# KRASOSLOVJE V RAZVOJNIH IZZIVIH NA KRASU II
# **GRADNJA, TURIZEM, EKOLOGIJA, VAROVANJE**

# KARSTOLOGY AND DEVELOPMENT CHALLENGES ON KARST II
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PROMETNIC

# CONSTRUCTION OF TRANSPORT ROUTES

# 1

# NAČRTOVANJE, RAZISKAVE IN KRASOSLOVNA SPREMLJAVA GRADNJE AVTOCEST PREK SLOVENSKEGA KRASA

# PLANNING, RESEARCH AND KARSTOLOGICAL ACCOMPANYING THE CONSTRUCTION OF EXPRESSWAYS ACROSS SLOVENE KARST

V zadnjem desetletju in pol je gradnja sodobnih avtocest v Sloveniji eden večjih gradbenih projektov, s katerimi želimo povezati pomembne predele države in jih odpreti Evropi. Skoraj polovica Slovenije je kraške in več kot polovica vode, s katero se oskrbujemo, je iz kraških vodonosnikov. Slovenija je dežela klasičnega krasa, po katerem se imenuje ta svojevrstna pokrajina na karbonatnih kamninah v številnih jezikih sveta in kjer je zibelka krasoslovja. Občutljiva kraška pokrajina, ki je pomemben del naše naravne in kulturne dediščine, zahteva torej od nas dobro poznavanje in trud za njeno ohranjanje.

Odlično sodelovanje z načrtovalci in graditelji avtocest (DARS, DDC) ter s sodelavci novogoriških območnih enot Zavoda za varstvo kulturne dediščine Slovenije in Zavoda RS za varstvo narave nam krasoslovcem omogoča preučevanje in beleženje vrste zanimivih kraških pojavov, ki se razkrivajo pri gradnji. Obenem pa se temeljno krasoslovno znanje sveže prenaša v načrtovanje življenja v tej pokrajini.

Predstavljava naše večletne izkušnje, pridobljene pri preučevanju kraških pojavov ob gradnji cest, kjer sodelujemo pri načrtovanju in spremljanju gradnje. Povzemava tudi najnovejša krasoslovna spoznanja. Ugotovili smo, da je nekaterim, sicer znanim kraškim pojavom posvečeno premalo pozornosti. Osredotočili smo se na primere s klasičnega Krasa, dolenjskega nizkega krasa in krasa v brečah Vipavske doline.

Pokrajini Kras, ki se dviga nad skrajnim severovzhodnim delom Jadranskega morja in jo na jugovzhodu obroblja obširno flišno območje z nadmorsko višino prek 600 m, smo pri raziskavah posvetili posebno pozornost. Med 200 in 500 m visoka planota s površino 440 km² pripada v širšem smislu ozemlju Zunanjih Dinaridov. Z vidika teorije tektonike plošč leži na severnem deformiranem robu Jadranske plošče in je rezultat narivne tektonike. Tu zasledimo le kredne in paleogenske kamnine. Zanje je značilna izredna pestrost apnencev, ki so večinoma nastajali v relativno plitvih sedimentacijskih bazenih z bujno favno in floro. Na Krasu ni sledov površinskih tokov, s katerimi so v preteklosti razlagali razvoj planote. Sprva je bil obdan in prekrit s flišem ter zato poplavljen. Navpično prenikanje je bilo minimalno. Pozneje se je talna voda spustila več 100 m nižje v kras. Na

Over the last fifteen years the construction of modern expressways in Slovenia has been one of the major construction projects aimed at connecting important parts of the country and opening them to Europe. Almost half of Slovenia is karst and more than half of water for supply of the population comes from karst aquifers. Slovenia is home to the classical karst region of Kras that gave its name for this unique carbonate rock landscape to numerous world languages and is also the cradle of karstology. We need to better understand this fragile karst landscape and do everything to preserve it since it is an important part of our natural and cultural heritage.

Excellent cooperation with the planners and builders of expressways (DARS, DDC) and collaboration with the regional units Nova Gorica of the Institute for the Protection of Cultural Heritage of Slovenia and the Institute of the Republic of Slovenia for Nature Conservation have made it possible for the karstologists from the Karst Research Institute to study and record a number of interesting karst phenomena revealed during the construction. At the same time, fundamental karstological knowledge has brought a fresh approach to planning life in this sensitive region.

We present the long-term experience we have acquired in studying karst phenomena during the construction of expressways as we cooperated in the planning and monitoring of the construction and relate it to the latest karstological discoveries. We demonstrate that too little attention has been devoted to several known karst phenomena. We focused on examples from the classical Karst, the low karst of the Dolenjska region, and the karst in breccia of the Vipava valley.

Special attention is devoted to Kras, a karst plateau rising above the northeasternmost part of the Adriatic Sea that is bordered in the southeast by a vast flysch area with elevations exceeding 600 m. Lying between 200 and 500 m above sea level, the plateau covers 440 km² and in a broad sense belongs to the Outer Dinaric Alps. From the viewpoint of the theory of tectonic plates, the plateau lies at the northern deformed edge of the Adriatic plate and is the result of tectonic overlapping. Only Cretaceous and Paleogenic rocks are found here. They are characterized by exceptionally varied limestone that mostly formed in relatively stiku med karbonati in flišem pa površinski vodotoki ustvarjajo značilen in obsežen kontaktni kras. Danes vse kraške reke poniknejo na mestih, kjer pritečejo iz fliša na apnenčevo podlago. Podzemeljska voda odteka proti izvirom Timave v Italiji. Največji vodotok je reka Reka, ki ponikne v Škocjanskih jamah, 65 % vode pa razpršeno prenika s površja. Kras je z ekološkega stališča eden najbolj ranljivih naravnih sistemov v državi.

Nizki dolenjski kras je večinoma prekrit z različnimi naplavinami, pod katerimi se je oblikovalo svojevrstno kraško površje, še zlasti izraziti so kamniti gozdovi (*Knez* idr. 2003). Podtalna voda je pogosto plitko pod površjem, podolja so občasno celo poplavljena.

Kras se je razvil tudi v brečah, ki so nastale iz grušča na pobočjih Nanosa in ležijo na bolj ali manj neprepustnem flišu. Voda, ki se pretaka na stiku, je izdolbla največje jame na tem območju.

Krasoslovci že vrsto let sodelujemo pri načrtovanju in izgradnji avtocest na Krasu (*Kogovšek* 1993, 1995; *Knez* idr. 1994; *Knez* in *Šebela* 1994; *Šebela* in *Mihevc* 1995; *Slabe* 1996, 1997a, 1997b, 1998; *Mihevc* in *Zupan Hajna* 1996; *Mihevc* 1996, 1999; *Kogovšek* idr. 1997; *Mihevc* idr. 1998; *Šebela* idr. 1999; *Knez* idr. 2003, 2004a, 2004b; *Bosák* idr. 2000; *Knez* in *Slabe* 1999, 2000, 2001, 2002, 2004a, 2004b, 2005, 2006a, 2006b, 2007, 2009, 2010).

Pri izbiri trase avtocest in železniških prog načrtovalci upoštevajo najprej celovitost kraške pokrajine, zato se izogibajo pomembnejšim površinskim kraškim pojavom (vrtače, polja, udornice, kraške stene) in že znanim jamam. Posebno pozornost krasoslovci posvečamo vplivu gradnje in uporabe avtocest na kraške vode. Avtoceste naj bi bile zato neprepustne, vode s cestišča se namreč zberejo najprej v lovilcih olj in so nato prečiščene spuščene v kras.

Preučevali smo vplive prometnic na kraško vodo. Kogovškova (1993, 1995a) je ugotavljala sestavo onesnaženosti voda, ki se vsakodnevno stekajo z avtocest. V stoječih vodah, katerih manjše količine smo našli v jamah ob prometnicah, so bile tudi sledi mineralnih olj (*Knez* idr. 1994).

Ob gradnji avtocest pa opravljamo krasoslovni nadzor (1). Preučujemo na novo odkrite kraške pojave kot pomemben del naše naravne dediščine, svetujemo, kako jih ohraniti, če je zaradi gradbenih del to

shallow sedimentation basins with lush fauna and flora. On the Kras plateau there are no remains of the surface waters used in the past to explain the development of the plateau. Originally, the plateau was surrounded and covered with flysch and therefore flooded. Vertical percolation was minimal. The water table later dropped several hundred metres into the karst. At the contact between the carbonate rock and flysch, surface waters create characteristic and extensive contact karst. Today, all Kras rivers sink where they flow from flysch onto limestone bedrock and flow underground towards the springs of the Timava river in Italy. The largest stream is the river Reka which sinks in Škocjanske jame (Škocjan caves) while 65 % percent of the water sinks from the surface in a dispersed fashion. From the ecological standpoint, Kras has one of the most vulnerable natural systems in Slovenia.

The low karst of the Dolenjska region is mostly covered with a variety of alluvia under which a unique karst surface formed with stone forests as one of its most distinctive features (*Knez* et al. 2003). The water table is often just below the surface, and the valley systems are occasionally flooded.

Karst areas also developed in the breccias that formed from the scree on the slopes of Mount Nanos. They lie on more or less permeable flysch, and water flowing at the contact carved the largest caves in this area.

For a number of years, karstologists have been cooperating in the planning and construction of expressways in the Kras region (*Kogovšek* 1993, 1995; *Knez* et al. 1994; *Knez* and *Šebela* 1994; *Šebela* and *Mihevc* 1995; *Slabe* 1996, 1997a, 1997b, 1998; *Mihevc* and *Zupan Hajna* 1996; *Mihevc* 1996, 1999; *Kogovšek* et al. 1997; *Mihevc* et al. 1998; *Šebela* et al. 1999; *Knez* et al. 2003, 2004a, 2004b; *Bosák* et al. 2000; *Knez* and *Slabe* 1999, 2000, 2001, 2002, 2004a, 2004b, 2005, 2006a, 2006b, 2007, 2009, 2010).

In the selection of expressway and railway routes, the main consideration is the integrity of the karst landscape and therefore the routes chosen avoid the more important surface karst features (dolines, poljes, collapse dolines, karst walls) and already known caves. Special attention is devoted to the impact of the le mogoče, naša nova spoznanja pa so tudi v pomoč graditeljem. Pridobili smo vrsto novih izsledkov o oblikovanju in razvoju kraškega površja, epikrasa in prevotljenosti vodonosnika.

## 1.1 Raziskovanje kraškega površja in novih jam med gradnjo

Odstranitev prsti in rastja s kraškega površja in seveda večja zemeljska dela pri kopanju cestnih usekov in predorov so razkrili površinske, epikraške in podzemeljske kraške pojave. Naša naloga je te pojave preučiti kot del naravne dediščine, svetovati, kako jih ohraniti, in seveda seznanjati graditelje z novimi spoznanji, ki izsledke uporabljajo pri premoščanju gradbenih ovir.

Kraško površje členijo vrtače (2) in jame brez stropa (3). Vrtače so znak današnjega oblikovanja površja s padavinsko vodo, ki navpično prenika skozenj in nato po nezalitem delu vodonosnika pronica do podzemeljskih voda. Nekatere vrtače so bolj, druge manj izrazito zapolnjene s prstjo. Na njihovem dnu se odpirajo brezna in špranje, skozi katere odteka voda. Ob gradnji cest je treba prst odstraniti iz vrtač in dna utrditi s svodasto zloženimi skalami (4); ustja brezen so namreč pogosto manjša kot bližnje votline pod njimi. Vrtače nato zapolnijo s plastmi grušča (5). Podobnih oblik ali pa bolj podolgovate so jame brez stropa. To so stare jame, ki so spričo znižanja kraškega površja pogledale na dan, torej nimajo več zgornjih delov oboda. Tudi iz njih je treba odstraniti drobnozrnate zapolnitve, v tem primeru so to stare jamske naplavine, ter jame nato zapolniti s skalami in gruščem. Voda bi drugače naplavine sčasoma verjetno odnesla in na površju bi se lahko pojavil grez.

Epikras prepredajo špranje, ki so zlasti izrazite v krednem, manj pa v paleogenskem apnencu. Več se jih je odprlo na dnu in pobočjih vrtač. Večinoma so zapolnjene s prstjo in njihove stene razčlenjene s podtalnimi skalnimi oblikami. Zaradi znižanja kraškega površja je veliko brezen že tik pod tlemi.

Na 70 km trase avtocest, ki so bile zgrajene v zadnjih letih na Krasu, se je odprlo več kot 350 jam (6), ki jih glede na razvoj vodonosnika delimo na stare

**1** Raziskovanje jame, katere strop se je udrl zaradi miniranja med gradnjo avtoceste pri Divači.
Research of a cave whose ceiling collapsed because of blasting during the motorway construction near Divača.

**2** Zapolnjevanje vrtače, iz katere je bila najprej odstranjena naplavina z gruščem in ki danes leži pod avtocesto med Kozino in Divačo.
Filling up a doline from which sediment was removed with gravel and which now lies under the motorway between Kozina and Divača.

**3** Jama brez stropa pri Povirju, iz katere so bile odstranjene naplavine in siga.
A cave without ceiling near Povir from which sediments and flowstone were removed.

jame, skozi katere so se pretakali vodni tokovi, ko je bil kraški vodonosnik višje obdan in prekrit s flišem, in brezna, skozi katera se voda navpično pretaka s prepustnega kraškega površja do podzemeljskih voda (7). Najgloblje brezno je merilo 109 m. Stare jame so prazne ali pa zapolnjene z naplavino. Slednjih sta skoraj dve tretjini, ena tretjina jam pa je že brez stropa.

Jame se odpirajo pri odstranjevanju rastja in prsti s površja in še zlasti veliko se jih je odprlo pri kopanju cestnih usekov (8). Pri miniranju kamnine so se vdrli njihovi stropi, v brežinah pa so se ohranili prečni preseki rovov. Največ brezen se je odprlo na dnu vrtač, ko so iz njih odstranili prst in naplavine.

Vse jame smo preučili, narisali njihove načrte, jim opredelili obliko in skalni relief, zbrali smo vzorce naplavin za paleomagnetne in pelodne raziskave ter vzorce sig za mineraloške raziskave in določanje starosti. Na podlagi oblike jam in geoloških danosti smo predvideli njihova nadaljevanja, kar je še zlasti koristno za graditelje cest pri njihovem delu.

## 1.2 Raziskave, ki so spremljale gradnjo, so prinesle tudi nova spoznanja o razvoju krasa

Posebna in pogosta kraška oblika so jame brez stropa (3). Ta, danes tudi pomembna površinska kraška oblika, je že znan pojav, ki pa do zdaj ni bil celovito preučen. Posvečene mu je bilo premalo pozornosti, saj so domnevali, da je delež tovrstnih površinskih pojavov precej manjši. Število objav o jamah brez stropa je povezano tudi z gradnjo novih odsekov avtocest (*Knez* in *Šebela* 1994; *Šebela* in *Mihevc* 1995; *Slabe* 1996, 1997a, 1997b, 1998; *Mihevc* in *Zupan Hajna* 1996; *Mihevc* 1996; *Kogovšek* idr. 1997; *Mihevc* idr. 1998; *Šebela* idr. 1999; *Knez* in *Slabe* 2000, 2001, 2002, 2004a, 2004b, 2005, 2006a, 2007, 2010). Oblika jame brez stropa je posledica vrste in oblike jame ter razvoja kraškega vodonosnika in njegovega površja v različnih geoloških, geomorfoloških, podnebnih in hidroloških razmerah. Izrazitost površinske oblike jame brez stropa pa je narekovana s hitrostjo odnašanja naplavin iz jame v primerjavi z nižanjem okolnega površja. Na površini

construction and use of expressways on karst waters. Expressways should therefore be impermeable so that runoff water from the road is first gathered in oil collectors and then released clean onto the karst surface.

We studied the impact of traffic routes on karst waters. Kogovšek (1993, 1995) determined the contents of polluted water flowing daily from the expressways. Small quantities of stagnant water found in caves along the expressways contained traces of mineral oils (*Knez* et al. 1994).

During the construction of expressways we also perform karstological monitoring (1). We study newly revealed karst phenomena as an important part of our natural heritage and advise on how to preserve them if the construction work allows it. At the same time our new findings are of great help to the construction companies. We have acquired a number of new findings on the formation and development of the karst surface, epikarst and the perforation of the aquifer.

## 1.1 Exploring the karst surface and new caves during the expressway construction

The removal of soil and vegetation from the karst surface and of course major earthworks such as the excavation of cuts and tunnels reveal surface, epikarst and subsoil karst features. Our task is to study these features as part of the natural heritage, advise on how to preserve them, and of course share our new findings with the builders. These findings are used to overcome construction obstacles.

The karst surface is dissected by dolines (2) and unroofed caves (3). Dolines are a sign of the current shaping of the surface by precipitation water that percolates vertically through it and passes through the vadose part of the aquifer to the underground water. Some dolines are more distinctly filled with soil than others. There are shafts and fissures at their bottoms through which water flows. The soil must be removed from the dolines and their bottoms reinforced with rocks arranged in a vault-like pattern (4); the mouths of shafts are namely often smaller than the chambers beneath them. After that the dolines are filled with lay-

**4** Zapiranje špranjaste jame.
Closing up a fissured cave.

**5** Razkritje delane vrtače.
Disclosure of an artificial doline.

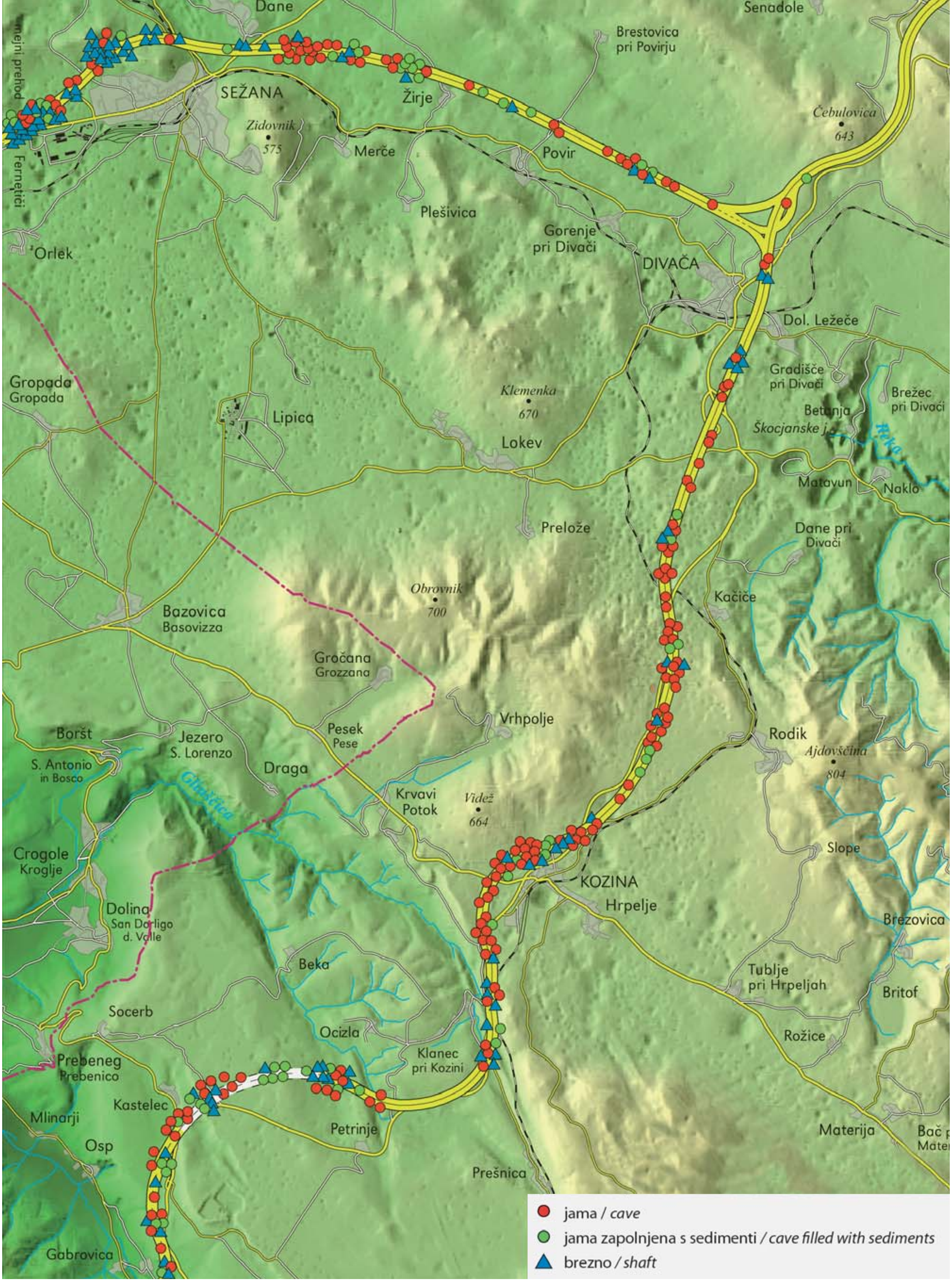
ers of rubble (5). Unroofed caves have a similar form or are more oblong. These are old caves that appear on the surface due to the lowering of the karst surface and no longer have the upper part of their circumference. The fine-grained fill, in this case old cave alluvia, must be removed and replaced with rocks and rubble. Otherwise, water could gradually carry the alluvia away and cause subsidence on the surface.

The epikarst is criss-crossed with fissures that are more distinctive in Cretaceous than in Paleogenic limestone, and many of them open at the bottoms and slopes of dolines. In most cases they are filled with soil and their walls are dissected with subsoil rock relief forms. Due to the lowering of the karst surface, many shafts are now located just below the surface.

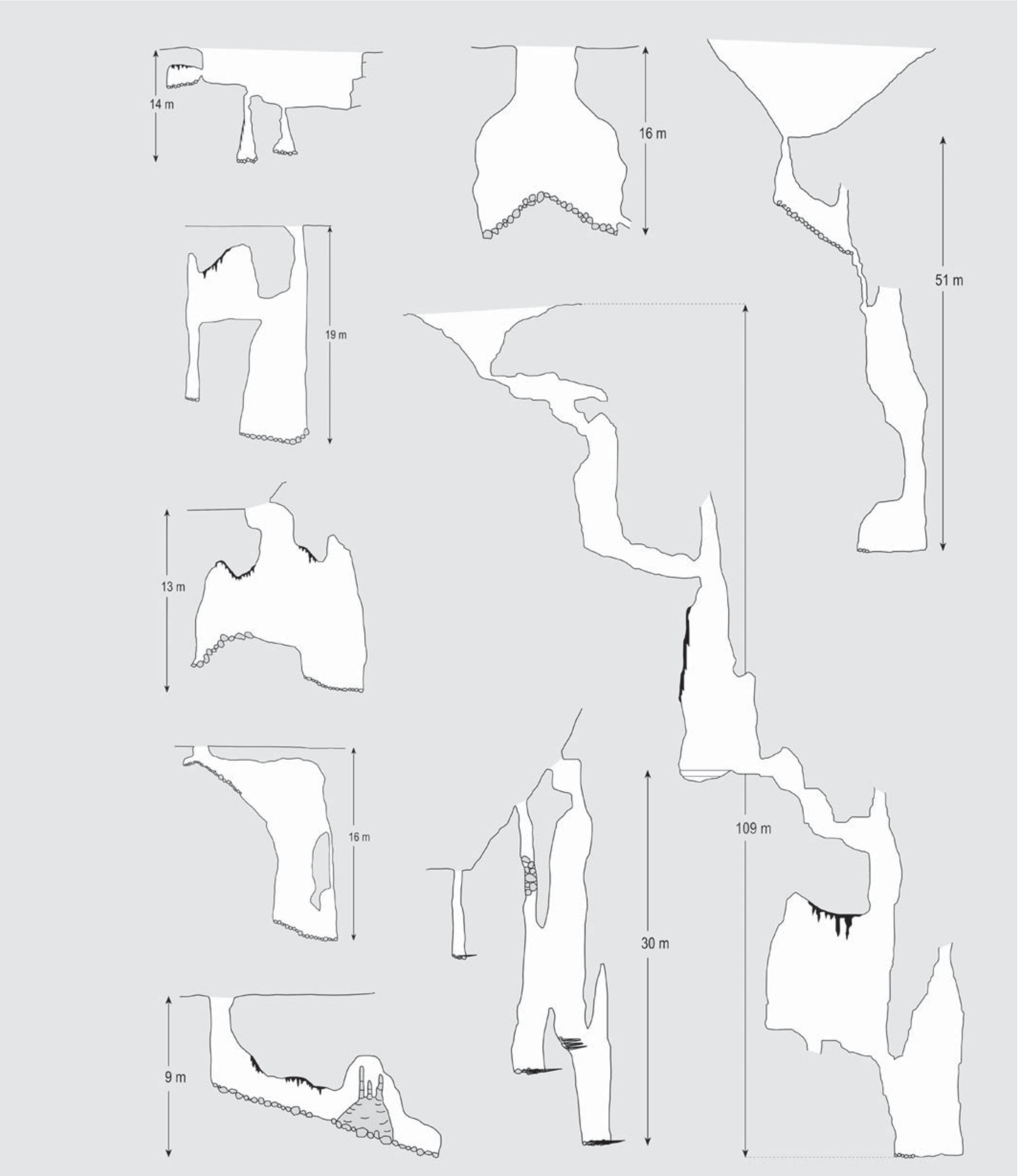
More than 350 caves were opened on the 70-km section of the expressway built in Kras in the last few years (6). Relative to the development of the aquifer, we distinguish between old caves through which watercourses flowed when the karst aquifer was surrounded and covered by flysch and shafts through which water vertically percolates from the permeable karst surface to the underground water (7). The deepest shaft found measured 109 m. Some old caves are empty, almost two thirds of them are filled with alluvia, and one third are unroofed caves.

Caves are opened when vegetation and soil is removed from the surface, and a large number of caves were opened during the excavation of cuts (8). Blasting caused their roofs to collapse, and cross-sections of passages were preserved in embankments. The most shafts were opened at the bottoms of dolines when the soil and alluvia were removed.

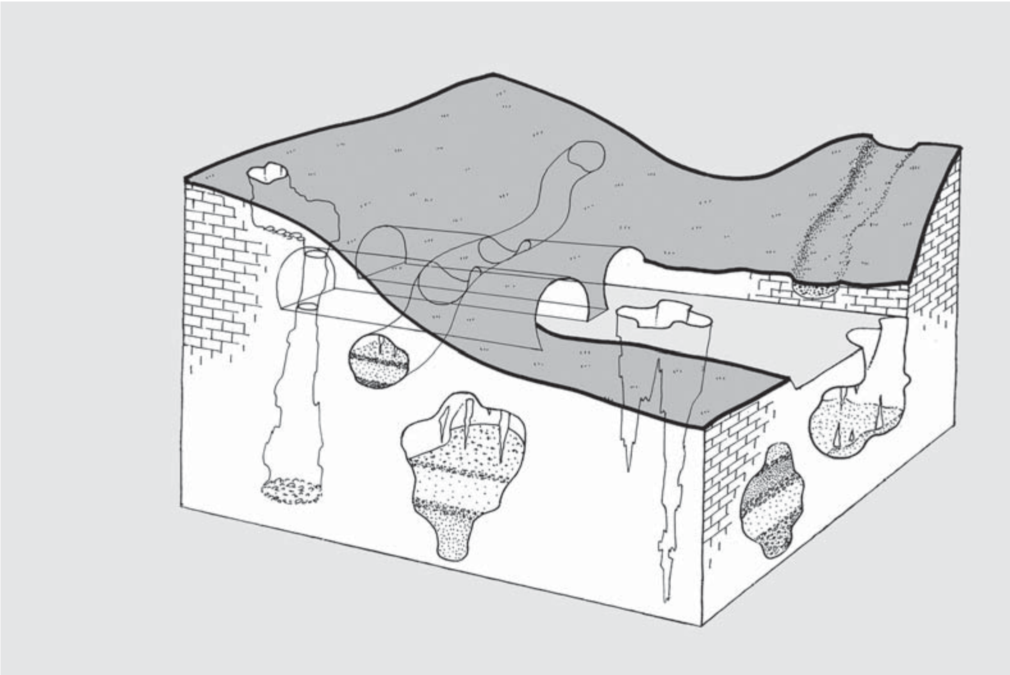
We studied all the caves, drew their plans, determined their shape, examined the rock relief, collected samples of alluvia for paleomagnetic and pollen analyses, and sampled flowstone for mineralogical analyses and age determination. We extrapolated the further extent of the caves on the basis of their shapes and the geological conditions, which is especially useful for road builders.




**6** Jame, ki so se odprle pri gradnji med Razdrtim, Fernetiči in Črnim Kalom.
Caves opened during the construction work between Razdrto, Fernetiči and Črni Kal.




**7** Različne jame, odprte med gradnjo avtoceste (*Knez* in *Slabe* 2005).
Different caves uncovered during the motorway construction (*Knez* and *Slabe* 2005).



**8** Med gradnjo so se odprle jame različnih oblik in velikosti, kar je narekovalo tudi nadaljnja gradbena dela.
During the construction caves of various shape and largeness were revealed dictating further earthworks.

razberemo prst in rastje ali pa pasove naplavine in sige, če je odnašanje počasno; ko pa je hitrejše, so jame brez stropa na kraškem površju podobne vrtačam, nizom vrtač ali pa so podolgovate zajede. Pogosto so splet različnih starih oblik, jam torej, in današnjega oblikovanja krasa z vrtačami in brezni. Skratka, so vse bolj prepoznaven pojav na kraškem površju, so pomemben del epikrasa in izjemna sled razvoja kraškega vodonosnika.

Velik delež jam je bil zapolnjen z naplavinami (9). Največkrat so to poplavne drobnozrnate flišne naplavine, vmes pa so tudi plasti proda. Vzorce naplavin smo vzeli za paleomagnetne raziskave. V jamah pri Kozini in Divači smo ugotavljali, da so iz starejše olduvai dobe. Zato sklepamo, da so bile zapolnjene po messinski krizi, torej pred približno 5,2 milijona let (*Bosák* idr. 2000). Z določanjem starosti naplavin razbiramo najstarejša obdobja zakrasevanja in ugotavljamo, da so najstarejše jame na krasu precej starejše, kakor so predvidevali krasoslovci pred nami.

## 1.2 Studies that accompanied the construction produced new findings on karst development

The unroofed cave is a special and frequent karst form (3). Today, this significant karst surface feature is a familiar phenomenon, but it had not been thoroughly studied before the construction of the expressway across Kras. Great attention has been devoted to unroofed caves since the occurrence of this phenomena turned out to be considerably higher than previously expected, and numerous articles on unroofed caves and the construction of new expressways are now available (*Knez* and *Šebela* 1994; *Šebela* and *Mihevc* 1995; *Slabe* 1996, 1997a, 1997b, 1998; *Mihevc* and *Zupan Hajna* 1996; *Mihevc* 1996; *Kogovšek* et al. 1997; *Mihevc* et al. 1998; *Šebela* et al. 1999; *Knez* and *Slabe* 2000, 2001, 2002, 2004a, 2004b, 2005, 2006a, 2007, 2010). The shape of an unroofed cave is the consequence of the type and shape of a cave and the development of the karst aquifer and its surface in various geological, geomorphological, climatic and hydrological conditions. The distinctiveness of the surface shape of an unroofed cave is dictated by the speed at which the alluvium was washed out of the

## 1.3 Posebno pozornost namenjamo načrtovanju cest

Pred gradnjo na terenu preverimo verodostojnost znanih podatkov o jamah ter jih dopolnimo z morebitnimi novimi meritvami in razlago njihovega razvoja. Zaradi boljšega razumevanja predstavimo dosedanje poznavanje prevotljenosti vodonosnika in izdelamo prognozne podpovršinske karte s posebnim poudarkom na pričakovanih litotektonskih spremembah kamnine. Pred začetkom del poskušamo kraško prevotljenost kar najbolj natančno predstaviti. Lego podzemnih jam lahko določimo z vrtanjem. Takrat poleg merskih kazalcev določimo tudi vrsto morebitnega polnila (siga, naplavina). Obliko, tip in pogostnost votlin v soseščini delno predvidimo s pomočjo védenja o znanih površinskih in podzemskih pojavih.

Gradnji avtocest na Krasu daje izrazit pečat njegova prevotljenost (10). Na našem krasu, ki ga poleg pestrega razvoja zaznamujeta tudi zelo živahna tektonika in litostratigrafska različnost, je odpiranje jame težko vnaprej določljiv pojav. Na stikih fliša z apnencem se jame pojavljajo praviloma pogosteje. Prevotljenost kraškega vodonosnika določamo torej predvsem na podlagi dobrega in celostnega poznavanja krasa ter temeljitega sprotnega dela pri načrtovanju in gradnji avtocest.

Zaradi povezanosti površinskih in podzemnih kraških pojavov pri načrtovanju cest s krasoslovnega vidika ovrednotimo tako kraško površje kot kraško podzemlje in hidrološke posebnosti ter ocenimo predstavljene različice. Povsod na Krasu, kjer gradijo ceste, naletimo na številne kraške pojave: vrtače, zapolnjene ali prazne votline ter dele starih in novodobnih drenažnih poti skozi kras. Številne jame pa je nižanje površja razgalilo in jih zato lahko prepoznamo že na samem površju Krasa. V zadnjem času je jamam brez stropa, 'odkritim' prav med gradnjo avtocest, posvečena posebna pozornost. Zavedamo se, da kvalitetna krasoslovna študija ozemlja, na katerem se načrtuje prometnica, omogoča dober izbor trase in je eno temeljnih izhodišč za načrtovanje gradnje v svojevrstni in lahko ranljivi kraški pokrajini.

S pomočjo objavljene literature, arhivov in različnih zbirk zberemo znanje o površinskih kraških pojavih, med katerimi še posebej izločimo vrtače, udore in

cave relative to the lowering of the surrounding surface. If the speed was low, we can often see soil and vegetation or areas of alluvium and flowstone on the surface; where it was faster, unroofed caves on the karst surface resemble dolines, a string of dolines, or oblong depressions. Frequently they are an interweaving of various old forms such as caves and recent shaping of the karst with dolines and shafts. In short, unroofed caves are an increasingly recognized feature of the karst surface, an important part of the epikarst, and an exceptional trace of the development of the karst aquifer.

A large proportion of the caves were filled with alluvia (9), in most cases fine-grained flysch alluvia with intervening layers of gravel. We took alluvia samples for paleomagnetic research from caves at Kozina and Divača and determined they originated in the Lower Olduvai period. We therefore concluded that the caves had been filled after the Messinian crisis approximately 5.2 million years ago (*Bosák* et al. 2000). Determining the age of the alluvia helps us understand the oldest periods of karstification and has proven that the oldest caves in Kras are much older than the earlier karstologists thought.

## 1.3 Special attention is paid to the planning of the road construction

Before the construction starts we verify the accuracy of known data about caves in the field and add possible new measurements and explanations of their development. To throw light on the situation we present existing data on perforation of the aquifer and elaborate prognosis subsurface maps with special emphasis on the anticipated lithological and tectonic changes in rock composition and structure. Before the start of construction work we try to present the perforation of the karst as accurately as possible. We can determine the position of underground caves by drilling, and along with measurement indicators we also determine the type of potential fill material (flowstone, alluvia). To a certain extent we can anticipate the shape, type and occurrence of caves in the vicinity using our knowledge of the known surface and underground features.

**9** V avtocestnem useku odkrita, s sedimenti v celoti zapolnjena jama.
A cave uncovered in the expressway cut and completely filled with sediments.

**10** Udor stropa jame med gradnjo useka pri počivališču pri Divači.
Collapse of a cave ceiling during the cut construction at the resting place near Divača.

druge morfološke oblike. Po terenskem ogledu določimo izhodišča za kartiranje območja izbrane trase. Na terenu s krasoslovnega vidika ovrednotimo različne kamnine. Na kartah tematsko predstavimo znane vhode v podzemske prostore in jih dopolnimo z morebitnimi novimi. Na podlagi površinskega kartiranja in razlage razvoja morfološko izraženih in v reliefu zaznavnih jam brez stropa predvidimo razvejanost podzemeljskih votlin. Če je potrebno, na osnovi površinskega kartiranja predvidimo tudi možnost odlagališč viškov materiala.

Iz izkušenj vemo, da v sleherni trasi, ki prečka Kras, med gradnjo naletimo na podzemne votline in dele jamskih sistemov. Obliko in tip votlin lahko delno predvidimo s pomočjo poznavanja površinskih in podzemskih pojavov. Jamam, ki jih zasledimo v širši okolici trase, določimo vrsto, njihov položaj in vlogo v vodonosniku, obliko, skalni relief, naplavine in sigo v njih ter jih predstavimo na ustreznih kartah. Zaradi boljšega razumevanja predstavimo dosedanje poznavanje prevotljenosti vodonosnika in izdelamo napoved s posebnim poudarkom na pričakovanih litotektonskih spremembah kamnine.

Kraške vode, ki poniknejo na obravnavanem območju, zaradi posebnih lastnosti karbonatne kamnine brez težav najdejo neposredne poti v podzemlje (kraški vodonosnik); 100 m debele kamnine lahko preidejo že v dobri uri. Kljub temu da so flišne kamnine, ki so na Krasu v stalnem neposrednem stiku s karbonati, pogosto predstavljene kot izključno neprepustni skladi, moramo poudariti, da je fliš (marsikje manjših debelin) le izolirana leča na prepustnih karbonatnih kamninah. Poleg tega je treba tudi vedeti, da se v flišnih kamninah prav tako oblikujejo, sicer manj številni, podzemni prevodni kanali in da na flišu zbrana padavinska voda odteka v kras. Zato opravimo terensko hidrogeološko kartiranje. V ta namen razmejimo in določimo osnovne značilnosti hidrogeoloških enot na širšem območju trase, popišemo hidrološke objekte (zajeti in nezajeti izviri, površinski tokovi, vodne jame, vrtine, merilne postaje in drugo) in določimo fizikalno-kemične lastnosti izvirov. Po potrebi izvedemo sledilna poskusa ob nizkih in visokih vodah predvsem za določitev smeri in hitrosti podzemnega toka na širšem območju trase. Z rezultati terenskega kartiranja in sledilnih poskusov izdelamo in nadgradimo obstoječe hidrogeološke

Perforation puts a special stamp on the construction of expressways in the Kras region (10). In addition to its varied development, Slovenian karst is marked by tectonic and lithostratigraphic diversity and it is therefore difficult to determine in advance where caves will occur. As a rule, caves occur more frequently along the contacts of flysch and limestone. The perforation of the karst aquifer is therefore determined primarily on the basis of good and comprehensive knowledge of the karst and continuous intensive work in planning and constructing the expressways.

When planning expressways, the link between surface and underground karst features requires the karstological evaluation of the karst surface as well as the karst underground, the hydrological situation, and the presented variables. On all the expressway construction sites in Kras we encountered numerous karst phenomena including dolines, filled and empty caves, and sections of old and current drainage systems through the karst. The lowering of the karst surface exposed many karst caves that are now visible in the Kras region. In recent years, we have focused on unroofed caves 'discovered' during the construction of expressways. We are certain that a quality karstological study of the area where a road is planned enables the better selection of the route and is one of the basic starting points for planning expressway construction in this unique and vulnerable landscape.

We begin by assembling published literature, archives, and various unpublished studies to learn about the surface karst features, and thus identify dolines, collapse dolines, and other morphological features in particular. Through a field survey we establish the starting points for mapping the areas of the selected route. In the field, we evaluate different types of rock from the karstological aspect. On theme maps we present the known entrances to underground caves and supplement them with potential new entrances. We anticipate the branching of underground cave systems on the basis of surface mapping and explanations of the development of morphologically identified unroofed caves visible in the relief. On the basis of surface mapping we also consider possibilities for dumping waste material if necessary.

karte, izdelamo zbirko podatkov o stanju okolja in opravimo oceno vpliva gradnje na kraške vode.

Temeljne smernice načrtovanja prometnic lahko kratko strnemo na naslednje:

- izbor trase temelji na podlagi celostne presoje krasa s poudarkom na lokalnih značilnostih;
- izbrani potek trase se tudi izogiba posameznim izjemnim kraškim pojavom;
- eden prednostnih ciljev načrtovanja je ohranjanje kraškega vodonosnika.

## 1.4 Ohraniti čim več kraških jam

Najlažje smo ohranjali brezna, pri katerih smo manjše vhode zaprli z betonskimi ploščami (11). Prav tako je bilo moč ohraniti stare jame, katerih obodi so bili trdni. Jame, ki so bile v pretrti kamnini in so se odprle zaradi miniranja, je bilo treba zasuti, tiste, ki so jih presekali useki in katerih vhodi so v njihovih brežinah, pa smo zaprli s skalnatimi zidovi (12). Njihovi obodi so namreč preveč pretrti in so zato neprimerne za nadaljnje obiskovanje. Iz jam, zapolnjenih z naplavinami, pa bi voda na cestišče lahko odnašala ilovico. Eno takšnih, sicer dobro ohranjeno, smo pustili odprto in je na ogled potnikom, ki prestopajo mejo z Italijo (13). Najbolj zanimive in dobro ohranjene jame pa smo v celoti zaščitili in so dostopne, čeprav so pod avtocesto ali se, kot v predoru Kastelec, vijejo okrog tunelske cevi. Do njih namreč vodijo betonske cevi, ki se ob cesti končajo z zaprtim jaškom (14), v predoru pa z vrati. Preučevali smo tudi posledice različnih miniranj v jamah, kar bo v pomoč pri nadaljnji gradnji in ohranjanju kraških pojavov.

## 1.5 Zaščita krasa med gradnjo avtocest in njihovo uporabo

Izkušnje s sledenji voda in nesrečnimi izlitji različnih snovi na kraškem površju so nas opozarjale na veliko prevotljenost kraškega vodonosnika. To so potrdila nova odkritja številnih votlin ob gradnji. Slabo prepustne so le posamezne, razmeroma majhne površine, bodisi dna vrtač, kamor je sprano ponavadi

We know from experience that during construction every route crossing Kras will sooner or later encounter underground caves or parts of cave systems. To a certain degree we can predict the shape and type of caves using our knowledge of surface and underground phenomena. We trace the caves in the wider area of the traffic route, determine their type, position, and role in the aquifer, their shape, rock relief, the alluvia and flowstone found in them, and present them on suitable maps. To make the maps easier to read, we present the previous data on the perforation of the aquifer and elaborate predictions with special emphasis on anticipated lithological and tectonic changes in the rock.

Due to the special characteristics of carbonate rock, karst rivers and stream that sink in the studied area easily find direct routes into the underground (karst aquifer); it only takes them an hour to percolate through 100-m thick rock beds. Although the flysch rock beds in Kras found in permanent direct contact with carbonate rock are often presented as exclusively impermeable beds, it must be emphasized that the flysch (often in thin beds) is only an isolated lens lying on permeable carbonate rock. Furthermore, it must also be observed that a smaller number of underground conductive channels do occur in flysch and that precipitation water collecting on flysch runs off onto carbonate rock. We therefore undertake hydrological mapping in the field. For this purpose we delineate and define the basic characteristics of hydrogeological units in the wider route area, identify hydrological objects (captured and uncaptured springs, surface streams, water caves, boreholes, measuring stations, etc.), and establish the physical and chemical properties of springs. When necessary, we perform tracing experiments during low and high waters, primarily to determine the direction and velocity of underground flows in the wider area of the traffic route. With the results of field mapping and tracking experiments, we elaborate and upgrade the existing hydrogeological maps, build a database on the state of the environment, and assess the impact of the construction on karst waters.

The basic guidelines for planning traffic routes include:

več zemlje – v vrtačah na paleogenskem apnencu Divaškega podolja so bili v deževnih obdobjih kali – bodisi še manjše površine ilovice, ki je zapolnjevala stare jame. Zato je potrebna skrajna previdnost tako pri gradnji cest kakor tudi pri njihovi uporabi. Vsakodnevna vožnja namreč pušča na cestišču številne okolju škodljive snovi (*Kogovšek* 1993), v stoječih vodah jam blizu prometnic pa smo odkrili mineralna olja (*Knez* idr. 1994). Avtoceste naj bi bile zaradi opisanih spoznanj in tudi naše vztrajnosti neprepustne. Ob cestišču so cevi (15) in žlebovi (16), ki vodijo do lovilcev odplak (17). Neprečiščena voda naj ne bi dosegla prepustnega kraškega površja. Tem željam pa je treba prilagoditi tudi tehnično izvedbo odvodnjavanja. Lovilci so pogosto premajhni in po izdatnem deževju voda lahko usedlino iz njih odplakne.

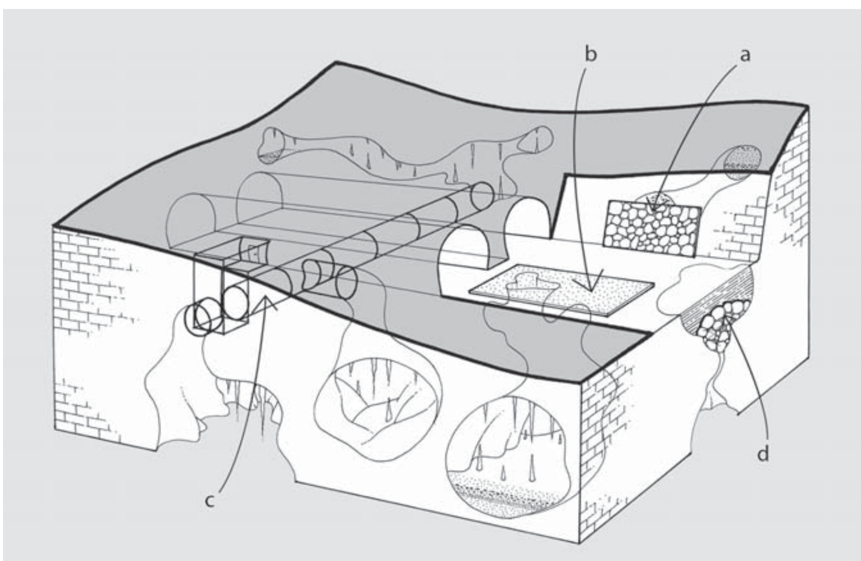
## Sklep

Ugotavljamo, da je sodelovanje krasoslovcev pri gradnji avtocest na Krasu koristno. Pomembno je, da se vključujemo tako v načrtovanje kot v izgradnjo avtocest, kasneje pa tudi spremljamo vplive, ki jih imajo avtoceste na okolje, torej v celostni proces poseganja v občutljivo kraško pokrajino. S smiselnim sodelovanjem ohranjamo naravno dediščino, poglabljamo temeljno znanje o nastanku in razvoju krasa ter o gradnji avtocest v tem svojevrstnem okolju. Poznamo več

- the selection of a route shall be based on a comprehensive assessment of the karst with emphasis on local features;
- the selected traffic route shall avoid specific exceptional karst features;
- the conservation of karst aquifers shall be one of the priority goals of the planning.

