. Evolved clayey, sandy soils and leptosols with low fertility are on covered karst areas.

Military training activities from last century caused serious damages of the soil profile and grass cover in the karst region. Ironically, after the army has abandoned the place, it was discovered and conquered by off-road motorbike riders and all-terrain vehicle riders. Consequently, due to the lack of any regulation, the area is still a "battlefield", so there is little chance that the soil and vegetation to recover in the near future (Fig. 6).

Quality and quantity changes in surface waters and karst waters

The once abundant karst water resources of the Tapolca karst are nowadays heavily diminished due to the karst water leve0, the lowering was caused by the bauxite mining during the last century. The previous equilibrium state of the karst water system is damaged which caused drying up of some springs, streams and lakes, and other have become temporary water bodies.

For example, the water extraction related to the deep mining of bauxite from Nyirád led to the dry out of the Holy spring that is in the vicinity of the Véndek Mount (Fig. 2). The Holy spring arose at 165 m above sea level, which is one of the highest points of the Tapolca karst terrain. After the mining activities were closed, the water extraction has not ceased. The karst groundwater extraction continues due to continuous increase of the need for drinking water in the region. In conclusion, it is improbable that the karst water to entirely recharge the water table in order to be recovered at the former level. The Szentkút spring probably dried out forever.

Small running waters were also impacted. Due to the karst water depression caused by the bauxite mining in and around Nyirád village, the Viszló creek, that crosses the western part of Tapolca town, is practically dried out because its main source, the karst water, was disturbed. Tapolca town is crossed by the Tapolca creek that is the main drainer of the karst system in this area and flows into the Balaton Lake.

The water of the Tapolca Lake cave is drained by a karst spring that rises on the bottom of the Mill Lake. The connection between the Mill Lake and the lakes from the Tapolca cave is clearly proven. Apart from the water tracer tests that were used, there is a living creature which proves the hydrological connection between the underground lakes and the Mill Lake. It is the small species of freshwater fish common minnow (*Phoxinus phoxinus* L.) that lives in the underground lakes of the Tapolca cave that migrates between lakes (Fig. 7). The water of the Tapolca creek and the Mill Lake has been artificially heightened. This has been done with the aim of keeping the water at a constant level so that the visitors of the lake may go boating.

The Tapolca creek serves as a very important indicator of the changes that occur within the underground karst-hydrological system. After the extraction of water for mining purposes during the eighties of the last century, the first sign of impacts on karst water was the cooling and freezing of the Mill Lake water in the winter because the amount of thermal water from caves that flows in the lake has significantly decreased. But, the most conspicuous impact was the disappearance of the water from the Tapolca Lake Cave, which affected the tourism interests for the town. At one point, the authorities were forced to decide whether the thermal karst waters will continue to be used for mining and industrial activities, with negative consequences on the karst system, or tourism, recreation and nature conservation will prevail. However, even if the extraction of karst water has not ceased, because of the water supply needs of the settlements from the Balaton Lake shore, there are positive signs that the underground karst water system has begun to regenerate slowly. Thereby, today, the level of Tapolca Lake Cave has almost returned to its natural state.

The karst water of the Tapolca karst system is thermal with curative properties. Considering this natural source and its value for economic development of the town, the medium-term development plans of Topolca town include the construction of several tourism infrastructures that will use the thermal water for medical treatments, beauty and well-being. The implementation of this plan needs extreme caution in order to prevent the harmful effects on the karst system, considering that the establishment and operation of these kinds of infrastructures involve extraction and consumption of considerable amount of karst water. In the meantime, it has already been built and opened for use a thermal bath at a four stars' hotel which is the first great step of the implementation phase of the program.

The results of chemical analysis of all water samples collected in 2010 from the Tapolca karst are showed in table 1. The pH of the water samples was neutral or slightly alkaline. The conductivity and total hardness data suggests that the main source of the Anonym Lake, Hell Lake and Lower Cser Lake is mainly rainwater (Fig. 2).

The low values of constant hardness (less than 2, in each case) shows that the lakes are relatively clear. Inorganic anions from the samples (sulphate, chlorite and nitrate) are also low or below the limit of detection.

Regarding the occurrence of the nitrogen forms, the amount of ammonium ion exceeded 2 mg/l, which represent the lower limit of pollution.

This fact could be connected with the intensive grazing. The orthophosphate content of the Lower Cser Lake and the Pokol Lake was higher compared to previous determinations that were made in 2009 (Knáb et al., 2010).