## 1.4 Preserving as many karst caves as possible

The shafts were easiest to preserve and concrete plates were used to close the smaller entrances (11). It was similarly possible to preserve old caves with solid circumferences but caves located in fractured rock or opened during blasting had to be filled. Rock walls were used to close caves crossed by road cuts with entrances on embankments (12). Their circumferences were fractured to such an extent that they were unsuitable for visiting, and water could wash clay from caves filled with alluvia and deposit it on the roads. One well preserved cave was left open for travellers crossing the border with Italy to visit (13). The most interesting and best preserved caves were completely secured and made accessible for visiting even though they were located under the expressway or even wound around a tunnel as with the Kastelec tunnel. They are accessible via concrete culverts closed at the roadside (14)




**11** Zapiranje in ohranjanje jam.
a – jame v brežinah usekov so skrite za skalnimi zidovi, b – jame v cestišču so prekrite z betonskimi ploščami, c – vhod v jamo, ki se vije okoli predorske cevi, d – ustja brezen in špranj so zaprta z obokano zloženimi skalami.
Closing and protecting the caves.
a – in road cuts the caves are hidden behind rocky scarps, b – the caves lying below the road are covered by concrete lids, c – entrance into the cave meandering around the tunnel, d – bottom of karst fissures and tops of shafts are often closed by arches of rocks.

**12** Zapiranje jame v brežini useka.
Closing a cave in the slope of the cut.

**13** Jama, ki je ostala odprta pred mejnim prehodom Fernetiči.
A cave which remained open in front of the Fernetiči border passing.

**14** Gradnja umetnega vhoda ob cestišču.
Building of an artificial entrance near the roadway.

**15** Priprava na polaganje cevi za odvodnjavanje s cestišča.
Preparing for laying draining pipes under the roadway.

**17** Gradnja lovilca olj.
Building of an oil collector.

različnih vrst krasa in vsaka od njih zahteva svojstven pristop, zato mora biti sodelovanje med graditelji in krasoslovci stalno in sprotno. V zadnjih desetih letih je sodelovanje med načrtovalci in graditelji avtocest ter krasoslovci obrodilo spoznanja, uporabna tudi pri načrtovanju in izvedbi drugih posegov v kras.

and in the tunnel with a door. We also studied the consequences of blasting in caves, which will help us in the road construction and preservation of karst features in future.

## 1.5 Protecting the karst during the expressway construction and use

Experience acquired tracing waters and accidental spillages of various substances on the karst surface drew attention to the great perforation of the karst aquifer, which the number of caves newly discovered during construction confirmed. Low permeability

**16** Žlebovi za odvodnjavanje na robu cestišča.
Gutters for drainage water at the edge of the roadway.

occurs only on individual relatively small patches such as the bottoms of dolines heavily covered with soil washed from their slopes—dolines on the Paleogene limestone of the Divača valley system used to be transformed into ponds during rainy periods—and smaller patches of clay that filled old caves. Maximum precaution must therefore be employed during both the construction and use of the roads. Daily traffic leaves numerous environmentally harmful substances on the road surface (*Kogovšek* 1993), and mineral oils were found in stagnant waters in caves located near traffic routes (*Knez* et al. 1994). Due to these findings and the persistence of karstologists, expressways are made to be impermeable. Pipes (15) and gutters (16) along the roads lead to wastewater collectors (17). Untreated water should never reach the permeable karst surface and the specifications for drainage systems must meet this requirement. The existing wastewater collectors are often too small and abundant precipitation can easily wash the sediments from them.

## Conclusion

It is clear that the cooperation of karstologists in the construction of expressways in the Kras region has brought positive results. It is important that karstologists participate in the planning and construction of expressways and later that they monitor the impact of the expressways on the environment, that is, throughout the entire process of encroachment on the vulnerable karst landscape. This logical cooperation helps preserve natural heritage and increase our basic knowledge about the creation and development of karst and about the construction of expressways in this unique environment. There are many types of karst and each one requires a unique approach which calls for permanent and continuous cooperation between road builders and karstologists. Over the last ten years, the cooperation between the planners and builders of expressways and karstologists has resulted in knowledge used in the planning and implementation of other encroachments in karst areas.

# 2

# KRAŠKI POJAVI, RAZKRITI MED GRADNJO AVTOCESTE NA MATIČNEM KRASU (ODSEK DIVAČA–FERNETIČI)

# KARST FEATURES DISCOVERED DURING THE MOTORWAY CONSTRUCTION ON THE CLASSICAL KARST (THE ROAD SECTION DIVAČA–FERNETIČI)

Pri razgaljanju kraškega površja in zemeljskih delih, ki so potrebna za izgradnjo ceste, so bili odkriti številni kraški pojavi. To so stare jame, ki so votle ali zapolnjene z naplavino, brezna, skozi katera prenika voda s površja v kraško notranjost, in različne vrtače. Na novo odkrite jame smo raziskali, izmerili in narisali njihove načrte. Pridobili smo nova spoznanja o kraškem površju, ki ga členijo tudi jame brez stropa in je sled celostnega razvoja kraškega vodonosnika.

Denuding of the karstic surface and construction works for new roads reveal numerous karst phenomena. These are old karst caves which are hollow or filled up with alluvium, shafts with waters percolating from the surface underground, and various dolines. The recently discovered caves have been researched, surveyed and their plans completed. We acquired new knowledge about the karst surface which is also dissected by roofless caves and is a trace of the complete development of the karst aquifer.

## 2.1 Kras med Divačo in Fernetiči

Trasa med Čebulovico in Divačo (1) poteka prečno po vzhodnem robu kraškega hrbta, ki se razteza od Štorij proti Čebulovici do vrtačastega ravnika zahodno od Škocjanskih jam, med Divačo in Danami pa po manj zakraselem Divaškem podolju (*Melik* 1960, 199).

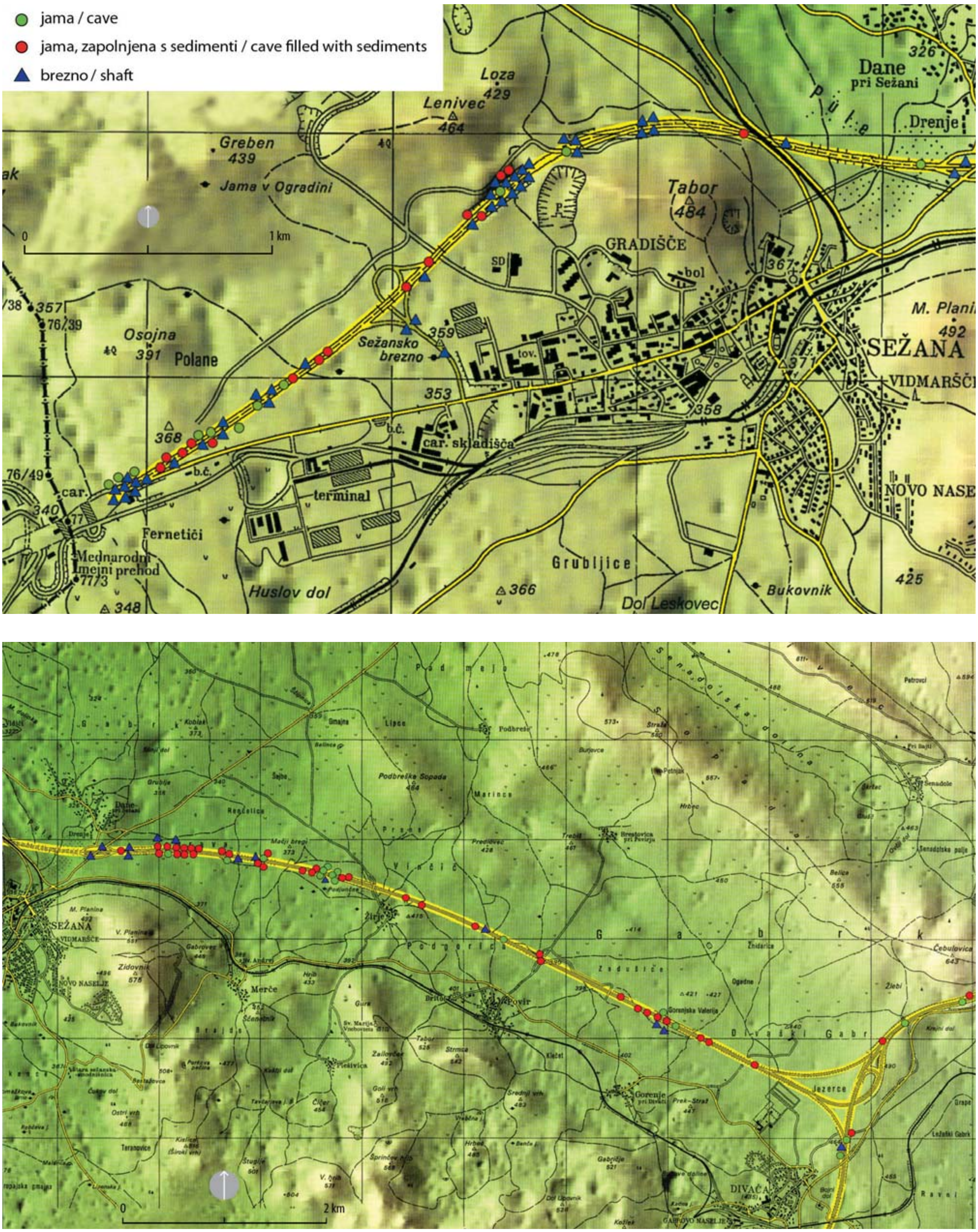
Krasoslovci so ugotavljali, da so na Krasu ohranjene sledi prvotnega površinskega odtoka vode proti severozahodu. Melik (1960, 201) je o tem sklepal po strmcih na današnjem površju, Radinja (1972, 13) pa po opuščenih dolinah in ostankih naplavin na kraškem površju. Apnenci naj bi bili, ko so se začele razkrivati karbonatne kamnine, namreč zaprti in podzemeljska voda zajezena, kar je ohranjalo površinske vodne tokove. Nekdanji površinski odtok z Brkinov čez Kras je oblikoval vzdolžno podolje od Divače proti Brestovici (*Habič* 1974, 8). Gams (1965a, 90) je pri preučevanju razvoja površja med Postojnskim in Cerkniškim poljem ugotovil, da so nekateri morfološki procesi pospešili kraško razčlenjevanje in nastanek dolinastih oblik, ki so jih vse prepogosto pojmovali za ostanke rečnih dolin. Reliefne značilnosti Divaškega podolja so tudi zgradbeno in litološko pogojene, saj so različni litostratigrafski elementi in glavni prelomi usmerjeni od jugovzhoda proti severozahodu (*Habič* 1974, 8).

Pri Divači se stikajo paleocenski apnenci brkinske sinklinale ob izrazitem dinarsko usmerjenem prelomu s spodnjekrednimi temnosivimi bituminoznimi dolomiti (*Habič* 1974, 4). Del cestne trase južno od Divače poteka po temnosivem skladovitem krednem apnencu, ki se menjuje z rudistnim apnencem. Med Divačo in Danami, torej ob divaškem prelomu, ki se

## 2.1 Karst between Divača and Fernetiči

The Čebulovica–Divača road section (1) runs transvers along the eastern edge of the karstic ridge which extends from Štorje towards Čebulovica as far as the doline-pitted plain west of Škocjanske jame (Škocjan caves); between Divača and Dane the road section runs along the less karstified Divaško podolje (Divača valley system) around Divača (*Melik* 1960, 199).

Karstologists have come to the conclusion that in the Kras, traces of the primary surface run off of water towards north-west are well preserved. Melik (1960, 201) made such conclusions on the basis of the slopes of the present surface, and Radinja (1972, 13) on the basis of the abandoned valleys and sediment remains on the karstic surface. In the past when carbonate rocks started to be denuded, the limestones must have been blocked and groundwater held behind the barriers, which preserved the surface streams. The former surface run off from the area of the Brkini hills across the Kras formed a longitudinal system of valleys between Divača and Brestovica (*Habič* 1974, 8). In his study of the surface development between the poljes of Postojna and Cerknica Gams (1965a, 90) came to the conslusion that some morphological processes accelerated karstic dissection and the formation of doline-like features which had been too often regarded as the remains of fluvial valleys. Relief characteristics of Divaško podolje are also dependent on the structure and lithology as various lithostratigraphic elements and the main faults are directed from southeast towards northwest (*Habič* 1974, 8).




**1** Jame, odkrite pri gradnji avtoceste med Čebulovico in Fernetiči.
Caves in the motorway between Čebulovica and Fernetiči.

odraža tudi v reliefu, teče trasa po paleocenskem, na manjših odsekih tudi krednem apnencu, in temnosivem krednem dolomitu. Tektonsko pretrto kamnino in številna prelomna zrcala z drsami, ki kažejo na premikanje blokov kamnine v različne smeri, so odkrila tudi zemeljska dela na trasi. V območju prelomov je apnenec zdrobljen v grušč in milonit.

Trasa med Danami in Fernetiči (1) predre kraški hrbet pri Sežani in nato poteka po ravniku do italijanske meje. Kras se je oblikoval v krednih apnencih, presekanih z manj izrazitimi prelomi, ki so bili najlepše razvidni pri kopanju predora. V kraški ravnik se zajedajo večinoma večje, lijakaste vrtače. Tudi na ostalem, večinoma poraslem površju je le malo zemlje. Površje prepredajo večje zajede, v katerih je ilovica. Ugotovili smo, da so to stare jame, ki so že brez stropa in zapolnjene z drobnozrnato naplavino.

Z litološkimi značilnostmi tega dela Krasa se ujemajo tudi sedanje hidrološke razmere. Današnji podzemeljski tokovi se pretakajo 200–300 m globoko pod površjem. Južno od Divače teče Reka od Škocjanskih jam vzporedno s traso, jo pri Divači preči in se nato nadaljuje pod Divaškim podoljem proti severozahodu k izvirom Timave. Padavinske vode jih dosegajo z navpičnim prenikanjem.

## 2.2 Vrtače

Vrtače na območju obravnavanih avtocestnih odsekov je Habič (1974, 6-7) po obliki razdelil na lijakaste, iz katerih je ilovica večinoma sprana, skledaste, kjer je na dnu večja ilovnata površina, in zasute plitve vrtače, v katerih je ilovica malo prepustna. V zasutih vrtačah se pogosto zadržuje voda. Pri Divači je 11, med Divačo in Sežano pa 5 vrtač na kilometer trase. Na južnem delu odseka avtoceste Čebulovica–Divača so v krednih apnencih velike lijakaste vrtače z le malo ilovice. Na apnencu Divaškega podolja prevladujejo skledaste in zasute vrtače. Slednje so manjše, s 30–50 m premera in 5–15 m globine. Največja globina vrtače, ki so jo dosegli z vrtanjem, je bila 27,5 m (*Habič* 1974, 5). V vrtačah prevladuje rdeča in rjava kraška ilovica, nastala s preperevanjem skalne podlage in sprana s pobočij vrtače na gruščnato podlago. V nekaterih vrtačah so tudi flišni pesek in prod ter rumenkasta in pasovita glina,

Near Divača the Palaeocene limestones of the Brkini syncline are in contact with Lower Cretaceous dark grey bituminous dolomites along a distinctive Dinaric-directed fault (*Habič* 1974, 4). One part of the road section south of Divača is directed along the dark grey bedded Cretaceous limestone alternating with the rudist limestone. Between Divača and Dane, that is along the Divača fault which is reflected also in the relief, there is a road section directed along the Palaeocene limestone (in smaller sections also along the Cretaceous limestone) and the dark grey Cretaceous dolomite. Construction works for the road section also revealed tectonically fissured rock and numerous fault mirrors indicating the movement of the rock blocks into different directions. In the fault area the limestone is crushed into rubble and mylonite.

The motorway between Dane and Fernetiči (1) cuts the karst ridge near Sežana and runs over the lowland towards the Italian border. Karst developed in Cretaceous limestones was intersected by smaller faults that were seen the best during the tunnel digging. The karst surface is dotted by larger, mostly funnel-like dolines. Other parts, although covered by vegetation, have a lack of soil. At the surface the longitudinal depressions are filled up by loam. We assessed that these were old caves already without roof and filled up with fine-grained sediments.

Characteristics of this part of the karst accord with the present hydrologic conditions. The present underground streams run at a depth of 200–300 m. South of Divača the river Reka, running from the sink at Škocjanskr jame, is directed parallely to the road section, crosses it near Divača and runs beneath Divaško podolje towards north-west and the sources of the Timava river. Precipitation waters reach the springs by vertical percolation.

## 2.2 Dolines

Due to their shape, dolines in the highway section were divided by Habič (1974, 6-7) into funnel-shaped dolines from which loam is mostly rainwashed, bowl-shaped dolines with an extensive loam surface at the bottom, and shallow infilled dolines with slightly permeable loam at the bottom. The filled up dolines often

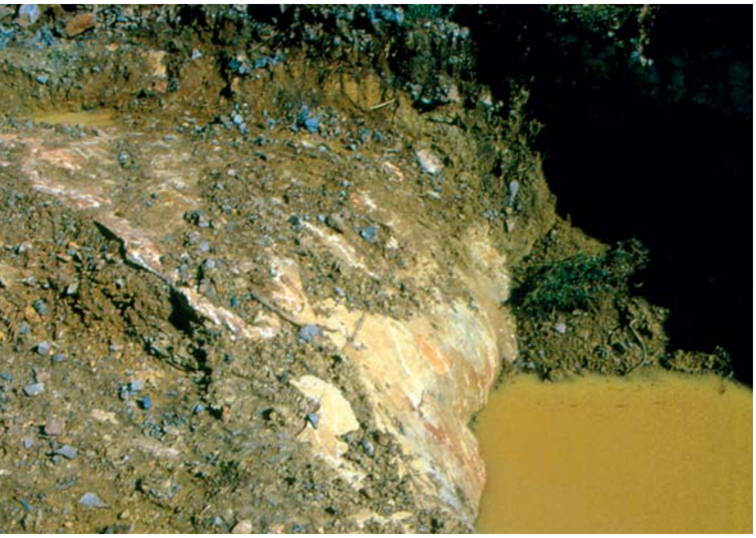
**2** Zapolnjevanje vrtače.
Filling up a doline.

ki je verjetno naplavina nekdanjih vodnih tokov (*Habič* 1974, 6). Habič (1987) je z vrtanjem preučeval delno odkopano vrtačo pri Sežani. V grbinasto dolomitno površje, prekrito s tanjšo plastjo zemlje, se zajedajo manjše in redko posejane zasute vrtače. Zgornja plast zapolnitve vrtač je rjava zemlja in 1,5 m pod površjem rdeča ilovica.

Pri gradnji avtoceste je bilo treba iz zasutih vrtač najprej odstraniti naplavine (2). Potrdila so se dognanja, pridobljena med predhodnimi raziskavami z vrtanjem v naplavine v vrtačah. Pogosto so bile v vrtačah tudi precejšne količine starejših, večinoma flišnih naplavin. V vrtači na odseku Divača–Dane je flišni prod segal skoraj do površja. Poudariti pa je treba, da je veliko zasutih vrtač sredi starih jam, ki so zapolnjene z naplavinami in že brez stropa. Pod rovi, skozi katere se je pretakal vodni tok in v zadnjih izrazitih razvojnih obdobjih odložil tudi flišno ilovico in pesek, v sušnejših obdobjih pa se je odlagala siga, so nastala brezna. Po njih prenika

contain water. Near Divača there are 11 dolines per kilometre of the road section, and between Divača and Sežana there are only 5. In the southern part of the Čebulovica–Divača motorway section there are in Cretaceous limestone large funnel-shaped dolines with only little loam. In the limestone of Divaško podolje bowl-shaped and filled up dolines prevail. The latter are small, 30–50 m in diameter and 5–15 m deep. The greatest depth of dolines, established by means of drilling, was 27.5 m (*Habič* 1974, 5). Red and brown karst loams prevail in the dolines formed by weathering of the rocky bedrock and rainwashed from the slopes onto the rubble base. Some dolines also contain flysch sand and gravel as well as yellowish and layered silt which is probably alluvium left behind by the former watercourses (*Habič* 1974, 6). By means of drillling Habič (1987) studied one partly excavated doline near Sežana. Small and rarely pitted filled up dolines etch into a hummocky dolomite surface which is covered by a thin layer of soil. The upper layer of the doline

**3** Kal z vodo.
A water pound.



**4** Siga in naplavine v brezstropi jami, v kateri je bil kal.
Flowstone in the unroofed cave where the water pond was.

voda proti podzemeljskim tokovom, ki so danes že globoko pod površjem. V flišnih naplavinah, ki jih je spirala površinska voda, so nastale lijakaste zajede, zapolnjene z rjavo in rdečo kraško ilovico ter gruščem.

Pri Povirju je bil na vzpetini, na temenu antiklinale, kal (3) z obzidanimi stenami in stalno vodo na dnu. Vzpetino je bilo treba presekati z vkopom, zato kala ni bilo moč ohraniti. Po odkopavanju kala se je potrdila predpostavka, da vodo na površju ohranja neprepustna ilovica, ki je bila odložena v starem rovu, katerega tla je prekrivala velika kopa sige (4).

Na dnu ali na robu vrtač v apnencu in dolomitu so se pogosto odprla brezna. V večjih, večžrelnih vrtačah (*Šušteršič* 1985, 94) je več brezen, kar se odraža tudi v njihovi obliki.

Pri Žirjah in Danah so bile z zemeljskimi deli presekane zasute, delane vrtače (*Gams* 1974, 177; 1991, 39). V prečnem prerezu izkopane vrtače je bilo jasno razvidno zasutje s skalami in kamenjem, ki so jih domačini nabrali pri čiščenju zemlje v vrtači in s kraškega površja v okolici. Kamenje in skale so zmetali v odkopano vrtačo in jo nato prekrili s prstjo. Tako so dobili več ravne obdelovalne zemlje.

Pri gradnji ceste sta bila iz vrtač najprej odstranjena ilovica in grušč. Dno, še zlasti če je bilo prevotljeno, pa je bilo utrjeno s skalami, ki jih je povezal beton. Vrtače so bile nato zasute s 30-cm plastmi kamnitega grušča, ki je bil sproti utrjen z vibracijskim valjarjem (2). Z izkopano zemljo, ilovico, so zapolnili več vrtač v bližini trase.

## 2.3 Jame v trasi

Razdelimo jih lahko na stare jame (5), ostanke nekdanjega podzemeljskega pretakanja vode, in brezna.

Novoodkriti rovi starih jam imajo 1,5–8 m velike prečne premere. Večina jih je zapolnjena z drobnozrnato naplavino, le posamezne manjše jame, ki praviloma ne presegajo 50 m$^3$ prostornine, so votle. V njih so pogosto kapniki, na dnu in na stenah pa kope sige. Stropi nad takšnimi jamami so tanki, merijo največ 1–2 m. Kot kažejo spleti rovov, njihova oblika in skalni obodi, so jame večinoma nastale zaradi počasnega pretakanja vode v zaliti coni.

fill consists of brown soil, and 1.5 m below the surface there is red loam.

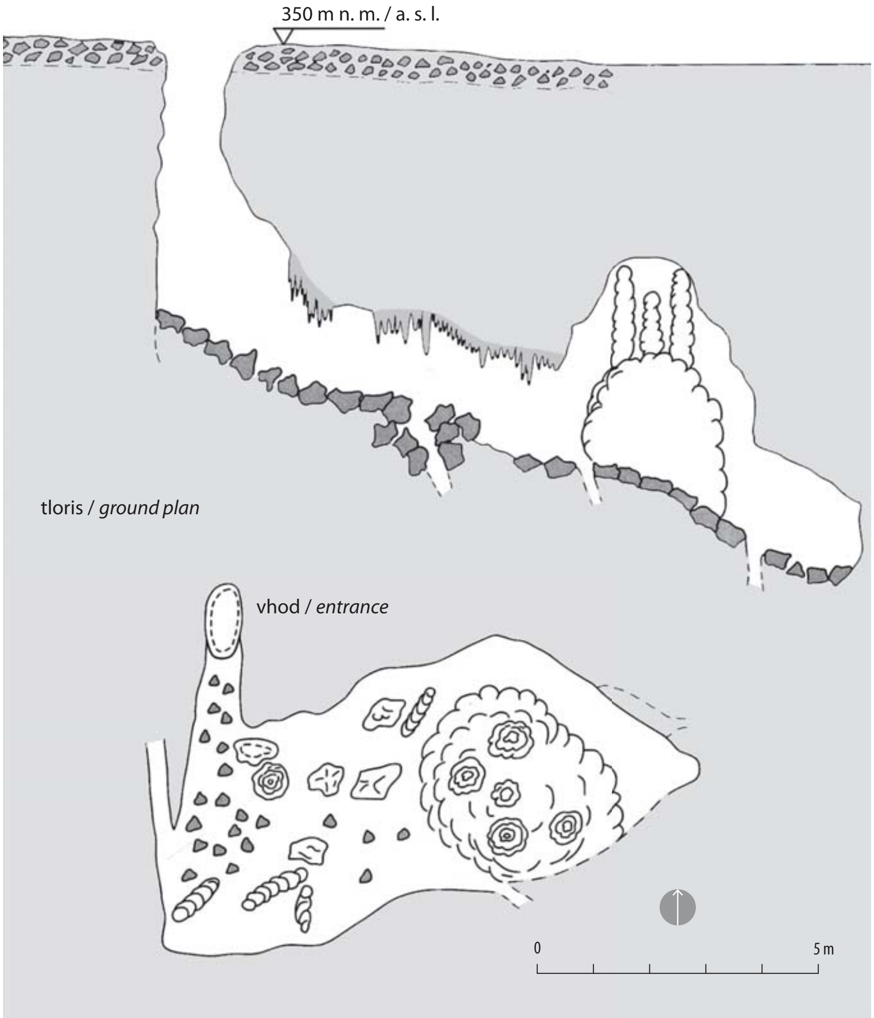
The motorway construction works demanded removing the alluvium from the filled up dolines (2). The results obtained during the previos research by means of drilling into the doline alluvium were thus confirmed. The dolines often consisted of a considerable amount of older, mostly flysch alluvium. A doline in the Divača–Dane section consisted of flysch gravel reaching almost up to the surface. It has to be pointed out that there are many filled up dolines within the old caves, which are filled with alluvium and already roofless. Shafts were formed beneath the channels once having been filled with water streams which in their youngest development stages also deposited flysch loam and sand while in dry periods flowstone was deposited there. Water percolates through them towards underground streams being nowadays already deep under the surface. In the flysch alluvium rainwashed by the surface water, there formed funnel-shaped indentations filled with brown and red karst loam and rubble.

Near Povir there was a sinkhole pond (3) with permanent water at the bottom which was surrounded by walls. The pond was located on an elevation, on top of the anticline. The elevation had to be cut through, so the pond could not be preserved. The digging works confirmed a supposition that surface water was held by impermeable loam which was deposited in an old channel, the floor of which was covered by a large mound of flowstone (4).

Shafts frequently opened up at the bottom or on the edge of the dolines in limestone and dolomite. Large dolines (*Šušteršič* 1985, 94) contain many shafts which was reflected also in their shape.

Near Žirje and Dane, the construction works cut through filled up artificial dolines (*Gams* 1974, 177; 1991, 39). The cross-section of an excavated doline gave clear evidence of filling up with rocks and stones which had been collected during the removing of soil in the doline and clearing of the surrounding karstic surface. The stones and rocks had been put into the excavated doline and covered by soil. In this way much more level cultivatable land was obtained.

During the road construction, loam and rubble were first removed from the dolines, and the bottom,




**5** Jama, katere strop se je udrl med utrjevanjem grušča na trasi.
A cave with the roof beeing collapsed during consolidation works on the road.

Veliko starih jam, zapolnjenih z drobnozrnato naplavino, je že brez stropa (6, 7). Rovi se zato kot plitve zajede vijejo po kraškem površju in jih je lahko razbrati že pred zemeljskimi deli. V usekih in predoru so takšni rovi dostopni v prečnem prerezu. Jame so zapolnjene s plastmi rumene ilovice in peska, ki so pogosto strjene, nad njimi pa sta večkrat rdeča ilovica in rjava zemlja. Naplavine prekrivajo kapnike in kope sige, redkeje pa je naplavina prevlečena s sigo. Razmeroma redke sledi hitrejših vodnih tokov so manjše fasete. Prodnih naplavin, ki so bile pogoste v starih jamah na trasah avtoceste v okolici Divače, pri Fernetičih nismo našli. Rove starih jam pogosto presekajo brezna in naplavina je zato lijakasto odnesena. Stare jame so presekane tudi z vrtačami. Manjša količina vode je vijugasto razčlenila

particularly when cavernous, was stabilized with rocks which were fastened by concrete. The dolines were later filled up with 30-cm layers of rocky rubble which was simultaneously consolidated by means of the vibration roller (2). Soil and loam which had been dug out from the dolines were used for filling up some dolines near the road laying out.

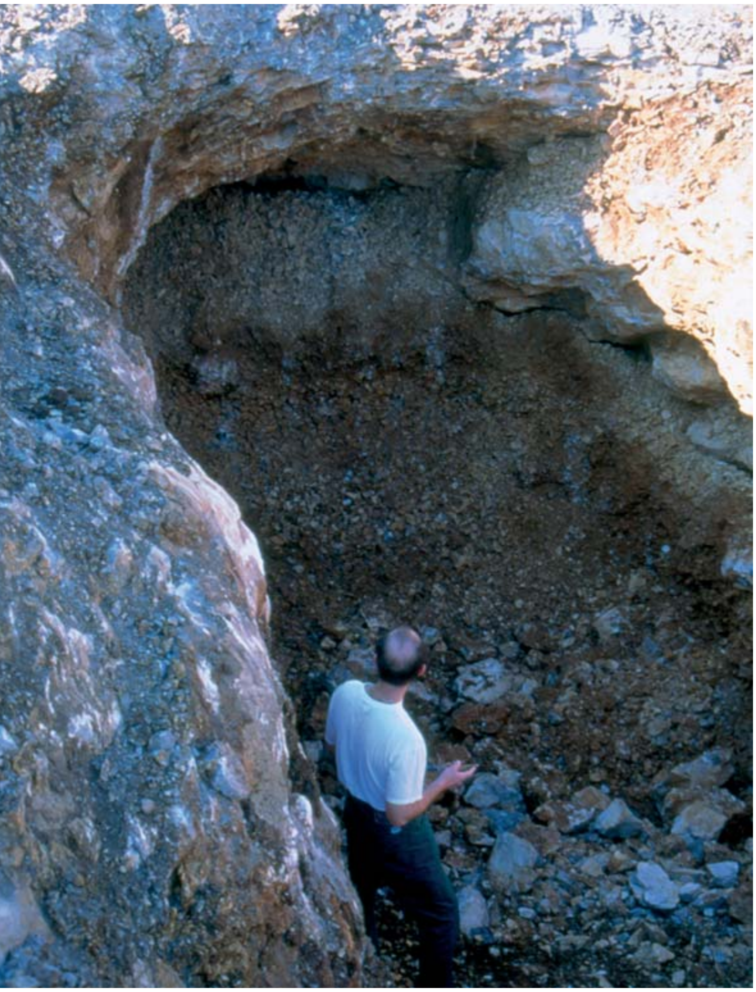
## 2.3 Caves in the motorway

The caves may be divided into old caves (5), remnants of former underground drainage, and shafts.

Cross-sections of newly discovered passages in old caves are 1.5–8 m in diameter. They are mostly filled up with fine-grained sediments, only smaller caves

**6** Ohranjene stene jame brez stropa.
Preserved walls of an unroofed cave.

**7** Raziskave jame brez stropa pri Povirju.
Research of an unroofed cave at Povir.



**8** Jama, zapolnjena z gruščem.
A cave that was filled with rubble.

dna nekaterih praviloma manj prostornih rovov. Flišne zaplate so na površju ponekod ostale dlje časa in iz njih se je voda stekala v apnenec.

Deli novoodkritih rovov so zapolnjeni z ostrorobatim gruščem (8). Grušč s premerom do 5 cm je posledica razpadanja kraškega površja v hladnih obdobjih pleistocena. Je večinoma v delih jam, iz katerih je bila zaradi velike navpične prevodnosti vodonosnika odnesena drobnozrnata naplavina, tanek strop pa je bil podrt tik pred zapolnitvijo z gruščem. V rovih se namreč izmenjavajo odseki, zapolnjeni z ilovico in gruščem.

Kaže, da so posamezne novoodkrite in razmeroma prostorne stare jame v zahodnem delu trase, ki so votle ali pa zapolnjene z drobnozrnato naplavino ali gruščem, deli večjega vodoravno in navpično razvejanega jamskega spleta, razkrivajočega se ob gradnji ravne trase, ki je presekala rahlo valovito kraško površje.

which by rule do not exceed 50 $m^3$ of volume are void. Speleothems in them are frequent, flowstone covers either walls or floor. The ceilings above such caves are thin, 1–2 m at the most. The network of passages, their form and the rocky perimeters of these caves indicate that they were mostly controlled by slow water drainage in the phreatic zone.

Many old caves filled up by fine-grained sediments are already without roof (6, 7). The passages wind like shallow indentations over the karst surface and may be perceived even before the earthworks start. In road cuttings and tunnels such passages are seen in cross-section. The caves are filled up by layers of yellow loam and sand, frequently consolidated, and above them are usually red loam and brown soil. The deposits cover the speleothems and calcite formations, rarely the deposit is covered by flowstone. Relatively

S površja voda prenika do podzemeljskih voda skozi brezna in špranje. Na trasi sta bili znani dve brezni, globlje je segalo 20 m globoko. Pri razgaljanju površja in zemeljskih delih pa so bila v razmeroma gosto prevotljenem apnencu odkrita številna brezna. Razdelimo jih lahko na brezna z izrazitimi sledmi prenikajoče vode in s pogostejšimi okroglimi prečnimi prerezi ter na špranje različnih velikosti, ki so nastale ob razpokah in katerih stene so pogosto prekrite s sigo. Večje špranje so nastale ob zmikih kamnine v razpoklinskih conah (*Čar* 1982). Prostornejša, močno zasigana brezna, so tudi deli razčlenjenih spletov starih jam, oblikovanih, kot kaže, v zaliti coni. Breznom podobne votline so nastale tudi med podornimi skalami v razpadajočih starih jamah. Najpogostejša pa so bila novoodkrita brezna, skozi katera prenika voda v vodonosnik. Največ jih je bilo v dnu in na pobočjih večjih, lijakastih vrtač. Večina brezen je bila brez vidnega naravnega vhoda. Ozka in neprehodna ustja so se pokazala, ko je bila odstranjena zemlja. Najgloblje je doseglo 109 m (9). Prostornejša brezna pa so bila največkrat odkrita in raziskana pri kopanju večjih usekov in predora, torej že 10–30 m pod površjem. Je to posledica združevanja vode, ki razpršeno prenika skozi prepustno površje, in so prostornejša brezna – tudi tista z naravnim vhodom, površje se je namreč že precej znižalo (*Slabe* 1996) – zbiralci te vode? Tudi Klimchouk (1995) ugotavlja razpršeno prenikanje vode skozi epikras in združevanje v vodne tokove na stiku z vadozno cono.

## 2.4 Jame in gradnja ceste

Med gradnjo avtoceste se jame odpirajo pri odstranjevanju rastja in zemlje s kraškega površja. Tako smo naleteli na precejšnje število starih jam z vodoravnimi rovi, zapolnjenimi z naplavino. Na dnu in bokih vrtač se je odprlo tudi več brezen.

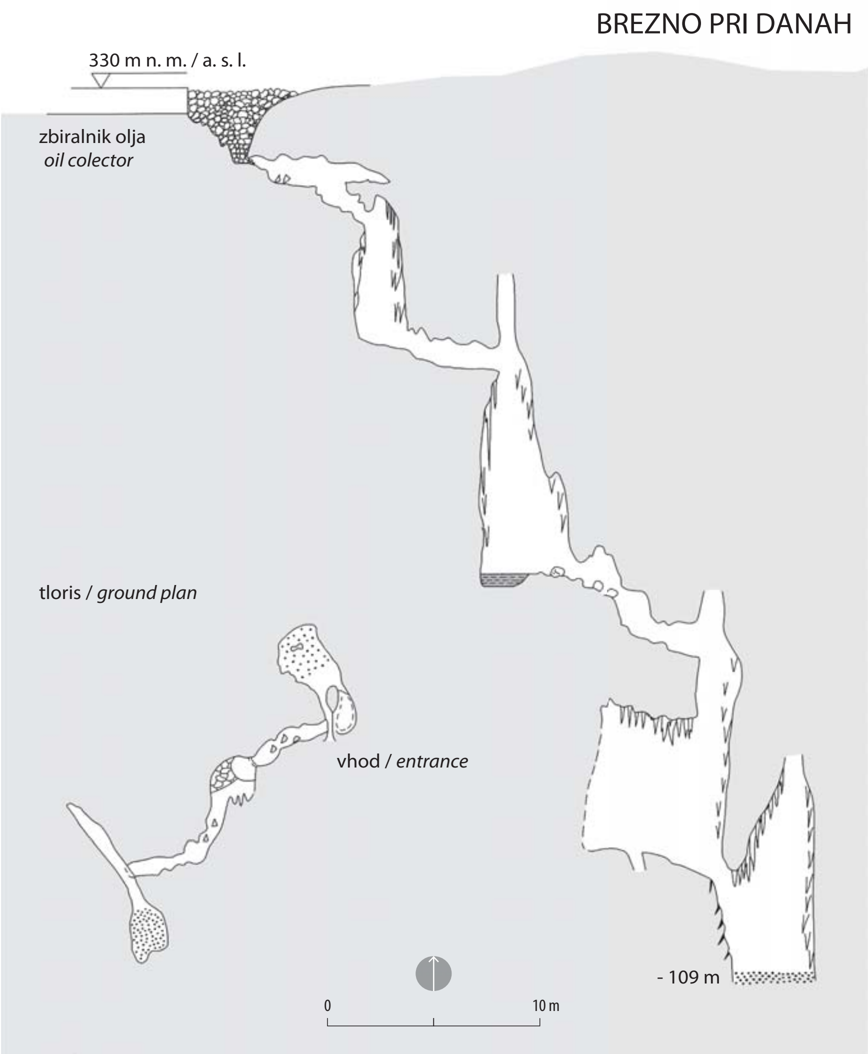
Druge jame se odkrivajo ob izkopavanju usekov, bodisi pod skalnimi tlemi ali pa v stenah. To so votle jame ali z naplavino zapolnjene stare jame in brezna. V useku, blizu nadvoza magistralne ceste, se je z udorom stropa nad rovi odprla večja stara jama (10). Podor je nastal ob navpičnem prelomu, ki poteka vzporedno z osjo trase. Ob istem prelomu poteka tudi največji rov v

rare are traces of faster flows, such as small scallops. There were no pebble deposits found in the caves near Fernetiči though they are frequent in old caves near Divača. The passages of old caves are frequently intersected by shafts and the sediments are there removed in a funnel shape. Old caves may also be intersected by dolines. A modest amount of water meanderingly dissected the bottoms of some, usually smaller, passages. At some places on the surface the patches of flysch remained for a longer time and water drained them off into the limestone.

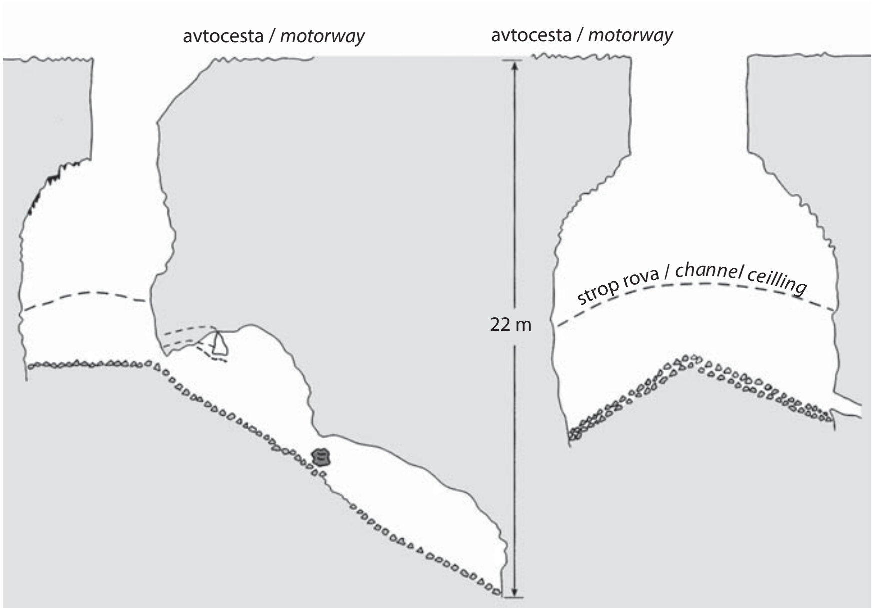
Parts of newly discovered passages are filled up by coarse rubble (8). Rubble, with sides mostly 5 cm in length, is the consequence of the karst surface weathering in the Pleistocene cold periods. Mostly it is found in parts of caves from where the fine-grained sediments were removed due to vertical permeability of the aquifer, and the thin roof collapsed just before the infill by rubble. In the passages the sections filled by loam and rubble alternate.

It seems that some newly discovered and relatively large old caves, either void or filled up by fine-grained sediments or rubble, in the western part of the motorway actually make part of a larger horizontal and vertical cave system that was unearthed during the motorway construction over slightly undulating karst surface.

The water from the surface infiltrates underground by shafts and fissures. On the planned motorway two shafts were already known, the deeper one reaching 20 m deep. By denuding the surface during the earthworks several other shafts were discovered in relatively cavernous limestone. They may be divided into shafts with distinctive traces of percolating water, having ususally circular cross-sections, and cracks of various dimensions that developed along the fissures and with their walls often covered by flowstone. Larger cracks developed along wrench-faults in fissured zones (*Čar* 1982). Spacious, well decorated shafts make part of old cave systems that supposingly developed in the phreatic zone. Hollows, similar to shafts, also developed among the breakdown boulders within disintegrated old caves. The most frequent were newly discovered shafts through which the water percolates into the aquifer and were located mostly in the slopes or in the bottom of larger, funnel-shaped dolines. Most of




9 Najgloblje brezno pod cestno traso.
The deepest shaft below the roadway.




10 Jama, katere strop se je udrl pri kopanju avtocestnega useka.
A cave the ceiling of which collapsed during the road cutting.

jami z 10 m debelim stropom nad njim (11). Dno jame in morebitno nadaljevanje, ki ga je videti skozi neprehodne ožine, sta bila zaradi podora zasuta. Na vznožju stene useka na trasi Divača–Dane se je odprla jama ob razpoki, pravokotni na traso. Jama se zajeda v brežino, del pa se nahaja tudi pod traso. V tem delu trase se je odprlo še več ožjih (do 4 m) in do 20 m globokih jam. Jame so se odpirale med izkopavanjem useka in tudi pozneje pri utrjevanju gruščnatega nasipa tal.

Zaradi miniranja pri izkopavanju usekov se je pretrla tudi kamnina v bližnjih jamah. V jami na trasi Čebulovica–Divača, ki se je odprla z udorom stropa, je bila kamnina pretrta v kose velikosti nekaj $cm^3$ do globine 12 m. Razpoke, ki so nastale zaradi miniranja in so široke do 1 cm, segajo vse do dna jame. Večina kapnikov na dnu jame pa se je obdržala na stenah. Tudi v jami, ki se je odprla na brežini useka na isti trasi, je bila močno pretrta kamnina v vhodnem delu. Njegov obod je deloma razpadel, s stropa dvoranice v notranjosti jame pa so odpadle manjše skale. V špranjastem breznu na trasi Divača–Dane je razpokala kamnina v vhodnem delu. Del stropa je zato razpadel in z njega se je odluščila siga. Globlje v breznu posledic miniranja ni bilo opaziti.

V južnem delu se je trasa Čebulovica–Divača približala Hankejevemu kanalu v Škocjanskih jamah na 400 m, torej je segla vse do zahodnega roba predvidenega regijskega parka Škocjanske jame. Menili smo, da miniranje na trasi ne bo vplivalo na Škocjanske jame, toda vseeno smo se odločili za opazovanje morebitnih posledic v jami. Resda je jama razmeroma daleč od krajev miniranja, vendar so v zadnjem delu jame veliki podzemeljski prostori, kot je 140 m visoka Martelova dvorana z 2,000.000 $m^3$ prostornine. Kje natančno vodni tok Reke preči traso, še ni znano. Previdnost je torej narekovala sprotno opazovanje morebitnih posledic miniranja, ki je bilo zaradi opozoril temu primerno z ustreznimi zakasnitvami eksplozij v vrtinah. Useki na tem delu trase so razmeroma majhni, zato je bilo miniranje manj globoko in šibkejše. Neposrednega vpliva gradnje avtoceste na Škocjanske jame ni bilo.

Ohraniti smo skušali čim več jam, seveda če sta to dopuščali izgradnja trdne podlage ceste in njena varna uporaba, tiste, ki jih zaradi tehnično zahtevne gradnje ceste ni bilo mogoče, pa vsaj preučiti. Vendar je bilo

shafts were without visible natural entrances. Narrow openings of difficult access appeared when the earth had been removed. The deepest one reached 109 m (9). On the other hand, more spacious shafts were discovered and explored during digging the road cuts and tunnel, some 10–30 m below the surface. Is this the consequence of water accumulation coming from a scattered infiltration through the permeable surface, which is being considerably lowered (*Slabe* 1996), and shafts are, also those with a natural entrance, collectors of this water? Klimchouk (1995) likewise assessed the diffuse water percolation into epikarst and converging of this water into water courses at the contact with vadose zone.

## 2.4 Caves and road construction

During the motorway construction the caves were opening up when vegetation and soil were removing from the karstic surface. In that way we found a pretty large number of old caves with horizontal passages filled up with alluvium. And at the bottoms and slopes of dolines more shafts were revealed.

Other caves have been revealed during excavations of cuttings either under the rocky surface or in the walls. These are hollow caves or old caves filled up by sediment and shafts. In the cut near the crossover of the main road a larger old cave opened up (10) due to the breakdown of its ceiling about the passages. That rockfall occured at the vertical joint running parallel with the motorway laying out. The largest passage of the cave with the ceiling of thickness up to 10 m runs at the same joint (11). The cave floor and its eventual continuation, which can be seen through impassable straits, were filled up due to the breakdown. At foot of the cut wall on the road section Divača–Dane a cave opened up at the joint perpendicular to the motorway laying out. The cave is indenting to the slope, part of it laying beneath the roadway. At this road section still more narrower (up to 4 m) and up to 20 m deep caves were revealed. Caves opened up during the excavation of cuts and after that during metalling of the roadway.

Blasting and excavation of cuttings resulted in the fracturing of rock in the surrounding caves. A larger

**11** Ob prelomu udrt strop jame.
Along fault collapsed ceiling of a cave.

tudi slednje pri izkopavanju večjih usekov izjemno težko. Kamnino ob tem namreč razminirajo v razmeroma droben grušč in od jam ostane zelo malo, največkrat kosi sige v grušču. Tako je razpadla tudi Golobja jama pod Čebulovico, ki je bila precej velika, a se je nahajala sredi trase. Ohranile pa so se jame v brežinah usekov. Kamnina je zaradi miniranja pogosto zelo pretrta in jame so manj primerne za obisk. Vhode nekaterih je bilo treba tudi zazidati z večjimi skalami.

Manjše in speleološko manj pomembne jame sredi trase so zasute, prav tako stare jame, iz katerih je bila izkopana drobnozrnata naplavina, in vrtače. Večje izkope se je zasipalo s 30-cm plastmi grušča, ki so jih utrdili s tresočim valjarjem. Večje jame in brezna s kamini, ki so segali tik pod traso, je bilo treba razminirati in nato na opisani način zasuti. Nad globljimi brezni, ki imajo ožje vhodne dele, so betonski pokrovi. Ko smo raziskovali jame in ugotavljali njihov morebitni vpliv na izgradnjo ceste, smo naleteli tudi na ožine. Sklepali smo, da je v breznu na trasi Divača–Dane za ozko špranjo večji prostor, ki sega pod traso. Ožino smo skušali razširiti z vibracijskim kladivom, uspelo pa nam je šele z miniranjem. Jame, ki so v brežinah

old cave opened up in the road section Čebulovica–Divača after the ceiling breakdown. In this cave rock is fractured into pieces with a volume of some cm$^3$ to a depth of 12 m. The fissures which were formed by blasting are up to 1 cm wide and reach down to the cave bottom. The majority of dripstone decorations at the bottom of the cave remained hanging from the walls. In another cave which opened up in the side of the same road section, the entrance part was highly fractured. For this reason the circumference of the entrance passage is partly disintegrated. In a small chamber within the cave small pieces of rock fell off the roof. The entrance part of the fissured pothole located in the Divača–Dane road section contains fractured rock. For this reason part of the roof was disintegrated together with a flowstone coating which fell off the roof. In the deeper section of the pothole, no consequences of the blasting could be noticed.

In the southern part, the road section of Čebulovica–Divača approached the canyon passage Hankejev kanal in Škocjanske jame within 400 m, that is as far as the western boundary of the planned Škocjanske jame Regional Park. Although it was presumed that the blasting in the road section would not have any influence upon the cave, it was decided to observe eventual consequences in there. The cave is relatively far away from the sites of blasting but in the terminal section of the cave there are immense underground caverns such as the 140 m high hall Martelova dvorana with 2,000,000 m$^3$ in volume. Besides, the site of the crossing of the Reka river watercourse with the road section has not been precisely determined yet. Precaution has thus demanded continuous observing of eventual consequences of the blasting. Due to warnings it occured with small retarded explosions in the boreholes. The cuttings in this part of the road section are relatively small, that is the reason why the blasting was weaker and less deep. There has been no indirect influence of the highway construction on the known parts of the Škocjanske jame.

As far as the construction of the solid base of the road and its safe use are concerned it has been tried to preserve as many caves as possible and to investigate the ones which could not be preserved due to the technically road construction, which was an extremely v trdni kamnini, lahko ostanejo takšne, kot so. Treba pa je presoditi, kako vpliva miniranje na obstojnost njihovega oboda, ter očistiti razmajano in porušeno kamnino. Kamnina je bila zlasti neobstojna v dolomitu. Jame v brežinah, ki so zapolnjene z naplavino in dostopne v prečnem prerezu, je bilo treba obzidati, ker naplavina na površju ni obstojna in bi jo voda sprala na cestišče.

## Sklep

Jame, ki so se odpirale v trasi avtoceste, smo raziskovali sproti. Speleološko pomebnejšim oziroma zanimivejšim smo namenili prav posebno pozornost. Osnovne raziskave smo dopolnili z raziskavami kamnin, v katerih so jame in iz katerih so sige v jami. Različna karbonatna kamnina je resda različno gosto prevotljena, a jame so v vseh njenih vrstah. To potrjuje tudi primer paleogenskega apnenca, ki je pri Čebulovici le malo prevotljen, nasprotno pa je zelo prevotljen pri Povirju. V vseh vrstah apnenca in v dolomitu so stare jame, brezna in površinske skalne oblike. Brezen je največ v krednem apnencu.

Ohraniti smo skušali čim več jam, kar pa je bilo zaradi izdelave varne ceste precej težko. Tudi ob zadnjem čiščenju površja, tik pred nasipanjem in utrjevanjem grušča, so se odpirale jame. Grezi so lahko nastajali celo med tem delom (12). Mogoče je, da je plitvo pod traso ostala še kaka jama. Lahko pride do ugreza na cesti? Predlagali smo, da bi traso pregledali z georadarjem. Na ta način bi lahko razkrili vsaj morebitne večje jame, ki so skrite očem.

Iz spoznanj, pridobljenih pri preučevanju novoodkritih kraških pojavov, so se porodile razlage razvoja tega dela Krasa. V starih jamah, ki so najstarejša sled zakrasevanja, lahko razberemo več obdobij razvoja. Votle in zapolnjene stare jame se nahajajo tako v Divaškem podolju kot v kraškem hrbtu, ki ga obdaja na severovzhodu. Jame so po vsej verjetnosti nastajale v zaliti coni. Kasneje so bile deloma preoblikovane s hitrejšim vodnim tokom, ki je v njih odlagal tudi prod in pesek ter ponekod na stenah izdolbel manjše fasete. Od kod so pritekali vodni tokovi? S flišnega brkinskega roba, ki je bil bližje jamam? So naplavino prinašali vodni tokovi s fliša, ki je Kras obrobljal na severu, ali pa

difficult demanding task in the digging of the more extensive cuttings. Here the rock was blasted into relatively small rubble particles and there was not much left of the caves, in most cases only flowstone pieces and rubble. In this way a relatively large cave within the road section, Golobja jama under Čebulovica, was destroyed. The caves preserved were those located in the excavation sides. Due to the blasting, the rock is often too crushed and smaller caves are inappropriate for visiting. The entrances to some caves had to be walled up with large rocks.

Minor and speleologically less important caves within the road section are filled up, as well as dolines and old caves from which thin-granular deposits were removed. Large excavations were filled in with 30-cm thick layers of rubble which were consolidated with the vibration roller. Large caves and potholes with chimneys reaching up as far as the road section had to be blasted and filled up in the previously described way. Above the deeper potholes with narrow entrance parts there are concrete covers. During the investigation of the caves and the establishment of their eventual influence upon the road construction, some narrow sections were encountered. It was concluded that in the pothole within the road section Divača–Dane there is a large cavern beyond a narrow fissure which extended up to the road section. The narrow part was tried to be widened with a vibration hammer, but the result was achieved only by blasting. In the excavation sides composed of solid rock, caves can remain untouched, but nevertheless it is necessary to consider the influence of blasting upon the permanence of their vaults and to remove unstable and crushed rock. The rock was unsolid particularly in dolomite. The caves in the excavation sides which are filled up with deposits had to be walled up because alluvium on the surface is not consolidated and could be washed down by water onto the road.

## Conclusion

Caves can be found in all rock types. This is evidenced by the Palaeogene limestone at Čebulovica, which is only slightly cavernous regarding large caves but in single beds there are plenty of small channels;

**12** Udor na cestišču.
The collapse in the roadway.

potoki z vzpetin, kjer se je ohranil fliš po bočenju antiklinale (*Gams* 1974, 197)? V pliocenu je bil Kras kljub antiklinalni zgradbi nižji od flišnega površja vipavske in tržaške sinklinale (*Radinja* 1972, 212). Flišni prodniki se zaradi drobljenja in mletja ne prenašajo daleč v podzemlje (*Kranjc* 1986, 114). V vmesnih sušnejših klimatskih obdobjih in po znižanju gladine podzemeljske vode se je v jamah odlagala siga. Nekatere jame, ki so jih pozneje dosegle poplavne vode, so ostale zapolnjene s flišno ilovico. Ponekod je ilovico že odnesla prenikajoča voda. Tudi strop nad višje ležečimi starimi jamami, zapolnjenimi z naplavino, je že odnesen. Jame kot korita členijo kraško površje. Po sigi v jamah lahko sklepamo, da je bil strop nad njimi debel več metrov. Meritve so pokazale, da se kraško površje, ki je izpostavljeno vremenskim vplivom, znižuje za 0,02 mm na leto (*Cucchi* idr. 1994, 61). Gams (1965a, 86) ugotavlja, da se je v kvartarju znižalo površje nad Postojnsko jamo za okrog 40 m. Površje se je že temeljito spremenilo. Naplavine vodnih tokov so se torej kot prvotne večinoma ohranile le v jamah. Vrtače so namreč pogosto nastale z odpiranjem brezen pod starimi rovi. Poleg grušča in kraške ilovice, ki sta nastala s preperevanjem na površju, je zato moč pogosto najti tudi starejše flišne naplavine.

Velika prevotljenost je eden izmed najbolj zanesljivih kazalcev prepustnosti, kar nas še enkrat opozarja na izredno pazljivost tako pri gradnji ceste kot pri nje-

on the contrary a part of the same limestone at Povir is extremely cavernous. Old caves and potholes are to be found in all types of limestone and in dolomite. The majority of bigger potholes is in the Cretaceous limestone. General properties of rock lithology are outweighed, regarding cavernosity, by composition of a particular rocky bed, how it is crushed and by competence of bedding-planes and fissures that the caves develop along them.

It has been tried to preserve the largest number of caves as possible which was rather difficult in the construction of a safe road. Caves opened up also during the final clearing of the surface, that is short by before the metalling and consolidation works on the road. Examples of subsidence occured even during these works (12). It is possible that there are even other caves located not far below the road. Is there any possibility of road subsidence? It has been suggested to check the road section with the georadar. In this way at least the largest eventual caves, hidden below, could be discovered.

Experience obtained during the study of the new discovered karst phenomena have led to explanations of the development of this part of the karst. In the old caves, which are the oldest remains of karstification here, several development phases can be recognized. Empty and filled up old caves are located in Divaško podolje as well as in the karst ridge to the northeast. The caves were probably formed in the flooded, phreatic zone. Subsequently they were partly modified by rapid water streams which deposited gravel and sand within the caves and in places hollowed out small scallops on the walls. Where is the origin of the watercourses? Perhaps it is the Brkini flysch edge, which was closer to the caves. Was the alluvium carried along by the watercourses from the flysch which surrounded the Kras in the north, or by the streams from the elevations where the flysch was preserved after the folding of the anticline (*Gams* 1974, 197)? In the Pliocene Kras was lower than the flysch surface of the Vipava and Trieste syncline despite the anticline construction (*Radinja* 1972, 212). Flysch pebbles are not carried far underground due to crumbling and grinding (*Kranjc* 1986, 114). In the intermediate dry climatic periods and after the lowering of the underground ni uporabi. Cestišče mora biti neprepustno, tako da se bodo z njega resnično stekale le prečiščene vsakodnevne vode, površje okrog cestišča pa bi moralo biti zavarovano tudi pred morebitnimi nesrečnimi razlitji škodljih snovi.

water level, flowstone was deposited in the caves. Some caves which subsequently were reached by flood waters remained filled with flysch loam. In places loam was carried away by means of percolation water. Also the roofs above the old caves situated at higher levels and filled up with alluvium were already carried away. Caves dissect the karst surface like furrows. According to the flowstone in the caves it can be concluded that the roofs above were several metres thick. Cucchi with colleagues (1994, 61) have made some surveys which show that the karst surface exposed to climatic conditions is lowered by 0.02 mm a year. Gams (1965a, 86) explains that in the Quaternary the surface above Postojnska jama (Postojna cave) was lowered by about 40 m. The surface has been profoundly changed. The alluvium of watercourses is present mostly only in caves. Dolines were frequently formed by the opening of potholes below the old channels. Beside rubble and karst loam formed by weathering on the surface, it is often possible to find also old flysch alluvium.

Great cavernosity is one of the most reliable indicators of permeability, warning us again how carefully the rodas must be constructed and later used. The roadway should be impermeable in order to assure that only treated waters drain off it each day, and the road surface should be protected against accidental spills of harmful substances.

# 3

# KRAŠKI POJAVI, RAZKRITI MED GRADNJO AVTOCESTE NA NIZKEM KRASU DOLENJSKE

# KARST FEATURES DISCOVERED DURING CONSTRUCTION OF THE EXPRESSWAY ON THE DOLENJSKA LOW KARST

Krasoslovna spremljava gradnje dolenjske avtoceste se je izkazala za zelo koristno tako pri razkrivanju naše naravne dediščine kot pri poglabljanju védenja o oblikovanju in razvoju tega dela slovenskega krasa. Pod bolj ali manj debelimi plastmi naplavin, ki prekrivajo kraško površje, se je to značilno podtalno oblikovalo. Podtalno oblikovanje karbonatnih kamnin daje pečat tudi vsej epikraški in vadozni coni. Površje je razčlenjeno v podtalne kamnite gozdove (1), kraške uvale z estavelami in škraplje, odkritih pa je bilo tudi veliko votlih in z drobnozrnatimi naplavinami zapolnjenih brezen. Svojevrstna oblikovanost kraškega površja je predvsem posledica velikih površin kamnitih gozdov, ki pa jih je pred zemeljskimi deli oziroma geofizikalnimi raziskavami težje razbrati. Večina površja leži višje nad gladino podzemeljske vode. Kraški pojavi, razkriti pri gradnji, omogočajo vpogled v značilnosti in način oblikovanja krasa na širšem območju južne Slovenije, torej razkrivajo še eno posebnost naše kraške naravne dediščine in nam narekujejo smernice za načrtovanje posegov v tamkajšnje površje.

## 3.1 Značilnosti kraškega Dolenjskega podolja

Ozemlje med vzhodnim robom Ljubljanskega barja, Krško kotlino, Dobrepoljem in Želimeljsko kotlino ter Gorjanci prištevamo k nizkemu, pokritemu dolenjskemu krasu (*Gams* 2004; *Kranjc* 1990).

Habič (1982) z litološkega vidika posebej poudarja t. i. nepopolni karbonatni kras, razvit pretežno na triasnih dolomitih, na katerih sicer prevladuje površinski odtok, vendar razpokana in porozna kamnina vpije precejšen del padavin. Po obsegu zavzemajo dolomiti različne površine, od njihovega položaja sredi krasa pa so odvisne tudi njihove kraške značilnosti. Na dolomitnem površju se oblikuje redka rečna mreža, znaten del povirnih in stranskih grap pa navadno nima stalnih tokov. Pogosti so manjši izviri podzemeljskih vod, ki se pretakajo po posameznih, korozijsko večinoma skromno razširjenih razpokah v kamnini. Površinski in podzemeljski kraški pojavi so redki, vendar ponekod prav značilni za dolomitni kras, ki ga lahko označimo tudi kot poseben tip fluviokrasa.

The monitoring of the construction of the Dolenjska motorway by karst researchers has proved to be of a great value in the exploration of our natural heritage through the deepening of our knowledge about the formation and development of this part of the Slovenian karst. This characteristic subsoil karst surface was formed under a cover of sediment of varying depth. Subsoil formation of carbonate rock also marks the entire epikarst and vadose zone. The surface is carved into subsoil stone forests and karst uvalas with estavelles (1), karren and numerous hollow shafts filled with fine-grained sediment were also found. The outstanding characteristics of the karst surface are primarily the result of large surfaces of stone forests, which are difficult to detect prior to earthwork or geophysical research. Most of the surface is above the underground water level. Karst features discovered during construction works give us insight into the characteristics and manner of formation of the karst in the wider area of southern Slovenia; they thus unveil yet another characteristic of our karstic natural heritage and also provides guidelines for planning activities on the surface.

## 3.1 Characteristics of the karst Dolenjska lowland

The area circumscribed by the eastern edge of the Ljubljana marshland, Krško basin, Dobrepolje, Želimlje basin and Gorjanci belongs to what we call low, covered Dolenjska karst (*Gams* 2004; *Kranjc* 1990).

Habič (1982) points to what in lithological terms is referred to as incomplete carbonate karst, developed in the main on Triassic dolomites where cracked and porous rock absorbs a considerable amount of precipitation. Dolomites extend over surfaces of different magnitude and their position in karst also determines their karstic features. A thinly scattered river network forms on the dolomitic surface and a considerable portion of drainage-basin ravines and lateral ravines are usually without permanent flows. Smaller sources of the underground waters flowing over rocks with moderately widened corrosion-provoked fissures are a frequent occurrence. Surface and underground karst formations are few and far between, but in some places

**1** Podtalni kamniti gozd.
Subsoil stone forest.

Po dolenjskem podolju je veliko pliokvartarnih naplavin. Na ravnini naj bi nastale še v času, ko je bila gladina podzemne vode bližje površju. Ker so tla (prst) na triasnih dolomitih bolj sklenjena kot na apnencih in so bila v pleistocenskem hladnem podnebju zaradi sezonske zamrznjenosti vodno delno neprepustna, je v tem podolju več znakov nekdanjih pritokov voda na robni apnenec (*Gams* 1998).

Na prevladujoči dolomitni podlagi je z morfološkega vidika razvit relief z dolinami in ponekod s površinsko rečno mrežo (*Habič* 1982). Oblikovanje reliefa poteka v posameznih predelih tega delnega krasa različno hitro, odvisno je od splošnega morfogenetskega razvoja. Tako so dolomitne grape najgloblje zarezane na območju visoke Notranjske in Dolenjske, medtem ko je precej nižji in blažji relief izoblikovan na dolomitu severne Dolenjske. Kraške značilnosti dolomita se odražajo v drobnem grbinastem površju, v značilnih suhih dolinah, redkih vrtačah in plitvih uvalah. Na podzemeljsko drenažo opozarjajo razmeroma gladka nerazčlenjena pobočja slemenastih vzpetin. Očiten znak zakrasevanja pa so tudi grezi, ki se odpirajo v

they are typical of dolomitic karst that can be designated as a specifc type of fluviokarst.

In the Dolenjska lowland there are many Plio-Quaternary sediments. Those in the flat land are supposed to have formed at the time when the level of underground water was closer to the surface. As the soil on Triassic dolomites is less porous than on limestones, and as it was, due to seasonal freezing in the cold Pleistocene climate, partly impermeable to water, this landscape shows many signs of former tributary streams in the border limestone area (*Gams* 1998).

In morphological terms, an almost normal relief with valleys and a sporadic surface-river network has developed on a predominantly dolomitic base (*Habič* 1982). The shaping of relief in different areas of this partial karst proceeds at a different pace, depending on general morphogenetic evolution. Thus dolomitic ravines are deepest in the Notranjska and Dolenjska uplands, whereas the relief formed on the northern Dolenjska dolomite is much lower and gentler. Karstic features on dolomite are manifest in a mildly bumpy surface, characteristic dry valleys, infrequent dolines debelejše plasti dolomitne preperine na dnu globeli.

Glavne hidrografske značilnosti dolomitnega krasa so nakazane z razporeditvijo dolin in s pripadajočo rečno mrežo. Doline v dolomitu so večji del leta suhe, po nalivih pa se v njih pojavijo potoki in poplave. Kraška voda napaja majhne, a stalne izvire. Nihanje pretokov v izvirih je majhno, redko pa izdatnejše, kar je odraz večje prepustnosti in prevotljenosti. Podzemno pretakanje vode je plitvo pod površjem, zato kras s takšnimi značilnostmi imenujemo tudi 'plitvi kras'. Tudi to je ena od značilnosti fluviokrasa. Za dolomitne predele z večjo reliefno razčlenjenostjo je značilen izdaten površinski odtok visokih voda. Hudourniški odtok vpliva na oblikovanje strmih in globokih grap, ki so večinoma zarezane v bolj pretrte in zdrobljene prelomne cone.

## 3.2 Odkriti kraški pojavi

### 3.2.1 Uvale z estavelami

Med najbolj značilnimi estavelami so tiste južno od Biča na dnu morfološke uravnave, ki spominja na občasno poplavljeno kraško polje. Vhodi so odprti v naplavini. Dobska uvala je ena mnogih značilnih kotanj vzdolž dolenjskega podolja s prevladujočim fluviokrasom. Leži na stiku zgornjetriasnega dolomita, ki ga sledimo na severni strani doline, in jurskega oolitnega apnenca na južni strani. Glede na pestro geološko sestavo je pričakovati lokalno različno vodno prepustnost oz. slabšo vodno prepustnost nasploh. Uvala je najnižji del šentviške okolice. Zaradi dna večjih razsežnosti bi kotanjo lahko imenovali kraško polje. Ker pa na dnu ni večje naplavne ravnine ter večina oboda ni sklenjena in nima podobe značilnega dinarskega kraškega polja, jo imenujejo uvala (*Gams* 1987). Površinski tokovi, ki pritečejo iz dolomita, poniknejo v oolitnih apnencih. Ob močnejših padavinah priteka voda v uvalo tudi z zahoda in vzhoda. Manjši izviri ob višjih vodah zelo narastejo in si podaljšujejo površinski vodni tok proti jugovzhodnemu robu uvale. Pred izgradnjo hitre ceste so obsežnejše poplave na tem območju včasih ovirale promet na stari magistralni cesti (*Gams* 2004). Hitrejši odtok površinske vode in manjši obseg poplav ob dobroprepustnih požiralnikih

and shallow uvalas. Relatively smooth, undissected slopes of crested elevations are an evidence of underground drainage. Another obvious sign of karstification are collapses opening into thicker strata of dolomitic weathering products at the bottom of valleys.

The chief hidrographic features of dolomitic karst are indicated by the disposition of normal surface valleys and by the associated river network. Dolomitic valleys are dry for the greater part of the year, with streams and floods appearing after heavy rainfalls. Infiltrated water feeds small but permanent springs. Flow oscillation in the springs is small, which is an indication of greater permeability and karstification. Underground water flows close to the surface, so karst having such characteristics is called 'shallow karst'. This is also one of the characteristics of fluviokarst. A feature of high-relief dolomitic areas is abundant surface drainage of high flows. Torrent drainage influences the formation of steep and deep ravines cut predominantly into broken and crushed fault zones.

## 3.2 Uncovered karst formations

### 3.2.1 Karst uvalas with estavelles

South of Bič, at the bottom of a morphologic reminiscent of a periodically flooded polje, there are many estavelles and swallow holes. Entrances are opened in the sediment. The Dob uvala is a typical depression along the Dolenjska lowland, with fluviokarst the predominating landscape type. It lies at the contact of the Upper Triassic dolomite on the northern side of the valley and the Jurassic oolite limestone on the southern side. Because of its diversified geologic composition we can expect locally differing water permeability, or poorer water permeability in general. The uvala is the lowest part of the Šentvid environment. Given the dimensions of its bottom, the depression could be defined as polje. However, because of the absence of a larger sedimentary flat land at the bottom, and because most of the rim has not been closed and therefore does not have the form of a typical Dinaric polje, the depression is termed uvala (*Gams* 1987). Surface streams flowing from dolomite sink in ookažeta na široko izoblikovan podzemski splet kanalov plitvo pod površjem. O tem pričajo tudi pogosti grezi in oblike na skali, ki so posledica nihajoče vode.

### 3.2.2 Škrapljasto površje

Večino površja višjega sveta – doli so prekriti s plastmi naplavin – členijo škraplje. Karbonatna kamnina je razčlenjena ob razpokah, na skali pa lahko razbiramo sledi njenega nekdanjega podtalnega oblikovanja pod prstjo (*Slabe* 1999; *Slabe* in *Knez* 2004), ki jih je razmeroma malo, posrednega preoblikovanja s padavinami in drobnega členjenja z biokorozijskimi dejavniki. Površje je bilo namreč večinoma poraslo z gozdom.

Še posebej na hribih Strmec in Dobrava smo zasledili in opazovali zelo močno biokorozijsko delovanje na številnih škrapljastih izdankih karbonatne kamnine. Močno biokorozijsko je raztopljena kamnina na bolj osojnih ali senčnih predelih. Tam prevladujejo mahovi, medtem ko so lišaji pogosti tudi na soncu bolj izpostavljenih mestih. Biokorozijski procesi se ne odvijajo po celotni površini skale enakomerno, temveč selektivno (2). Najverjetneje litološko rahlo različni klasti v zdrobljeni in ponovno zacementirani skali so različno globoko raztopljeni ali pa so na različnih sosednjih klastih različni organizmi. Še posebno so korozijsko raztopljeni stiki med posameznimi klasti, ponekod celo več milimetrov globoko.

Večji del površja, poraslega z gozdom, pa so členile večinoma posamezne, a različno obsežne skale z deloma podobnimi sledmi oblikovanja kot zgoraj opisane škraplje. Pogosto so razčlenjene z lijakastimi ustji večjih navpičnih podtalnih žlebov. Dosegale so 1–2 m višine in bile proti vrhu zožene, med njimi pa so bile večje površine prsti. Zemeljska dela so jih razkrila kot vrhove večjih površin kamnitih gozdov.

### 3.2.3 Podtalne škraplje

Podtalne škraplje na tem območju lahko razdelimo v dve vrsti. Prve nastajajo zaradi enakomernega navpičnega prenikanja vode skozi bolj ali manj debelo plast prsti, ki prekriva razpokano karbonatno kamnino. Pod debelejšo plastjo naplavin in prsti so na izrazito pretrti kamnini nastale špranje, ki imajo

lite limestones. During heavier precipitation water flows into the uvala from the west and east as well. At higher waters smaller springs increase exceedingly and prolonge the surface water course towards the uvala southeastern edge. Before the expressway construction floods in this area occasionally hindered the traffic on the old main road (*Gams* 2004). Quicker drainage of the surface water and smaller scope of the floods at the well permeable swallow holes indicate a widespread underground net of channels lying shallowly under the surface. Frequent collapses and shapes on the rock surface which are the consequence of oscillating water confirm that as well.

### 3.2.2 Karren surface

Most of the surface of the higher-lying land—bottoms of dales are covered by sediment beds—is karren. Carbonate rock is dissected along cracks, and on rock we can detect traces of its former subsoil formation (*Slabe* 1999; *Slabe* and *Knez* 2004) that are relatively few, indirectly transformation by precipitation, and tiny dissecting by bio-corrosive factors. However, the surface was mostly forested.

Especially in the area of the Strmec and Dobrava hills we observed well-expressed bio-corrosive activities on numerous karren outcrops of carbonate rock. The rock was more diluted by bio-corrosion on the shadier sides. Moss mostly grows there while lichen can also be found on the areas exposed to the sun. Bio-corrosive processes do not take place on the entire rock surface equally, but selectively (2). Most probably lithologically slightly different clasts in crushed and then cemented rock are diluted to various depths or else there are different organisms in the various neighbouring clasts. The contact areas between the various clasts are especially corroded, in some spots up to several millimetres deep.

The major part of the forest-covered surface was dissected mainly by individual rocks of various size with partially similar traces of formation to the karren described above. They are frequently defined by funnel-shaped mouths of larger subsoil channels. The rocks reach up 1–2 m in height, with a narrowing on top and with large areas of soil between them. The

**2** Biokorozijsko razjedena površina škrapelj.
Bio-corrosively etched surface of karrens.

**3** Podtalne, občasno poplavljene škraplje pri Biču.
Periodically flooded subsoil karrens near Bič.

oblike podobne bolj ali manj široki črki V. Globoke so lahko več metrov. Oblika med njimi spominja na podtalne zobe, ki so oblikovani v močno zdrobljeni kamnini. Iz redkeje razpokane in ponekod proti koroziji odpornejše kamnine pa so nastali pravi kamniti zobje s koničastimi ali z rezilastimi vrhovi, ponekod celo manjši kamniti gozdovi (*Knez* idr. 2003). Členijo jih podtalni žlebovi. Njihova površina je značilno podtalno razjedena, razmeroma gladka na enakomerno in drobnozrnati kamnini in bolj hrapava na raznovrstno sestavljeni ali pretrti kamnini. Pred odstranitvijo prsti so na površje štrlele le manjše škraplje ali pa kosi kamnine. Površje je bilo poraslo in njihova površina pogosto prekrita z mahom. So pa bile na njih škavnice, podtalne vdolbine in deloma že preoblikovane podtalne oblike, žlebovi in zajede (*Slabe* 1999). Zadnje so sled počasne erozije prsti.

Drugo vrsto podtalnih škrapelj (3) so odkrila arheološka izkopavanja na dnu podolja pri Biču. Škraplje so se v celoti oblikovale pod tlemi. Plast naplavine in prsti je ponekod precej debela, drugod pa škraplje segajo skoraj do površja. Njihovi vrhovi so priostreni. Zanimiv in poveden je njihov skalni relief. V zgornjem delu prevladuje razmeroma gladka, za oblikovanje pod prstjo in drobnozrnatimi naplavinami značilna skala. V spodnjem delu škrapelj so najbolj izrazite podtalne zajede. Večje in vodoravne dosežejo meter premera, manjše so ena nad drugo. Polkotličaste zajede so zaključki navpičnih podtalnih žlebov, ki so nastali ob najbolj prevodnih poteh. Posamezni vrhovi podtalnih zob nad najbolj izrazitimi zajedami so gobasti. Podtalne žlebove na teh škrapljah lahko razdelimo na navpične in vodoravne. Prvi so prevodniki nihajoče vode ob najbolj prevodnih poteh. Drugi, ki prepredajo položnejše, tudi večje površine skale, pa se sooblikujejo z vlago, ki se v njih zadrži najdlje časa, tudi po znižanju gladine podzemeljske vode. Podobno se ob šibkostih v kamnini, največkrat so to drobne razpoke, oblikujejo podtalne vdolbine, ki sčasoma lahko prerastejo v cevi. Med vdolbinami in žlebovi so torej podtalne cevi, ki prepredajo skalo v različnih naklonih.

Podobno oblikovanje podtalnih škrapelj je ponazoril tudi poskus z mavčnimi stebrički, ki smo jih prekrili s prstjo in nato izpostavili umetnemu dežju (*Slabe* 2005). Voda je na spodnji strani odtekala iz

earthwork uncovered them as the tips of the larger areas of stone forests.

### 3.2.3 Underground karrens

Underground karrens in this area can be divided into two types. The first one has formed by the steady vertical penetration of water through the more or less thick layer of soil covering broken carbonate rock. Under the thicker layer of sediment and soil there are wider or narrower V-shape fissures formed on crushed rock. They resemble underground teeth developed in a heavily crushed rock. In places where fissures are more thinly scattered and the rock is more corrosion resistant, genuine stone teeth with pointed or bladed tops, and sometimes even smaller stone forests, have developed (*Knez* et al. 2003). They are dissected by subsoil channels. Their surface is corroded subcutaneously in a characteristic fashion—it is relatively smooth on the uniformly grained and small-grained rock and rough on diversely composed or crushed rock. Before the removal of the soil only smaller karrens or pieces of rock were sticking out on the surface. The surface was covered with vegetation and often with moss as well, and there were also subsoil cups and partly reshaped subsoil forms, channels and notches (*Slabe* 1999). The latter are indications of slow erosion of the soil.

The other type of underground karrens (3) was discovered during archaeological excavations at the bottom of the valley near Bič. They were formed entirely subcutaneously. In some places the layer of sediment and soil is relatively thick, and in other places karrens almost reach the surface. They have sharpened tops and an interesting rock relief that speaks volumes. A relatively smooth rock, characteristic of formation beneath the soil and small-grained sediment, prevails in the upper part. In the lower part of the karrens the most expressive feature are underground notches. Larger and horizontal notches reach one metre in diameter, and smaller ones are placed on top of each other. Semi-cylindrical notches represent the ends of vertical underground channels formed along the most conductive ways. Some of the tops of the underground teeth located above the most expressive notches are mushroom like. The underground grooves on these

**4** Obsežnejši podtalni stebri.
Wider subsoil stone pillars.

**5** Razkrivanje podtalnega kamnitega gozda.
Uncovering the subsoil stone forest.

modela. Zgornji del stebričkov je oblikovala voda, ki je razpršeno prenikala skozi prst, spodnji pa se je oblikoval v lokalno zaliti coni. Odtok vode je bil namreč prepočasen in voda je zato zalila spodnji del modela.

Če strnemo, lahko iz oblike škrapelj in njihovega skalnega reliefa izluščimo dva prevladujoča načina njihovega oblikovanja. Poseben pečat jim dajejo skalne oblike, ki so sled pogostega nihanja gladine podtalne vode, ki škraplje poplavlja od spodaj. V času nizkih podtalnih vod jih oblikuje voda, ki občasno in razpršeno prenika s površja skozi prst in enakomerno polzi po skali navzdol. Dlje časa se zadrži v podtalnih vdolbinah in položnih žlebovih ter ob manj prepustnih stikih kamnine z naplavino, ki jih obdaja.

### 3.2.4 Podtalni kamniti gozdovi

Razmeroma velike površine podtalnih kamnitih gozdov (4, 5) pričajo o načinu in dolgotrajnem podtalnem oblikovanju tega dela kraškega površja, prekritega z drobnozrnatimi naplavinami in prstjo. Kamniti stebri so v celoti pod naplavino in prstjo ali pa so na površju le njihovi vrhovi.

Površje je razčlenjeno z manjšimi in večjimi vrtačami. Največje imajo premer več 10 m. Nekatere so zapolnjene s sivo ilovico, katere izvor še preučujemo. So pa oboje razčlenjene s podtalnimi kamnitimi gozdovi.

Podtalne kamnite gozdove sestavlja gosta mreža bolj ali manj čokatih in koničastih stebrov (6), ki dosegajo 8, redkeje 10 m višine, večina pa je nižjih. Ožji stebri s premerom 1–2 m imajo na vrhu eno, ostro ali zaobljeno, konico, čokati, ki so široki tudi 5 m, pa več ali pa imajo njihovi vrhovi obliko bolj ali manj priostrenih in vijugastih razov. Med njimi so večinoma lijakasta ustja navpičnih podtalnih žlebov in pa bolj ali manj vodoravni podtalni žlebovi.

V skalnem reliefu stebrov prevladujejo podtalne skalne oblike (*Slabe* 1999; *Slabe* in *Knez* 2004), ki pričajo o pretakanju vode s površja. To so predvsem podtalni žlebovi (7), od katerih so najbolj značilni navpični s premerom meter in več. Največje, kot ugotavljamo v nadaljevanju, lahko poimenujemo tudi podtalna brezna, ki se na vrhu razširijo v lijakasta ustja. V njih se zbira voda s površja, ki polzi po skalah in se steka iz prsti. Lijakasta ustja so v prečnem prerezu različnih

karrens can be divided into vertical and horizontal ones. The former are the conduits of oscillating waterflow along the most conductive ways. The latter criss-cross more gently sloping rocks, including larger ones, and are co-shaped with moisture, which stays in them for the longest time, even after the level of underground water decreases. Formed along flaws in the rock that occur mostly as small fissures are underground solution cups which can develop into pipes. Between solution cups and channels are then the underground tubes that criss-cross the rock at different inclinations.

Similar formation of underground karrens was illustrated by an experiment in which we covered gypsum columns with soil and then exposed them to artificial rain (*Slabe* 2005). The water drained from the model at the bottom. The upper part of the columns was formed by water penetrating the soil dispersively, and the lower part formed in the locally watered zone. The drainage was too slow and that explains why the water filled the bottom of the model.

To sum up, two prevailing ways of karren formation can be inferred from their shape and their rock relief. The shapes of rock which are the traces of frequent oscillations in the level of underground water that floods karrens from underneath give them a special character. During low levels of underground streams, karrens are formed by water flowing slowly and dispersively from the surface through the soil and gliding over the rock downwards. It stays longer in underground solution cups and gently sloping channels as well as along less permeable interfaces between rock and surrounding sediment.

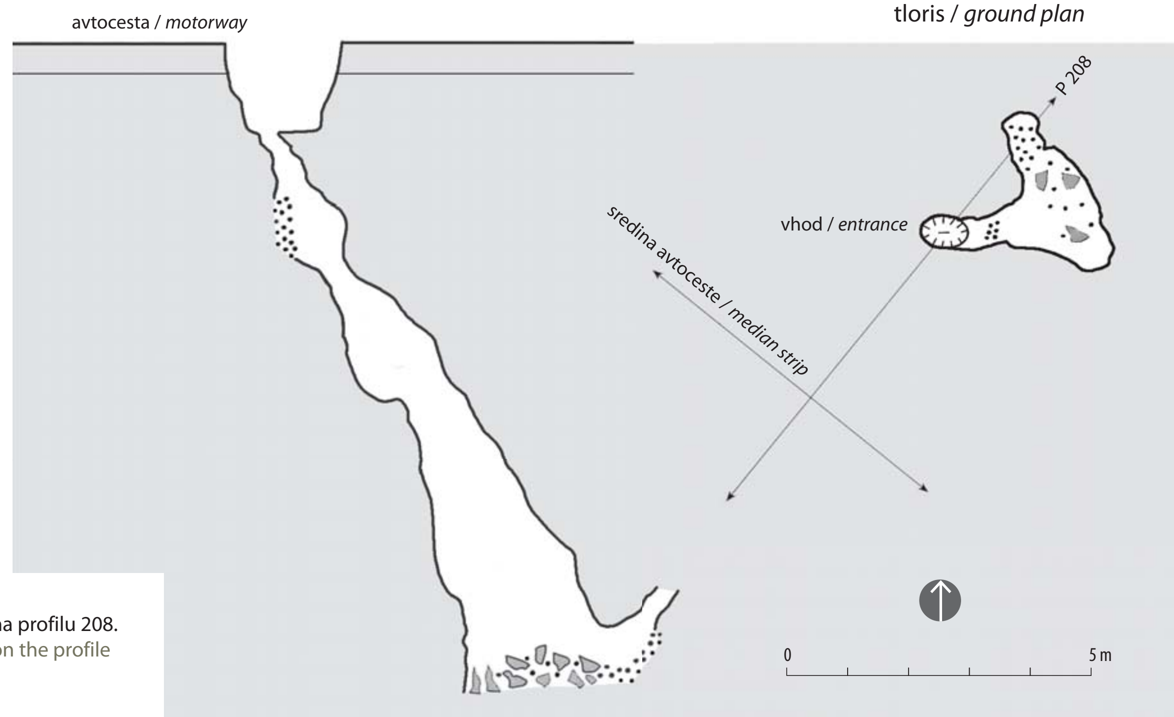
### 3.2.4 Subsoil stone forests

Relatively large areas of subsoil stone forests (4, 5) illustrate the manner and long-lasting subsoil formation of this part of the karst surface covered by fine-grained sediment and soil. The stone pillars are completely covered by the sediment and soil or their tips are protruding onto the surface.

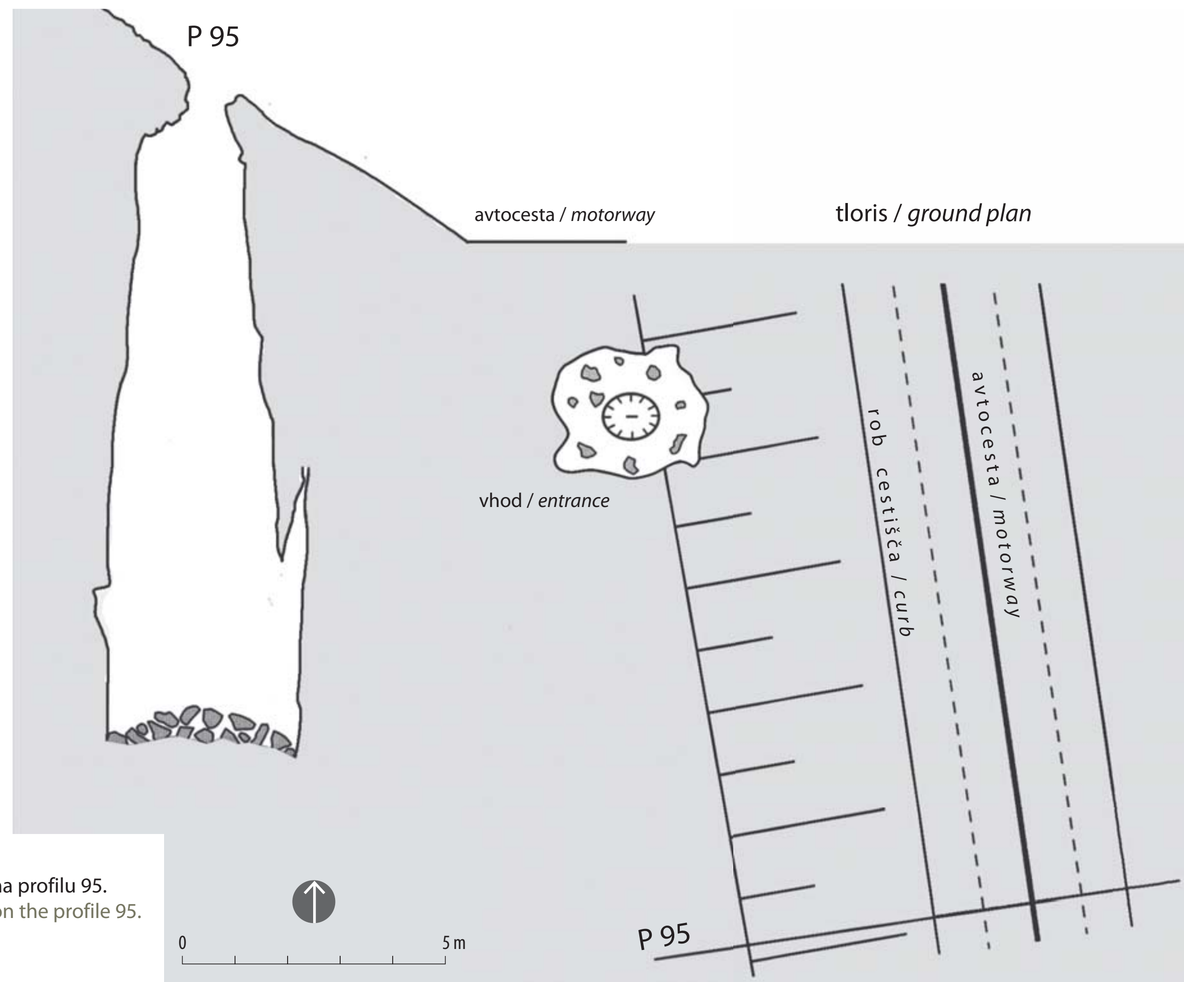
The configuration of the surface includes smaller or larger dolines. The largest have a diameter of several 10 m. Some are filled with grey clay the origins of

**6** Podtalno oblikovan steber kamnitega gozda.
A subsoil shaped pillar of the stone forest.

**7** Podtalni žleb.
A subsoil channel.




**8** Brezno na profilu 208.
A shaft on the profile 208.




**9** Brezno na profilu 95.
A shaft on the profile 95.

oblik. Lahko so odprta, polkrožna ali skoraj krožna. Njihova oblika je pogosto posledica prepustnosti stika med skalo in naplavino, po katerem odteka voda navzdol. Dolgotrajno oblikovanje ustja ob slabo prepustnem stiku povzroči, da se skalna oblika zajé globlje v skalo. Redkeje si je voda utrla pot skozi skalo, torej so nastali pravi lijaki. Ob slabše prepustnem stiku ali kadar se na površju zbira manjša količina vode, to je značilno seveda za ožje stebre, katerih konice štrlijo iz prsti, nastanejo manjši in vijugasti žlebovi. Redke so podtalne fasete, ki praviloma pričajo o prepustnem stiku skale z naplavino, ki jo obdaja. Še več, na stenah stebrov lahko najdemo tudi podolgovate zajede, ki so sled zastajanja vode ob slabše prepustnem delu stika in pospešenega zajedanja skale ob njem.

Skalna površina kamnitih stebrov je tik pod površjem, kjer skalo prekriva prst, razmeroma gladka, globlje, ob stiku z naplavinami, ki prekrivajo površje, pa grobo hrapava, pogosto razčlenjena z manjšimi zaobljenimi štrlinami. Kamnina je namreč preperela, z debelino preperele plasti do 1 cm. Vlažna je mehka, ko pa je dlje časa na površju in iz nje izhlapi voda, potem se strdi. Preperelost povrhnjice kamnine je posledica stika z naplavino, ki je večino časa vlažna. Stik je razmeroma neprepusten, zato voda, ki pronica po njem navzdol, le počasi spira raztopino. Medtem pa je stik s poroznejšo prstjo bolj prepusten.