Table 1: The result of chemical assessment of the epikarst and endokarst waters from the Tapolca karst system in 2010

Parameter	Name of the sampled sites					
	Anonym spring (A)	**Lower Cser Lake (B)**	**Upper Cser Lake (C)**	**Creek (D)**	**Anonym Lake (E)**	**Pokol Lake (F)**
pH	7.5	7.4	7.2	7.7	7.5	6.8
Conductivity (μS/m)	514	446.0	214.0	503.0	362.0	240.0
Hydrogen carbonate	154.9	135.1	59.1	152.0	112.6	67.6
Calcium (mg/l)	46.8	24.8	15.3	46.8	31.5	15.3
Magnesium (mg/l)	31.5	29.3	12.1	37.4	47.7	68.5
Chloride ion (mg/l)	0.7	1.1	1.1	0.4	0.0	0.7
Nitrate (mg/l)	5.80	0.96	1.0	4.33	0.02	0.64
Nitrite (mg/l)	0.01	0.04	0.08	0.02	0.02	0.14
Ammonium (mg/l)	0.295	2.365	2.941	0.472	0.855	1.253
Phosphate (mg/l)	0.004	4.349	0.124	0.005	0.006	0.547
Total-hardness (°dH)	8.13	6.8	2.8	8.67	11.07	15.87
Alkalinity (mg/L $CaCO_3$ equivalent)	7.11	6.20	2.71	6.98	5.17	3.1
Constant hardness (°dH)	1.03	0.6	0.09	1.69	5.90	12.77

The characteristic household nitrate and phosphate values are indicators of significant or excessive nutrient content of water and advanced eutrophication process of lakes, excepting the Anonym Lake. According to water quality standards from Hungary, the water from Anonym spring and the Creek, which drains the spring, the water belongs to good and excellent quality class.

Intrinsic vulnerability of groundwater resource from the Tapolca karst area

To consider and to treat the karst as a complex ecosystem, in order to protect the integrity of karst systems as well as individual karst features represents an important key element of karst research and karst management (BC Ministry of Forestry, 2003).

In the present study we examined the vulnerability of the semi-confined Tapolca karst that is outside of the area of the Balaton Upland National Park based on the semi-quantitative COP Method. Consequently, the study area has been strongly affected by human activities for very long time. Currently, besides of the limestone quarries and grazing, numerous waste disposal sites threat the karst water from Tapolca.

In the study area, the aquifer is formed mostly by Upper Triassic Great Dolomite Formation, which is covered with Miocene – Pliocene deposits (Budai & Császár, 1999; Futó, 2003). The thick dolomite has good transmissibility, water-yield capacity and water retention capacity. The Upper Miocene limestones, towards Tapolca town, are partially associated with the main karst water aquifer of the Transdanubian Central Range (Alföldi & Kapolyi, 2007). The limestone of the Upper Miocene Tinnye Formation is very important in recharge. The Upper Pannonian volcanism produced significant basalt beds that restrain the underground water flow (Budai & Császár, 1999).

In order to assess the vulnerability, the data for each factor were computed following the assessment scheme of COP method. The O factor represents the natural protective capability of the soil and lithological layers above the saturated zone. While percolating through the soil, contaminants may be subjected to mechanical, physicochemical and microbial processes leading to their degradation or dilution (Ravbar, 2007). The AGROTOPO spatial soil information system (scale 1:100000) was used as a base map to evaluate the O_S sub-factor (soil texture, structure, thickness) in the study area. These data were refined on the bases of field observations (Kiss, 2012) and of satellite images (e.g. the O_S values were corrected to 0 in the area of quarries). To determine the lithology sub-factor (O_L), data on confining conditions (cn), lithology and fracturing (ly), and thickness (m) of each stratum of the unsaturated zone is needed. These data were gained from geological maps, with and without quaternary deposits, and by compilation of available literature (Budai & Császár, 1999; Gondárné Sőregi & Gondár, 1988; Alföldi & Kapolyi, 2007; Selmeczi, 2003). The total thickness of the unsaturated zone was obtained by subtracting the estimated elevation of the groundwater table from the digital terrain model.

The C factor refers to the surface conditions that control water flowing towards the water table. The assessment scheme of the C factor distinguishes between the recharge areas of swallow holes and the rest of the catchment. Since within the study area the recharge through swallow holes or sinking streams is not typical, the guidelines of the second

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scenario were followed. In order to assess the C values, geomorphological features (sf: surface karst features, permeability of surface layers), slope inclination (s) and vegetation cover (v) were taken into account. The resulting O and C maps are represented in Fig. 9.

The P factor considers the ability of the precipitation to transport contaminants from the surface to the groundwater.