### 3.2.5 Jame

Razkrite votline so večinoma sled navpičnega prenikanja vode skozi epikraški in vadozni del vodonosnika. Brezna lahko razdelimo na votla (8, 9) in tista, zapolnjena z naplavino, ki jih zaradi podobnosti oblikovanja s podtalnimi skalnimi oblikami, seveda predvsem navpičnimi podtalnimi žlebovi, imenujemo podtalna.

Podtalna brezna (10) so bolj ali manj navpične votline, podobne navadnim breznom, po katerih prav tako prenika voda s kraškega površja, so pa skoraj v celoti zapolnjena z naplavinami, le posamezni navpični odseki so lahko votli. Voda, ki se pretaka skoznje, prinaša in odlaga naplavino, s katero je pokrito površje. Imajo bolj ali manj krožni prečni prerez ali so razpotegnjena ob razpokah in lezikah. Njihov premer

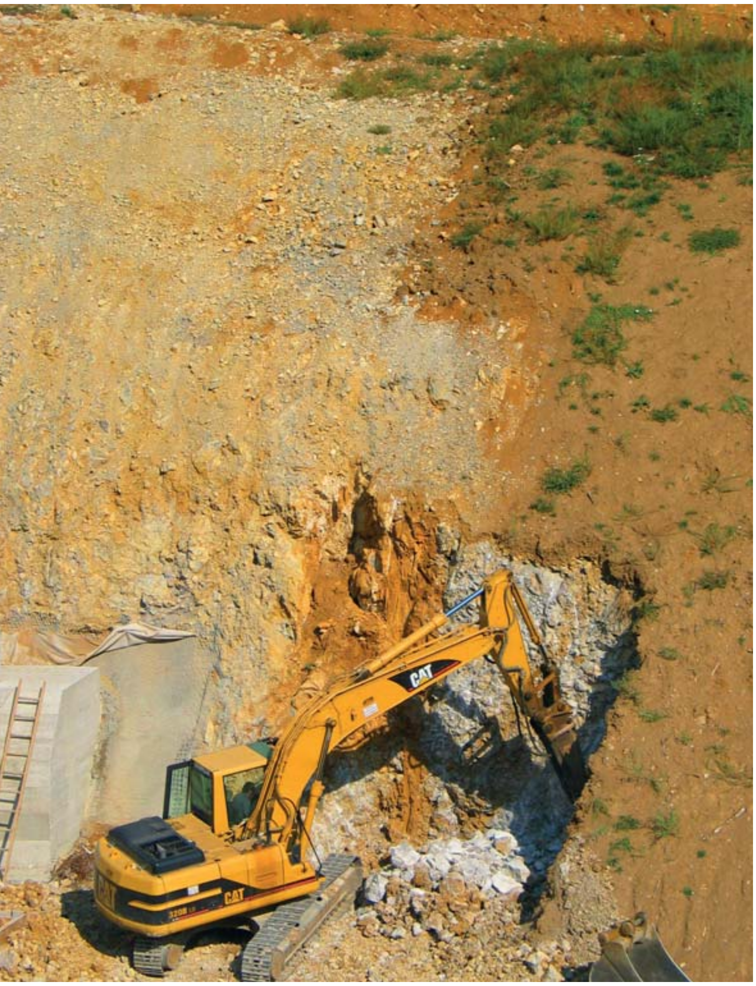
which we are still investigating. Both are dissected by subsoil stone forests.

The subsoil stone forests are composed of a dense network of more or less thick and pointed pillars (6) which reach up to 8, sometimes even 10 m, although mostly they are lower. The narrower pillars, 1–2 m in diameter, have a sharp or rounded spire, while the thickest ones reaching up to 5 m in width have more spires or their tops are composed of more or less curved crests. Among them in most parts are funnel mouths of the perpendicular subsoil channels or horizontal subsoil channels.

Subsoil rock features predominate in the rock relief of the pillars (*Slabe* 1999; *Slabe* and *Knez* 2004), which indicates gravitational flow of water from the surface. These are mainly subsoil channels (7). The most typical are the vertical ones with diameters that can reach up to one metre, the largest of which, as we shall explain below, can also be called subsoil shafts which at the top develop into funnel-shaped mouths. Surface water that flows from the soil along the rocks collects in them. In cross-section the funnel-shaped mouths can take various shapes. They can be open, semicircular or nearly round. Their shapes are often a result of permeability of the rock and sediment contact along which the water flows downwards. Long, drawn-out formations of the mouth at less permeable connections causes the rock features to erode deeper into the rock. The water found its way through the rock less frequently and veritable funnels were shaped. Smaller and curving channels are formed at less permeable connections or when minor quantities of water collect on the surface. This is characteristic for smaller pillars with tops that project out of the earth. Subsoil scallops are rare and generally indicate a well-permeable rock connection with the sediment that surrounds it, and moreover, we find elongated notches on the pillar walls, which are traces of water accumulation at the less permeable part of the connection and accelerated corrosion of the rock next to it.

Close below the surface where rock is covered with soil the rock surface of stone pillars is relatively smooth, while deeper, at the connection with the sediment that covers the surface, it is coarse and often has a configuration of rounded pendants. The rock there

**10** Podtalno brezno, zapolnjeno z drobnozrnato naplavino.
A subsoil shaft filled with fine-grained sediment.



**11** Jama, zapolnjena z drobnozrnatimi naplavinami in sigo.
A cave filled with fine-grained sediment and flowstone.

is weathered. The thickness of the weathered layer measures up to 1 cm. It is soft when moist, but as it dries out after being exposed on the surface for a longer period and the water evaporates from it, it hardens. The state of weathering of the top layer of the rock is the result of the connection with the sediment, which is moist most of the time. The connection is relatively less permeable and the water that does permeate it only slowly washes the solution. The connection with more porous soil is correspondingly also more permeable.

### 3.2.5 Caves

Uncovered hollows are generally a result of vertical water percolation through the epikarst and the vadose parts of the aquifer. Shafts can be classified as hollow (8, 9) and those filled with sediment. The latter are termed subsoil due to similarity of their features with subsoil rock, mainly with vertical subsoil channels.

Subsoil shafts (10) are more or less vertical hollows, similar to ordinary shafts, through which water also percolates from the karst surface, but they are almost entirely filled with sediment, with only individual vertical sections hollow. Water that flows through them deposits sediment that covers the surface. They have more or less round cross-sections or extend at cracks and bedding planes. Their diameters reach 2 m. Sediment filling facilitates the shaping of their periphery, and notches appear at less permeable connections. Subsoil shafts are formed at local dense flow of larger quantities of water. They can develop from subsoil channels. Their walls are carved with along-sediment rock features, which are traces of formation at the connection with fine-grained sediment. With greater permeability in the karst interior, the subsoil shafts can be emptied.

Above-sediment channels often occur on horizontal bedding planes and in cracks, or networks of anastomoses, traces of paragenetic stratification. Thus, temporarily flooded areas occur locally and water which carries fine-grained sediment and deposits cuts its way upwards.

There are few larger caves in the explored area. A few more are found on the higher-lying margins of depressions. As long as the karst water level was closer dosega 2 m. Zapolnjenost z naplavinami omogoča členjenje njihovega oboda, ob manj prepustnih stikih nastanejo zajede. Podtalna brezna nastajajo ob lokalno strnjenem pretoku večjih količin vode. Lahko se razvijejo iz podtalnih žlebov. Na njihovih stenah so obnaplavinske skalne oblike, ki so sledi oblikovanja na stiku z drobnozrnato naplavino. Ob povečani prevodnosti v kraški notranjosti se podtalna brezna lahko izpraznijo.

Ob vodoravnih lezikah in razpokah so pogosto nadnaplavinski žlebovi ali pa mreže anastomoz, sledi paragenetskega členjenja skale. Lokalno torej nastanejo občasno zaliti predeli in voda, ki prenaša drobnozrnato naplavino ter jo odlaga, se vrezuje navzgor.

to the surface, thick Plio-Quaternary sediments undoubtedly hindered karstification deep below the surface (*Gams* 2004). Because the level of underground water in the explored lowland was high and erosion was modest thick layers of weathering material which in the geologic past covered a large part of Slovenian karst remained preserved.

During the main work several caves were uncovered. Some of them were filled with fine-grained sediment (11) and some potholes were empty (12). The diameter of the largest passages reached more than 5 m, they are mostly 1–2 m wide and up to 25 m deep. The rocky circumference of passages was transformed at the contacts with the sediment. The brokenness of the rock is most often reflected in the position and

**12** Jama, oblikovana v pretrti kamnini.
A cave formed in crushed rock.

**13** Špranjasta jama, zapolnjena z drobnozrnato naplavino.
A fissure cave filled with fine-grained sediment.

Večjih jam je na raziskanem območju malo. Nekoliko več jih je na višje ležečih obrobjih uval. Dokler je bila kraška vodna gladina bližje površju, so debeli pliokvartarni sedimenti nedvomno zavirali globinsko zakrasevanje (*Gams* 2004). Na obravnavanem podolju se je zaradi visoke gladine podzemne vode in skromne erozije ohranila namreč debela plast preperine, ki je v triasu prekrivala velik del slovenskega krasa.

Pri zemeljskih delih je bilo odkritih več jam. Del jam je bil zapolnjen z drobnozrnato naplavino (11), medtem ko so bila nekatera brezna votla (12). Največji rovi so dosegli premer prek 5 m, večinoma pa merijo 1–2 m ter so globoki do 25 m. Skalni obod rovov je bil obnaplavinsko preoblikovan. V njihovem položaju in obliki se največkrat odslikava pretrtost kamnine. Tla brezen so pogosto prekrita z naplavino oziroma naplavina zapolnjuje njihov spodnji del.

Posebna vrsta so špranjaste jame (13), ki so nastale ob izrazitejših pokončnih razpokah in prelomih ter sečiščih plasti in tektonskih deformacij. V preseku so bolj ali manj navpične, ponekod tudi vijugaste. V vseh primerih sledijo litotektonskemu stanju kamnine. Širina in prostornina zapolnjenih prostorov v kamnini ustrezata lokalni pretrtosti kamnine. Takšne jame pogosto sledijo ožjim prelomnim conam, iz katerih je material iz notranje prelomne cone odnesen v podzemlje in nadomeščen s površinskim sedimentom. Na stenah teh jam, ki niso širše od metra ali dveh, so še vidne sledi zadnjega premikanja blokov kamnine. Navpično pretakanje ni potekalo samo na eni točki, temveč vzdolž celotne razširitve preloma oziroma vzdolž enake pretrtosti kamnine. Njihova oblika kaže na posebnost razvoja, oblikovale so se kot podnaplavinske votline. Manjše votline so nastale tudi v izrazito v drobne kose pretrti in deloma v brečo sprijeti kamnini in je njihov obod zato grobo hrapav.

## Sklep

Dejstvo je, da je apnenec vzdolž trase dolenjske avtoceste močno tektonsko pretrt v široke porušene in zdrobljene cone. Tukajšnji kras je v primerjavi z jugozahodno Slovenijo, kjer prevladujejo kredni apnenci, razvit v triasnih in jurskih apnencih, prekritih tudi z debelejšo preperino. Najbolj vidni kraški pojavi so

form of passages. The floors of the shafts are often covered by sediment or sediment fills their lower parts.

A special type of cave are fissure caves (13) formed along more perceptible upright fissures and fractures and at intersections of bedding-planes and tectonic deformations. In cross-section they are more or less vertical and sometimes meandering, too. In all cases they conform to the lithotectonic state of the rock. The width and volume of filled spaces in the rock correspond to the local brokenness of the rock. Such caves often follow narrower fault zones from which the interior fault zone material was transported underground and replaced with superficial sediment. On the walls of some caves whose width does not exceed one or two metres traces of the last movement of rock blocks are still visible. Vertical circulation of water did not take place at one point alone but alongside the entire spread of the fracture or alongside the equivalent brokenness of the rock. That is why these caves display a somewhat specific evolution pattern and present-day appearance, they formed as subsedimentary caves. Smaller caves also developed in a markedly broken, atomized and sometimes brecciated rock which explains why their circumference is very rough.

## Conclusion

It is the fact that limestone along the motorway route in Dolenjska lowland is tectonically powerfully deformed and broken into broad demolished and crushed zones. Unlike karst in south-western Slovenia where Cretaceous limestones prevail, this karst developed in Triassic and Jurassic limestones and dolomites which are covered with thicker sediment. The most conspicuous karst formations are swallow holes and estavelles at the bottom of morphologic depressions or uvalas and peaks of stone forests. During the construction work also underground karrens and caves were uncovered. Those that developed at the bottom of valleys and are often flooded by underground streams are of exquisite shapes and have specific rock relief. Old caves through which streams were once flowing testify to the lowering of the level of groundwater, which reaches the surface only in the lowest-lying valleys, and to probable tectonic dissection of the požiralniki na dnu uval in vrhovi kamnitih gozdov. Gradbena dela pa so razkrila tudi podtalne škraplje in jame. Izjemnih oblik so tiste, ki so nastale na dnu podolij in jih podtalne vode pogosto poplavijo. Imajo povsem svojstven skalni relief. Stare jame, skozi katere so se nekoč pretakali vodni tokovi, pričajo o zniževanju gladine podzemeljske vode, ki površje dosega le v najnižjih podoljih. Dobršen del jam je zapolnjen z drobnozrnato naplavino in pod njo tudi preoblikovan. Oblikovanje špranjastih jam, ki so večinoma ob navpičnih razpokah, pa bi lahko opredelili kot podtalno. Voda, ki je širila razpoke v špranje, jih je sproti zapolnjevala z naplavinami.

Skratka, razkrivajo se nam značilnosti plitkega (podzemeljska voda je blizu površja) in z naplavinami pokritega, za Slovenijo svojevrstnega krasa. Te značilnosti bi bilo treba kar v največji meri upoštevati pri nadaljnjih posegih v tukajšnji kras, saj so nam na prvi pogled skrite, vsakršno poseganje v kraška tla pa nam jih razkrije in mnoge od njih (jame, podtalne škraplje ali kamniti gozdovi) so vredne, da jih zaščitimo in ohranimo.

karst surface. A good part of the caves are filled with fine-grained sediment and have been transformed underneath the sediment. The shaping of fissure caves located predominantly along vertical cracks can be defined as having occurred subterraneously. Water widened cracks into fissure caves and at the same time filled them with small-grained sediment.

The characteristics of the shallow (underground water is close to the surface), sediment-covered, specifc type of Slovenian karst are brought to light. These characteristics should be fully taken into consideration in future encroachments upon karst. They are not visible at first sight, but each encroachment on karst reveals them, many of which (caves, underground karrens or stone forests) are worth to be protected and preserved.

# 4

# GRADNJA V ZAKRASELI POBOČNI BREČI IN FLIŠU POD NANOSOM V VIPAVSKI DOLINI

# CONSTRUCTION IN THE KARSTIFIED SLOPES OF BRECCIA AND FLYSCH BELOW MOUNT NANOS IN THE VIPAVA VALLEY

Krasoslovci sodelujemo pri načrtovanju in krasoslovnem spremljanju gradnje slovenskih avtocest (*Kogovšek* 1993, 1995; *Knez* idr. 1994; *Knez* in *Šebela* 1994; *Šebela* in *Mihevc* 1995; *Slabe* 1996, 1997a, 1997b, 1998; *Mihevc* in *Zupan Hajna* 1996; *Mihevc* 1996, 1999; *Kogovšek* idr. 1997; *Mihevc* idr. 1998; *Šebela* idr. 1999; *Knez* idr. 2003, 2004a, 2004b; *Bosák* idr. 2000; *Knez* in *Slabe* 2000, 2001, 2002, 2004a, 2004b, 2005, 2006a, 2006b, 2007, 2009, 2010; *Knez* idr. 2008). Velik del jih namreč vodi po krasu. Naše poslanstvo je razpoznati in razložiti na novo odkrito naravno dediščino, a tudi naša spoznanja, zlasti o prevotljenosti krasa, so pogosto v tehnično pomoč graditeljem cest.

Vipavska dolina leži med visokima kraškima planotama Trnovskim gozdom in Nanosom na severu ter nizko planoto matičnega Krasa na jugu. Nanos je narinjen na fliš. Pod njegovim strmim zahodnim robom se na nagnjenem flišnem pobočju kopiči grušč in strjuje v brečo, v kateri se razvija poseben mladi kras (1).

V brečah, ki leže na nagnjeni neprepustni osnovi fliša, so se razkrili za tovrstni kras značilni in pri nas razmeroma redki kraški pojavi. Razločili smo značilne vrste jam in začetne stopnje razvoja vrtač.

## 4.1 Geomorfološki razvoj terena

Hitra cesta poteka po treh geomorfološko različnih enotah, po jugozahodnih pobočjih Nanosa (Rebrnice in Breg) in po dnu Vipavske doline (2). Pobočja Nanosa – Breg in Rebrnice – so izrazita geomorfološka enota. Posebna geološka narivna zgradba, klimatska prehodnost ozemlja ter posebni pobočni procesi in sedimenti so se tu odrazili v morfologiji pobočij (*Knez* in *Slabe* 2007) in botaničnih posebnostih. Te lastnosti so pripeljale do razglasitve krajinskega parka Južni in zahodni obronki Nanosa. A. Mihevc (2001a) je podrobno geomorfološko kartiral pobočja Nanosa, preko katerih teče hitra cesta v območju krajinskega parka.

Površje pobočja so oblikovali mehansko razpadajoča kamnina in podori, ki so se na flišni podlagi spreminjali tudi v plazove. Razčlenile so ga tudi vode, ki se pretakajo nad flišem (3). Debelina plasti grušča oziroma breče je različna. So pa v breči nastale bolj

Karstologists have cooperated in planning and studying the construction of Slovene expressways (*Kogovšek* 1993, 1995; *Knez* et al. 1994; *Knez* and *Šebela* 1994; *Šebela* and *Mihevc* 1995; *Slabe* 1996, 1997a, 1997b, 1998; *Mihevc* and *Zupan Hajna* 1996; *Mihevc* 1996, 1999; *Kogovšek* et al. 1997; *Mihevc* et al. 1998; *Šebela* et al. 1999; *Knez* et al. 2003, 2004a; *Bosak* et al. 2000; *Knez* and *Slabe* 2000, 2001, 2002, 2004a, 2004b, 2005, 2006b, 2007, 2009, 2010; *Knez* et al. 2008). A large part of the expressway system runs across karst areas. Our mission is to identify and describe the newly discovered natural heritage, and our knowledge, especially about the caves in the karst, is frequently of technical help to road builders.

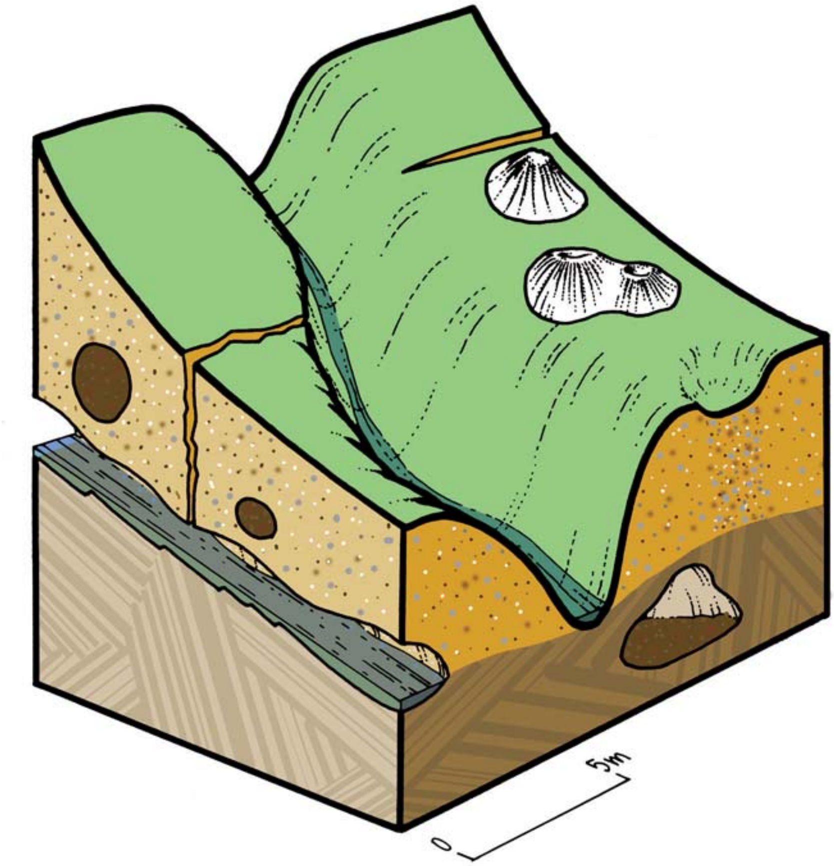
The Vipava valley lies between the high karst plateaus of Trnovski gozd and Mount Nanos to the north and the low plateau of the Classical Karst to the south. Mount Nanos is overthrust on flysch. Below its steep western edge on the sloping flysch, scree material accumulated and consolidated into breccia that developed into a special young karst (1).

Characteristic but for Slovenia relatively rare karst phenomena were discovered in breccia that lies on a sloping foundation of impermeable flysch. We distinguished characteristic types of caves and early stages in the development of dolines.

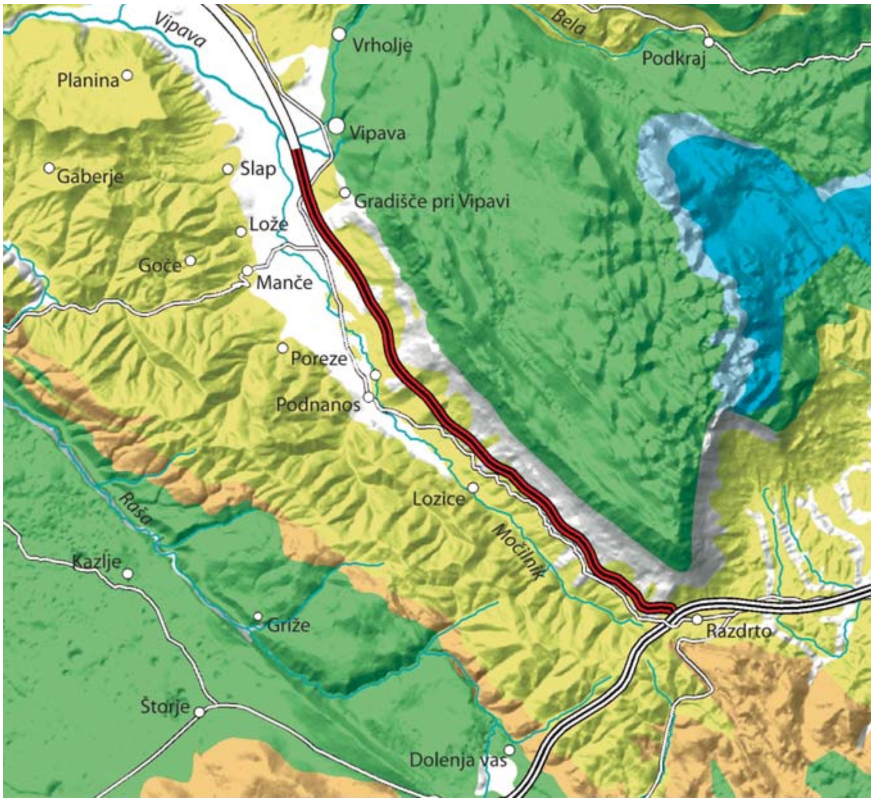
## 4.1 Geomorphological development of the site

The expressway runs across three geomorphologically diverse units along the southwestern slopes of Mount Nanos (Rebrnice and Breg) and the floor of the Vipava valley (2). The Breg and Rebrnice slopes are distinct geomorphological units. A specific geological thrust structure and specific slope processes and sediments are reflected here in the morphology of the slopes (*Knez* and *Slabe* 2007) and in botanical anomalies. These features have led to the proclamation of a landscape park covering the southern and western slopes of Mount Nanos. Mihevc (2001a) geomorphologically mapped the slopes of Mount Nanos in detail over part of the expressway laying out that runs through the landscape park area.

1 Zakraselost breče in fliša na pobočjih Nanosa v Vipavski dolini: s škrapljami na površju, z manjšo vrtačo in s pasom izprane kamnine pod njo ter z jamami v breči, na stiku breče in fliša in v flišu.
Karst in breccia and flysch below Mount Nanos in the Vipava valley: surface karren, with small doline and washed belt of breccia below it and caves in breccia, at its contact with flysch and in flysch.




2 Potek avtoceste po pobočju Nanosa.
Expressway laying out along the slopes of Mount Nanos.



ali manj navpične razpoke, ki kažejo na napetosti v pobočju. Ob gradnji, ko se je trasa globlje zasekala v pobočje, je stik med gruščem, brečo in flišno podlago izkazal izredno krhko ravnotežje. Po obilnih padavinah je po stiku med flišem in brečo, ki so ga razkrili useki, na dan privrela množica manjših vodnih tokov, od katerih je več zajetih za oskrbo z vodo.

Voda bolj ali manj enakomerno razpršeno prenika s površja skozi večinoma dobro prepustno brečo do stika s flišem. Na posameznih mestih v prečnem prerezu breče in grušča pa je že moč jasno razločiti sledi strnjenega prenikanja vode. To so 1–2 m široki pasovi spranega grušča in breče, zametki brezen (4). Nad njimi so nastale majhne vrtače, katerih premer ne presega 3 m in so prekrite s prstjo. Voda s površja prenaša tudi prst z organskim materialom, zato je raztapljanje karbonatne kamnine hitrejše.

Na večjih skalah, ki štrlijo na kraško površje, so skalne oblike, ki jih dolbe deževnica. Najbolj izraziti so žlebiči in škavnice. Za zrelo obliko žlebičev je potrebnih 2000 let razvoja (*Gams* 1990). Torej se površje podorov in plazov na delih pobočja že dlje časa ni izrazito spreminjalo.

## 4.2 Geološke značilnosti

Pobočja Nanosa in Trnovskega gozda so prvi preučevali geologi pri geološkem kartiranju ozemlja. Na pobočjih so podrobno določili stik fliša in apnenca ter razširjenost kvartarnih pokrovov grušča in večjih podorov (*Buser* idr. 1967; *Mlakar* 1969; *Placer* 1981). Raziskani so bili tudi stiki apnencev in flišev na vzhodni strani Nanosa ob robu Pivške kotline (*Čar* in *Juren* 1980). Plazenje grušča in breče je opisal Jež (2007). Mlajša melišča, ki nastajajo pod steno, potiskajo starejši grušč in breče, ki plazijo navzdol. Manj preučevanj je bilo z geomorfološkega vidika. Izrazita pobočja je opisal Melik (1960) v svoji monografiji. Habič (1968) se je lotil pobočja Nanosa v sklopu raziskav visoke kraške planote Nanosa in Trnovskega gozda. Opisal je različne pobočne materiale, grušče, konglomerate, ostanke podorov, večja melišča in vršaje. V Rebrnicah je opazil inverzni relief, pri katerem so debelejše plasti gruščev in breč v nekdanjih grapah, vrezanih v flišno podlago. Grušči in breče so odpornejši, zato so se potoki

The surface of the slopes was formed by the mass movement and mechanical weathering of rock accompanied on the flysch bedrock by landslides. Water that flowed above flysch also dissected the slopes (3). The thickness of the layers of scree material or breccia varies from place to place. More or less vertical fissures developed in breccia that indicate tensions in the slopes. During the expressway construction when the laying out cuts deeply into the slope, the contact between scree material and breccia and the flysch bedrock showed an extremely fragile balance. After abundant precipitation, numerous smaller streams appeared along the contact between flysch and breccias revealed by the cuts. Many of these streams are exploited for water supply.

Water percolates from the surface in a more or less evenly dispersed fashion through mostly well permeable breccia to the contact with flysch. However, in individual places, traces of continuous percolation of water can be clearly seen in the cross-section of breccia and scree material. These are 1–2 m wide belts of washed scree and breccia, the beginnings of shafts (4). Above them, small dolines formed whose diameters do not exceed 3 m and are covered with soil. The water from the surface also carries soil containing organic material that further accelerates dissolving of carbonate rock.

Rainwater has carved rock relief forms on the larger rocks that protrude from the karst surface, the most distinct being flutes and solution pans. Mature flutes take 2000 years to develop (*Gams* 1990). Therefore, the surface of mass movements and landslides on parts of the slopes has not changed significantly for a long time.

## 4.2 Geological characteristics

Geologists first studied the slopes of Mount Nanos and the range of Trnovski gozd during geological mapping of the area. On the slopes they established in detail the contact between flysch and limestone and distribution of the Quaternary cover of scree material and larger mass movements (*Buser* et al. 1967; *Mlakar* 1969; *Placer* 1981). They also studied the contact between limestone and flysch on the eastern side of Mount

**3** Dolina, vrezana v breči nad neprepustnim flišem.
A valley cut in breccia above impermeable flysch.

**4** Začetno obdobje razvoja vrtače.
The early stage of doline development.

Nanos along the edge of the Pivka basin (*Čar* and *Juren* 1980). Jež (2007) described slides of scree material and breccia. The younger talus that formed below the wall pushed older scree material and breccia that slid downwards. Melik described distinctive slopes in his 1960 monograph, and Habič (1968) studied the slopes of Mount Nanos in his examination of the high karst plateaus Nanos and Trnovski gozd. He described various slope materials, scree material, conglomerate, remains of mass movements, and larger talus and fans. In the Rebrnice area he observed inverse relief where there are thicker layers of scree material and breccia in former ravines carved in the flysch bedrock. Around Črniče, Radinja (1962) observed various slope sediments and sliding of slope scree material on flysch and attempted to determine individual genetic types of gravel.

Limestone outcrops in the vicinity of the expressway laying out in only a few places. In the Mlake area at the military firing range, limestone composed of nummulitic breccia has built a smaller elevation between flysch layers. Several smaller areas in the slopes are composed of Cretaceous rudist limestone, for example at Šembijski zatrep above Podnanos and the smaller patch of Cretaceous limestone near Orešje above Lozice.

### 4.2.1 Breccia

In cross-sections of the slope exposed by cuts for the expressway it is frequently possible to observe many layers of scree material and breccia (5). Their total thickness often exceeds 10 m and in individual places exposed during digging foundations for the viaduct pillars even reached 25 m. As a rule, the layers differed relative to the degree of cementation of breccia. Only individual layers were relatively well cemented. The carbonate cement connected scree material in breccia first and most firmly around larger rocks. The excavation work frequently revealed chunks of breccia several $m^3$ in size surrounded by uncemented or poorly cemented scree material. Between the larger and smaller pieces of scree material and rock forming breccia were hollow spaces partly filled with flowstone. The degree of cementation of breccia is therefore the consequence of the age of the mass movements, a pozneje vrezali v nekdanje flišne hrbte. Radinja (1962) je pri Črničah pod Čavnom opazoval različne pobočne sedimente in polzenja pobočnih gruščev na flišu ter poskušal določiti posamezne genetske tipe drobirja.

V bližini trase hitre ceste izdanjajo apnenci le na nekaj mestih. Na območju Mlak, na vojaškem strelišču, gradijo apnenci med flišnimi plastmi manjšo vzpetino iz numulitnih breč. V pobočjih je tudi nekaj manjših območij iz krednega rudistnega apnenca, npr. Šembijski zatrep nad Podnanosom in manjša krpa krednega apnenca pri Orešju nad Lozicami.

### 4.2.1 Breča

V prečnih prerezih pobočja, ki so jih razkrili cestni useki, je bilo pogosto moč razločiti več plasti grušča in breč (5). Njihova skupna debelina je največkrat dosegala 10 m, na posameznih delih, pri kopanju vodnjakov za stebre viadukta, celo 25 m. Praviloma se plasti razlikujejo po stopnjah sprijetosti grušča v brečo. Razmeroma dobro sprijete so bile le posamezne plasti. Karbonatno vezivo povezuje grušč v brečo najprej in najbolj trdno okoli večjih skal. Zemeljska dela so namreč pogosto razkrila več $m^3$ velike gmote breč, okrog katerih je bil še nesprijet ali slabo sprijet grušč. Med večjimi in manjšimi delci grušča ter skalami, ki tvorijo brečo, so votli prostori, delno zapolnjeni s sigo. Sprijetost v brečo je torej posledica starosti podorov, položaja globlje ali plitveje pod površjem, plazenja in lomljenja starejših breč ter značilnosti voda, ki enakomerno prenikajo s površja; le-to je prekrito s tanko plastjo prsti in poraščeno. Breča je na posameznih mestih že, seveda svojevrstno, zakrasela.

Voda, ki je prenikala skozi grušč in ga sprijemala, je s seboj prenašala in še prenaša raztopljen kalcijev karbonat. Vezivo klastov breče na pobočju Nanosa je skoraj izključno karbonatne narave. Breče so večinoma že trdno vezane. Ponekod na površju ali lateralno imajo manjšo trdnost. Kosi v brečah so odlomki senonskih, turonskih in cenomanijskih ter najverjetneje tudi spodnjekrednih apnencev. Spodnjekredne plasti so v zgornji polovici pobočja Nanosa namreč razvite podobno kot zgornjekredni cenomanijski apnenci (*Pleničar* 1970; *Buser* 1973) in zato na kartah niso ločeni med seboj (*Buser* idr. 1967; *Buser* 1968).

deep or shallow position below the surface, sliding and breaking of older breccia, and characteristics of water that percolates regularly from the surface, which is covered by a thin layer of soil and vegetation. Of course, in individual places breccia is already uniquely karstified.

The water that percolates through scree material and breccias carries dissolved calcium carbonate with it. The cement between clasts of breccia on the slopes of Mount Nanos is almost exclusively carbonate in nature. Pieces in breccia are fragments of Senonian, Turonian, and Cenomanian limestone and most probably of Lower Cretaceous limestone as well. The Lower Cretaceous layers in the upper half of the Mount Nanos slopes developed similarly to the Upper Cretaceous Cenomanian limestone (*Pleničar* 1970; *Buser* 1973) and therefore are not shown separately on the maps (*Buser* et al. 1967; *Buser* 1968).

The porosity of breccia varies according to the composition of the material forming it and the local percolation. The material building breccias is of different size, from tiny sand to the blocks of larger dimensions. The most of breccias is very porous and their clasts do not exceed 5–10 cm in diameter. The space between them does not contain any fine material and it is not covered with flowstone. A similar structure is observed in seemingly similar breccias, only their clasts are completely covered with 1–2 mm of layered, mostly porous or white flowstone. There is also no fine material between them. This type of breccia is very porous. Only partially porous breccias formed where water between the clasts brought weathered debris and fewer fine limestone clasts from the surface. In places where fine limestone fragments with the size of sand accumulated between clasts that are several centimetres in diameter, breccia is substantially less porous. It also contains weathered debris cemented in flowstone. In some cases, calcium carbonate in which water deposited major quantities of weathered debris served as a cementing agent to bind the clasts. Even in this case, breccia is poorly or almost non-porous, and the cement is of characteristic red-brown colour. In places, cavities formed between the clasts where the beginnings of larger calcite crystals can be observed.

Poroznost breč se spreminja glede na sestavo materiala, ki breče gradi, in glede na lokalno prenikanje. Material, ki gradi breče, je različnih velikosti: od drobnega peska do blokov metrskih dimenzij. Večina breč je še zelo poroznih. Klasti tam največkrat ne presegajo 5–10 cm premera, med njimi ni drobnega materiala in tudi niso prekriti s sigo. Podobno strukturo kažejo na pogled podobne breče, le da so tam klasti popolnoma prekriti z 1–2 mm plastovite, večinoma prozorne ali bele sige. Med njimi prav tako ni drobnega materiala in je ta breča zelo porozna. Kjer je voda med klaste prinašala tudi preperino s površja, drobnih odlomkov apnenca pa manj, je nastala le delno porozna breča. Na mestih, kjer so se med klaste s premerom nekaj centimetrov vgradili tudi drobci apnenca v velikosti peska, so predeli breče bistveno manj porozni in vsebujejo med sigo vezano preperino. V nekaterih primerih je klaste povezal kalcijev karbonat, med katerega je voda nanašala večje količine preperine. Tudi v tem primeru so breče malo ali skoraj neporozne, vezivo je značilne rdeče rjave barve. Med klasti so se ponekod oblikovale sigaste votline, v katerih lahko opazimo zametke večjih kalcitnih kristalov.

Siga pogosto zapolnjuje manjše prostore med delci kamnine, ki sestavljajo brečo. Kjer je prostor, nastajajo na stropu votlin cevčice. Kadar so sestavni deli breče skale, nastajajo manjše sigaste kope, katerih plastovitost ponekod kaže na sprva zapolnjeno votlino. Na stenah pobočnih razpok pa so rebraste sigaste prevleke. Večje kope sige so bile seveda odkrite v jamah, ki so nastale ob stiku s flišem.

### 4.2.2 Fliš

Pod brečami ležijo flišne plasti (6). Na južni strani Nanosa, na območju pri Razdrtem in v Rebrnicah, upadajo plasti fliša generalno proti severovzhodu. Pri Podborštu, severozahodno od Podnanosa, pa upadajo v isto smer, a so veliko strmejše. Še dlje proti severozahodu, pri Vipavi, so plasti apnenca in tudi fliša že skoraj navpične (7).

V tem delu Rebrnic se v flišnih kamninah prevladujoče menjavajo sivi do črni skrilavi, ponekod masivni laporovci ter apnenčevi in kremenovi peščenjaki.

Flowstone often fills the smaller spaces between the rock fragments that compose breccia. Where there is room, straws form on the ceiling of cavities. When parts of breccia are composed of rocks, smaller flowstone domes form whose stratification in places indicates the originally filled cavity. A ribbed flowstone coating occurs on the walls of slope fissures. Larger domes of flowstone were naturally discovered in caves originating along the contact with flysch.

### 4.2.2 Flysch

Flysch layers lie beneath breccia (6). On the south side of Mount Nanos in the area near Razdrto and in the Rebrnice slope the flysch layers dip generally towards southeast. Near Podboršt, northwest of Podnanos where they dip in the same direction, they slant much more steeply. Farther to the northwest near Vipava, the layers of limestone and flysch are almost vertical (7).

In the flysch rocks the dominant grey to black shale marlstone and massive marlstone alternates with carbonate and quartziferous sandstone. The latter contains a significant amount of carbonate particles and carbonate cement. Occasionally, the almost black marlstone laterally transforms into brown ochre. In most cases, it has a characteristic conchoidal fracture.

In places, we observed that the marlstone layers alternated with thicker layers of dark grey calcarenite, siltstone, and claystone. The clastic rocks have a very steep dip, lying 70°–90° relative to the slope, and the general direction of the dip is towards north or northeast. In places, the layers are subvertical.

The lithological contact between Cretaceous limestone and Eocene flysch runs mainly high up on the slopes of Mount Nanos, mostly around 200 m above the expressway laying out. The contact is morphologically distinct since the slopes are steep or even vertical on limestone and more gently sloping on the flysch rock.

## 4.3 Caves in breccia and flysch

Many characteristic types of caves formed in breccia that developed on steep and dissected flysch slopes. The largest and most frequent are caves that devel-

Slednji vsebujejo znatno količino karbonatnih delcev in karbonatnega veziva. Skoraj črni laporovci lateralno občasno prehajajo v rjavo okraste in imajo večinoma značilen školjkast lom.

Na nekaterih mestih smo med laporovci zasledili debelejše plasti temnosivih kalkarenitov, meljevcev in glinavcev. Klastične kamnine upadajo pod strmimi koti, 70°–90° v pobočje, generalna smer upada pa je proti severu oz. severovzhodu. Upad plasti ponekod prehaja v subvertikalnega.

Litološki stik med krednimi apnenci in eocenskimi fliši poteka v glavnem visoko v pobočjih Nanosa, v večjem delu okrog 200 m nad traso ceste. Stik je morfološko izrazit, v apnencih so pobočja strma ali celo navpična, na flišnih kamninah pa položnejša.

**5** Primer porozne breče (širina slike je 25 cm).
An example of porous breccia (picture width is 25 cm).

## 4.3 Prevotljenost breče in fliša

V breči, ki nastaja na nagnjenem in razčlenjenem flišnem pobočju, se oblikuje več značilnih vrst votlin. Največje in najbolj pogoste so jame, ki so nastale v breči nad stikom s flišem, manjše in največkrat z drobnozrnato naplavino zapolnjene so jame, ki so sredi breče, posebnega porekla pa so razpoklinske jame, prečne na padec pobočja. Sledi strnjenega navpičnega prenikanja vode so manj izrazite. Jame nastajajo tudi v flišu.

Remškar (2006) je zbral podatke o jamah v brečah Vipavske doline ter opredelil vrste jam in njihov nastanek. Deli jih na tiste, ki so nastale ob razpokah, na jame, ki jih je oblikoval vodni tok, in spodmole.

**6** Stik grušča in fliša (širina slike je 4 m).
The contact between scree material and flysch (picture width is 4 m).

### 4.3.1 Votline na stiku breče in fliša

To so najbolj pogosto razkrite votline v tem mladem krasu. Premer manjših rovov meri le decimeter, višina največjih pa dosega 2 m in njihova širina 3 m (8). Največji deli rovov so kupolaste razširitve, ki so ob razpokah ožje in višje. Velikost in oblika prečnega prereza je torej izrazito različna iz metra v meter dolžine rovov. V obliki jame se odslikava različna sprijetost grušča v brečo. Bolj je breča strjena, manjši so v enakih razmerah prečni prerezi rovov. Sestava kamnine narekuje tudi drobno razčlenjenost oboda rovov. Tla jam,

**7** Plasti fliša.
Layers of flysch.

skozi katere se pretaka vodni tok, so flišna, le delno prekrita s kosi grušča, tla suhih jam pa prekrivajo gušč in kope sige, breča namreč razpada. Na obstojnejšem delu oboda so manjši kapniki. Debelejše skorje sige, ki so različno visoko v jamah, pričajo o nekdanjih zapolnitvah z drobnozrnato naplavino.

Največkrat so se odprli posamezni rovi votlin, le ponekod se je razkrila njihova povezanost v vejnato mrežo. Največja jama, ki se je razkrila, je bila dolga 15 m. Njen osrednji del je predstavljal kupolasto razčlenjen rov (9) s premerom kupol do 3 m. Na tleh smo naleteli na večji kapnik. Sledi vode ni bilo zaznati, lahko pa se je precejala manjša količina skozi gušč, ki je večinoma prekrival tla.

Med zemeljskimi deli ohranjeni del jame s stalnim vodnim tokom je bil dolg 10 m, širok 3 m in visok 1,5 m, skozenj pa se je pretakal potoček.

oped in breccia above the contact with flysch, while caves that occur in the middle of breccia are smaller and most often filled with fine-grained sediment. Fissure caves that cross the slopes are of a special origin. Traces of continuous vertical percolation of water are less distinct. Caves also occur in flysch.

Remškar (2006) collected data on caves in breccia in the Vipava valley, specifying types of caves and their origins. He divided them into those that developed along fissures, those formed by streams of water, and rock shelters.

### 4.3.1 Caves at the contact of breccia and flysch

These are the most frequently discovered caves in this young karst. The diameter of smaller tubes

Posamezne votline so zapolnjene s flišno drobnozrnato naplavino. Voda, ki se pretaka na stiku, dolbe flišno podlago in zapolnjuje slabše prepustne dele votlin. Kot kaže, se je del votlin oblikoval ob sprotnem zapolnjevanju z naplavino, ki se je ponekod ohranila, drugod pa je bila spričo povečane prevodnosti votlin odnesena. Sledi nekdanjih zapolnitev so skorje sige, ki so v prečnih prerezih rovov ohranjene različno visoko. Spodnji deli večjih votlin so zajedeni globlje v flišno kamnino.

Pogosto pa so v prečnem prerezu pobočja vidni le manjši strnjeni vodni tokovi, ki še niso izoblikovali izrazitih votlin. Po izdatnejših padavinah so eden ob drugem. To je posledica velike prepustnosti breče in njenega stika s flišem. Fliš se največkrat izkaže kot slabše prepustna kamnina, še posebej njegova zgornja plast, ki je preperela in zaglinjena.

Rovi razkritih jam potekajo vzdolžno s pobočjem. Nastale so zaradi pretakanja vode na stiku breče in fliša, ki ga breča prekriva (10). Voda, ki prenika skozi grušč in brečo, se zbira na nagnjenem flišu. Ob večjih strnjenih tokovih pride do razmer, ugodnih za nastanek jam. Na več mestih je breča odnesena in ob potokih so nastale manjše doline.

**8** Jama na stiku breče in fliša.
A cave at the contact of breccia and flysch.

**9** Kupolasta razširitev jamskega rova (širina slike je 3 m).
A cupola-shaped widening of the cave passage (picture width is 3 m).

## 4.3.2 Votline, zapolnjene z naplavino

Premeri teh votlin ne presegajo enega metra, praviloma so manjši (11). Prerezi votlin so bolj ali manj okrogli oziroma elipsasti, saj so največkrat nastale ob stikih plasti različnih breč in ob razpokah. Najdemo jih v vseh prečnih prerezih breč, predvsem v najbolj strjenih in najmanj poroznih delih. Praviloma so zapolnjene z rjavo naplavino, s prstjo, ki jo voda spira s površja.

Stik med spodnjim flišem in brečo nad njim ni raven, temveč izrazito valovit, tudi drobno razčlenjen. To je posledica pestre geološke sestave fliša in njegovih različno ležečih skladov ter erozijskega delovanja voda, ki so se in se še pretakajo, bodisi na stiku z brečo bodisi v manjših dolinah po flišu. Čeprav je močno porozen kras na pobočju, nastajajo lokalno in občasno manj prepustni odseki, če ne celo zalite cone, v katerih se oblikujejo v breči votline. V njih se odlaga naplavina, predvsem prst, ki jo voda spira s površja, in ob njej se

**10** Jama z vodnim tokom na stiku breče in fliša.
A cave with the water flow at the contact of breccia and flysch.

**11** Jama, zapolnjena z naplavino.
A cave filled with sediment.

measures only a decimetre while the height of the largest ones can reach 2 m and their width 3 m (8). The largest parts of passages are cupola-shaped widenings which are narrower and higher along fissures. The size and shape of their cross-sections varies distinctly from metre to metre along the length of the passage. In places, the shape of the cave reflects different stages of breccia cementation. The more consolidated the breccia, the smaller the cross-sections of passages are in the same conditions. The composition of rock also dictates the fine dissection of the circumference of passages. The floors of caves through which water flows are flysch that is only partly covered with pieces of scree material while the floors of dry caves are covered by scree material and domes of flowstone since breccia tends to disintegrate. There are smaller stalactites on the longer enduring part of the circumference. The thicker layers of flowstone found at various heights in the cave bear witness to times when the caves were filled with fine-grained sediment.

In most cases, individual passages were opened and their connection to a branched network was revealed in only a few places. The largest cave revealed was 15 m long. Its central part was a dome-shaped dissected passage (9). The diameter of the largest dome measured 3 m. On the floor a larger stalagmite had formed. We did not observe any traces of water, but a small quantity of water could percolate through the scree material covering the floor of the cave.

The part of a cave with a permanent stream preserved during the excavation work was 10 m long, 3 m wide and 1.5 m high, and a small stream flowed through it.

Individual caves are filled with fine-grained flysch sediment. Water flowing along the contact carves the flysch bedrock and fills poorly permeable parts of caves. It appears that some of the caves were formed while they were in the process of filling with sediment that is preserved in places and elsewhere was washed away due to the increased conductivity of the caves. Traces of the earlier fillings are found in the flowstone crusts preserved at different heights in the cross-sections of passages. The lower parts of larger caves are carved deeper into the flysch rock.

**12** Špranjaste votline.
Fissure caves.

votline obnaplavinsko širijo. V enem izmed vodnjakov, uporabljenem za temelje mostu, se je začela v breči pojavljati voda več metrov nad stikom s flišem.

### 4.3.3 Špranjaste (razpoklinske) votline

Oblikujejo se ob razpokah, nastalih v breči (12). Praviloma so prečne na naklon pobočja. Največje,

Often, only smaller continuous streams that have not yet formed distinctive caves are evident in the cross-sections of the slopes. After abundant precipitation, they flow side by side. This is the consequence of high porosity of breccia and its contact with flysch. In most cases, flysch proves to be a poorly permeable rock, especially its upper layer which is weathered and clayey.

The passages of the revealed caves run alongside the slope. They occurred due to flowing of water at

**13** Vhod v jamo v flišu.
The entrance to a flysch cave.

dolge tudi več deset metrov in ponekod do meter široke, so dostopne. Večina pa je ožjih in njihova širina ne presega decimetrske velikosti. Globina takšnih jam je pogojena z debelino plasti breče in značilnostjo razpoke. Sooblikuje jih voda, ki prenika vanje. Del jih je zapolnjenih z drobnozrnato naplavino in prstjo, ob kateri se kamnina raztaplja hitreje, del pa ima stene prevlečene s sigo, najmanjše siga lahko tudi zapolnjuje.

### 4.3.4 Prevotljenost fliša

Poleg votlin, ki so se odprle na stiku breč in fliša, smo naleteli tudi na jame, ki so se oblikovale v sklopu flišnih kamnin, na stiku laporovcev in kremenovih peščenjakov ter apnenčevih peščenjakov in kalkarenitov.

Na stikih karbonatne (prepustne) in nekarbonatne (neprepustne) kamnine smo ponekod opazili znatno pretakanje vode. Stik z neprepustno kamnino ni le vodna pregrada, temveč območje, kjer voda lahko zastaja ali njena gladina niha. S tem spira in odnaša material, tam prihaja do spremembe pritiskov in voda lahko oblikuje večje kanale. Po teh poteh se prenašajo tako apnenec kot flišni delci.

Poleg tega smo že na več mestih ugotovili, da se v flišnih kamninah prav tako oblikujejo sicer manj številni podzemni prevodni kanali. Kjerkoli so flišne

the contact of breccia and flysch which breccia covers (10). The water permeating through scree material and breccia congregates on the sloping flysch. Conditions for the formation of caves occur along larger continuous streams. Breccia was carried away in a number of places, and smaller valleys formed alongside the streams.

### 4.3.2 Sediment-filled caves

The diameters of these caves do not exceed one metre, and as a rule they are smaller (11). The cross-sections of the caves are more or less circular or elliptical in shape because they usually formed along the contacts between layers of different types of breccia and along fissures. They are found in all the cross-sections of breccias, but primarily in the most consolidated and least porous parts of breccia. As a rule they are filled with brown sediment, the soil washed from the surface by water.

The contact between flysch at the bottom and breccia above is not flat but distinctly undulating and finely dissected. This is the consequence of the diverse geological structure of flysch, its variously lying layers, and the erosive action of water that has flowed and continues to flow either on the contact with breccia or in smaller valleys on flysch. Even though there is very porous karst on a slope, less permeable sections, sometimes even flooded zones, form locally and occasionally where caves form in breccia. Sediments, mainly soil washed from the surface, are deposited in them, and the caves widen along-sediment. In one of the wells used as a foundation for a bridge, water began to appear in breccia several metres above the contact with flysch.

### 4.3.3 Fissure caves

Fissure caves form along fissures that developed in breccia (12). As a rule they cross the dip of the slopes. The largest caves which are several metres or even several dozen metres long, and in places up to one metre wide are accessible. Most, however, are narrower and do not exceed one decimetre in width. The depth of such caves is conditioned by the thickness of the breccia layers and the characteristics of the fissure. They plasti razlomljene ali nagubane, se po razpokah ali razmiku med plastmi pretaka voda. Močno pretakanje vode je, tudi zaradi ponekod skoraj vertikalnih plasti, po medplastnih stikih. Voda, ki se pretaka po teh stikih, odnaša flišni material, širi razpoke in hkrati obdobno ali lateralno različno odlaga kalcijev karbonat. Pogosto vidimo tudi več centimetrov debele kalcitne zapolnitve razpok. Razpoke so ponekod že popolnoma zapolnjene, drugod so v razpokah do 1 cm veliki skalenoedrični kalcitni kristali, veliko razpok je prekritih s tanjšo (nekaj mm) plastjo sige. V laporovcih, ki se lomijo izrazito školjkasto, je več razpok že zapolnjenih z debelokristalnim kalcitom. Pomembno je poudariti, da je vezivo karbonatno in da je v marsikateri plasti lahko tudi znatno več kot 10 % delcev karbonatnega izvora. Med pretakanjem vode skozi razpoke in vzdolž prelomov torej ne poteka le erozija, temveč tudi korozija. Nedvomno pa zakrasevanje poteka v zelo majhnem obsegu.

Vzdolž razpok in prelomov, po katerih se pretaka padavinska in površinska voda, prihaja do močnega preperevanja kamnine v notranjost nepretrtega bloka. Po večini takšnih stikov se izloča kalcijev karbonat (siga).

Relativno večje votline, značilne za te kamnine, so bile globoke in široke le do 5 m. Nastale so na stiku laporovcev in kalkarenitov (13). Ena značilnejših se je odprla severno od predora Tabor, kjer so do 0,5 m debele plasti laporovcev temnosive do črne barve, ki imajo zaradi svoje kompaktnosti dobro opazen školjkast lom. Kalkareniti so močno pretrti, tako da številne kalcitne žilice še dodatno povečujejo vsebnost karbonata. Ker imajo plasti upad okrog 70°–90°, voda z lahkoto prehaja med plastmi, razmaknjenimi zaradi tektonskega zmika. Kljub temu da deževnica intenzivno raztaplja kalkarenitne plasti, pa zaradi zdrobljene kamnine tu ne nastajajo večje votline ali celo jame.

## Sklep

Raznovrstnost slovenskega krasa, tako geološka, geomorfološka, speleološka in hidrološka, se je izkazala tudi pri preučevanju zakraselosti breč, ki nastajajo pod zahodnim pobočjem Nanosa. Voda, ki večinoma razpršeno prenika skozi prepustno površje grušča ali breče do bolj ali manj neprepustne flišne podlage, ustvarja mlade kraške pojave.

are shaped by the water percolating in them. Some of these caves are filled with fine-grained sediments and soil where the rock dissolves more rapidly, and the walls of other caves are coated with flowstone. The smallest caves can be completely filled with flowstone.

### 4.3.4 Caves in flysch

In addition to caves that opened at the contact of breccia and flysch, we also encountered caves that formed in the framework of flysch rock at the contact of marlstone and quartziferous sandstone and of carbonate sandstone and calcarenite.

In some places we observed significant water flow at the contact of carbonate and non-carbonate rock. The contact with non-carbonate rock is not only a water barrier but also an area where water can stagnate and where its level can fluctuate. This causes washing and carrying away of material, changes in pressure can occur here, and water can form larger channels. Both limestone and flysch particles are transported along these paths.

In addition, we determined in many places that a small number of underground conducting channels had formed in the flysch rock. Wherever the flysch layers are fractured or folded, water flows along the fissures or spaces between the layers. There is a flow of water along the interbedded contacts due to the almost vertical layers. Water flowing along these contacts carries away flysch material, widens the fissures and simultaneously periodically or laterally deposits calcium carbonate in different ways. We can frequently observe calcite fillings of fissures that are several centimetres thick. In places the fissures are completely filled, elsewhere up to one centimetre large scalenoedric calcite crystals formed in the fissures, and a number of fissures are covered by a thin (a few mm) coat of flowstone. In marlstone with distinctly conchoidal fractures, a number of fissures have been filled with coarse-crystal calcite. It is important to emphasize that the cement is carbonate and that a number of layers can contain much more than 10 % of particles of carbonate origin. Therefore both erosion and corrosion occur when water flows through the fissures and along the faults. There is no doubt that karstification takes place to a very small extent.

Večje skale na kraškem površju deževnica prekriva z žlebiči in škavnicami. Razpoke, ki kamnino prečijo vzdolžno s pobočjem, pa kažejo na napetosti v kamninski gmoti in izpostavljenost plazenju. Breča in grušč ležita namreč na nagnjenem flišu in na stiku z njim se pretaka večina voda, kar povzroča njegovo nestanovitnost.

Na delih najbolj strnjene breče se prenikajoča voda združuje. Zemeljska dela so nam razkrila začetna obdobja oblikovanja svojevrstnih vrtač in brezen.

V mladi in le mestoma strjeni in močno porozni breči, ki leži na bolj ali manj nagnjenem flišu, torej na neprepustni osnovi, so se razvile značilne vrste votlin. Prave kraške votline so majhne in na njihov razvoj je vplivala naplavina, ki jih praviloma zapolnjuje. Nastale so v lokalno in občasno poplavljeni coni, pogosto so paragenetsko povečane. Največje votline so nastale nad stikom z neprepustno flišno podlago, na kateri so se zbrali večji vodni tokovi. V njihovi obliki se odraža tudi raznovrstna strjenost breče. V delih manj kompaktne breče in ob razpokah so povišane v kupole. Ob razpokah, ki so posledica drsenja breče in grušča po nagnjeni podlagi pogosto razmočenega fliša, so prečno na smer padca pobočja nastale špranjaste votline, nekatere zelo dolge in ponekod dovolj široke, da so dostopne. Njihove stene so praviloma prekrite s sigo.

Zakrasevanje v zelo majhnem obsegu poteka tudi znotraj flišnih plasti, kjer laporovci ali peščenjaki vsebujejo vsaj kalcitno vezivo. Pomembnejše pa je zakrasevanje na stikih laporovcev in kalkarenitov, kjer nastajajo votline nekajmetrskih dimenzij. Voda ob marsikje skoraj navpičnih plasteh hitro prenika v podzemlje, zaradi močno pretrtih plasti pa ne nastajajo večje jame.

Čeprav je opisani kras razmeroma mlad, razkrit v začetnih razvojnih obdobjih, nam razkriva vse značilnosti zakrasevanja breče v značilnih geoloških, geomorfoloških in hidroloških razmerah. Obenem širi naše poznavanje raznovrstne slovenske kraške naravne dediščine in je podlaga za nadaljnje načrtovanje posegov v okolje.

Heavy weathering of the rock in the interior of the tectonically undeformed block of rock occurs along fissures and faults where the precipitation and surface water flow. Calcium carbonate (flowstone) is deposited at the majority of such contacts.

Caves formed at the contact of marlstone and calcarenite (13). One of the more characteristic caves of this type, measuring up to 5 m in depth and width, opened to the north of the Tabor tunnel at the northwestern part of laying out. Here there are layers of dark grey to black marlstone up to 0.5 m thick that due to their solidity have a clearly visible conchoidal fracture. The calcarenite is heavily fractured so that numerous calcite veins further increase the content of carbonate. Because the layers have a dip 70°–90°, water passes easily between them. Although the calcarenite layers are being intensely dissolved by rainwater, larger cavities or even caves do not form due to the fractured rock.

## Conclusion

The geological, geomorphological, speleological, and hydrological diversity of Slovene karst has been demonstrated also by the study of karstification of breccia that formed beneath the western slopes of Mount Nanos. Water, in most cases percolating diffusely through the permeable surface of scree material or breccia to the more or less impermeable flysch bedrock, creates young karst phenomena.

Rainwater covers large rocks on the karst surface with flutes and solution pans. Fissures crossing the rock alongside the slope indicate tensions in the rock mass and its exposure to sliding. Breccia and scree material lie on slanting flysch, and the majority of water flows along the contact causing its instability.

The percolating water collects where breccia is most consolidated. Earthworks have revealed the early stages in the formation of unique dolines and shafts.

Characteristic types of caves developed in the young and very porous breccia which is consolidated only in places lying on the more or less slanting flysch, an impermeable bedrock. The true karst caves are small and their development was influenced by the sediment that as a rule fills them. They formed in a locally and periodically flooded zone and they are often paragenetically enlarged. The largest caves formed above the contact with the impermeable flysch bedrock where the largest streams join. Their shape reflects the varying degrees of consolidation of breccia. In areas where breccia is less solid and along fissures they rise into domes. Along fissures that are the consequence of sliding of breccia and scree material down the slanting bedrock of frequently saturated flysch, fissure caves formed across the slope; some of them are very long and wide enough in places to make them accessible. As a rule, their walls are covered with flowstone.

To a very small extent, karstification also takes place inside flysch where marlstone or sandstone contains at least calcite cement. Karstification at the contacts of marlstone and calcarenite where caves several metres in size form is more significant. In places with almost vertical layers, water quickly percolates into the underground, but the heavily fractured layers hinder the formation of larger caves.

Although the described karst is relatively young, discovered in its early development stages, it still reveals all the characteristics of the karstification of breccia in characteristic geological, geomorphological, and hydrological conditions. Learning about it expands our knowledge of Slovenian diverse natural karst heritage and forms the basis for future planning of interventions in the environment.

# UREJANJE JAM ZA TURISTIČNE NAMENE

# ARRANGING CAVES FOR TOURISTIC PURPOSES

# 5

# STROKOVNI NADZOR IN SVETOVANJE PRI UPRAVLJANJU Z JAMSKIMI SISTEMI: PRIMER POSTOJNSKEGA JAMSKEGA SISTEMA

# PROFESSIONAL SUPERVISION AND CONSULTING IN THE MANAGEMENT OF CAVE SYSTEMS: AN EXAMPLE OF THE POSTOJNA CAVE SYSTEM

V okviru projektov »Strokovni nadzor in svetovanje pri upravljanju z jamskimi sistemi«, »Klimatski in biološki monitoring jamskih sistemov« (financer Postojnska jama d.d.) ter »Meritve in analiza izbranih klimatskih parametrov v kraških jamah: primer sistema Postojnskih jam« (L6-2156, ki ga sofinancirajo Javna agencija za raziskovalno dejavnost RS (ARRS), Postojnska jama d.d. in Meiss d.o.o.) od leta 2009 opravljamo vlogo jamskega skrbnika v Postojnskem in Predjamskem jamskem sistemu.

V kratkoročnem programu (2009–2013) rabe naravne vrednote Postojnski jamski sistem so med najpomembnejšimi deli jamskega skrbnika zapisani: klimatski in biološki monitoring, monitoring lampenflore, redno obveščanje Zavoda RS za varstvo narave, OE Nova Gorica, o izvajanju koncesije in stanju jame, izdelava sanacijskih programov za odpravo posledic vpliva rabe naravne vrednote, opozarjanje na zunanje dejavnike ogrožanja jame, spremljanje večjih posegov in prireditev v jami ter nadzor nad njimi, evidenca raziskav in popis posegov v jamo.

V dolgoročnem programu (2009–2028) rabe obeh naravnih vrednot so v okviru del jamskega skrbnika predvideni tudi naravovarstveni ukrepi, upoštevajoč rezultate petletnega opazovanja in monitoringa jamske klime in favne.

Biološki monitoring v Postojnskem jamskem sistemu kaže na pomembnost varovanja bogate podzemeljske favne in spremlja obstoječe stanje.

Kot jamski skrbnik smo dosegli izvajanje popisa kulturne dediščine v jamskem sistemu, kar je bilo izvedeno v začetku leta 2011. Pripravili smo tudi nekaj strokovnih mnenj o vplivu postavitve biološke čistilne naprave v Koncertni dvorani. Postavlja se več pomembnih vprašanj o obratovanju čistilne naprave za odpadne vode v jami, predvsem pa je nujno njegovo temeljito spremljanje.

Velik vir prahu v Postojnskem jamskem sistemu je posipanje tirov, zato bi bila nujna obsežna sanacija železnice v jami.

Vseskozi redno delamo zapisnike naših obiskov z opisi opazovanj in ugotovitev o upravljanju jamskega sistema in imamo tudi redne sestanke o perečih in običajnih zadevah s koncesionarjem in predstavniki Zavoda RS za varstvo narave, OE Nova Gorica.

Since 2009 the Karst Research Institute (IZRK) ZRC SAZU has had the role of a cave custodian for the Postojna and Predjama cave systems. This duty is performed within the projects »Expert control and recommendations for the management of cave systems«, »Climatic and biological monitoring of cave systems« (financed by Postojnska jama d.d.) and »Measurements and analysis of selected climatic parameters in karst caves: example of the Postojna cave system« (L6-2156, cofinanced by Slovenian Research Agency (ARRS), Postojnska jama d.d. and Meiss d.o.o.).

Among the most important tasks included in the short-term programme (2009–2013) for use of the natural asset Postojna cave system are: climatic and biological monitoring, lampenflora monitoring, regularly informing the Nova Gorica Regional Unit of the Institute of the Republic of Slovenia for Natural Conservation regarding the implementation of the concession contract and the state of the cave, implementing improvement programmes for elimination of impacts caused by the use of the natural asset, calling attention to external factors that can harm the cave, monitoring and supervision of large-scale interventions and performances in the cave, and providing evidence of research and an inventory of interventions in the cave.

Within the long-term programme (2009–2028) for the use of the natural asset the role of the cave custodian also includes natural protection precautions based on the results of five-year monitoring of the cave climate and fauna.

Biological monitoring in the Postojna cave system reflects the importance of protection of the rich underground fauna and requires monitoring their existing status.

In the beginning of 2011 the cave custodian carried out an inventory of cultural heritage in the cave. Expert opinions were prepared regarding the impact of setting up a biological cleaning station inside the hall Koncertna dvorana, in anticipation of important issues that could arise from operation of the cleaning station for waste waters inside the cave. It is therefore necessary to organize a fundamental monitoring system for water quality.

Finally, sanding of the train lines is a large source of dust in the Postojna cave and requires extensive improvement of the railway in the cave.

**1** Postojnski jamski sistem, kapniška simbola Briljant in Diamant.
The Postojna cave system, speleothem symbols 'Briljant' (Brilliant) and 'Diamant' (Diamond).

**2** Lepe jame, Postojnski jamski sistem.
Lepe jame, the Postojna cave system.

## 5.1 Monitoring v Postojnskem jamskem sistemu

### 5.1.1 Načrt klimatskega monitoringa

Leta 2009 je bil izdelan načrt klimatskega monitoringa z namenom spremljanja možne spremembe rabe jamskega sistema v turistične namene, predvsem pa ugotavljanja vpliva rabe na jamsko klimo. Zato je bilo takoj treba začeti s sistematičnim merjenjem osnovnih parametrov jamske klime (temperature zraka, vlage in deleža $CO_2$ v zraku ter gibanja zraka). Klimatski monitoring je v kratkoročnem načrtu predviden za obdobje 2009–2013. Z njim nameravamo ugotoviti značilnosti jamske klime v posameznih jamskih segmentih, spremljati človekove posege in rabo jame v turistične namene oziroma izdelati letna poročila o stanju okolja v jami.

### 5.1.2 Načrt biološkega monitoringa

Pri načrtu biološkega monitoringa so sodelovali Slavko Polak (Notranjski muzej, Postojna), Tanja Pipan (IZRK ZRC SAZU) in predstavniki Zavoda RS za varstvo narave, OE Nova Gorica. Osnovni namen je ugotoviti trenutno stanje in izdelati inventar jamskih živali, ki občasno živijo v jami, pomembnem habitatu v njihovem življenjskem ciklu. Potrebno je opazovanje različnih vrst jamskih živali kot pokazateljev splošnih sprememb v celotnem jamskem sistemu.

Predstavniki Zavoda RS za varstvo narave, OE Nova Gorica, so predlagali še eno lokacijo monitoringa v jami, in sicer tam, kjer poteka čiščenje kapnikov, zlasti zaradi alg, tako da bi obenem preučili tudi vpliv čiščenja kapnikov na jamsko živalstvo (npr. v Lepih jamah).

V obdobju 2011–2013 naj bi bile izdelane smernice za dolgoročno ohranitev podzemeljske favne in trajnostno naravnan razvoj turizma.

V biološki monitoring je vključen tudi monitoring favne v prenikli vodi. Določene vrste lahko uporabimo za indikatorske vrste pri presoji vplivov na okolje. Sistematične študije v sistemu Postojnske

The cave custodian writes regular records of cave visits, with observations and findings about management of the cave system. Regular meetings about general and urgent matters are organized with the concessionaire and representatives of the Nova Gorica Regional Unit of the Institute of the Republic of Slovenia for Natural Conservation.

## 5.1 Monitoring in the Postojna cave system

### 5.1.1 Plan for climatic monitoring

The plan for climatic monitoring was prepared in 2009. Its intention is to monitor long-term changes in the cave due to touristic use of the cave system, and especially tourist impact on the cave climate. For this purpose in 2009 we began systematic monitoring of basic parameters of the cave climate (air temperature, humidity, $CO_2$ in the air and air circulation). Climatic monitoring is mandated within the short-term programme 2009–2013. The intention is to observe the characteristic cave climate for the selected cave segments, to quantify human impacts that attend the use of the cave for touristic purposes and to formulate an annual report regarding the state of the cave environment.

### 5.1.2 Plan for biological monitoring

The plan for biological monitoring was developed as collaboration by Slavko Polak (Notranjska Museum, Postojna), Tanja Pipan (IZRK ZRC SAZU) and representatives of the Nova Gorica Regional Unit of the Institute of the Republic of Slovenia for Natural Conservation. Its principal intention is to determine the current state of the cave ecosystem and to make an inventory of cave animals that occasionally live in the cave and for which the cave represents an important habitat for their life cycle. It is important to monitor different species of cave animals as indicators of general changes in the whole cave system.

Representatives of the Nova Gorica Regional Unit of the Institute of the Republic of Slovenia for Natural Conservation suggested adding another monitoring jame so bile že opravljene in večina vrst kot indikatorjev je že določenih (*Culver* in *Pipan* 2009).

Z Zavoda RS za varstvo narave, OE Nova Gorica, so za biološki monitoring priporočili še naslednje:

- k monitoringu naj se dodata bakteriološki monitoring in monitoring indikatorskih vrst makroinvertebratov reke Pivke v povezavi z javnim straniščem v Koncertni dvorani. Stranišče je bilo leta 2011 opremljeno z biološko čistilno napravo. Zato naj bi spremljali stanje kakovosti vode podzemeljske Pivke na ponoru ter v Spodnjem Tartarju in sifonu v Pivki jami;
- izvede naj se monitoring vnosa organskih snovi v jamo v povezavi s turisti (uvedba 'predpražnikov' za turiste, ki vstopajo v jamo) in z železnico (leseni železniški pragovi morajo biti ustrezno sanirani oziroma zamenjani).

### 5.1.3 Rezultati spremljanja jamske klime

Postojnski jamski sistem (20.570 m) je najdaljša in najbolj obiskana kraška jama v Sloveniji (1, 2). Jamo je leta 2010 obiskalo skoraj 500.000 obiskovalcev. Gre za vrednoto državnega pomena, saj je jama vpisana v Register naravnih vrednot (*PrDVNV*, 2004) pod ident. št. 241. Postojnska jama d.d. v okviru koncesijske pogodbe upravlja z jamo do leta 2028.

Jamsko klimo smo začeli redno spremljati leta 2009. Po dveh letih merjenja z različnimi inštrumenti se je pokazalo, da najbolj ustrezajo najbolj natančne naprave.

Na več lokacijah opravljamo merjenje temperature, in sicer z različnimi merilnimi inštrumenti, kakor tudi merjenje zračnega tlaka, relativne vlage, $CO_2$ in vetra (3). Interval merjenja temperature zraka je največkrat vsako uro, občasno pa merimo tudi v manjših intervalih. V manjši ponvici z vodo v Lepih jamah, tik ob turistični poti, merimo temperaturo vode in tlak vsako uro. Želimo ugotoviti možno spreminjanje temperature vode v ponvici zaradi povečanega turističnega obiska. V Lepih jamah, ob turistični poti, občasno (ob prireditvah Jaslice, Velikonočni prazniki, Prvomajski prazniki, 'Ferragosto') merimo koncentracijo $CO_2$ v zraku. Ob večjem številu obiskovalcev se običajne vrednosti $CO_2$ od dva- do trikrat povečajo (*Gabrovšek*

location in part of the cave where cleaning of algal growth from flowstone is organized (for example in the passage Lepe jame). In this way the impact of flowstone cleaning on the cave animals can be studied.

In the period 2011–2013 guidelines for long-term preservation of the underground fauna and sustainable development of tourism will be prepared.

Monitoring of fauna in percolated waters is included within the biological monitoring. Certain species can be used as indicator species for estimation of impacts on the environment. Systematic studies in the Postojna cave system have already been accomplished and most indicator species have already been defined (*Culver and Pipan 2009*).

Additional recommendations for biological monitoring from the Nova Gorica Regional Unit of the Institute of the Republic of Slovenia for Natural Conservation include:

- bacteriological monitoring and monitoring of the indicator species of macroinvertebrates of the Pivka river in connection with the public toilets in the hall Koncertna dvorana must be included. The toilets were reconstructed and in 2011 the biological cleaning station began treating waste waters. Thus monitoring of the quality of the underground river Pivka at the ponor, in the Lower Tartarus passage and at the Pivka cave syphon must be performed;
- monitoring of organic material input into the cave in connection with tourists (with introduction of 'door-mats' for tourists who enter the cave) and with the railway (wooden train cross-ties must be suitably improved or changed).

### 5.1.3 Results of the cave climate monitoring

The Postojna cave system (20,570 m) is the longest and most heavily visited karst cave in Slovenia (1, 2). In 2010 the cave received nearly 500,000 visitors. The cave is an asset of state importance listed in the Register of natural assets (*PrDVNV*, 2004) under the ident. no. 241. The company Postojnska jama d.d. is managing the cave within a concession contract up to the year 2028.

idr. 2010, 2011). Obenem smo zasledili tudi zvišanje temperature zraka. Ko se povečan obisk vrne v normalne okvire, tudi vrednosti $CO_2$ in temperature spet dosežejo prvotno stanje.

V Postojnskem jamskem sistemu na štirih točkah zvezno merimo tlak in temperaturo (3). Na Veliki gori je najvišja temperatura izmerjena v obdobju poletje–jesen, medtem ko je na točki 2 (Postojna 2) v tem obdobju najnižja temperatura. Merilna točka na Veliki gori leži 561,4 m nad morjem, točka v stranskem rovu pri Lepih jamah (Postojna 2) pa 526 m (*Šebela* in *Turk* 2011a, b). Na slednji gre za obratno korelacijo med temperaturo površja in jame, kar pomeni, da so tu najnižje temperature poleti in najvišje pozimi. Postojna 2 predstavlja kraj, ki je verjetno povezan s površjem preko odprtih razpok na razdalji 58 m, v ozadju pa bi lahko bili tudi neznani rovi (*Šebela* in *Turk* 2011a).

Merilna točka Postojna 3 v Lepih jamah leži samo 3–4 m stran od turistične poti ter predstavlja vmesno klimatsko situacijo med razmerami na Veliki gori in v stranskem rovu pri Lepih jamah. Krivulja letnega trenda temperature je na tem mestu, generalno gledano, dokaj konstantna.

V času prireditve Jaslice v Postojnski jami (predstave v dneh od 25.–28. decembra 2009 ter 2. in 3. januarja 2010 ob 14:00, 15:00 in 16:00) smo inštrumenta za merjenje temperature in tlaka na točkah 2 in 3 namestili na vsakih 15 minut (3). Tako smo dobili natančnejšo odvisnost od močno povečanih obiskov v jami. Predvsem na točki 3, ki je v neposredni bližini turistične poti, je bil opazen dvig temperature v dneh, ko se je odvijala prireditev. Dvig temperature zaradi povečanega obiska (25.–28. decembra 2009) je bil za okrog 0,3 °C. Nato se je do 2. januarja 2010 temperatura spet povrnila v stanje pred tem.

Po podatkih Postojnske jame d.d. je bilo decembra 2009 v Postojnski jami 15.198 obiskovalcev, novembra pa 9.524; pri tem si je prireditev Jaslice v Postojnski jami ogledalo 10.530 obiskovalcev v šestih dneh. Povišanje temperature za okrog 0,3 °C torej lahko pripišemo temu povečanemu številu obiskovalcev.

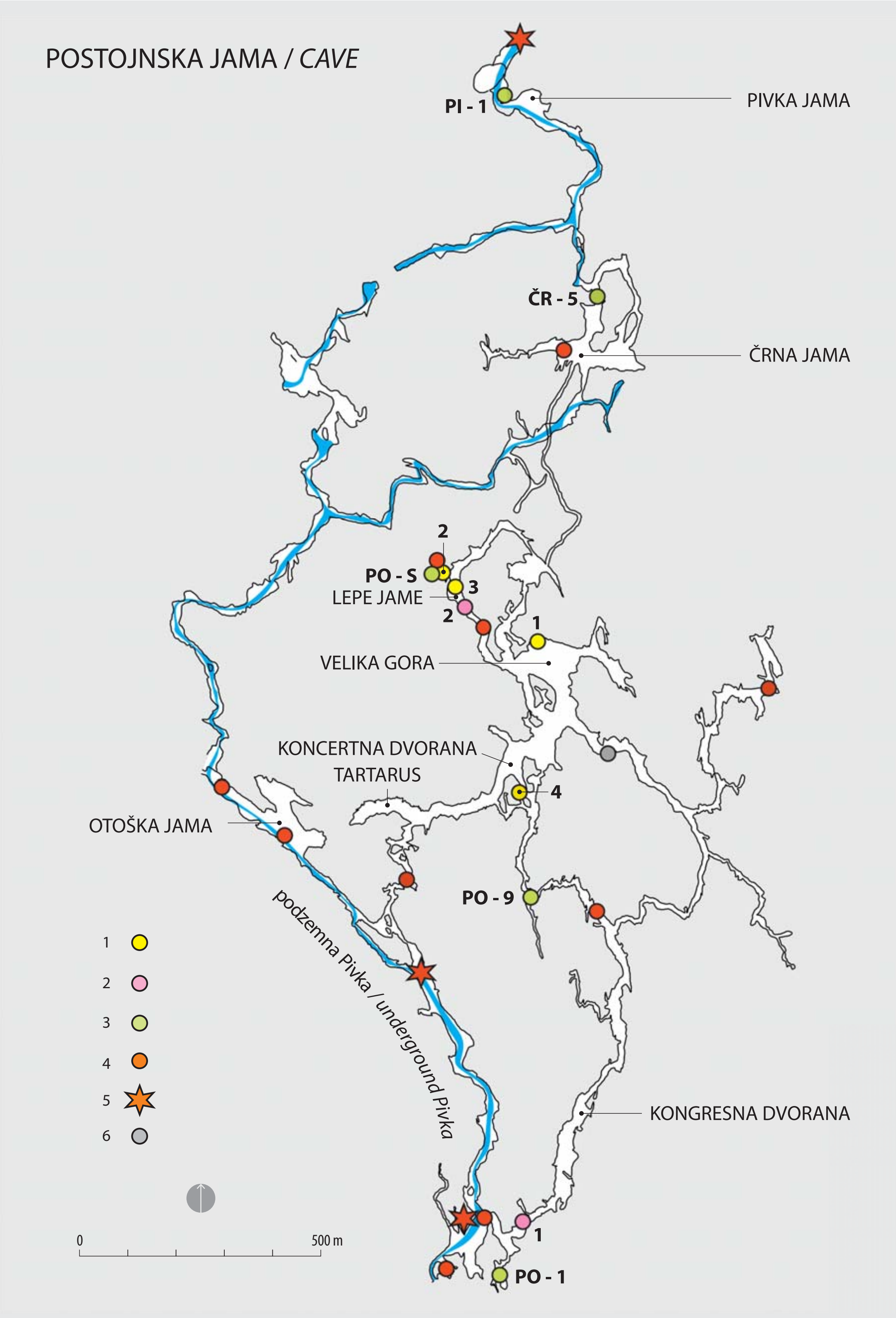
Leta 2010 smo nadaljevali s klimatskim monitoringom na podlagi rezultatov iz prejšnjega leta in ga razširili še z dvema meteorološkima postajama (3, 4, 5). Dejstvo je, da na obeh merilnih postajah v gibanju

We began regular monitoring of the cave climate in 2009 using various instruments. After two years of monitoring it is clear that the most suitable instruments are the most precise ones.

At many locations the air temperature monitoring is conducted with different instruments, as well as the monitoring of air pressure, relative humidity, $CO_2$ and wind (3). The measuring interval for air temperature is generally every hour; ocassionally data are taken at shorter intervals. In a small flowstone pool with water in the part Lepe jame, just at the tourist path, the water temperature and air pressure are measured hourly. The goal of these measurements is to detect possible increases in water temperature due to increased tourist visits. In Lepe jame, near the tourist path, the $CO_2$ concentration in the air is measured occasionally (during performances at Christmas, Easter and First of May holidays and *Ferragosto*). With higher visitor numbers the $CO_2$ concentration increased above regular values by two- to three times (*Gabrovšek* et al. 2010, 2011). At the same time the air temperature slightly rose. After the number of visitors returned to normal values, the $CO_2$ and temperature returned to previous values, too.

Continuous measurements of pressure and temperature are conducted at four monitoring sites in the Postojna cave (3). In the hall Velika gora the highest detected temperature was in the period of summer–autumn, while at the sampling point no. 2 (Postojna 2) it was the lowest in the same period. The measuring site at Velika gora is situated at 561.4 m a.s.l. while the other site in the side passage near Lepe jame (Postojna 2) is at 526 m a.s.l. (*Šebela* and *Turk* 2011a, b). Here an inverse correlation between outer and cave temperature takes place what means that at the site Postojna 2 the lowest temperatures are in summer and the highest in winter. This site is probably connected with the surface by open fissures over a distance of 58 m; in the background there may be unknown passages as well (*Šebela* and *Turk* 2011a).

The measuring site in Lepe jame (Postojna 3) is situated only 3–4 m from the tourist path. This site represents a climatic situation in between conditions in the hall Velika gora and the side passage near Lepe jame. The annual temperature at this site is generally rather constant.


POSTOJNSKA JAMA / *CAVE*
PI - 1
PIVKA JAMA
ČR - 5
ČRNA JAMA
2
PO - S
3
LEPE JAME
2
1
VELIKA GORA
KONCERTNA DVORANA
TARTARUS
4
OTOŠKA JAMA
podzemna Pivka / underground Pivka
PO - 9
1
2
3
4
5
6
KONGRESNA DVORANA
0
500 m
1
PO - 1

vetra zaznamo premike zračnih mas tudi zaradi gibanja vlakov v jami (*Gabrovšek* idr. 2011).

Najvišja temperatura leta 2010 je bila na merilnem mestu Postojna 1 na Veliki gori (11,2 °C), potem na mestih Postojna 3 (11,04 °C) in Postojna 2 (10,85 °C). Najnižja temperatura je bila na točki Postojna 2 (9,82 °C), sledi točka Postojna 3 (10,34 °C) in nato Postojna 1 (10,64 °C). Povprečna temperatura zraka skozi vse leto je na točki Postojna 1 znašala 10,845 °C, na Postojna 3 10,635 °C in 10,141 °C na Postojna 2. Med točkama Postojna 1 (Velika gora) in Postojna 2 (Lepe jame, stranski rov) je torej povprečna letna razlika 0,7 °C v korist Velike gore.

Prireditev Jaslice v Postojnski jami 2010/11 je potekala med 25. in 29. decembrom 2010 ter 1. in 2. januarja 2011. S povečanim obiskom jame se je temperatura zraka na vseh treh opazovanih mestih povečala. Najmanj se je dvignila na Veliki gori (Postojna 1), in sicer za manj kot 0,1 °C. V Lepih jamah, kjer je rov manjši, kot je npr. podorna dvorana Velika gora, je bil dvig temperature bolj izrazit. Na merilnem mestu Postojna 3, tj. tik ob turistični poti v Lepih jamah (6), se je temperatura zraka dvignila največ za 0,2 °C. Na točki Postojna 2 (Lepe jame, stranski rov, oddaljen od turistične poti okrog 10 m) pa je bil npr. 2. januarja 2011 dvig temperature za 0,3 °C. Podobne temperaturne spremembe smo opazovali že leto poprej.

Leta 2010 smo monitoring razširili tudi na opazovanje temperature vode v ponvici v Lepih jamah. Nihanje temperature vode je manjše, kot je nihanje temperature zraka. Kljub temu pa je bil 1. in 2. januarja 2011 ob prireditvi Jaslice v Postojnski jami opazen dvig temperature vode za okrog 0,1 °C. Po koncu prireditve se je temperatura na vseh štirih opazovanih mestih znižala in stabilizirala na 'običajne' vrednosti.

During the 2009/10 Christmas crib performance in the Postojna cave (performances from 25 till 28 December 2009, on 2 and 3 January 2010 at 14:00, 15:00 and 16:00) the instruments at the measuring sites 2 and 3 were set to collect data every 15 minutes (3). This helped to get more precise correlations with increased visits to the cave. Especially at the site 3 which is near the tourist path, an increase in temperature was detected on performance days. The temperature rise due to the heavier visits (25–28 December 2009) was about 0.3 °C. After that till 2 January 2010 the temperature returned back to the state before.

According to the data from the company Postojnska jama d.d. there were 15,198 visitors to the Postojna cave in December 2009, and 9,524 visitors in November the same year. The Christmas performance was visited by 10,530 visitors in six days. The temperature increase of 0.3 °C can thus be attributed to an increased number of the visitors.

In 2010 we continued climatic monitoring based upon the results from 2009. Monitoring was expanded by two meteorological stations (3, 4, 5). Air movements due to the train traffic in the cave are detected at both station locations (*Gabrovšek* et al. 2011).

The highest temperature at Postojna 1 in 2010 was 11.2 °C, at Postojna 3 it was 11.04 °C and at Postojna 2 it was 10.85 °C. The lowest temperature was 9.82 °C at Postojna 2, 10.34 °C at Postojna 3 and 10.64 °C at Postojna 1. The average air temperature during 2010 was 10.845 °C at Postojna 1, 10.635 °C at Postojna 3 and 10.141 °C at Postojna 2. The average annual temperature at Postojna 1 (Velika gora) is 0.7 °C greater than at Postojna 2 (Lepe jame, side passage).

The Christmas performances in 2010/11 took place from 25 till 29 December 2010, and on 1 and 2 January

**3** Klimatski in biološki monitoring ter monitoring podrtega stalagmita v Postojnskem jamskem sistemu v letu 2010: 1. klimatski monitoring, merjenje temperature zraka in zračnega tlaka, merjenje temperature vode v ponvici v Lepih jamah, občasno merjenje $CO_2$ (1 = Postojna 1 – Velika gora, 2 = Postojna 2 – Lepe jame v stranskem rovu, 3 = Postojna 3 – Lepe jame ob turistični poti, 4 = Koncertna dvorana); 2. meteorološki postaji (1 = Stara jama, 2 = Lepe jame); 3. biološki monitoring favne v prenikli vodi; 4. biološki monitoring, spremljanje jamske klime; 5. biološki monitoring, spremljanje podzemeljske Pivke; 6. monitoring podrtega stalagmita.
Climatic and biological monitoring and monitoring of the overturned stalagmite in the Postojna cave system in 2010: 1. climatic monitoring, air temperature and pressure measuring, water temperature measuring in a flowstone pool in Lepe jame, occasional measuring of $CO_2$ (1 = Postojna 1 – Velika gora, 2 = Postojna 2 – Lepe jame in the side passage, 3 = Postojna 3 – Lepe jame near the tourist path, 4 = Koncertna dvorana); 2. two meteorological stations (1 = Stara jama, 2 = Lepe jame); 3. biological monitoring of fauna in percolating water; 4. biological monitoring, cave climate monitoring; 5. biological monitoring, underground Pivka river; 6. monitoring of the overturned stalagmite.

**4** Meteorološka postaja pred Kongresno dvorano.
The meteorological station in front of Kongresna dvorana.

**5** Meteorološka postaja v Lepih jamah.
The meteorological station in Lepe jame.

**6** Lepe jame, točka merjenja jamske klime tik ob turistični poti (Postojna 3).
Lepe jame, the cave climate monitoring site near the tourist path (Postojna 3).

Prireditev Jaslice v Postojnski jami si je decembra 2010 in januarja 2011 ogledalo 9.984 obiskovalcev, celoten mesec december 2010 pa je imel (skupaj z Jaslicami) 13.417 obiskovalcev. Ob povečanju števila obiskovalcev za 75 % se je temperatura zraka v obdobju desetih dni povečala za največ 0,3 °C, vendar se je ob znižanju obiska vrnila na izhodiščno stanje.

Močno povečan obisk kaže na dvig vrednosti temperature zraka in $CO_2$, predvsem v predelu Lepih jam.

### 5.1.4 Monitoring voda

V obdobju 2009–2013 monitoring voda predvideva merjenje ponikalnice Pivke (ponor, več točk v jamskem sistemu, sifon v Pivki jami, v Planinski jami) ter

2011. The increased visits to the cave raised the air temperature at all three monitoring sites. At Velika gora (Postojna 1) the rise was the lowest, only about 0.1 °C. In Lepe jame where the passage is smaller than the Velika gora collapsed hall, the temperature rise was clearer. At Postojna 3, near the tourist path (6), the temperature increased for 0.2 °C. At Postojna 2 (Lepe jame, side passage about 10 m off from the tourist path) the temperature rise was 0.3 °C on 2 January 2011. Similar temperature changes were observed the year before.

In 2010 the monitoring was expanded to include measurements of the water temperature in a flowstone pool in Lepe jame. Although oscillation of the water temperature is generally lower than that of the air

**7** Reka Pivka pri Modrijanovem mlinu 23. oktobra 2009.
The Pivka river near the Modrijan mill on 23 October 2009.

prenikle vode na več merilnih mestih v turističnem in neturističnem delu jame. V skladu z zakonodajo naj bi izvajali merjenje fizikalnih parametrov, kemijske analize in meritve koncentracije raztopljenega organskega ogljika ter ugotavljali biološke in mikrobiološke indikatorje. Namen je opazovanje sprememb kakovosti Pivke in prenikle vode v Postojnskem jamskem sistemu in stopnje mineralizacije, ker zunanje onesnaženje vode lahko močno vpliva na stanje v jami. Ta del monitoringa voda naj bi po zakonodaji opravljala Agencija Republike Slovenije za okolje (ARSO) pri Ministrstvu za okolje in prostor (MOP).

Izpostavlja se vprašanje onesnaženosti Pivke (7), predvsem v povezavi s pravilnim delovanjem komunalne čistilne naprave, ki mora zajeti vse vode, ponikajoče v jamski sistem. Podzemeljska Pivka ne sme biti dodatno onesnažena iz drugih virov znotraj jamskega sistema (npr. iz sanitarij v jami).

V okviru državnega monitoringa kakovosti voda ARSO spremlja kakovost površinskih voda na merilnih mestih Pivka pri Slovenski vasi in Pivka Postojna.

## 5.2. Strokovni nadzor pri posegih v Postojnskem jamskem sistemu

Pred začetkom gradbenih del v Koncertni dvorani v prvi polovici oktobra 2010 (8) smo 5. oktobra namestili napravo za merjenje temperature zraka v predelu pri postaji podzemne železnice (9). Obsežna večmesečna gradbena dela so obsegala podiranje obstoječe stavbe, izkop v tleh in novo konstrukcijo stavbe za trgovino s spominki in sanitarije.

Dejstvo je, da je bilo obnašanje temperature v Koncertni dvorani v obdobju do prvih dni novembra 2010 bolj enotno kot npr. po 7. novembru, ko je bilo opaznih več sprememb. Te so prav gotovo povezane tudi z zunanjo temperaturo, saj je Koncertna dvorana namreč na stiku več rovov. Obratovanje gradbišča v njej bi lahko imelo opaznejši vpliv na temperaturo zraka v drugi polovici novembra 2010.

Zanimivo je tudi, da gradbišče med božično-novoletnimi prazniki ni obratovalo, je pa bil skozi dvorano v tem obdobju speljan povečan obisk. Dne 25. decembra 2010 se je temperatura dvignila skoraj za

temperature, during the Christmas performance on 1 and 2 January 2011 we detected a water temperature rise of about 0.1 °C. After the end of performances the temperature at all four monitoring sites decreased and stabilized at 'regular' values.

The Christmas performance in 2010/11 was visited by 9,984 visitors; the entire month of December 2010 received (together with the Christmas performance) 13,417 visitors. This increase of 75 % in the number of visitors (for 9,984 visitors in December–January 2010/11) caused the air temperature to increase by a maximum of 0.3 °C during ten days, but after the increased visits stopped the temperature returned to the previous state.

In conclusion, strong increases in visits correlate with a rise of the air temperature and $CO_2$, especially in the passage Lepe jame.