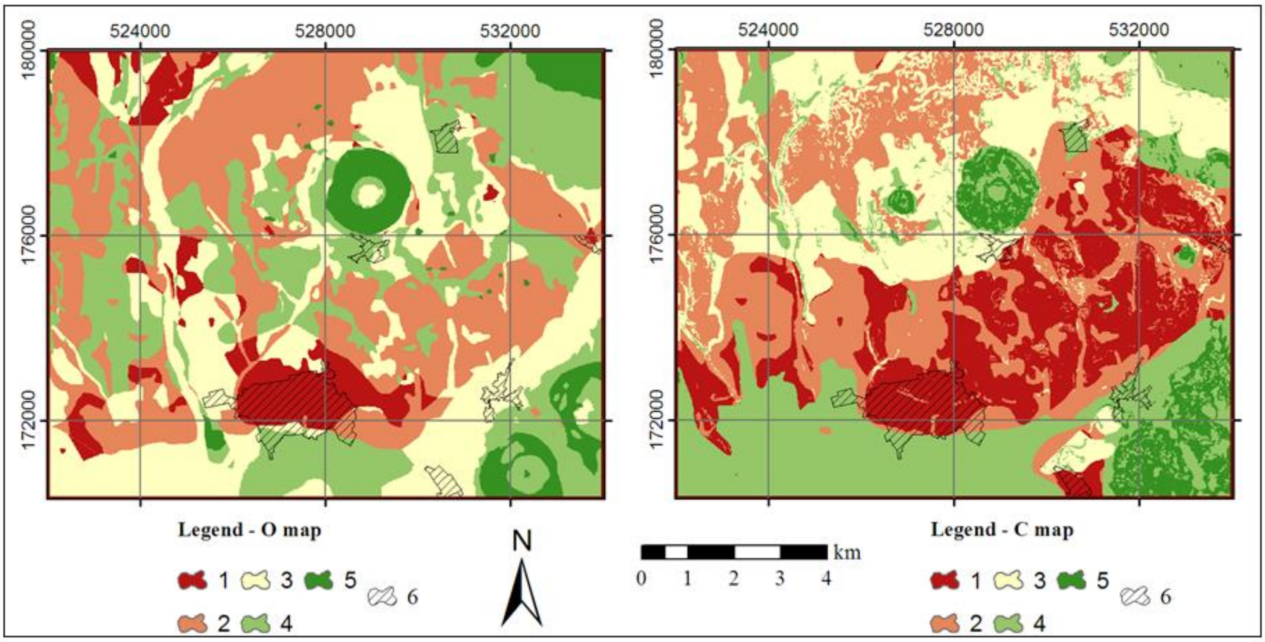

Fig. 9: The maps of O and C factors in the Tapolca karst area. O map: Protection value: 1- very low; 2-low; 3 medium; 4- high; 5- very high. 6 -settlement. C map: Reduction of protection: 1- very high; 2- high; 3- medium; 4- low; 5 - very low; 6 – settlement

Its assessment is based on the quantity (P_Q) and temporal distribution (P_T) of the precipitation. After processing and computing the recorded precipitation data at the local meteorological stations, the obtained P factor value was homogenously 9 for the entire area. This value means that the reduction of protection caused by the precipitation is very low. Lastly the C, O and P scores were multiplicated and the resulting COP scores were devided into five classes, where class 1 represents areas with extreme vulnerability, and class 5 shows the areas of very low vulnerability.

According to the resulting COP intrinsic resource vulnerability map (Fig. 10), the highest vulnerability in the Tapolca karst corresponds to sites where outcrops of the Tinnye limestone formation are located.

In those places where quaternary deposits are absent above the karstified limestone, and the slope gradient is low, the thin soil layer associated with sparse vegetation are unable to prevent the quick infiltration. It is important to note, that numerous illegal or inappropriate waste deposits occur exactly in the areas of extreme vulnerability.

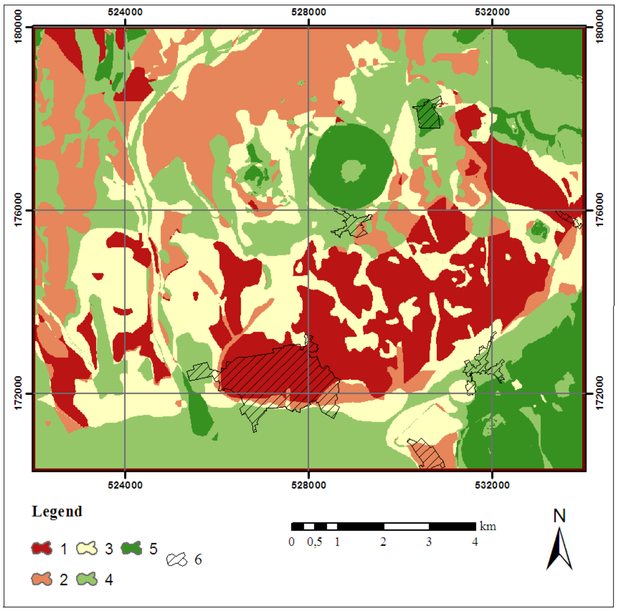

Fig. 10: Resource vulnerability map of the studied area. Vulnerability classes: 1- very high; 2- high; 3- medium; 4- low; 5- very low, 6 - settlements

The outcrops of the Great Dolomite formation that stretches to North -West of the Haláp Mountain are also categorized as highly vulnerable.