### 5.1.4 Water monitoring

Water monitoring in the period 2009–2013 entails measurements of the Pivka sinking river (ponor, other sites in the cave system, syphon in the Pivka cave, in the Planina cave) as well as percolated water at additional sites in tourist and non-tourist parts of the cave. The measurements must include physical parameters and chemical analyses consistent with legislation, concentrations of dissolved organic carbon and detection of biological and microbiological indicators. The intention is to monitor changes in water quality of the Pivka river and percolated water of the Postojna cave system and to determine the degree of mineralization where pollution outside the cave can strongly influence the state in the cave. This part of the monitoring should be performed by Slovenian Environment Agency (ARSO) at the Ministry of the Environment and Spatial Planning (MOP) as is stated in legislation.

The question of pollution of the Pivka river is exposed connected with a proper working of the urban waste water treatment plant which should catch all waters entering the cave system. The underground Pivka must not be additionally polluted from other sources inside the cave system (e.g. from the toilets in the cave).

Within the governmental monitoring of water qual-

**8** Koncertna dvorana pred rušenjem obstoječega in gradnjo novega objekta.
Koncertna dvorana before demolition of the existing and construction of the new building.


**9** Z elipso je označeno mesto, kjer sta od 5. oktobra 2010 dalje napravi za merjenje temperature zraka v Koncertni dvorani.
The air temperature monitoring site in Koncertna dvorana is marked with yellow; measurements have been taken since 5 October 2010.


**10** Gradbena dela v Koncertni dvorani.
Construction works in Koncertna dvorana.

0,4 °C glede na stanje tri dni prej. Prireditev Jaslice v Postojnski jami je torej močneje dvignila temperaturo zraka v Koncertni dvorani kakor v Lepih jamah. V obeh primerih se je po koncu prireditve temperatura vrnila na izhodiščno vrednost.

## 5.3. Opazovanja in priporočila jamskega skrbnika

Vpliv gradbišča na dvig temperature zraka v Koncertni dvorani je težje dokazati. Opazen pa je bil dvig temperature v dvorani (do 0,4 °C) ob prireditvi Jaslice v Postojnski jami 2010/11, ko gradbišče ni delovalo.

Podiranje in gradnja sta v Koncertni dvorani povzročila dviganje in usedanje velikih količin prahu, ki je bil delno spran po naravni poti z intenzivnim prenikanjem vode skozi jamski strop. Potrebno bi bilo sprotno preprečevanje dvigovanja prahu, ki ni bilo izvedeno v polni meri.

Podiranje, vrtanje in druga dela so v jami povzročala precej hrupa. Nekatera dela (npr. rezanje lesa ipd.) so bila tudi izvedena v jami (10), kar ni najbolj primerno za jamsko okolje. Čimveč del naj bi se opravilo zunaj, izdelke pa v jamo le dostavilo.

Odvoz in dovoz materiala sta bila organizirana z jamskim vlakom do delovnih strojev in tovornjakov na glavnem vhodu oziroma izhodu iz jame (11). Pri tem je v jamsko okolje zašlo veliko izpušnih plinov, kar je povsem neprimerno.

Za morebitno prihodnjo sanacijo in gradbena dela v jami predlagamo, da se izvoz oz. dovoz materiala uredita po stranskem tiru v predelu, kjer je upravna stavba družbe, ki upravlja z jamo. Pri tem bo treba urediti dostop za tovornjake in delovne stroje, saj so zdaj vrata premajhna. Tako bi se izognili prometu z izpušnimi plini v vhodnih delih jame.

Kulturna dediščina v sistemu Postojnskih jam je bila popisana na začetku leta 2011. V primeru najdbe novih dokazov se je v zvezi z varovanjem in ohranjanjem kulturne dediščine treba obrniti na ustrezne ustanove.

Za vsako predvideno sanacijo oziroma poseg v jami je treba obvestiti jamskega skrbnika. Sanacije in posegi, ki potrebujejo dodatne analize in diskusije strokovnjakov, so: zavesa na vhodu v jamo v

ity ARSO additionally analizes surface water quality in the Pivka river near Slovenska vas and in Postojna.

## 5.2 Expert control on interventions in the Postojna cave system

On 5 October 2010, before begining of the construction work in Koncertna dvorana (8) in the first half of October, an instrument for measuring air temperature was positioned in part of the hall near the station of the underground train (9). This extensive months-long construction project in Koncertna dvorana includes demolition of an existing building, digging in the ground and new construction of the tourist shop and toilets.

The temperature behaviour in Koncertna dvorana was more unitary in the period before the beginning of November 2010 than it was after 7 November when more changes were detected. Those changes are certainly also connected with outer temperature because Koncertna dvorana is situated at the intersection of multiple passages. The construction activity may have had a noticeable impact on the air temperature in the second half of November 2010.

It is also interesting that although the construction was not active during the Christmas–New Year holidays, the expanded visits due to the holidays passed through Koncertna dvorana. On 25 December 2010 the temperature increased by almost 0.4 °C compared to the state three days before indicating that the Christmas performance in the Postojna cave increased the air temperature more strongly in Koncertna dvorana than in Lepe jame. In both cases the temperature returned to the original state after the end of performances.

## 5.3 Observations and recommendations of the cave custodian

The impact of the construction in Koncertna dvorana on the air temperature rise is hardly proven. However, the temperature rise (up to 0.4 °C) was detected there during the Christmas performance in

**11** Delovni stroj v vhodnih delih Postojnske jame.
The construction machinery in the entrance portion of the Postojna cave.


**12** Železnica v Postojnskem jamskem sistemu.
The railway in the Postojna cave system.

**13** Posipanje tirov v Postojnskem jamskem sistemu 24. januarja 2011.
Sanding of train lines in the Postojna cave system on 24 January 2011.

zimskem obdobju, prah v jami, spiranje kapnikov z vodo pod pritiskom (primer Lepe jame, Tartarus), odstranjevanje lampenflore, večje gradnje v jami (npr. akvarij za človeške ribice). Vse to lahko močno poslabša stanje jamske klime. Za prizore jaslic predlagamo, da se zanje ne uporabljajo mesta z lepim kapniškim okrasjem, ampak le 'umetno' spremenjeni deli jame.

Ob sanacijah in gradbenih delih v jamskih sistemih morata biti upoštevana ranljivost jamskega okolja ter zagotovljeno maksimalno spoštovanje okolja in naravovarstvenih predpisov, kar naj redno spremljajo odgovorne ustanove na državnem nivoju.

Pri čiščenju starega odpadnega materiala v jamah kakor tudi pri čiščenju jame (spiranju kapnikov in poti) in sanaciji ponvic s kovanci ter odstranjevanju ostankov lesa in drugega materiala naj se sproti obvešča jamskega skrbnika in druge ustanove, zato da se ovrednotijo in zavarujejo morebitni predmeti kulturne in naravne dediščine ter poiščejo ustreznejše metode čiščenja, če bi se pokazalo, da npr. spiranje kapnikov z vodo pod pritiskom poškoduje kapnike in sigo. Redno spiranje turističnih poti z vodo je nujno. Kljub temu se je treba zavedati, da se voda, ki tako odplakne umazanijo, prineseno z obutvijo obiskovalcev, neočiščena steka v kraški sistem in podzemeljsko Pivko.

Predlagamo celovito rešitev železniške proge (12), da bi tako zmanjšali oziroma odstranili usedanje prahu v jami kakor tudi posipanje (13) in mazanje tirov. Lesene tirne pragove je treba zamenjati z drugim materialom, ker les v jami gnije in za to okolje ni primeren.

Ob delovanju podzemne biološke čistilne naprave v Koncertni dvorani je treba organizirati redni monitoring njenega obratovanja in vplivov na jamsko okolje. V primeru negativnih vplivov na jamo (npr. smradu, hrupa, povečane rasti lampenflore itd.) je treba čistilno napravo ustaviti in pomanjkljivosti odpraviti.

Predlagamo celovito rešitev primernosti različnih kulturnih dogodkov v jamskem sistemu, saj jama ne sme biti kulisa za določene prireditve. Tiste z večletno tradicijo so zaenkrat še sprejemljive. Nove prireditve naj bodo tematsko vezane na kraško jamo (s področja geologije, speleologije, zgodovine, arheologije ipd.).

Na regionalnem in državnem nivoju si je treba prizadevati za spremljanje kvalitete reke Pivke pred

the Postojna cave in 2010/2011 when the construction was not active.

Demolition and construction in Koncertna dvorana raised large amounts of dust that were partly washed away in the natural way by strong water percolation through the cave ceiling. Dust elevation must be prevented and this was not carried out properly during the project.

Demolition, drilling and other works made a good deal of noise in the cave. Some tasks (such as wood cutting, etc.) were done inside the cave (10) which is not appropriate for the cave environment. The majority of such work should be done outside the cave, and final products must be transported inside.

Material was transported to and from the construction site by the cave train to the principal entrance of the cave where working machines and trucks were waiting (11). This caused unsuitably large amounts of exhaust to enter into the cave environment.

In the case of future improvements and construction works in the cave we recommend that material transport should be arranged in a way to use the side train lines in the part near the administration building of the company that manages the cave. Such a solution will require arranging access for trucks and working machines because the current doors are too small. In this way the strong traffic with exhaust in the cave's entrance could be avoided.

Inventory of the cultural heritage in the Postojna cave system was accomplished in the begining of 2011. In the case that additional material is found, the appropriate institutions responsible for protection and conservation of the cultural heritage must be informed.

For every planned improvement or intervention the cave custodian must be informed. Current proposed improvements or interventions that need additional analyses and expert discussions are: a curtain at the cave entrance during winter, mitigation of dust in the cave, washing of speleothems with water under pressure (for example in Lepe Jame, Tartarus), elimination of lampenflora, larger construction projects in the cave (such as a *Proteus anguinus* aquarium). Such activity could make the state of the cave climate worse. For the Christmas performance scenes we suggest not using the parts of the cave with rich flowstone decoraponorom v Postojnski jamski sistem in za čiščenje odpadnih voda.

Jamski skrbnik vodi zapisnike svojih ogledov, ki so shranjeni na IZRK ZRC SAZU, redno pa jih posreduje tudi koncesionarju in Zavodu RS za varstvo narave, OE Nova Gorica.

## Sklep

Od leta 2009 IZRK ZRC SAZU opravlja dela krasoslovnega strokovnjaka ali jamskega skrbnika pri izvajanju koncesijske pogodbe za upravljanje s Postojnskim jamskim sistemom, to je predvsem strokovno spremljanje stanja jame s poudarkom na vplivu rabe jame kot naravne vrednote.

Glavne naloge jamskega skrbnika so strokovni nadzor in svetovanje pri upravljanju za trajnostni razvoj jamskega sistema, oblikovanje smernic za rabo jamskega sistema kot naravne vrednote ter klimatski in biološki monitoring.

Med najpomembnejše uspehe, ki smo jih dosegli v obdobju 2009–2011, lahko štejemo:

- oblikovanje načrta klimatskega in biološkega monitoringa;
- izvajanje klimatskega in biološkega monitoringa na ustreznih mestih v jamskem sistemu z različnimi inštrumenti;
- spremljanje gradnje novega objekta prodajalne spominkov in sanitarij v Koncertni dvorani in priporočila za nujne naravovarstvene ukrepe;
- priporočila za celovito sanacijo železnice v Postojnskem jamskem sistemu;
- organiziranje in svetovanje pri popisu kulturne dediščine;
- ozaveščanje o onesnaženosti reke Pivke že pred ponorom v Postojnski jamski sistem;
- ugotovitve o 2- do 3-kratnem povečanju $CO_2$ v Lepih jamah in povečanju temperature zraka od 0,1 do 0,4 °C ob povečanih obiskih v jami;
- novi ukrepi pri odstranjevanju in preprečevanju lampenflore.

tions but 'artificially' changed places in the cave only.

During improvements and interventions in the cave system the vulnerability of the cave environment must be taken into account as well as maximal respect of the environment and natural protection legislation. This must be regularly addressed by the responsible institutions on the state level.

The cave custodian and other institutions must be informed about activities regarding cleaning of the cave (washing of speleothems and tourist paths), coin clean-up from the flowstone pools and removal of wooden residue and other materials. With cleaning works new pieces of the cultural and natural heritage can be found, which must be valued and protected. This demands that appropriate cleaning methods must be applied if cleaning water under pressure harms flowstone. Regular washing of tourist paths is necessary, but we must be aware that the water used to wash dirt originating from tourists' shoes is not cleaned and runs into the karst system and underground Pivka river.

We suggest a complete solution for the railway (12) in order to reduce or eliminate dust deposition in the cave, as well as a solution to eliminate sanding (13) and oiling the train lines. Wooden train cross-ties must be replaced by other material. The wood decomposes and is not suitable for the cave.

During the underground biological cleaning station operation in Koncertna dvorana it is necessary to organize regular monitoring of its activity and its impacts on the cave environment. In the case of negative impacts on the cave (such as bad odour, noise, increased lampenflora growth, etc.) the operation of the cleaning station must be stopped and imperfections eliminated.

We suggest complete assessment of the appropriateness of different performances in the cave system. The cave cannot be the stage for all proposed performances. Those performances in the cave that already have a long-standing tradition are for now acceptable. New ones should be thematically connected with karst caves (geology, speleology, history, archaeology, etc.).

On the regional and state level we must strive for monitoring of the Pivka river quality in front of the ponor to the Postojna cave system and for cleaning of waste waters.

The cave custodian records minutes of our visits which are kept at IZRK ZRC SAZU and are regularly sent to the concessionaire and to the Nova Gorica Regional Unit of the Institute of the Republic of Slovenia for Natural Conservation.

## Conclusion

Since 2009 IZRK ZRC SAZU has been practising the role of karstology consultant or cave custodian in the implementation of the concession contract for managing the Postojna cave system. This role entails expert control on the state of the cave with an emphasis on the impact of the use of the cave as a natural asset.

The principal duty of the cave custodian are expert control and recommendations for management for sustainable development of the cave system, formulation of directives for the use of the cave as a natural asset and climatic and biological monitoring.

Among the most important successes that have been realized by the cave guardian in the period 2009–2011 are:

- formulation of the climatic and biological monitoring plan;
- realization of climatic and biological monitoring at suitable places in the cave system with various instruments;
- oversight of the construction of the new building (tourist shop, toilets) in Koncertna dvorana and formulation of recommendations for necessary natural protection arrangements;
- recommendations for a comprehensive improvement of the railway in the Postojna cave system;
- organization and recommendations for the inventory of the cultural heritage;
- considerations about the Pivka river pollution in front of the ponor to the Postojna cave system;
- observation that $CO_2$ in Lepe jame increased by 2–3 times and air temperature increased by 0.1–0.4 °C during the periods of increased visits;
- new arrangements for elimination of and prevention against lampenflora.

# 6

# VPLIV TURIZMA NA RABO PREDJAME KOT NARAVNE VREDNOTE

# IMPACT OF TOURISM ON THE USE OF THE PREDJAMA CAVE AS A NATURAL ASSET

Tako kot za Postojnski je tudi za Predjamski jamski sistem v kratkoročnem programu (2009–2013) rabe naravnih vrednot zahtevano mesto jamskega skrbnika, ki je od leta 2009 IZRK ZRC SAZU. Med najpomembnejšimi deli jamskega skrbnika so: strokovni nadzor in svetovanje pri upravljanju za trajnostni razvoj jamskega sistema, oblikovanje smernic za rabo jamskega sistema kot naravne vrednote, klimatski in biološki monitoring, redno obveščanje Zavoda RS za varstvo narave, OE Nova Gorica, o izvajanju koncesije in stanju jame, izdelava sanacijskih programov za odpravo posledic vpliva rabe naravne vrednote, opozarjanje na zunanje dejavnike ogrožanja jame, spremljanje večjih posegov v jami in nadzor nad njimi, evidenca raziskav in popis posegov v jamo.

V dolgoročnem programu (2009–2028) rabe Predjame so v okviru del jamskega skrbnika predvideni tudi naravovarstveni ukrepi, glede na rezultate petletnega opazovanja in monitoringa jamske klime in favne.

Biološki monitoring v Predjamskem jamskem sistemu kaže na pomembnost varovanja bogate podzemeljske favne in spremlja obstoječe stanje. Rov netopirjev v Fiženci je zaprt za obiskovalce v obdobju prezimovanja netopirjev.

Jamski skrbnik je dosegel izdelavo popisa kulturne dediščine v jamskem sistemu, kar je bilo izvedeno na začetku leta 2011.

Vseskozi opravljamo redno pisanje zapisnikov naših obiskov z opazovanji in ugotovitvami o upravljanju jamskega sistema.

## 6.1 Monitoring v Predjamskem jamskem sistemu

### 6.1.1 Načrt klimatskega monitoringa

V načrtu klimatskega monitoringa je poleg osnovnih parametrov (temperatura zraka, tlak, $CO_2$, veter, vlaga) poudarek tudi na analizi vpliva zmrzovanja v jami. Jama ima namreč več vhodov, kjer se spremembe klime in vdor zunanjega zraka v jamo čutijo precej daleč v notranjost. Ob mrzlih zimah lahko najdemo ledene kapnike celo v Dvorani dvojčkov (*Habe* 1970).

As is the case for the Postojna cave system according to the short-term programme (2009–2013) on the use of natural assets the Predjama cave system also requires a cave guardian. Since 2009 this work has been performed by IZRK ZRC SAZU. Among the most important tasks of the cave custodian are: expert control and recommendations in managing the sustainable development of the cave system, guideline formation for the use of the cave system as a natural asset, climatic and biological monitoring, regular notification of the Nova Gorica Regional Unit of the Institute of the Republic of Slovenia for Natural Conservation, regarding the implementation of the concession and the state of the cave, implementation of improvement programmes for elimination of impacts caused by the use of the natural asset, calling attention to the external factors that can harm the cave, monitoring and supervision of large-scale interventions and performances in the cave, and providing evidence of research and inventory of interventions in the cave.

Within the long-term programme (2009–2028) for the use of Predjama the role of the cave custodian also includes natural protection precautions based on the results of five-year-long monitoring of the cave climate and fauna.

Biological monitoring in the Predjama cave calls attention to the importance of protection of the rich underground fauna and records their existing state. As a result Rov netopirjev in Fiženca is closed for visitors during the period of bat hibernation.

In a separate project, the cave custodian succeeded in carrying out an inventory of the cultural heritage in the cave system at the beginning of 2011.

Throughout the project, the regular written documentation is made about our visits, with observations and recommendations for management of the cave system.

Namen monitoringa je opazovati spremembe v jamski klimi zaradi rabe jame v turistične namene. Raziskave so omejene na Konjski hlev, Veliko dvorano in Fiženco, to so vhodni turistično obiskani deli jame. Kljub temu pa smo za boljše razumevanje klime v celotni jami občasno opravljali meritve tudi v notranjosti jame (npr. v Vetrovni luknji).

### 6.1.2 Načrt biološkega monitoringa

Pri biološkem monitoringu v Predjami je poudarek na populacijskih gibanjih netopirjev, tj. rednem letnem štetju njihovih kolonij. Nadaljevali naj bi z rednim spremljanjem navzočnosti in velikosti kolonij netopirjev na štirih vzorčnih mestih in ugotovili trenutno stanje ter izdelali inventar drugih jamskih živali in živali, ki samo občasno živijo v jami. V obdobju 2011–2013 naj bi bile izdelane smernice za dolgoročno ohranjanje netopirjev in ohranitev podzemeljske favne ter za trajnostno naravnan razvoj turizma v Predjamskem jamskem sistemu. V okvir biološkega monitoringa je vključen tudi monitoring favne v prenikli vodi (1).

## 6.1 Monitoring in the Predjama cave system

### 6.1.1 The plan for climatic monitoring

In the plan for climatic monitoring beside basic parameters (air temperature, pressure, $CO_2$, wind and humidity), there is also an emphasis on analysing the impact of frost in the cave. The cave has namely multiple entrances where climate changes and inflow of cold air into the cave can be felt deep inside. Ice stalagmites can during cold winters be found even as far as in Dvorana dvojčkov (*Habe* 1970). The aim of monitoring is to analyse the changes in cave climate due to use of the cave for tourist purposes. The research has been mainly limited to the parts Konjski hlev, Velika dvorana and Fiženca, which represent entrance regions of the touristically visited parts of the cave. Nevertheless, for better understanding of the whole cave climate occasional measurements have been done even in deeper parts of the cave (such as Vetrovna luknja).

**1** Vzorčenje favne v prenikli vodi, Predjamski jamski sistem (PR-2).
Monitoring of fauna in percolated waters, the Predjama cave system (PR-2).

### 6.1.3 Rezultati klimatskega monitoringa

Predjamski jamski sistem (2, 3) je s 13.092 m druga najdaljša kraška jama v Sloveniji. Jama je vpisana v Register naravnih vrednot kot vrednota državnega pomena (*PrDVNV*, 2004) pod ident. št. 243. Postojnska jama d.d. v okviru koncesijske pogodbe upravlja s Predjamskim jamskim sistemom in Predjamskim gradom do leta 2028.

V Predjamskem jamskem sistemu od 6. avgusta 2009 na dveh mestih opravljamo zvezne meritve zračne temperature in tlaka na vsakih 10 minut. Merilna točka 1 je v Konjskem hlevu, kjer se močno čuti vpliv zunanje temperature, druga točka 2 pa v Veliki dvorani, 1–2 m severno od turistične poti, ki vodi v Fiženco (4).

Klimatski monitoring v Predjamskem jamskem sistemu je pokazal velik vpliv zunanjih vremenskih razmer na vhodne dele, ki so turistično obiskani, zato o vplivu obiskovalcev na jamsko klimo v tem primeru težko govorimo.

Temperatura merilnega mesta v Konjskem hlevu je zelo močno odvisna od klimatskih razmer zunaj jame. Dobro so izražena tudi dnevno-nočna nihanja v obdobju od 6. avgusta do oktobra 2009. V Veliki dvorani je temperatura od avgusta do decembra 2009 malo nihala (6–9 °C). Dne 22. decembra 2009 smo na obeh merilnih mestih zabeležili močan padec temperature, povezan s padcem zunanje temperature. V Veliki dvorani je znašala temperatura 2 °C, v Konjskem hlevu pa le 0,4 °C. Leta 2010 je bila temperatura v Konjskem hlevu (*Gabrovšek* idr. 2011) od −0,353 °C do 18,667 °C (povprečje 8,48 °C) in v Veliki dvorani od 0,813 do 10,49 °C (povprečje 6,82 °C).

Glede na podatke Postojnske jame d.d. je leta 2009 Predjamo obiskalo 5.552 ljudi (obiski so od 1. maja do 30. septembra). Takšno število obiskovalcev značilno ne vpliva na klimo te jame.

Poleg zveznih meritev temperature zraka in tlaka smo občasno opravljali tudi meritve $CO_2$ in vetra (*Gabrovšek* idr. 2010, 2011). Tabela 1 prikazuje meritve hitrosti in smeri vetra v obdobju 2009–2011 na štirih mestih v Predjamskem jamskem sistemu (4).

Habe (1970) je v Predjamskem jamskem sistemu opisoval poletni in zimski režim ter vmesno dobo,

### 6.1.2 The plan for biological monitoring

The emphasis of biological monitoring in Predjama is related to bat population movement, i.e. regular annual counting of bat colonies. It is continuing with regular monitoring of the presence and size of the bat colonies at four monitoring sites. The aim is to learn the current population status and to make an inventory of other animals, including animals that occasionally live in the cave. In the period 2011–2013 the guidelines for long-term protection of the bats and preservation of the underground fauna in the Predjama cave system must be developed, as well as guidelines for sustainably oriented development of tourism. The monitoring of fauna in percolated waters is also included within the biological monitoring plan (1).

### 6.1.3 Results of climatic monitoring

The Predjama cave system (2, 3) with its 13,092 m is the second longest karst cave in Slovenia. The cave is enrolled in the Register of natural assets as an asset of national importance (*PrDVNV*, 2004) under the ident. no. 243. The company Postojnska jama d.d. manages the Predjama cave system and Predjama castle within a concession contract until 2028.

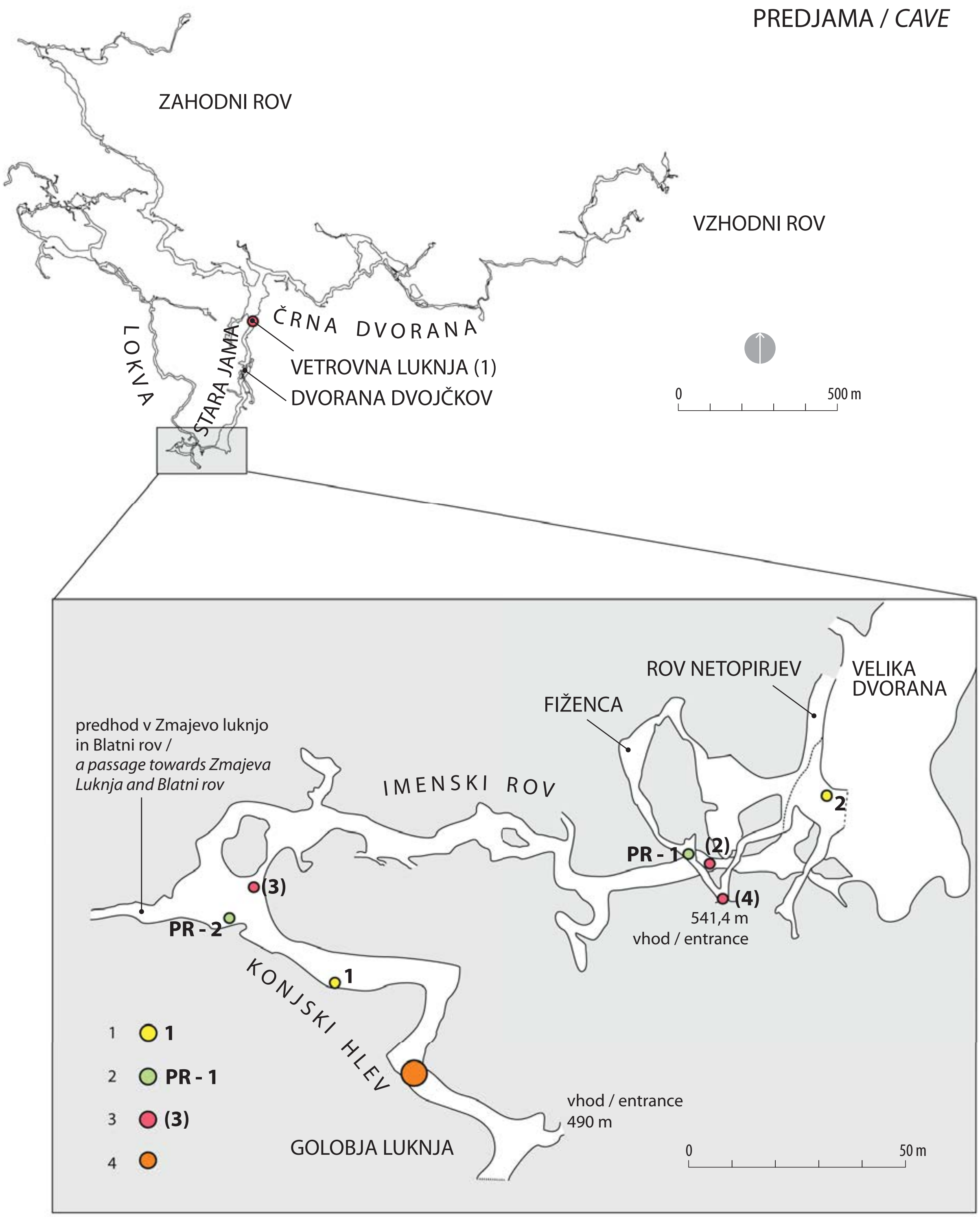
Continuous measurement of air temperature and pressure has been conducted every 10 minutes at two sites in the Predjama cave system since 6 August 2009. Monitoring point no. 1 is located in Konjski hlev where the strong influence of outer temperature is felt. The second site (no. 2) is in the hall Velika dvorana, 1–2 m north of the tourist path that leads to Fiženca (4).

Climatic monitoring in the Predjama cave system has revealed a large influence of outer climatic conditions on the cave's entrance sections visited by tourists. Thus, the influence of visitors on cave climate is in this case difficult to assess.

Air temperature of the monitoring site in Konjski hlev is especially strongly dependent on climatic conditions outside the cave. Day-night variations of temperature are easily observed in the period from 6 August to October 2009. In contrast, in Velika dvora-

**2** Dvorana dvojčkov, Predjamski jamski sistem.
Dvorana dvojčkov, the Predjama cave system.

**3** Konjski hlev, Predjamski jamski sistem.
Konjski hlev, the Predjama cave system.




**4** Mesta opravljanja klimatskega in biološkega monitoringa v Predjami: 1. klimatski monitoring, merjenje temperature zraka in tlaka (1 = Konjski hlev, 2 = Velika dvorana); 2. biološki monitoring, favna v prenikli vodi (PR-1 = Fiženca, PR-2 = prehod v Zmajevo luknjo in Blatni rov); 3. merjenje hitrosti in smeri vetra (1 = Vetrovna luknja, 2 = prelaz v Imenskem rovu, 3 = križišče k Zmajevi luknji, 4 = Fiženca); 4. ugrez.
The sites for climatic and biological monitoring in Predjama: 1. climatic monitoring, air temperature and pressure measurements (1 = Konjski hlev, 2 = Velika dvorana); 2. biological monitoring, fauna in percolated waters (PR-1 = Fiženca, PR-2 = a passage towards Zmajeva luknja and Blatni rov); 3. measurement of velocity and direction of the wind (1 = Vetrovna luknja, 2 = a pass in Imenski rov, 3 = a crossing to Zmajeva luknja, 4 = Fiženca); 4. a collapse.

ko prihaja do menjavanja zimske in letne smeri vetra. V poletnem zračnem gibanju teče zračni tok iz Zahodnega in Vzhodnega rova skozi Vetrovno luknjo do Velike dvorane, kjer se mu pridruži hladnejši zrak iz Fižence. Hladnejši jamski zrak tako uhaja iz vseh odprtin Lokve in Zmajeve luknje. Pozimi zračni tok vdira skozi Vetrovno luknjo v Črno dvorano. Največja hitrost vetra v Vetrovni luknji je bila februarja leta 1956 izmerjena na 8,3 m/s (*Habe* 1970).

Kranjc (1983) je v obdobju med 9. januarjem 1980 in 31. marcem 1981 opravljal meritve temperature zraka in vlage v Golobji luknji in Vetrovni luknji. Največja izmerjena hitrost vetra v Vetrovni luknji je bila dne 9. januarja 1981, in sicer 9 m/s. Največja hitrost vetra v Vetrovni luknji, ki smo jo zaznali mi, pa je 28. avgusta 2009 dosegla 5 m/s.

na the temperature changes little in the period from August to December 2009 (6–9 °C). On 22 December 2009 at both monitoring locations a strong drop in temperature was detected, connected with the temperature fall outside. In Velika dvorana the recorded temperature was 2 °C, and in Konjski hlev it was only 0.4 °C. During 2010 the temperature in Konjski hlev (*Gabrovšek* et al. 2011) ranged from –0.353 °C to 18.667 °C (average 8.48 °C), and in Velika dvorana from 0.813 to 10.49 °C (average 6.82 °C).

Based on data provided by Postojnska jama d.d. in the year 2009 there were 5,552 visitors to the Predjama cave (visits are from 1 May to 30 September). Such low visitor numbers cannot significantly influence the cave climate in this cave.

Besides continuous measurement of the air temperature and pressure occasional measurements

**5** Poplave v Konjskem hlevu 19. septembra 2010, kjer je po umiku vode naslednjega dne nastal ugrez (foto J. Hajna).
High floods in Konjski hlev on 19 September 2010 where the next day collapse occurred after the water withdrawal (photo J. Hajna).

### 6.1.4 Monitoring voda

Načrt monitoringa voda v Predjamskem jamskem sistemu za obdobje 2009–2013 zajema opazovanje kakovosti prenikle vode in ponikalnice Lokve in stopnje

of $CO_2$ and wind are performed (*Gabrovšek* et al. 2010, 2011). Table 1 shows measurements of the wind velocity and direction in the period 2009–2011 at four monitoring sites in the Predjama cave system (4).

**6** Po poplavi pred Predjamskim jamskim sistemom 20. septembra 2010.
After the high floods in front of the Predjama cave system on 20 September 2010.

**7** Ugrez v Konjskem hlevu.
A collapse in Konjski hlev.

mineralizacije ter biološke in mikrobiološke analize večkrat v sezoni, oziroma po potrebi. Merjenja naj bi vključevala ponikalnico Lokvo, Zahodni in Vzhodni rov ter preniklo vodo na več točkah v turističnem in neturističnem delu. V okviru državnega monitoringa kakovosti voda ARSO na Lokvi ne opravlja meritev.

Habe (1970) described the summer and winter regimes as well as the period in between when winter and summer wind directions change in the Predjama cave system. In the summer air flows from Zahodni rov and Vzhodni rov through Vetrovna luknja to Velika dvorana where it joins the colder air from Fiženca. Colder air in this way escapes through all openings of the passages Lokva and Zmajeva luknja that are the lowest passages of the cave system. In winter the air enters through Vetrovna luknja into Črna dvorana. The highest wind speed in Vetrovna luknja was measured on February 1956 at 8.3 m/s (*Habe* 1970).

## 6.2 Visoke vode in ugrez v Predjamskem jamskem sistemu

Izjemne poplave, ki so septembra 2010 zajele velik del Slovenije, so pečat pustile tudi v Predjamskem jamskem sistemu (*Šebela* 2011). V Konjskem hlevu (5) je voda 19. septembra 2010 segla do nadmorske višine 489,3 m, v Veliki dvorani pa do 489,1 m (*Hajna*, osebno sporočilo, 2010), tako da je bil prehod do Stare jame zalit. Izredno deževje leta 1965 opisuje tudi Habe (1970, 16), saj je 2. septembra pred Predjamskim jamskim sistemom nastalo jezero. Poplava septembra 2010 je v Predjami (6) segala najmanj 3 m višje od poplave leta 1965.

Dopoldne 20. septembra 2010, po umiku vode, ki je zajezila Lokvo, je Sergeja Kariž (osebno sporočilo, 2010) v Konjskem hlevu opazila ugrez na nadmorski višini 489,45 m s premerom okrog 3 m in globino 1–3 dm (7). Glede na jamske načrte (*Habe* 1970) so okrog 12 m pod njim rovi Zmajeve luknje (477 m nad morjem), približno 30 m pod njim pa rov Lokve (462 m). Območje, kjer se je pojavil ugrez, je bilo poplavljeno (5), na kar je opozoril Franjo Drole (osebno sporočilo, 2011). Ugrez se je pojavil po umiku vode, to je 20. septembra 2010 zjutraj oziroma dopoldne. V spodaj ležečih rovih je voda spodjedla sediment (verjetno iz razpoke ali iz brezna), umik vode pa je povzročil ugrez v sedimentu v zgornjem rovu. Dejstvo je, da bi ponovne poplave takih razsežnosti ugrez še poglobile.

## Sklep

Prvi dve leti klimatskega monitoringa v Predjamskem jamskem sistemu potrjujeta velik vpliv zunanje klime na jamsko klimo, tako da o vplivu obiskovalcev nanjo v vhodnih delih skoraj ne moremo govoriti. Predjamski jamski sistem v obdobju petih mesecev predstavlja le 1 % od skupnega letnega števila obiskovalcev Postojnskega in Predjamskega jamskega sistema.

V okviru biološkega monitoringa je glavna naloga spremljanje navzočnosti netopirjev (predvsem v Netopirjevem rovu), omogočanje njihovega nemotenega prezimovanja in ukrepanje ob občutnem zmanjšanju njihovega števila.

Kranjc (1983) performed measurements of the air temperature and humidity in Golobja luknja and Vetrovna luknja over the period from 9 January 1980 to 31 March 1981. The highest measured wind speed at Vetrovna luknja at that time was 9 m/s on 9 January 1981. The highest wind speed at Vetrovna luknja determined by our measurements was up to 5 m/s on 28 August 2009.

### 6.1.4 Monitoring of waters

The plan for water monitoring in the Predjama cave system in the period 2009–2013 includes analyses of the quality of percolated waters and the Lokva sinking river, as well as the degree of mineralization, and biological and microbiological analyses performed multiple times in the season, or as necessary. Measurements should include the Lokva sinking river, passages Zahodni rov and Vzhodni rov and percolated water at several locations in tourist and non-tourist parts of the cave. The ARSO currently does not monitor the river Lokva within the frame of nationally organized water quality monitoring.

## 6.2 High waters and collapse in the Predjama cave system

The high floods that occurred in September 2010 extended over a large part of Slovenia and also left their impact in the Predjama cave (*Šebela* 2011). In Konjski hlev (5) the water level reached 489.3 m a.s.l. on 19 September 2010; in Velika dvorana it reached 489.1 m a.s.l. (*Hajna*, personal communication, 2010). As a result the passage to Stara jama was under water. Earlier high floods were described in 1965 by Habe (1970, 16). On 2 September 1965 a lake formed in front of the Predjama cave entrance. The flood of September 2010 in Predjama (6) was at least 3 m higher than the one in 1965.

After the withdrawal of the 2010 floodwaters, which had made a lake in the river Lokva, a collapse (7) of 3 m in diameter and 1–3 dm deep occurred in Konjski hlev (*Sergeja Kariž*, personal communication, 2010). The collapse is situated at 489.45 m a.s.l. According to cave maps (*Habe* 1970) about 12 m under the collapse there are the passages of Zmajeva luknja (477 m), and more than 30 m under the collapse is the

| Datum<br>*Date* | Mesto merjenja<br>*Location* | Smer vetra<br>*Wind direction* | Hitrost vetra<br>*Wind velocity* | Čas<br>*Time* |
|---|---|---|---|---|
| 30.9.2009 | Fiženca (4) | Iz vhoda v jamo<br>*From the entrance into the cave* | < 1 m/s | |
| 01.10.2009 | Prelaz – Imenski rov (2)<br>*Pass – Imenski rov (2)* | Iz Velike dvorane proti Imenskemu rovu<br>*From Velika dvorana towards Imenski rov* | | 11:00 |
| 22.10.2009 | Prelaz – Imenski rov (2)<br>*Pass – Imenski rov (2)* | Iz Velike dvorane proti Imenskemu rovu<br>*From Velika dvorana towards Imenski rov* | Hitrost nezaznavna<br>*Velocity undetected* | 9:45 |
| 22.10.2009 | Vetrovna luknja (1) | Iz Črne dvorane v Staro jamo<br>*From Črna dvorana to Stara jama* | Do 2 m/s, pri dnu do 1,2 m/s<br>*Up to 2 m/s, at the bottom up to 1.2 m/s* | 10:00 |
| 04.12.2009 | Prelaz – Imenski rov (2)<br>*Pass – Imenski rov (2)* | Iz Imenskega rova proti Veliki dvorani<br>*From Imenski rov towards Velika dvorana* | | |
| 20.01.2010 | Prelaz – Imenski rov (2)<br>*Pass – Imenski rov (2)* | Iz Imenskega rova proti Veliki dvorani<br>*From Imenski rov towards Velika dvorana* | Do 1 m/s<br>*Up to 1 m/s* | 11:00 |
| 05.01.2011 | Prelaz – Imenski rov (2)<br>*Pass – Imenski rov (2)* | Iz Velike dvorane proti Imenskemu rovu<br>*From Velika dvorana towards Imenski rov* | 1 m/s | 11:30 |
| 15.03.2011 | Križišče k Zmajevi luknji (3)<br>*Crossing to Zmajeva luknja (3)* | Iz Velike dvorane proti Zmajevi luknji<br>*From Velika dvorana towards Zmajeva luknja* | < 1 m/s | 12:15 |
| 15.03.2011 | Križišče k Zmajevi luknji (3)<br>*Crossing to Zmajeva luknja (3)* | Iz Konjskega hleva proti Zmajevi luknji<br>*From Konjski hlev towards Zmajeva luknja* | < 1 m/s | 12:15 |
| 12.04.2011 | Vetrovna luknja (1) | Iz Črne dvorane v Staro jamo<br>*From Črna dvorana to Stara jama* | 2 m/s | 11:00 |
| 12.04.2011 | Prelaz – Imenski rov (2)<br>*Pass – Imenski rov (2)* | Iz Velike dvorane proti Imenskemu rovu<br>*From Velika dvorana towards Imenski rov* | 0.5 m/s | 10:40 |

**Tabela 1** Občasne meritve hitrosti in smeri vetra v Predjamskem jamskem sistemu.
**Table 1** Occasional measurements of the wind speed and direction in the Predjama cave system.

Monitoring kakovosti ponikalnice Lokve ne poteka. Glede na to, da Lokva po 15 km podzemlja prihaja na dan v izvirih Vipave, je smiselno, da bi se v prihodnjih letih tudi na Lokvi organiziralo redno merjenje osnovnih parametrov v okviru ARSO.

Potreben je sanacijski načrt turističnih poti v jami, saj je trenutna pot slabo izdelana (8). Obenem je treba zavarovati tudi številna mesta z zgodovinskimi podpisi in arheološkimi nahajališči ter poiskati rešitev za varnejši prehod turistov po strmi lestvi iz Velike dvorane v Fiženco.

Ugrez, ki je nastal v Konjskem hlevu zaradi izjemnih poplav septembra 2010, je treba ustrezno sanirati in opazovati nadaljnje ugrezanje, da bi bila tako zagotovljena varnost obiskovalcev.

**8** Potrebno je zavarovanje starih napisov in ureditev poti.
It is necessary to protect old inscriptions and improve the tourist path.

Lokva river passage (462 m). The area where the collapse occurred was flooded (5), as reported by Franjo Drole (personal communication, 2011). The collapse was visible after the withdrawal of water which occurred on 20 September 2010 in the morning or before noon. In lower passages water eroded the sediment (probably from a fissure or a shaft). The water withdrawal then caused sediment collapse in the upper passage. The prediction is that new high floods of similar extent would deepen the collapse.

## Conclusion

The first two years of climatic monitoring in the Predjama cave system confirmed the high influence of the outer climate on the cave climate. As a result it is hardly possible to discuss the effect of tourist visits on the cave climate in the entrance areas. Additionally, visitors to the Predjama cave in a period of 5 months represent only 1 % of the combined yearly visitation to the Postojna and Predjama cave systems.

The principal duty of the biological monitoring plan is observation of the bats' presence (especially in Netopirjev rov), to protect their hibernation and to take necessary steps in the case of decrease in bat numbers.

Water quality monitoring on the Lokva sinking river is not yet organized. Because the Lokva after 15 km underground re-emerges as a spring at Vipava it would be reasonable that in coming years the ARSO should organize regular measurements of basic parameters in the Lokva river, too.

It is necessary to design a restoration programme for the tourist paths in the cave, because the current path is in poor condition (8). At the same time it is necessary to protect numerous sites with historical inscriptions and archaeological finds, as well as to develop a suitable solution for safer tourist crossing on the steep-ladder from Velika dvorana to Fiženca.

The collapse that occurred in Konjski hlev due to high floods in September 2010 should be properly improved with further monitoring of the collapse site to ensure that visitors will be safe.

# 7

# UREJANJE NEBEŠKE JAME (THIEN DUONG, VIETNAM) ZA TURISTIČNE NAMENE

# DEVELOPMENT OF THE HEAVEN’S CAVE (THIEN DUONG, VIETNAM) FOR TOURISTIC PURPOSES

Leta 2006 smo na Inštitutu za raziskovanje krasa ZRC SAZU s strani vietnamskega podjetja CivideC dobili zanimivo ponudbo za sodelovanje pri turističnem opremljanju do tedaj slabo poznane vietnamske jame Thien Duong (Nebeška jama). Ker se na Inštitutu tradicionalno ukvarjamo s speleologijo, s tem v zvezi pa tudi z razvojem turističnih jam, smo povabilo sprejeli. Pridružila sta se nam tudi sodelavca Turizma KRAS d.d., upravljavca Postojnske jame, ki sta prevzela turistični del projekta, medtem ko smo sodelavci Inštituta poskrbeli za strokovni del. Sledila sta dva obiska v Vietnamu, ko smo jamo jamarsko raziskali, jo izmerili, opravili nekaj bistvenih speleoloških raziskav, fotografirali, določili turistične znamenitosti v njej, pripravili plan turističnih poti v jami in do nje ter izvedli trženjsko raziskavo zanimivosti jame oziroma območja, na katerem leži. Izsledke smo predstavili lokalni vladi province Quang Binh, ki je pozneje jamo tudi predala v turistično upravljanje. Strah, da se jama ne bi razvijala po načelih trajnostnega razvoja, je bil upravičen, saj izbrani upravljavec jame ni v ničemer spoštoval smernic naših raziskav, s čimer je bila jama delno degradirana, z naše strani predvidene poplave v jami septembra 2010 pa so jamsko infrastrukturo in z njo jamo še dodatno uničile.

## 7.1 Lokacija Nebeške jame – Unescov park Phong Nha-Ke Bang

Nebeška jama leži v provinci Quang Binh v osrednjem Vietnamu, približno 500 km od glavnega mesta Hanoi. Provinca je med najrevnejšimi v Vietnamu, zato se kot gospodarska možnost odpira nadaljnji razvoj turistične ponudbe in infrastrukture v Unescovem parku Phong Nha-Ke Bang, kjer je locirana Nebeška jama. Do zdaj je bila jama znana le redkim domačinom in britanskim jamarjem, ki so območje parka raziskovali v zadnjih desetletjih in tam našteli prek 300 jam (*Limbert* 2010).

Park Phong Nha-Ke Bang pokriva 857,54 km² veliko območje tipičnega kopastega krasa (*World heritage list…*, 2000) in na zahodu meji na Laos. Najvišji vrhovi segajo nekaj nad 1100 m. Letna količina padavin znaša 2000–2500 mm, kar je izredno ugodno za razvoj

In the year 2006, Karst Research Institute ZRC SAZU was invited by Vietnamese company CivideC to cooperate on development of the Thien Duong (Heaven's cave) for tourism. Till then the cave was poorly known. Since Institute traditionally deals with speleology and has been involved in the development of several caves for tourism in Slovenia, the invitation was accepted. Collaborators of the Institute decided to work on scientific part of development while touristic one was taken by the collaborators of the company Turizem KRAS d.d. that managed touristic development of the Postojna cave. We visited Vietnam two times and there we made a cave exploration and survey, some basic speleological research, defined cave's attractions and took photos of them, made a plan of touristic paths in and to the cave and made some marketing research in the area where the cave is situated. The report was presented to the provincial government of Quang Binh province that later gave a right to local company to develop the cave for touristic purposes. We were skeptical that local government will follow our sustainable guidelines and this became true in the following years when the cave was developed as a show cave. The cave work with considerable devastation was followed by floods in 2010 that had already been predicted with speleological research.

## 7.1 Location of the Heaven's cave—Unesco park Phong Nha-Ke Bang

The Heaven's cave is located in central Vietnam in the province Quang Binh some 500 km from the capital Hanoi. The province is one of the poorest in Vietnam. With the aim of improving the economic situation in the area, the possibility has been raised of marketing sights in the Phong Nha-Ke Bang National Park, a Unesco World Heritage Site as tourist attractions. Among these sights, as yet unexploited for tourism purposes, is the Heaven's cave. Till now the cave was known just to local inhabitants and to British cavers, which investigated this area and explored more than 300 caves in the last decades (*Limbert* 2010).

The Phong Nha-Ke Bang National Park covers an area of 857.54 km² of hilly tropical karst (*World* krasa. Osrednji del parka preči reka Song Chay, ki je z nadmorsko višino 80 m najnižja točka parka. Glavnino geomorfnih oblik predstavljajo stožčasti vrhovi z vmesnimi depresijami, globokimi tudi od 100 do 300 m. Pobočja so izjemno strma in praviloma presegajo naklonski kot melišč (30°–35°).

Pomembnost parka s strani Unesca je bila leta 2003 prepoznana zaradi več kot 400 milijonov let stare in čez 1000 m debele sekvence pretežno karbonatnih kamnin, dolgega geomorfnega razvoja in razvoja površja (preko 36 milijonov let, tj. od oligocena do danes) in posledično izredno pestrega nadzemnega in podzemnega krasa. Park izstopa tudi po vegetacijski in živalski pestrosti, saj ga v velikem delu prekriva dobro ohranjen tropski deževni gozd. Prav zaradi kraškega značaja je park Phong Nha-Ke Bang za razliko od ravnega obalnega območja izredno redko poseljen, praktično brez prometnic in večjih posegov ter zato zelo dobro ohranjen. Glavna turistična ponudba parka sta vodna jama Phong Nha, po kateri je park dobil tudi ime, in suha jama Tien Son. V parku se nahaja najdaljša raziskana podzemna reka na svetu v jamskem sistemu Hang Vom (15.310 m; *Limbert* 2010), leta 2009 pa je bil na istem območju (Ke Bang) odkrit tudi največji jamski rov (*Hamilton Smith* 2009). Glavna faktorja za nastanek tako dolgih vodnih jam z izjemno velikimi prečnimi preseki sta zelo dolga speleogeneza v tektonsko dokaj mirnem okolju in okolica iz neprepustnih kamnin, od koder ponikalnice pritekajo na kraško območje parka. Precej manjši delež zavzema druga turistična ponudba: vožnja po reki Chay in izobraževalni ekoturizem na območju Ke Bang. Vse te značilnosti so izvrsten potencial za razvoj kraškega turizma, ki pa je trenutno zelo slabo izrabljen.

Da bi jamo razvijali v turistične namene, smo opravili presojo vplivov na okolje, kar je stalnica pri trajnostnem razvoju jame in jo predlagata tudi Cigna in Burri (2000). Pri tem gre za določanje stanja nepoškodovane jame, oceno potencialnih vplivov, določanje mejnih zmogljivosti in nosilne kapacitete jame ter predloge za razvoj jamske infrastrukture, ki naj bi v čim manjši meri prizadela živo in neživo jamsko okolje. Seveda je treba upoštevati tudi smiselnost turističnega razvoja glede na občutljivost jame, njeno dostopnost in zanimanje potencialnih turistov, kar nam poda ekonomska analiza trga v tem delu Vietnama.

*heritage list...*, 2000) and border on Laos westwards. The highest peaks reach altitude over 1100 m a.s.l. Annual rainfall reaches 2.000–2.500 mm which is very suitable for intensive karst evolution. The central section is crossed by the river Song Chay, the lowest point in the park (80 m a.s.l.). Conical hills with 100–300 m deep depressions between them account for the majority of geomorphic forms. The slopes are very steep and as a rule exceed the slope angle of scree (30°–35°).

The park came under the Unesco protection in 2003 because of its extraordinary 400 million years old and over 1000 m thick sequence of mainly carbonate rocks, the long development of its topography (from the Oligocene to the present day—over 36 million years) and as the resulting extremely intensively developed karst formations. The park is important also from the viewpoint of biodiversity due to well-preserved rain forests. Because of karst characteristics park is sparsely populated, almost without roads and major impacts and therefore well-preserved. The most important touristic products are the water cave Phong Nha that gave the park its name and the dry cave Tien Son. The park is a place of the longest underground river in the world, Hang Vom cave system (15,310 m; *Limbert* 2010), and since 2009 the largest cave passage (*Hamilton Smith* 2009). The most important factor for speleogenesis of so long water caves with enormous cross-sections is a long speleogenesis in tectonically stable environment and vicinity of impermeable rocks from where the allogenic recharge reaches carbonate rocks. Other tourist attractions account for a considerably smaller share: tours on the river Song Chay and educational ecotourism in the Ke Bang area. Karst resources are a great potential for future touristic development that is in initial phase right now.

To develop the Heaven's cave tor tourism, environmental impact assessment as a guideline for sustainable development of the cave was done as suggested by Cigna and Burri (2000). We evaluated present-day conditions of the wild cave, potential impacts, defined carrying capacity of the cave and proposed the cave's infrastructure that would have the lowest possible impact to the biological and non-biological environment. The economical and marketing analysis of the regional market gave us an estimate of the visitors' interest to

## 7.2 Jamarsko raziskovanje, topografske meritve in splošni pristop k speleološkim meritvam

Vhodni del jame v dolžini 850 m (1, 2) je bil z naše strani raziskan aprila 2007, nadaljevanje jame pa januarja 2009. Primerjava naših načrtov Nebeške jame iz leta 2007 in načrta jamskega sistema Hang Vom iz leta 1992 je pokazala, da gre za identična dela jame, kar smo ugotovili tudi na podlagi odtisov škornjev večje skupine jamarjev v globljem delu jame. Nejasnost se je pojavila zaradi dejstva, da so Angleži v jamo Hang Vom vstopili skozi približno 8 km oddaljen glavni vhod in preko drugega vhoda, ki ga takrat niso poznali pod imenom Nebeška jama, prišli pod strmo skalnato steno na rob goste džungle. Ta jim je preprečevala, da bi izhod iz jame Hang Vom prepoznali kot vhod v Nebeško jamo, zato so se vrnili skozi prvotni vhod, lokacija drugega vhoda pa ni bila topografsko določena vse do našega obiska jame.

V sklopu jamskih topografskih meritev smo detajlno izmerili glavni poligon jame, izrisali tloris, iztegnjeni profil in prečne profile na pomembnejših mestih. Zaradi omejitev pri letalskem prevozu in samem dostopu do jame je bil osnovni poligon jame izmerjen na klasičen jamarski način, to je z meritvami razdalje, naklona in azimuta med poligonskimi točkami. Magnetni azimut smo korigirali s trenutno magnetno deklinacijo na tem območju.

Vzporedno s topografskimi meritvami jame je potekalo njeno stvarno speleološko vrednotenje, ki je zajemalo opis takratnega geološkega, geomorfološkega, hidrološkega in meteorološkega ter deloma speleobiološkega, arheološkega in mlajše paleontološkega stanja. Zaradi prostorske omejitve v tem prispevku navajamo le povzetek speleoloških raziskav. K trenutnemu stanju je sodila tudi fotografska inventarizacija bistvenih elementov jame. Na podlagi teh značilnosti sta sledili opredelitev ogroženosti in ranljivosti jame ter izpostavitev temeljnih naravovarstvenih smernic (fizičnih omejitev jame), na podlagi katerih so bili določeni nujni infrastrukturni posegi v jamo (poti, osvetlitev) in pot od glavne ceste do vhoda z izvenjamsko infrastrukturo. Za vse omenje-

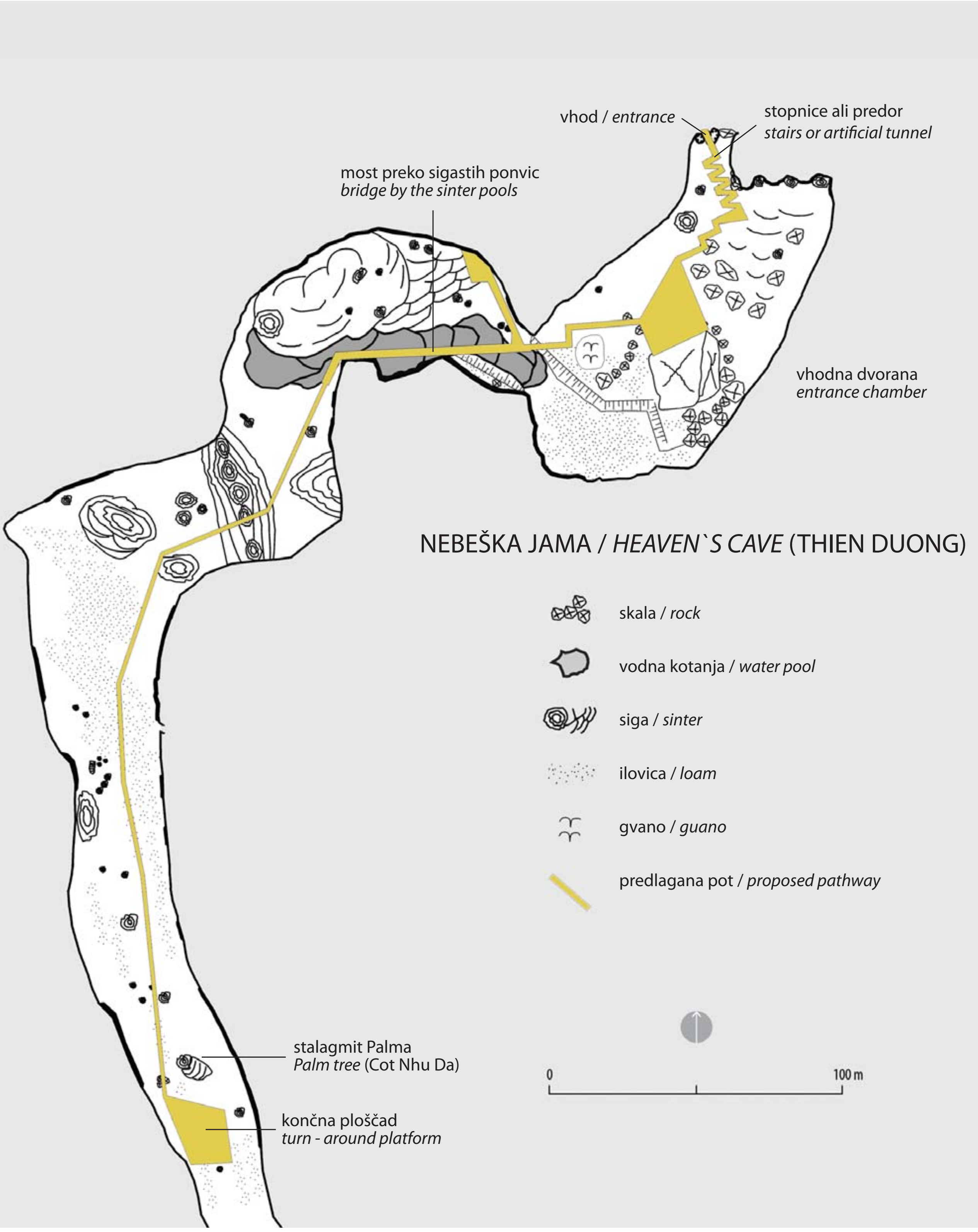
visit the show cave that is of course the crucial factor to the final decision if the touristic development of the cave is reasonable.

## 7.2 Cave exploration, topographical survey and general approach to the speleological measurements

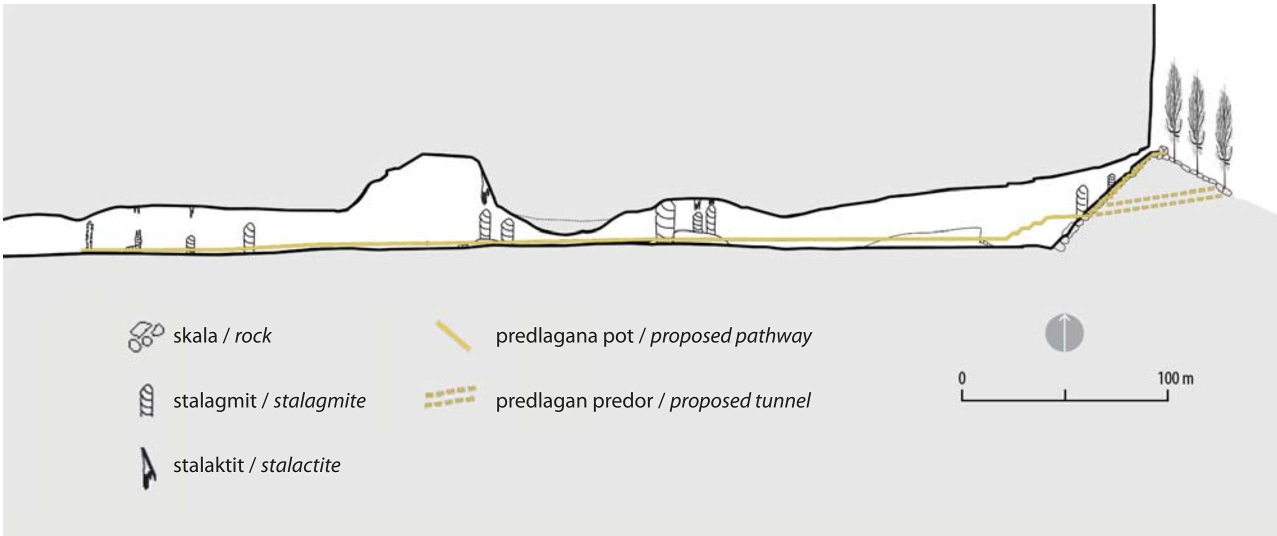
Exploration of 850 m of entrance parts of the cave (1, 2) took place in April 2007 while continuation of the cave was explored in January 2009. Comparison of our maps of the Heaven's cave and Hang Vom cave system from 1992 showed that the caves are the same. This was also realized from footprints of the larger group of cavers in the higher and more remote part of the Heaven's cave. Different names for the same cave are a result of two remote entrances. At that time, British cavers entered the cave system Hang Vom through the main entrance where water appears from the underground system. They left Hang Vom through the upper entrance which acts as a sink and through the narrow entrance under the steep cliff. Because of a dense jungle below the cliff they returned through the known, lower entrance. Therefore, the side exit of Hang Vom and Heaven's cave are supposed to be a part of the same cave system.

In the framework of topographical survey, the main polygon of the Heaven's cave was measured, ground-plan and profile were done. Cross-sections were measured at the most important sites. Cave survey was done with inclinometer, compass and measurement tape since we were limited in the air transport for the more appropriate devices (i.e. theodolite). Azimuth defined with compass was corrected for the local magnetic declination.

While one group made a cave survey, another one speleologically evaluated the cave. The latter included general present-day description of geological, geomorphological, hydrological, meteorological and partly biospeleological, archaeological and paleontological characteristics of the cave. Here we mention only basic speleological findings. Together with speleological research, photoinventarization of the cave's interior was also done. On the basis of the basic characteristics, we defined sensibility of the cave, major threats and put forward basic environmental guidelines (physical limits




**1** Tloris Nebeške jame s predlaganim potekom poti za klasični obisk.
Plan of the Heaven's cave with a proposed path for the classic cave visit.




**2** Iztegnjeni profil Nebeške jame s predlaganim potekom poti za klasični obisk.
Profile of the Heaven's cave with a proposed path for the classic cave visit.

ne posege v jamo pa je treba pridobiti tudi soglasje s strani Unesca.

### 7.2.1 Splošni opis jame

Vhod v Nebeško jamo leži na nadmorski višini 226 m in se odpira skozi podorne bloke pod več kot 50 m visoko steno. Najlažji dostop poteka skozi odprtino 3 × 4 m. Vhodni del predstavlja podorni stožec v dolžini 65 m in z vpadnim kotom 45°. V tem delu rasteta iz tal stalagmita s premerom okrog 3 m in višino preko 5 m. Proti dnu 120 m dolge in 60 m široke vhodne dvorane prekriva podorne bloke vse več poplavne mivke in ilovice. V osrednjem delu dvorane leži tudi meter visok kup gvana. Glavno nadaljevanje jame poteka proti zahodu. Dno prekrivajo nekaj decimetrov globoke in več metrov široke sigaste ponvice, ki se proti več metrov visokim kapniškim stebrom v nadaljevanju poglobijo in skrajšajo. Po ovinku proti jugu in zahodu sigaste ponvice sledimo še v enem delu. Nadaljevanje predstavlja približno 30 m širok in več kot 20 m visok rov (3), sredi katerega se po dnu vije ilovnata struga, na terasi, visoki do 3 m, pa izrašča več mogočnih stalagmitov in kapniških stebrov. Kapniške strukture se pojavljajo v gnezdih pod intenzivneje zakraselimi deli vadozne cone, ki omogočajo dotok sigotvorne vode v jamo. Zadnji na predvideni turistični poti je zaradi

of the cave). The latter were a basis to define appropriate tourist infrastructure in the cave (lightning, paths) and to the cave (from the main road). It is important to follow Unesco guidelines for all the impacts that change the natural conditions in the cave.

### 7.2.1 General description of the cave

The entrance to the Heaven's cave is located at about 226 m a.s.l. under the more than 50 m high vertical cliff. The easiest access leads through a 3×4 m void between collapse blocks. The continuation is developed as a 65 m long slope with inclination 45°. In the middle of scree, two over 5 m high and 3 m wide stalagmites are located. Foot of scree is covered by silty and loamy sediment and by bat guano. This part of the cave is actually a huge underground hall, 120 m long, 60 m wide and up to 30 m high. At the western side, a dry water channel is located. The bottom of the cave is covered with several metres wide rimstone dams, which are becoming smaller but deeper towards massive flowstone columns. Another area of rimstone dams is located south-west of the first ones. There, the cave passage is developed as about a 30 m wide and more than 20 m high nearly horizontal passage (3). All along this passage, the dry water channel is incised into the sediment terrace at both sides.

**3** Glavni, občasno poplavljeni rov Nebeške jame.
The occasionally flooded trunk passage in the Heaven's cave.

**4** Masiven stalagmit v vhodnem delu Nebeške jame.
The massive stalagmite in the entrance part of the Heaven's cave.

razvejane strukture dobil ime po palmi – Cot Nhu Da. Nadaljevanje jame poteka v podobno širokem in zasiganem rovu.

### 7.2.2 Turistična privlačnost Nebeške jame

Največja atraktivnost jame so lepo ohranjene sigaste ponvice, ki merijo ponekod preko 7 m v dolžino. Med obiskom leta 2009 so bile večinoma brez vode. Ob našem prvem obisku jame leta 2007 pa so bile brez vode vse ponvice. Njihova ohranjenost in odsotnost ilovice iz prvotnih obiskov jame kažejo, da se čeznje pretaka večja količina vode in so torej aktivne. V kolikor bi prišlo do neustrezne turistične rabe jame, bi jama zaradi uničenja sigastih ponvic izgubila največjo privlačnost.

Druga večja turistična atraktivnost v jami so masivni stalagmiti in kapniški stebri, ki kljub širini rova mestoma skoraj povsem zapirajo prehod. Večja skupina stalagmitov in stebrov leži tudi na vhodnem podoru, kjer iz tal izraščata stalagmita, debela precej več kot 2 m (4). Z evropske in ameriške perspektive je lokacija kapniških oblik tako blizu vhoda presenetljiva, vendar v tropskem podnebju zmrzalnega preperevanja ni.

Svojevrstna privlačnost je tudi vpetost Nebeške jame v dolg sistem jame Hang Vom, ene izmed najdaljših in najmogočnejših vodnih jam na svetu. Jama Hang Vom je zaradi pogoste in nenadne poplavnosti zelo nevarna za turistični obisk, medtem ko je dvig vode v Nebeški jami domnevno precej počasnejši in bolj predvidljiv, izhod iz jame pa je višji od najvišje možne poplave in precej blizu skrajni točki izmerjenega dela jame.

Nebeška jama ima bogat izobraževalni potencial, saj ponuja dober vpogled v speleološke in kraške pojave, dostop do nje pa lep ambient ob reki Song Chay in pester vpogled v biološke značilnosti vlažnega tropskega gozda na kraških kamninah.

Since the terrace is the driest part of the cave bottom, several stalagmites and columns appear there. Rather than individually, they are formed as a group under well-cracked and karstified carbonate rock. The most impressive one was named after a palm tree—Cot Nhu Da. Continuation of the passage is similar to the already described parts of the cave.

### 7.2.2 Tourist attractions of the Heaven's cave

The biggest attraction of the cave are well-conserved rimstone dams which in places are over 7 m wide. At the time of our visit in 2009 most of them had no water. During our first visit in 2007, all the rimstone dams were empty. Their state of conservation and absence of loam from the original visits to the cave show that a large quantity of water flows over them and therefore that they are active. Nevertheless, if an unsuitable use of the cave for the purposes of tourism occured, destruction of the rimstone dams would result in the cave losing its biggest attraction.

The second biggest attraction in the cave are massive stalagmites and dripstone pillars which at some places almost completely block the main underground passage. A large group of stalagmites and pillars also lies at the entrance scree where two more than 2 m thick stalagmites can be seen growing out of the floor (4). From the European and North American perspective, the location of cave formations so close to the entrance is surprising, but scientifically expected in a tropical climate due to the absence of frost weathering.

Another unique attraction is the cave's position as part of the long cave system of Hang Vom, one of the longest and largest water caves in the world. Hang Vom itself is very dangerous for visitors because of frequent and sudden floods, but the rise of water level in the Heaven's cave is presumably considerably slower, more predictable, and the exit from the cave is higher than the highest possible flood and quite near the furthermost point of the measured section in the cave.

The Heaven's cave has a very good educational potential since it offers a good and varied insight into speleological and karst phenomena while the route to the cave and the beautiful environment of the Somg Chay

## 7.3 Občutljivost jame, naravovarstvene smernice in nosilna zmogljivost jame

Jama je praktično neranljiva na meteorološkem področju, saj je vsaj v zimskem in poletnem obdobju izjemno dobro prezračena. Odsotnost arheoloških in mlajše paleontoloških ostankov jo ohranja neranljivo tudi na tem področju.

Najbolj ogrožena je na področju morfologije odloženih sedimentov (ilovice in sige). Izpostavimo lahko dva tipa sige v jami, ki se pomembno razlikujeta po stopnji občutljivosti: stalagmiti in stebri na eni ter sigaste ponvice in stalaktiti na drugi strani. Stalagmite in stebre varuje njihova velikost, medtem ko so precej bolj ranljivi sicer redki stalaktiti in sigaste ponvice. Pri slednjih veljajo za najbolj občutljive robovi, čez katere se preliva voda, in dna, ki jih sestavljajo drobni in krhki kristali sige. Z izmenično hojo po ilovici in sigastih površinah se ilovica prenaša na zasigane površine. Na mestih aktivnega toka vode se ilovica večinoma spira, zablatene površine pa ostajajo na krajih, kjer aktivnega toka vode ni. Prenosu ilovice se v sedanjem naravnem stanju jame praktično ne moremo izogniti, ravno tako se na posameznih mestih ni moč izogniti poškodbam drobnih kristalov v sigastih ponvicah. Robovi ponvic so nekoliko manj krhki, se pa poškodujejo pri nepravilni hoji ali pri preštevilnem obisku jame. Zaradi predvidoma zelo redkih poplav izven izoblikovane podzemne struge se stopinje v ilovici ohranjajo zelo dolgo, vendar se ob zelo visokem vodostaju hitro zabrišejo. V podzemni strugi se sledovi zabrišejo po vsakem bolj intenzivnem deževju, kolikor se sigaste ponvice ne nadaljujejo v podzemno strugo. V slednjem primeru je občutljivost enaka kot v primeru dna sigastih ponvic.

Speleobiološke ogroženosti s smernicami na podlagi sedanjih raziskav in znanja ni možno opredeliti. Potrebne bi bile nadaljnje raziskave, ki bi pokazale številčnost živalskih vrst, njihovo redkost in zaščitenost.

Na podlagi opravljene analize stanja in identificirane občutljivosti jame lahko podamo grobe naravovarstvene smernice. Vhodna dvorana jame tudi ob številčnejšem obisku ne bi bila posebej ogrožena.

river offer a good insight into biological characteristics of a humid tropical forest on karst rock.

## 7.3 Sensitivity of the cave, cave protection guidelines and carrying capacity of the cave

The cave is practically invulnerable in the meteorological sense, since at least in winter and summer it is extremely well ventilated. The absence of archaeological finds and paleontological remains keeps it invulnerable in this sense, too.

It is most vulnerable in the sense of the morphology of deposited sediments (speleothems and loam). We can highlight two types of speleothem deposit in the cave which differ significantly in terms of their level of sensitivity: stalagmites and pillars on the one hand, and rimstone dams and stalactites on the other. Stalagmites and pillars are very invulnerable because of their size. The rare stalactites and fragile rimstone dams are considerably more vulnerable. In the case of the latter, the most sensitive parts are their rims over which the water flows and their bottoms which are formed of tiny, fragile calcite crystals. Walking alternately over loam and calcite surfaces results in the loam being transferred to the speleothem-covered surfaces. In places where there is an active water flow, the loam is mostly washed away, but muddy surfaces remain in places where there is no active water flow. It is practically impossible to avoid the transfer of loam in the current natural state of the cave. Similarly, in some places it is not possible to avoid damage to the tiny crystals in the rimstone dams. The edges of the dams are slightly less fragile but they are damaged by incorrect walking or if there are too many visitors in the cave. Because floods outside the water channel are likely to be extremely rare, footprints in the loam will last for a quite long time, although they are quickly erased when the water level is very high. On the rimstone dams that are developed in the water channel, traces are erased after every heavy rainfall. If they are developed out of reach of high water level, they are very sensitive.

It is not possible to define speleobiological risks and guidelines on the basis of present research and knowledge.

Nadaljevanje je bistveno bolj občutljivo zaradi sigastih ponvic in prenosa blata na zasigane površine. Za vodenje manjših skupin turistov (t. i. alternativni ogled jame) je sprejemljiva le hoja po ozki in jasno označeni poti, na kateri bi sicer prišlo do določenih poškodb, ki pa bi bile omejene le na zelo majhen del. Za vodenje večjih skupin turistov je nujna ureditev poti po jami, ki bi preprečila hojo po zasiganih površinah, zmanjšala sledove na ilovnatih sedimentih in preprečila prenos ilovice na zasigane površine. Kolikor nam je znano, smernice trajnostnega razvoja glede ureditve poti v jami ob turistični otvoritvi niso bile upoštevane.

## 7.4 Možnost turistične ureditve jame

Ureditev jame v turistične namene je zaradi njene specifične geografske lege, dokaj nestabilnih sedimentov in naplavin, visokega stropa in nezanesljivega osciliranja vode tehnično zahteven projekt. Jama je občutljiv ekosistem, zato je bilo predlagano, da se pred kakršnimikoli posegi zagotovi vse strokovne podlage ter dovoljenja s strani vietnamskih ministrstev in Unesca.

Na zahtevo vietnamskih sodelavcev je bilo izdelanih več predlogov za izvedbo pohodnih poti in osvetlitve v jami:

- pohodna pot za tako imenovane 'doživljajske oglede',
- pohodna pot za 'masovni' turizem z vso pripadajočo infrastrukturo – klasični ogled jame in
- pohodna pot z umetnim tunelom zaradi lažjega vstopa in izstopa iz jame.

Izdelan je bil idejni načrt ureditve pešpoti za masovni turizem v dolžini 550 m (1, 2). Predlagano je bilo, naj bi bile pohodne površine v jami napravljene iz nekorozivnih materialov, lahke in odstranljive. Celotna pot naj bi bila zgrajena na nosilnih stebrih, da bi se izognili večjim gradbenim posegom in poškodbam tal v jami. Pripravljen je bil tudi predlog 60 m dolgega umetnega tunela, tako da bi se obiskovalci izognili stopnicam, ki bi bile sicer v vhodnem delu jame nujno potrebne. To bi verjetno tudi povečalo število obiskovalcev, vendar naj bi bilo v zvezi s tem odločujoče mnenje Unesca.

Further research indicating the numbers of animal species, their rarity and their protection would be necessary.

On the basis of the analysis of situation and identified vulnerabilities of the cave, we are able to lay down some rough cave protection guidelines. The entrance section of the cave should not be extra at risk even in the case of large numbers of visitors. The continuation of the cave is significantly more sensitive because of the rimstone dams and the transfer of mud onto calcite-covered surfaces. For guiding small groups of tourists through the cave (so-called alternative visits), the only acceptable method is walking along a narrow and clearly marked path. Although there would be a certain amount of damage to the path, this would be limited to a very small section. For larger groups of tourists, a constructed path urgently needs to be laid through the cave which would prevent visitors from walking on calcite-covered surfaces, reduce traces in loamy sediments and prevent the transfer of loam to calcite-covered surfaces. As we know, during tourist opening of the cave sustainable guidelines about laying the special path through it were not followed at all.

## 7.4 Suitability of the cave as a show cave

Adapting the Heaven's cave for tourism purposes is a technically demanding project because of its specific geographical position, somewhat unstable sediments and alluvial deposits, high ceiling and unknown fluctuation of water level. The cave is a sensitive ecosystem and it has therefore been proposed that all the scientific knowledge is taken into account, permissions from the side of Vietnamese ministries and from the side of Unesco.

At the request of the Vietnamese partners, several proposals for paths and lighting in the cave have been drawn up:

- the path for Adventure visits,
- the path for mass tourism with all relevant infrastructure—Classic cave visit, and
- the path with a man-made tunnel to enable easier access to and exit from the cave.

An outline plan has been drawn up for the laying-out of a 550 m long footpath for mass tourism (1, 2). It has been proposed that the walking surfaces in the

Izdelane so bile tri variante osvetlitve predvidenega turističnega dela jame:

- klasična osvetlitev (žarnice, reflektorji),
- osvetlitev z LED diodami in
- kombinacija klasične osvetlitve in LED diod.

Z vidika sedanjih idej o turistični opremi jame, značilnosti jame in stroškov se zdi najbolj ugodna klasična osvetlitev z možnostjo kombinacije z LED diodami. Zaradi močne razpršitve svetlobe v tako velikih prostorih in skoraj enkrat višje cene osvetlitev zgolj z LED diodami ne bi bila optimalna.

Za dostop do jame so bile predlagane tri variante:

- dostop po pešpoti,
- dostop po cesti in
- dostop z gondolo.

Pešpot bi potekala po že obstoječi stezi, skozi deževni gozd, ob reki in se končala s strmim vzponom proti vhodu v jamo. Zaradi pestre biodiverzitete in zgodovinske pomembnosti območja bi ob primerni razlagi rabila za učno pot, je pa problematična njena dolžina (vsaj pol ure v eno smer), ki onemogoča obisk slabše pripravljenim turistom.

V okviru dostopa po cesti je predvidena izgradnja 4–5 m široke ceste od parkirišča do ploščadi pred vhodom v jamo v dolžini 3 km. Cesta bi bila namenjena izključno prevozu obiskovalcev jame z manjšim avtobusom ali roadmobilom. Obiskovalci bi vozila puščali na parkirišču ob glavni cesti, kjer bi zgradili preostalo turistično infrastrukturo (informativni center, restavracijo, prodajalno spominkov, sanitarije ipd.).

Dostop do jame bi bil lahko izveden tudi s postavitvijo gondolske žičnice do vrha previsne stene nad jamo. Od tod bi obiskovalce prepeljali do jame z vozili. Ta ideja je bila predstavljena na željo vietnamskih sodelavcev, vendar je prevladovalo mnenje, da organi Unesca ne bodo dovolili tovrstnega posega v naravno okolje parka.

## 7.5 Razvoj celovitega trženjskega spleta

Projekt vzpostavitve nacionalnega parka Phong Nha-Ke Bang za turistični obisk je izredno zanimiv, saj združuje tako znanstveno-raziskovalno delo na področju krasoslovja in ekonomskih znanosti kakor

cave should be made of non-corrosive materials and be light and removable. The whole path should be built on pillars in order to avoid major building work and damage to the floor of the cave. A proposal has been prepared of a 60 m long man-made tunnel that would enable visitors to avoid the steps that would otherwise be urgently necessary in the entrance section of the cave. This would probably increase the number of visitors, but here the opinion of Unesco would be decisive.

Three variants for illumination of the cave's section planned to be opened to tourists were represented:

- traditional lighting (bulbs, spotlights),
- LED lighting, and
- combination of traditional and LED lighting.

From the point of view of present ideas for equipping the cave as a show cave, the characteristics of the cave and costs, the best option would appear to be traditional lighting with the option of combining it with LED lighting. LED lighting alone would not be the optimal solution because of considerable dispersion of light in such a large space, and because it is almost twice as expensive.

To access the cave three variants were proposed:

- access by the footpath,
- access by the road, and
- access by the cable car.

The footpath would follow an existing path through the rainforest, along the river and would end with a steep ascent towards the cave entrance. In view of great biodiversity and historical importance of the area, it could also serve as a nature/history trail if suitable explanations were provided. The most problematic is the length of the path since it takes at least half an hour in one way to access the cave. This hinders the visits from the tourists out of condition.

The construction of a road 3 km long and 4–5 m wide from the car parking place to an esplanade outside the cave entrance has been envisaged. The road would be exclusively intended for transporting visitors to the cave by minibus or roadmobile. Visitors would leave their vehicles in the parking place by the main road where other tourist infrastructure would be built (information centre, restaurant, souvenir shops, toilets, etc.).

The access to the cave could also be implemented by constructing a gondola-type cable car to carry visitors to the top of the overhanging cliff above the tudi aplikacijo rezultatov tega dela na konkretnem poslovnem primeru. Končni cilj projekta je predlagati koncept turističnega razvoja, ki bo trajnostno naravnan tako do naravnega okolja kot tudi socialno ekonomskega razvoja lokalnih skupnosti na območju nacionalnega parka. Obenem mora turistični razvoj temeljiti na ustreznem trženjskem spletu, ki je pri turističnih proizvodih še zlasti kompleksen.

Razvoj celovitega trženjskega spleta v prvi vrsti temelji na raziskovalnem delu, katerega ugotovitve bodo pripomogle k razumevanju turističnih tokov, preferenc obiskovalcev in značilnosti turistične ponudbe v azijskih državah ter tako pomembno doprinesle k naboru znanj v slovenski turistični industriji in znanstveno-raziskovalnih institucijah.

Projekt naj bi bil tudi referenca slovenskih turističnih podjetij in raziskovalnih institucij, sodelujočih pri njem, da se v svetu prepoznajo in potrdijo kot nosilci vrhunskih znanj, ter dokaz za njihovo sposobnost vodenja kompleksnih znanstveno-raziskovalnih projektov in aplikacije izsledkov znanstveno-raziskovalnega dela na konkretnih poslovnih projektih tudi izven Evropske unije.

Razvoj celovitega trženjskega spleta je sestavljen iz treh faz:

Prva faza obsega izvedbo vrste trženjskih raziskav. Turizem v provinci Quang Binh, kjer leži nacionalni park Phong Nha-Ke Bang, je trenutno na začetni razvojni stopnji. Da bi lahko ocenili potencial za turistični razvoj in pravilno oblikovali turistično ponudbo, je treba osnovne podatke o morebitnih obiskovalcih, njihovi strukturi, potrebah, preferencah ipd. še pridobiti.

Druga faza se nanaša na pripravo celovitega trženjskega spleta za vzpostavitev turizma v nacionalnem parku Phong Nha-Ke Bang. Na podlagi podatkov, zbranih z raziskavami, bodo oblikovani predlogi za nadaljnji razvoj primarne turistične ponudbe (ključnih atrakcij, ki pritegnejo obiskovalce in pomenijo razlog za obisk nacionalnega parka) in sekundarne turistične ponudbe (zvrsti ponudbe, nivo kakovosti, standardi ipd.). Končni cilj druge faze je oblikovati celovit trženjski splet, prilagojen ciljnim tržnim segmentom.

Tretja faza je namenjena razvoju idejnega koncepta za vzpostavitev podzemne kraške Nebeške jame za

cave. From here visitors would be transported to the cave by vehicles. The idea was presented at the request of the Vietnamese partners, although the prevailing opinion was that Unesco would not permit construction of this kind in the natural environment of the park.

## 7.5 Development of an integrated marketing mix

The project of opening up Phong Nha-Ke Bang National Park to tourism is an extremely interesting one in that it combines scientific research in the fields of karstology and economics and application of the results of this research to a specific business proposal. The final goal of the project is to present a concept of tourism development that will be sustainably oriented towards both the natural environment and the socioeconomic development of local communities in the area of the national park. At the same time, the development of tourism must be based on a suitable marketing mix which in the case of tourism projects is particularly complex.

The development of an integrated marketing mix is based first and foremost on research, the findings of which will contribute to understanding of tourist flows, visitor preferences and the characteristics of tourism in Asian countries, in this way making an important contribution to the range of knowledge in Slovenian touristic industry and scientific research institutions.

The project will serve as a reference for the Slovenian tourist companies and research institutions taking part in the project, enabling them to position themselves as specialists and demonstrate their ability to run complex scientific research projects and apply the findings of scientific research to specific business projects even outside the EU.

The development of an integrated marketing mix consists of three phases:

The first phase covers implementation of the market research. Tourism in Quang Binh Province where the Phong Nha-Ke Bang National Park is located is currently at the initial stage of development. In order to assess the potential for development of tourism and design a suitable range of tourist products, basic data on potential visitors, their structure, needs, preferences etc., still need to be obtained.

potrebe turističnega obiska in poteka vzporedno s prvima dvema fazama projekta.

Cilj raziskave trga je zbrati okrog 1500 popolnih anketnih vprašalnikov. Vprašalnik, pripravljen v več jezikih, temelji na lastni metodologiji, razviti načrtno za potrebe analize preferenc potrošnikov glede turističnih proizvodov. Z obdelavo zbranih podatkov bomo opredelili tržne segmente in njihove posamične preference, kar nam bo omogočilo pripravo celovitega trženjskega spleta. Projekt anketiranja tujih turistov v Vietnamu je prevzelo partnersko podjetje CivideC iz Hanoja.

## Sklep

Nebeška jama je kot del ene izmed najdaljših vodnih jam na svetu Hang Vom speleološko pomemben del parka Phong Nha-Ke Bang. Čeprav se tudi v njej občasno pojavljajo poplavne vode, so te verjetno dosti manj intenzivne in kratkotrajnejše od tistih v jami Hang Vom. S tega vidika je Nebeška jama zelo primerna za razvoj bolj izobraževalnega turizma v smislu krasoslovja in speleologije v širšem prostoru, ima pa tudi nekaj izjemnih kapniških oblik (sigaste ponvice, masivne stalagmite in kapniške stebre). Največja šibkost jame je dostop vanjo, ki bi ob večjih investicijah v jami terjal za park znatne posege v prostor. V zvezi s tem je nujno treba pridobiti soglasje s strani Unesca. Ocena turističnega potenciala bo tehtnejša po pridobitvi izpolnjenih anketnih vprašalnikov, na njej pa bo izdelan celovit trženjski splet za park in samo Nebeško jamo.

Turistični razvoj jame mora potekati postopno, korak za korakom. Kakršenkoli izjemno hiter razvoj z velikimi investicijami lahko pusti v naravnem, socialnem in ekonomskem okolju negativne posledice s trajnimi negativnimi vplivi, predvsem na okolje. S tega vidika je bil predlagan postopen razvoj alternativnega oz. doživljajskega turizma, ki se lahko glede na potrebe obiskovalcev razširi na bolj intenzivno izrabo naravnih znamenitosti (ureditev turistične poti po jami za klasični obisk, izgradnja ceste ipd.).

Turistična ureditev jame bi morala nujno vključiti še drugo turistično ponudbo s tega območja. Ena izmed priložnosti je Ho Ši Minhova pot (Ho Chi Minh Trail), ki jo sestavlja mreža tovornih cest, pešpoti in

The second phase is related to preparation of an integrated marketing mix for the establishment of tourism in the Phong Nha-Ke Bang National Park. On the basis of the data collected through the research, proposals will be prepared for the further development of primary tourist products (key attractions that bring in visitors and are the main reason for visiting the national park) and development of secondary tourist services (types of service, level of quality, standards, etc.). The final goal of the second phase is the formulation of an integrated marketing mix adapted to the target market segments.

The third phase is aimed at the development of an outline concept for setting up the Heaven's cave as a show cave and runs parallel to the project phases above.

The target of the market research is to collect around 1500 completed questionnaires. The multilingual questionnaire is based on our own methodology which we have developed specifically for the analysis of consumer preferences with regard to tourist products. By processing the collected data we will be able to define the market segments and their individual preferences. This will enable us to prepare an integrated marketing mix. Market research among foreign tourists in Vietnam will be carried out on our behalf by our partner company CivideC of Hanoi.

## Conclusion

The Heaven's cave, as part of one of the longest water cave systems in the world (Hang Vom), is a speleologically important part of the Phong Nha-Ke Bang National Park. Although flood waters occasionally appear in the cave, these are believed to be considerably less intensive and of shorter duration than those in Hang Vom. From this point of view the Heaven's cave is very suitable for development of a more educational form of tourism in the sense of karstology and speleology in the wider area while it also has a number of remarkable cave formations (rimstone dams, massive stalagmites and dripstone pillars). The biggest weakness of the cave is an access which in the case of major investment in the cave would require significant development in the park. From this point of view it would be essential to obtain the consent of Unesco. The assessment of tourist potential will carry more weight once the completed vodnih poti. Med vietnamsko vojno (1959–1975) je odigrala ključno vlogo pri vojaški oskrbi južne države Republike Vietnam s strani severne Demokratične republike Vietnam. Poti so potekale skozi gorato območje Laosa, Kambodže in delno Vietnama ter v veliki meri pripomogle k zmagi 'Severnega' Vietnama nad 'Južnim'. Izhodišče poti proti jugu je bilo prav v okolici parka Phong Nha-Ke Bang. Druga zanimivost je pot, ki nas vodi po tropskem deževnem gozdu v neposredni bližini reke Song Chay. Park Phong Nha-Ke Bang ima izjemno ohranjeno primarno vegetacijo, kar je v jugovzhodni Aziji redkost. Kljub temu da je bil ta kriterij le nekoliko prešibak za vključitev parka na seznam Unescove naravne dediščine, ga lahko vseeno ocenimo kot izjemnega. Nasprotno pa se zdi, da omenjeni turistični potencial ni dovolj izrabljen. Smiselno bi ga bilo torej ponuditi obiskovalcem na poti do Nebeške jame, pogled, ki se odpira na razgibano površje okrog jame, pa vključiti v izobraževanje o značilnostih in razvoju tropskega kopastega krasa.

questionnaires are obtained. On their basis an integrated marketing mix will be developed for the park and for the Heaven's cave.

The development of the cave as a show cave must proceed gradually, step by step. Any rapid development with major investments could have negative consequences in the natural, social and economic environment, with lasting negative impacts, above all on the environment. For this reason the gradual development of alternative or adventure tourism has been proposed. This could be expanded, depending on the needs of visitors, to a more intensive exploitation of natural sights (setting up a path through the cave for classic tourist visits, building a road, etc.).

Developing the cave as a show cave would necessarily have to include the other tourist attractions offered by this area. One opportunity is the Ho Chi Minh Trail which consists of a maze of cart tracks, footpaths and river routes. During the Vietnamese War (1959–1975) it played a key role in the supply of material to the Republic of Vietnam in the south from the Democratic Republic of Vietnam in the north. The trail ran through the mountainous area of Laos, Cambodia and part of Vietnam, and contributed a great deal to the victory of the 'North' over the 'South' Vietnam. The starting point of the route towards south was in fact in the area of the Phong Nha-Ke Bang Park. Another interesting feature is a path that leads us through tropical rainforest in the direct vicinity of the river Song Chay. The Phong Nha-Ke Bang Park has exceptionally well conserved primary vegetation which is a rarity in South-East Asia. Despite the fact that this criterion was considered slightly too weak for the park to be included on the Unesco's Natural Heritage List, we may still consider it to be exceptional. On the contrary, it appears that the potential for tourism is not being sufficiently exploited. It would make sense to include it in the route to the Heaven's cave. The view that opens up of the varied relief around the cave could be incorporated into education about the characteristics and development of the tropical cone karst.

# EKOLOGIJA PODZEMLJA

# UNDERGROUND ECOLOGY

# 8

# MONITORING EPIKRAŠKE FAVNE: BIOLOŠKE METODE PREUČEVANJA STANJA KRAŠKEGA EKOSISTEMA

# MONITORING OF THE EPIKARST FAUNA: BIOLOGICAL METHODS OF THE ECOSYSTEM KARST STUDY

Biologija podzemlja ali speleobiologija *sensu stricto*, kadar gre le za jame, je kot veda vznikila v Sloveniji. Podzemlje je kot življenjski habitat sorazmerno zaprt prostor, ki je zato tudi temen, dostop živali vanj pa otežen. Zaradi teme in omejene povezave s površjem proizvajalcev organskih snovi skoraj ni, hrana je količinsko pičla in kakovostno skromna. Najpomembnejši značilnosti podzemeljskega habitata sta odsotnost svetlobe in nizka stopnja bioprodukcije, odvisne predvsem od vnosa hrane s površja (*Culver* in *Pipan* 2009).