On the contrary, the basalt area of the Haláp and Csobánc mountains shows very low vulnerability, since in this area the karst water-table is at hundreds of meters below ground. It is important to note that the low vulnerability refers just to the karst aquifer. Along the border of limestone with basalts or the clayey Somlói Formation, springs are located 100-150 m higher than the karst water-table from Triassic limestone layers (Budai & Császár, 1999). Since these basalts are fissured, and there are open cast basalt mines, the water of these sources can easily became contaminated. On the vulnerability map, the open cast limestone mines are easily recognizable. These "scars on the landscape" appear on the vulnerability map as high vulnerability patches surrounded by areas where vulnerability is of 1-2 class lower.

Summary of factors that threat the Tapolca karst landscape and general conclusions

Based on the analysis of the land use, over half of study area is covered by agricultural land and forests. Most of the terrains are not suitable as arable land because of soils with low fertility. On the other hand, the pastoralism is a traditional activity in the area. Over decades, the pastures have been overgrazed by sheep flocks. As a consequence, pastures have poor quality. The intense trampling has caused significant soil erosion. The gross amounts of manure dropped by animals create an adverse aesthetic impact and source of nitrate pollution in groundwater.

To prevent degradation of shallow soils and to protect surface and groundwater quality it would be desirable to define the reasonable level of grazing on these sensitive areas. The biological, hydrological, physical, chemical and all anthropogenic processes related to the soil cover have a significant impact on the state of the Tapolca karst. The inappropriate use of the land, the inadequate agricultural practices combined with the uses of various chemicals has degraded soils profile and their buffering effects on pollution.

Traffic impacts are not negligible, also. Along the roads running through the karst region the technogen and transportation effects (*sensu* Erdösi, 1987) from traffic, should not be neglected, especially that recent studies have shown that chemical pollution from roads may adversely affect the aquatic environment (Maltby et al., 1995; Meland et al., 2010; Helmreich et al., 2010), even these kind of impacts span a much long time frame. Road runoff water contains a wide variety of chemical pollutants originating from vehicles (heavy metals - lead, copper, zinc, cadmium and oil), the road surface, technical infrastructure, maintenance such de-icing and vegetation control (Meland, 2010; Meland et al., 2010). It is expected that in the coming years, the road runoff water to be collected and treated in order to avoid its infiltration in karst system. This issue is more significant considering the current concerns of European Directors of Roads (2016) related to European Union Water Framework Directive (Directive/2000/60/EC). The spillage of anti-slippery substances, road salts, have negative effects, although for objectivity reasons it should be noted that in the Tapolca basin less harmful crushed basalt is used as roughening material against slipperiness instead of salts that are applied to lower the freezing point of road-ice or precipitation.

Industrial land use leads also to threats on the Tapolca karst. In previous years, soil pollutions events occurred several times because of the work done with hazardous materials. Thus, soil replacement was necessary at the Tapolca railway station due to the oil pollution in 2004. A land exchange was also needed at the local factory which produces building materials.

Waste disposal could become a serious problem. In 1988 it was set up a five-hectare landfill on the open karst area, in the north side of Tapolca town. From the very beginning, its establishment was a technical challenge due to local geological structure. Even the bottom of landfill was insulated with bentonite and clay, this huge waste dump where the wastes are collected which are produced by 22 settlements from the Tapolca karst area, it is a big environmental threat. Unfortunately, the establishment of the landfill has not eliminated the illegal dumping in the karst region. Furthermore, since the army gave up to its former training grounds, the illegal waste discharges have multiplied in the area of the Tapolca karst. All these potential hazards must be accounted and it would be practical to prevent such contaminations by means of effective control and anticipatory measures. With respect to all these risks, the vulnerability map is a useful tool that must be taken into account in the development of appropriate management practices for any human activities on karst terrains and for a sustainable natural resources management in the study area.

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Author contribution

The research of the epikarst has been carried out in teams, where the researchers participated according to their profession and skills. J. Móga fulfilled the geomorphological studies, M. Szabó and

D. Strat participated in the hydrological and ecological field investigations. The karst vulnerability researches were led by V. Iván, the microbiological and laboratory investigations were coordinated by A. Borsodi and K. Kiss, the specialist of the CORINE land cover researches was L. Mari. G. Csüllög participated in the editing of graphs and maps.

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