Doktrina o podzemlju, še zlasti o podzemeljskih vodah, kot o posebno negostoljubnem okolju, poseljenem z maloštevilnimi visoko specializiranimi vrstami, ki so se zatekle v podzemlje in ostale ujetniki novega habitata, je postala vprašljiva zlasti v zadnjem desetletju. Čeprav so nekateri taksoni (npr. žuželke) v podzemlju res zastopani z mnogo manjšim številom vrst kakor na površju, so drugi (npr. raki) lahko izjemno uspešni in po številu podzemeljske vrste celo prekašajo površinske.

Na specifične razmere so se živali, ki so naselile podzemlje, prilagodile z morfološkimi, fiziološkimi in vedenjskimi prilagoditvami (*Culver* in *Pipan* 2009). Specializirala so se jim čutila, reducirale oči, pigment, stanjšala se je kutikula (tabela 1). Redukciji so zapadli tudi fiziološki procesi in vedenjski vzorci. Populacije podzemeljskih vrst imajo lahko nekajkrat nižjo intenziteto metabolizma. Počasnejši metabolizem je povezan z upočasnjenim razvojem in mogočo podaljšano odraslo in s tem daljšo življenjsko dobo. Število potomcev je pri podzemeljskih živalih manjše, ker se zmanjša število jajc v samičjem telesu.

Slovenija velja za biotsko pestro deželo, kjer se vroče točke biotske raznovrstnosti kar vrstijo. Pomemben delež k raznolikosti našega živega sveta dodaja podzemeljski živelj. Danes je znano, da je Dinarski kras, v veliki meri prav njegov slovenski del, svetovna vroča točka podzemeljske biodiverzitete. Tu najdemo številne vrste, ki imajo široko biogeografsko razširjenost, pa tudi take, ki živijo na ozko omejenih območjih in jim pravimo endemiti.

Med najbolj znanimi in biološko raziskanimi podzemeljskimi vodami so ponikalnice, globinske freatične vode in izviri. Obstaja pa še vrsta drugih

The biology of subterranean habitats or speleobiology *sensu stricto* (if only caves are taken in consideration) is a science which was developed in Slovenia. Subterranean habitats are closed spaces, dark, and many times hardly accessible to animals. Because of darkness and limited connections with the surface there are no primary producers of organic matter, nutrients are scarce and of low quality. The complete absence of sunlight and low bioproduction level, dependent on transfer from the surface, are the most important physical properties in the subterranean domain (*Culver* and *Pipan* 2009).

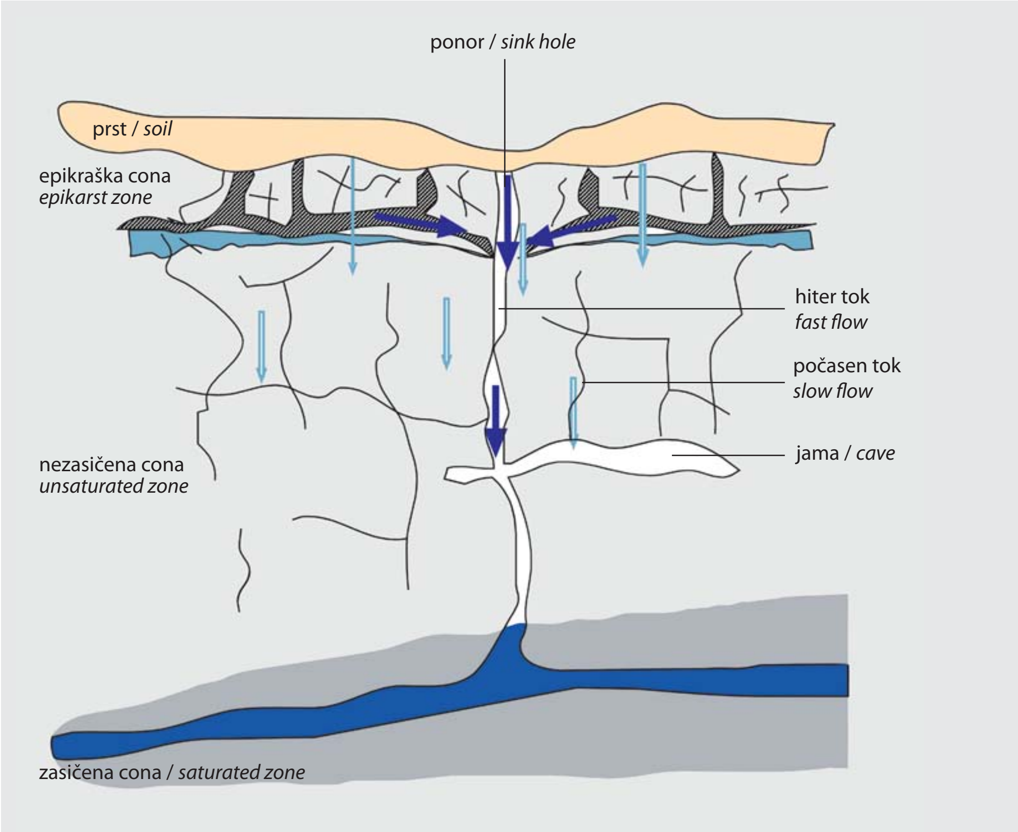
Doctrine about subterranean habitats and especially about groundwater as an inhospitable habitat, where only rare and highly specialized fauna having been captured there during climate changes can live, has become questionable in the last decade. Although some organisms (e.g. insects) are truly rare in subterranean habitats in comparison with surface habitats, others (e.g. crustaceans) are exceptionally successful and the overall number of subterranean species can exceed the number of surface ones.

Subterranean animals adapt to underground circumstances by developing morphological, physiological and behavioral adaptations (*Culver* and *Pipan* 2009). They have specialized sensory organs, reduced eyes and pigment, and a thin cuticle (table 1). Reductions are also found among physiological and behavioral patterns. Populations of subterranean species can have reduced metabolism which is connected with other reductions: reduced development and reduced egg number but increased egg volume. Life span is increased.

Slovenia is inhabited by the richest subterranean fauna in the world in addition to a rich variety of surface fauna and flora. It is well-known that Dinaric karst and especially its northwestern part in Slovenia is the world hot spot for subterranean animals. Beside many species that are widely distributed there are also endemic organisms restricted to narrow geographic areas.

Among the best known and biologically studied under-ground waters are under-ground streams, phreatic waters and springs. Additionally there are many other hypogenic waters including percolation water that drips from the cave ceiling (1). Inexorably

**1** Kapnica, ki pronica skozi plasti prsti in se pretaka skozi špranje in razpoke v kamnini, prinaša s seboj v jame tudi podzemeljske živali.
Water that percolates through soil layers and fissures in the bedrock also carries subterranean animals into caves.




**2** Konceptualni model epikrasa. Puščice označujejo smer vodnega toka (temne puščice za hiter tok, svetlejše puščice za počasno pretakanje).
Conceptual model of epikarst. Arrows indicate direction of the water flow (dark arrows for faster flow paths, lighter arrows for slow percolation).

| Morfološke adaptacije<br>*Morphological adaptations* | Ekološke in fiziološke adaptacije<br>*Ecological and physiological adaptations* | Vedenjske adaptacije<br>*Behavioral adaptations* |
|---|---|---|
| Redukcija oči, pigmenta in kril<br>*Reduced eyes, pigment and wings* | Upočasnjen metabolizem<br>*Reduced metabolism* | Nižja stopnja agregacije<br>*Reduced aggregation* |
| Specializacija čutil<br>*Specialization of extraoptic sensory organs* | Odpornost na stradanje<br>*Resistance to starvation* | Znižanje reakcije na alarmne snovi<br>*Reduced response to alarm cues* |
| Stanjšanje kutikule<br>*Cuticular thinning* | Redukcija cirkadianega ritma<br>*Reduction of circadian rhythm* | Povečanje občutljivosti na dražljaje<br>*Increased sensitivity to vibrations* |
| Modifikacija prehranjevalnih struktur<br>*Modification of feeding structures* | Zmanjšanje števila jajc in povečanje volumna<br>*Reduced egg number and increased egg volume* | Zmanjšanje intraspecifične agresije<br>*Reduced intraspecific aggressive behaviour* |
| Redukcija lusk pri ribah<br>*Reduction of scales at fish* | Podaljšanje življenja<br>*Increased life span* | |
| Podaljšanje okončin<br>*Elongation of appendages* | | |

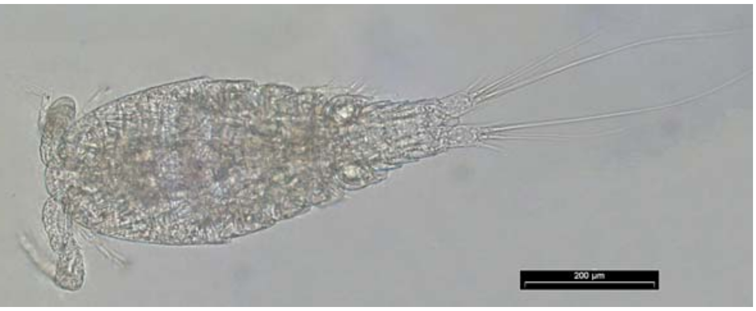
**Tabela 1** Morfološke, ekološke, fiziološke in vedenjske adaptacije na podzemeljsko življenje.
**Table 1** Morphological, ecological, physiological and behavioral adaptations to subterranean life.

hipogejičnih voda, kamor sodi prenikla voda, imenovana tudi kapnica v jami (1). Neizprosne sile narave, ki se kažejo tudi v podzemeljskem svetu, so še posebej intenzivne v kamninski plasti tik pod površjem, ko zaradi agresivnosti vode, tektonskih procesov in temperaturnih razlik prepredejo običajno apnenčasto kamnino v mrežo neštetih špranj in razpok. Če so nekatere od njih zapolnjene s prstjo iz zgoraj ležečega sloja, so druge napolnjene s padavinsko vodo in, neverjetno, a dokazano, nudijo ugodno bivališče mnogim organizmom. Morda celo bolj ugodno, kot je spodaj ležeči globoki podzemeljski svet.

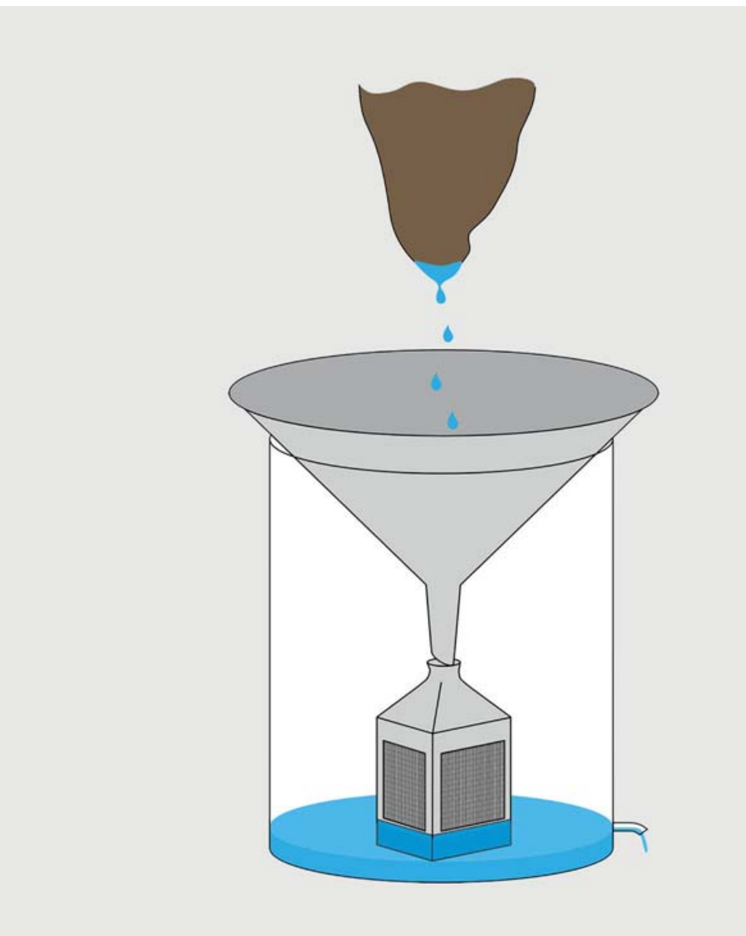
Epikras je viseči vodonosnik v nezasičeni coni (2). Voda se pretaka vertikalno skozi večje kanale in manjše špranje v freatično, stalno zasičeno cono. Lateralno se voda pretaka skozi slabše, med seboj lateralno povezane odprtine. Osnovna značilnost epikraške cone je velika heterogenost, kar pomeni, da ob močnem deževju del padavin v epikrasu hitro ponikne v sistemu špranj, del vode pa se začasno zadrži v epikrasu in počasi pronica skozi slabše prepustne plasti. Kemijske značilnosti epikraške vode so prav tako variabilne

nature is visible also underground, particularly in the bedrock below the surface where solid limestone rock becomes a network of fissures and cracks due to aggressive water from precipitation, erosion and tectonic processes and differences in temperature in this zone. Some of these cracks are filled with soil from the upper layer, but others are filled with water and offer suitable habitats for aquatic fauna. In some cases these shallow subterranean habitats in the epikarst are even more favourable than the deep subterranean zone.

Epikarst is a perched aquifer developed in the unsaturated zone (2). Water is transmitted vertically either through conduits or small fissures to the phreatic zone. Lateral transmission occurs through poorly integrated lateral openings. The principal characteristic of the epikarst is its heterogeneity, with many semi-isolated solution pockets whose water chemistry is also quite variable (*Williams* 2008). It forms a more or less permanently saturated zone, close under the surface. Eventually, water percolating through the epikarst reaches a cave stream which in turn exits at a spring and flows into a surface river. Beneath the cave stream



**3** Stigobiontski ceponožni rakec *Speocyclops infernus* (Cyclopoida) iz epikraške vode.
Stygobiotic copepod species *Speocyclops infernus* (Cyclopoida) from epikarst water.



**4** Shema naprave za filtracijo vode iz curkov. Planktonska mrežica na dveh straneh filtracijske plastenke omogoča iztekanje vode in zadrži organizme, ki jih prinaša prenikla voda.
Drip filtration unit. The mesh screens on the sides of the filtration bottle allow water to pass through but retain all organisms entering via drips.

is a permanently saturated (phreatic) zone that itself often contains large cavities.

Biologically, epikarst is an interface layer, an ecotone between surface and subsurface water. As it is inaccessible to man, direct sampling of epikarst habitats is not possible. Epikarst fauna must be explored indirectly by taking samples of percolation water. Epikarst communities are best sampled by taking samples of percolation water that drips directly from the ceiling or from pools filled by percolation water (*Pipan* 2003, 2005). Samples should be taken from the vertical flow of percolating water and not from the horizontal flow of a cave stream.

The most abundant organisms which are brought by percolation water to the cave are copepod crustaceans (3). The Slovene name highlights their split and forked leg morphology. Copepods are very diverse and are the most numerous crustaceans in the aquatic community. Copepod habitats range from freshwater to hypersaline conditions, from the highest mountains and cold polar ice-waters to the deepest ocean trenches. Sampling of any groundwater—cave stream, percolation water, deep phreatic water, hydrothermal water, interstitial or hyporheic water—yields many individuals of different copepod species. Such adaptation to different and also extreme environmental conditions is a result of their evolution, and probably several invasions into groundwater habitats occurred in different time periods making the group Copepoda very diverse.

## 8.1 Methods and results

Epikarst fauna or fauna in the percolation water were investigated in three caves of the Postojna-Planina cave system (Postojnska jama/Postojna cave, Pivka jama/Pivka cave, Črna jama/Črna cave), and in three other caves (Škocjanske jame/Škocjan caves, Dimnice and Županova jama/Županova cave). Unlike most subterranean habitats, continuous, long-term sampling of epikarst communities is possible. Epikarst communities are best sampled by collection and filtration of drip water over extended periods of time. The epikarst fauna in Slovenian caves were sampled indirectly by taking samples of percolation water that

(*Williams* 2008). Epikraška voda oblikuje bolj ali manj zasičeno plast tik pod površjem. S pronicanjem skozi spodnje plasti doseže horizontalni tok v podzemlju, ponikalnico, ki se na površje vrne na izviru. Pod ponikalnico se v odprtinah, običajno večjih razsežnosti, oblikuje stalno zasičena (freatična) cona.

Epikras predstavlja vmesno plast, ekoton, med površinskimi in podzemeljskimi vodami. Običajnemu človeku je ta predel podzemlja nedostopen, zato moramo organizme, ki so si našli svoje bivališče v razpokah tik pod plastjo prsti, ki jo strokovno imenujemo epikras, vzorčiti posredno. To počnemo s sicer preprosto, a učinkovito tehniko, prirejeno za zbiranje in filtriranje prenikle vode. V raziskavi smo uporabili metodo za vzorčenje curkov prenikajoče vode v jamah in jamskih luž, ki jih ti curki napajajo (*Pipan* 2003, 2005). Vzorce smo jemali iz vertikalnega toka prenikajoče vode in ne iz horizontalnega, podzemnega toka reke.

Med najpogostejšimi organizmi, ki jih kapljajoča voda prinese v podzemlje, so ceponožni rakci (3). Slovensko ime označuje razcepljeno, rogovilasto zgradbo njihovih nog. Ceponožci so zelo uspešna skupina rakov, ki poseljujejo vse tipe vodnih habitatov, tako sladke kot slane, na površju in v podzemlju. Tudi geografska višina jim ne dela težav, saj jih najdemo v visokogorskih in celo polarnih predelih ter v oceanih. Vzorčenje kateregakoli tipa podzemeljske vode – ponikalnice, prenikle, globoke freatične, hidrotermalne, intersticijske ali hiporejične vode – nas ne razočara ne po številu osebkov ne po številu njihovih vrst. Prav dejstvo, da so ceponožni rakci v svoji evoluciji naselili različne podzemeljske habitate, in to seveda v različnih časovnih intervalih, jim omogoča, da so prilagojeni na raznovrstne, tudi skrajne življenjske razmere, kar se kaže v pestri zgradbi skupine.

## 8.1 Metode in rezultati

Epikraško favno oziroma favno v prenikli vodi smo preučevali v treh jamah Postojnsko-Planinskega jamskega sistema (Postojnska jama, Črna jama, Pivka jama), v Škocjanskih jamah, jami Dimnice in Županovi jami. Vzorčenje epikraških združb je lahko, za razliko od večine drugih podzemeljskih habitatov, zvezno in dolgotrajno. Najučinkovitejše je z zbiranjem

**5** Vzorčenje epikraške vode v Postojnski jami.
Epikarst drip filtration unit placed in the Postojna cave.

drips directly from the ceiling. Water from a ceiling drip was directed via funnel into a filtering bottle fitted on two sides with plankton netting of 60 µm mesh size. The filtering bottle was placed within a sampling container which had a drain 3 cm from its base (4, 5).

The easiest way to collect epikarst fauna is from pools filled by water that seeps down the walls or drips directly from the cave ceiling. Pools were sampled by aspiration of the water (6) which was then filtered through the collecting container. Samples were preserved in 4 % formalin.

All together animals from 16 different groups were found: Turbellaria, Nematoda, Rotatoria, Gastropoda, Oligochaeta, Acarina, Araneae; among Crustacea were Ostracoda, Copepoda, Isopoda, Amphipoda and Bathynellacea; among Insecta were Colembolla, Coleoptera and larvae of Diptera (table 2). The most common and abundant were copepod crustaceans, typical inhabitants of epikarst waters (*Pipan* 2003, 2005). The

**6** Shematski prikaz naprave za črpanje vode iz luž.
Apparatus for aspirating water in pools.

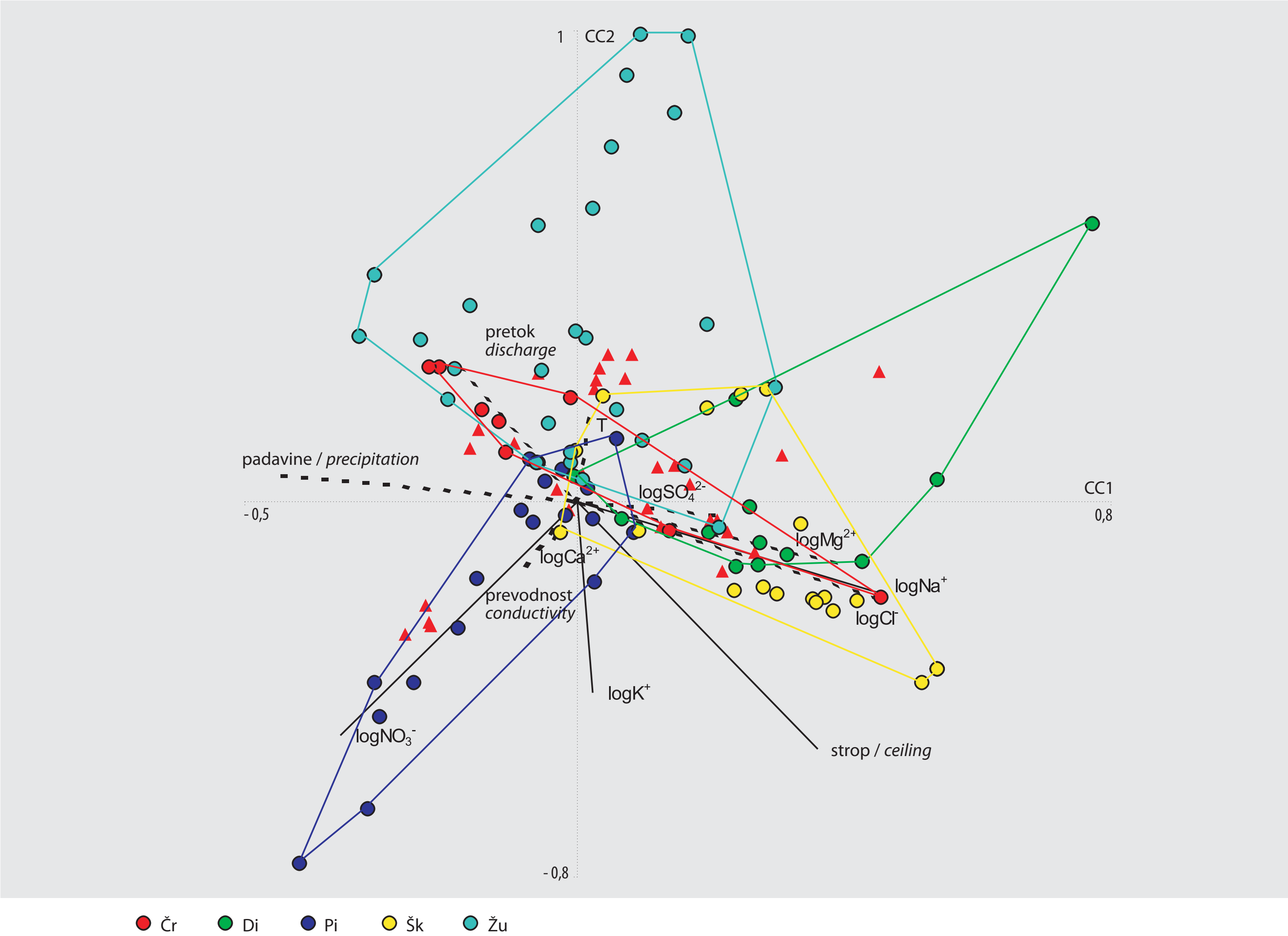

in filtriranjem vode iz curkov v določenem časovnem obdobju. Epikraška favna v slovenskih jamah je bila vzorčena indirektno z jemanjem vzorcev iz prenikle vode, ki je kapljala neposredno z jamskega stropa. Kapljajoča voda je spolzela po liju v filtracijsko plastenko, z dveh strani obdano s planktonsko mrežico, ki ima 60 µm velike odprtinice. Filtracijska plastenka je bila nameščena v večji plastični posodi z odtočno cevjo 3 cm nad njenim dnom (4, 5).

Najpreprostejši način zbiranja epikraške favne je iz luž, ki jih polni le mezeča ali kapljajoča voda z jamskega stropa. Vodo, ki smo jo črpali iz luž, smo prefiltrirali skozi filtracijsko plastenko (6) in vzorce shranili v 4 % formalinu.

V preniklih vodah smo našli 16 različnih skupin živali: vrtinčarje, gliste, kotačnike, polže, maloščetince, pršice, pajke, med raki dvoklopnike, ceponožce, enakonožce, postranice in batinele ter med žuželkami skakače, hrošče, ličinke dvokrilcev in drugih žuželk (tabela 2). Med njimi so bili najpogostejši rakci ceponožci, značilni predstavniki v epikraškem habitatu (*Pipan* 2003, 2005). To je skupina nižjih rakov, velikih od nekaj desetink milimetra do nekaj milimetrov. Večina vrst, ki so bile najdene v epikraškem habitatu, je stigobiontskih. Z izrazom 'stigobiont' označujemo na podzemeljske vode prilagojene in vezane organizme.

length of the body is between a few tenth of a millimetre and one or more millimetres. The majority of species in the epikarst water are stygobiotic. Stygobionts are obligate, permanent residents of aquatic subterranean habitats. Additionally many new, not yet described species were found which are epikarst specialists. These are species that are not only obligate subterranean species but are also epikarst species. Copepods comprise both free-living and parasitic species, but in subterranean waters only free-living species from four orders live. From percolation water specimens of Cyclopoida and Harpacticoida are known.

In the Postojna cave, Pivka cave and Črna cave, 23 species of copepods were found, one third of these were new to science. The most numerous specimens among Cyclopoida were from the species *Speocyclops infernus*. Among Harpacticoida 19 species were found, eight species from seven genera were new to science (*Bryocamptus, Elaphoidella, Maraenobiouts, Moraria, Nitocrella, Parastenocaris,* cf. *Stygepactophanes*). Research represents a concrete investigation of faunal and ecological conditions in habitats that are not directly accessible. Statistical results using Canonical Correspondence Analysis show that species composition and their abundance are directly correlated with ecological parameters in percolating water, such as




**7** Ordinacijski diagram vrstne sestave in števila ceponožnih rakov v curkih petih slovenskih jam (Črna jama, Dimnice, Pivka jama, Škocjanske jame, Županova jama). Vektorji označujejo okoljske parametre in orientacijo glede na kanonični osi CC1 in CC2. S trikotniki je označena pozicija vrst ceponožnih rakov glede na njihovo afiniteto do okoljskih dejavnikov.
Ordination diagram based on species composition and abundance data of copepods in epikarst drips of five caves in Slovenia (Črna cave, Dimnice, Pivka cave, Škocjan caves, Županova cave). Lines indicate the environmental variables and their orientation on the canonical axes CC1 and CC2. Triangles indicate different species in relation to the environmental variables.

Odkritih je bilo tudi relativno veliko število novih vrst ceponožnih rakov, ki so epikraški specialisti in jih do zdaj nismo našli v drugih habitatih, razen v epikraških vodah. Čeprav poznamo tako prosto plavajoče kot parazitske vrste ceponožcev, so bili v podzemlju ugotovljeni le prosto plavajoči predstavniki štirih, v prenikli vodi pa dveh redov (Cyclopoida in Harpacticoida).

V Postojnski jami, Pivki jami in Črni jami smo našli 23 vrst ceponožnih rakov, od tega dobro tretjino

concentration of ions, i.e. nitrate and sodium (7). The best example is a cluster of species found only in the Pivka cave and associated with high nitrate levels in percolation water (*Pipan* 2005). These results suggest that copepods from the epikarst zone show a high level of ecological specialization. Epikarst copepods can, for this reason, be used as bioindicators and important new tools for conservation priorities in groundwater habitats. Epikarst harbors exceptionally rich copepod

| Višje skupine *Higher groups* | Jame / *Caves* | | | | | |
|---|---|---|---|---|---|---|
| | Postojnska jama | Pivka jama | Črna jama | Škocjanske jame | Dimnice | Županova jama |
| Turbellaria | • | • | | • | • | |
| Nematoda | • | • | • | • | • | • |
| Rotatoria | | • | | | | |
| Gastropoda | • | • | • | • | | • |
| Oligochaeta | • | • | • | • | • | • |
| Araneae | | • | • | | | |
| Acarina | • | • | • | • | • | • |
| Ostracoda | • | • | • | • | • | • |
| Copepoda | • | • | • | • | • | • |
| Bathynellacea | | • | | | | |
| Isopoda | | | • | • | | • |
| Amphipoda | • | • | • | • | | • |
| Diplopoda | • | • | • | | | |
| Collembola | • | | • | • | • | • |
| Coleoptera | • | | • | | | |
| Diptera – larvae | • | • | • | • | • | • |
| Ostale žuželke *Other Insecta* | | | | | | • |

**Tabela 2** Seznam organizmov iz prenikle vode v šestih jamah Dinarskega krasa v Sloveniji.
**Table 2** List of fauna collected in percolation water of six caves in the Dinaric karst in Slovenia.

novih za znanost. Med ciklopoidi je bila najpogostejša vrsta *Speocyclops infernus*. Med harpaktikoidi je bilo ugotovljenih 19 vrst, od tega osem novih za znanost iz sedmih rodov (*Bryocamptus, Elaphoidella, Maraenobiouts, Moraria, Nitocrella, Parastenocaris,* cf. *Stygepactophanes*). Raziskava predstavlja zelo aktualno presojo favnističnih in ekoloških razmer v habitatih, ki niso neposredno dostopni za raziskave. S statističnim pristopom, pri katerem smo uporabili multivariantno kanonično korelacijsko analizo, smo ugotovili, da sta

fauna with a high frequency of endemism that particularly increases the conservation value of the epikarst.

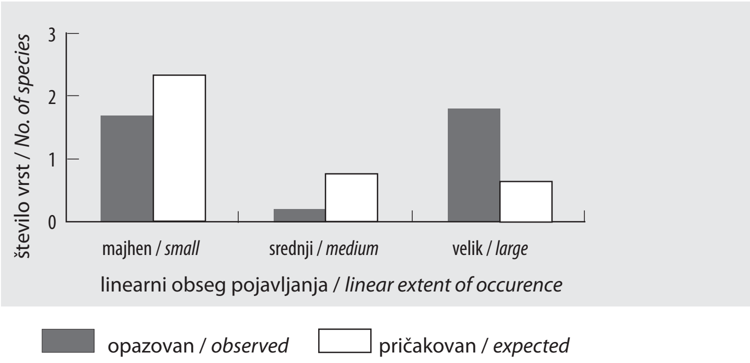
In the Škocjan caves we found 17 copepod species from 11 genera. Twelve species from the epikarst were stygobiotic, five of them from four genera were new to science: *Bryocamptus*, *Moraria*, *Parastenocaris* and cf. *Stygepactophanes*. Beside these new species, special attention was paid to a tiny Copepoda described as *Elaphoidella karstica*, previously *E. kieferi*, which is an endemic animal in the Škocjan caves, its only known sestava in število nekaterih vrst ceponožcev neposredno povezana z ekološkimi dejavniki v prenikli vodi, saj so bile statistično značilno soodvisne s koncentracijo nekaterih ionov, npr. nitratnih in natrijevih (7). Tak primer so štiri vrste, ki smo jih našli le v Pivki jami, in sicer v curkih vhodnega dela, kjer so bile povečane koncentracije nitrata v prenikli vodi (*Pipan* 2005). Vemo, da je veliko prenikajočih voda onesnaženih zaradi onesnaženja na površju. Zaradi ugotovljene visoke stopnje ekološke specializacije posameznih vrst bi lahko bile mnoge uporabne za bioindikatorje. S preučevanjem epikraške favne bi bilo moč celostno ocenjevati tudi vplive človekove dejavnosti na podzemeljske habitate.

V Škocjanskih jamah smo ugotovili 17 vrst ceponožcev, ki pripadajo 11 rodovom. Dvanajst vrst, ki naseljujejo epikraški habitat, je stigobiontskih. Od tega je pet za znanost novih vrst iz štirih rodov: *Bryocamptus*, *Moraria*, *Parastenocaris* in cf. *Stygepactophanes*. Poleg na novo odkritih vrst si posebno pozornost zasluži droben ceponožni rakec z znanstvenim imenom *Elaphoidella karstica*, opisan po primerku iz curka prenikle vode kot *E. kieferi*, ki je endemit Škocjanskih jam, te pa so za zdaj edino znano nahajališče te vrste na svetu.

V Županovi jami je bilo najdenih 16 vrst ceponožcev, ki pripadajo osmim rodovom in štirim družinam. Dve vrsti, ki pripadata dvema rodovoma, sta iz skupine ciklopoidov, med harpaktikoidi je šest rodov in 14 vrst. To so vrste, ki so zašle v jamsko okolje s preniklo vodo. Štirinajst vrst, ki poseljuje epikraški habitat, je stigobiontskih – so pravi predstavniki podzemeljskih voda. Pet vrst iz treh rodov (*Elaphoidella*, *Moraria* in *Parastenocaris*) je novih za znanost. Posebnost te jame je ceponožni rakec *Morariopsis dumonti* (8), ki je bil opisan po primerku iz jame v osrednji Sloveniji. Na obeh, do zdaj sicer edinih znanih lokacijah te vrste na svetu, je bil najden v prenikli vodi. Še en dokaz več, da je med prebivalci epikrasa veliko endemnih vrst in vrst, ki so specializirane na epikraške vode in jih v drugih habitatih ne najdemo.

V Dimnicah je bilo odkritih 12 vrst; razen ciklopoidne vrste *S. infernus* so vsi drugi predstavniki reda Harpacticoida. Med njimi je bilo kar pet novih vrst, ki pripadajo trem rodovom (*Nitocrella, Parastenocaris,* cf. *Stygepactophanes*) in jih označujemo za epikraške specialiste.


**8** Samček ceponožnega rakca iz rodu *Morariopsis*, najden v prenikli vodi.
The male of a copepod species from genus *Morariopsis* found in percolation water.




**9** Linearni obseg pojavljanja 37 vrst ceponožnih rakov v šestih jamah v Sloveniji.
Linear extent of occurrence of 37 species of copepods in six Slovenian caves.

location in the world. Scientific description was done on the basis of an animal found in one drip of percolation water in the cave.

In the cave Županova jama 16 copepod species from eight genera and four families were found. Two species of two genera belong to Cyclopoida; the remaining 14 species from six genera belong to the group Harpacticoida. All of them were found in percolation water, but 14 are stygobiotic—they are permanent residents of groundwater. Five species from three genera (*Elaphoidella*, *Moraria* and *Parastenocaris*) are new to science. The specialist of the cave is a copepod species, *Morariopsis dumonti* (8) which was described from a cave in central Slovenia. In both localities which are the only known habitats of the species in the world the animal was found in percolation water. This is another

V obširni bazi podatkov o epikraških ceponožnih rakih v Sloveniji smo poskušali analizirati razširjenost oz. pojavljanje posameznih vrst, saj bi na podlagi teh podatkov določene vrste lahko uporabili kot naravna biološka sledila pretakanja epikraških voda in njihove povezanosti v podzemlju, brez dodajanja umetnega sledila, živali ali vode. Določili smo največjo linearno razdaljo med curki in razdelili linearni obseg za vse pare curkov na preučevanem območju v tri kategorije (*Pipan* in *Culver* 2007):

- manj kot 100 m, kar ustreza curkom v posamezni jami;
- več kot 100 m in manj kot 1 km, kar ustreza curkom v različnih jamah Postojnsko-Planinskega jamskega sistema;
- več kot 1 km, kar ustreza curkom v različnih jamskih sistemih.

Na raziskovanem območju so prevladovale splošno razširjene vrste in tiste z ozko distribucijo (9). Ugotovljena je bila statistično značilna razlika med opazovanim številom maksimalnega linearnega obsega in pričakovanim številom, ki temelji na številu parov curkov iste kategorije ($p < 0{,}0001$, $\lambda^2 = 20{,}99$). V splošnem so prevladovale zelo razširjene vrste, najmanj je bilo tistih z vmesno razširjenostjo (> 100 m in < 1 km). Rezultati so podobni tudi v primeru, če analizo omejimo samo na stigobionte. Od vseh 27 stigobiontskih vrst je 11 imelo maksimalni obseg razširjenosti manjši od 100 m. Te vrste so pretežno omejene na posamezno jamo. Preostalih 16 vrst je imelo maksimalni obseg razširjenosti večji kot 1 km in so bile najdene v različnih jamah.

Samo dve vrsti – *Speocyclops infernus* in *Parastenocaris* n. sp. – sta bili najdeni v vseh vzorčenih curkih v Pivki jami. Večina drugih vrst ima precej omejen obseg razširjenosti. To nakazuje, da je razširjenost epikraških ceponožcev kot metoda za preučevanje pretakanja vode uporabna le na manjših območjih, najprimernejša je na nivoju posamezne jame (*Pipan* in *Culver* 2007). Zelo razširjene vrste predstavljajo multiple populacije ali celo kriptične vrste in niso učinkovite pri sledenju pretakanja epikraških voda.

proof that among epikarst inhabitants there are many endemic species and epikarst specialists that live only in this type of the shallow subterranean habitat and not in the other groundwater habitats.

In the cave Dimnice we found 12 species; one cyclopoid species *S. infernus* and the rest from the order Harpacticoida. Among them there were five new species from three genera (*Nitocrella, Parastenocaris,* cf. *Stygepactophanes*) which are described as epikarst specialists.

We use extensive Slovenian data to explore possibility of using epikarst copepods as natural tracers of water movements, a technique that does not require injection of dyes, animals or water. The maximum linear extent of occurrence in the study area was divided into three categories (*Pipan* and *Culver* 2007):

- less than 100 m which corresponds to drips within a single cave;
- greater than 100 m and less than 1 km which corresponds to drips in different caves in the Postojna-Planina cave system;
- greater than 1 km which corresponds to drips in different cave systems.

Common species and species with very small ranges were highly over-represented in the study area (9). There is a statistically significant difference between observed number of maximum linear extents and expected number based on the number of drip pairs in that category ($p < 0.0001$, $\lambda^2 = 20.99$). In particular, there was an excess of species with large linear extents and a deficiency of species with moderately sized linear extents (> 100 m and < 1 km). If the analysis is limited to stygobionts, very similar results are obtained. Out of 27 stygobiotic species, 11 had maximum linear extents of less than 100 m. They were limited to a single cave while the other 16 had ranges greater than 1 km and were found in multiple caves.

Only two species, *Speocyclops infernus* and *Parastenocaris* n. sp., were found in all sampled drips in the Pivka cave. The other species have more restricted ranges of occurrence. The results show that mapping of copepod microdistribution on the basis of their occurrence in drips is a potentially useful technique to determine the path of water within small karst system areas, such as that above a single cave (*Pipan* and

## Sklep

Preučevanje mikrodistribucije ceponožnih rakov, najpogostejših organizmov v epikraških vodah, lahko služi kot naravna metoda za sledenje voda v epikrasu.

Raziskave epikraške favne so pomembne z vidika preučevanja 'zdravja' ekosistema, saj se kakovost upravljanja na površju kraškega sveta neposredno odraža prav v pestrosti in številu na podzemlje specializiranih živalskih vrst. In dokler je njihovo število še 'dostojno', je tudi njihovo bivališče, ki ga razumemo kot kakovost podzemeljskih voda, še zdravo, torej primerno.

Površje in podzemlje delujeta kot samostojna organa v organizmu kraškega ekosistema, a kljub vsemu sta neločljivo povezani. In kakor koža varuje vse organe v organizmu, površje ščiti in varuje podzemeljski svet. Če ga z onesnaževanjem in grobimi posegi ranimo, mu preprečimo, da bi svojo vsestransko funkcijo varovanja in ohranjanja podzemeljskega okolja opravljalo še naprej.

*Culver* 2007). Species that are widespread have limited value in tracing the movement of water as they represent multiple populations or perhaps even cryptic species.

## Conclusion

Mapping of copepod microdistribution on the basis of their occurrence in drips is a potentially useful natural technique to determine the path of water in the epikarst.

Epikarst fauna studies are important as monitors of cave ecosystem 'health'. Management on the karst surface is directly reflected in diversity and number of specialized underground animals. As long as their number is 'proper' we can infer that their habitat, understandable as the quality of underground water, is healthy or suitable.

The surface and the subsurface act as independent organs within the organism of a karst ecosystem. Nevertheless, they are inseparably connected. As the skin protects all the organs of an organism, the surface protects and preserves the underground world. Its multiple functions of protection and conservation of subterranean habitats are limited if pollution and other inappropriate interventions wound it.

# 9

# PREUČEVANJE KRAŠKEGA EKOSISTEMA SKOZI PREUČEVANJE KRAŠKIH ZDRUŽB

# THE STUDY OF THE KARST ECOSYSTEM THROUGH THE STUDY OF KARST COMMUNITIES

Ekosistem si najpreprosteje lahko zamislimo kot črno škatlo, v kateri se vhodni elementi, zaradi biološke aktivnosti znotraj nje, spreminjajo v določene produkte (*Odum* 1953). Četudi podzemeljski ekosistemi ustrezajo konceptualnemu modelu ekosistema kot črne škatle, so speleobiologi v splošnem zadržani pri sprejemanju tega koncepta (*Culver* in *Pipan* 2009). Neznanki, ki begata uporabo osnovnega koncepta ekosistema tudi v primeru podzemeljskega ekosistema, sta zlasti velikost črne škatle ter definicija vnosnih in izhodnih elementov.

Ena izmed prvih natančnih raziskav ekosistema je bila opravljena na primeru kraškega izvira Silver Springs na Floridi (*Odum* 1957). Silver Springs predstavlja, tako kot večina drugih izvirov na Floridi, glavna vrata, ki vodijo iz spodaj ležečega plitvega podzemeljskega vodonosnika (the Floridan aquifer). Odumu je ekosistem pomenila šele porajajoča se voda na izviru. Z vidika podzemeljskih ekosistemov pa je predmet raziskovanja tisto, kar se nahaja takoj za izvirom. Šele po letu 1970 so ekologi, ki so preučevali tekoče vode, v svoje študije vključili tudi podzemeljske vode (*Hynes* 1983). Tako sta se razvila izraza za kraški ekosistem in intersticijski ekosistem. Rouch (1977) je razvil primerne shematične modele za podzemeljske kraške sisteme, medtem ko sta Stanford in Gaufin (1974) to storila za rečne vodonosnike.

Za razumevanje prenosa energije in kroženja snovi v podzemeljskem ekosistemu je predvsem pomembno osnovno vprašanje, povezano z določitvijo komponent ekosistema, kaj so vhodni elementi s površja. Sama velikost črne škatle oz. ekosistema je manj kritična, ima manj možnih odgovorov. Vhodni elementi v kraške sisteme so značilno zapleteni. Raziskavo podzemeljske favne na področju Moulisa v Franciji je Rouch (1968), tako kot večina speleobiologov, pričel z raziskovanjem favne v jamah. Vendar vzorčenje kopepodov v jami Grotte de Sainte-Catherine ni bilo zadovoljivo, zato je sklepal, da je raziskoval na napačnem mestu. Ugotovil je, da je pravi kraj vzorčenja izvir, ki zbira vodo iz jame in okoliškega področja – kraškega bazena Baget. S filtriranjem skozi planktonsko mrežico je v 19 mesecih zveznega vzorčenja na izviru našel preko 18.000 kopepodov. Ocenil je, da je bilo več kot 500.000 kopepodov letno odplavljenih iz podzemeljskega sistema in preko

In its simplest version, an ecosystem is a black box with inputs which are altered by biological activities inside the black box to produce the output (*Odum* 1953). Although subterranean ecosystems are literal black boxes to match the conceptual black boxes of ecosystem studies, subterranean biologists have in general been slow to take up the conceptual framework of ecosystem studies (*Culver* and *Pipan* 2009). The problem was that the appropriate size of the black box and definition of the inputs and outputs were not clear.

One of the very first detailed ecosystem studies was made on the example of a karst spring Silver Springs in Florida (*Odum* 1957). Silver Springs, like most springs in Florida, is essentially a window dissolved through the bedrock into the underlying shallow groundwater aquifer (the Floridan aquifer). However, for Odum the ecosystem began with boils of water emerging in the springs. From the point of view of subterranean ecosystems, the object of study is immediately upstream of the emerging spring. It was not until the 1970's when stream ecologists became aware of the need to incorporate groundwater into stream studies (*Hynes* 1983). So, conceptualizations for both karst and interstitial ecosystems were developed then. Rouch (1977) provided an appropriate conceptual model for subterranean karst systems while Stanford and Gaufin (1974) did the same for fluvial aquifers.

The critical conceptual question related to understanding subterranean energy and nutrient fluxes is what are the components of the ecosystem, particularly what are the inputs from the surface. The size of the ecosystem black box is less critical, or at least can have not so many answers. Inputs in subterranean karst systems are typically complicated. In his studies of the subterranean fauna of the area around Moulis, France, Rouch (1968) began, as do most subterranean biologists, with study of fauna in caves. In his sampling of copepods in Grotte de Sainte-Catherine, Rouch could only find an occasional copepod, and he concluded that he was basically looking in the wrong place. The right place turned out to be the spring that drained the cave and the surrounding area—the Baget karst basin. He collected more than 18,000 copepods in 19 months of continuous filtering. He estimated that 500,000 co-

10 milijonov s površja v podzemlje, zlasti v času poplav (*White* idr. 1995). Na podlagi morfoloških razlik (troglomorfizem) med podzemeljskimi in površinskimi vrstami harpaktikoidov je Rouchu uspelo slediti povezavam med vnosi in izhodi iz podzemlja. Dokazal je, da glavnih vnosov v podzemlje ne pomenijo ponikalnice, temveč prenikajoča voda, zlasti v epikraški coni. V nizu 20 člankov z območja majhnega (11,4 $km^2$) kraškega bazena Baget je določil vhodne in izhodne elemente iz podzemlja, opisal časovno spremenljivost ter opozoril na tesno povezavo med površjem in podzemljem (*Rouch* 1968). V raziskavi pa se ni osredotočil na meritve količin organskega ogljika, dušika itd. Za vhodne sisteme je določil ponikalnice, prenikajočo vodo in globoko freatično vodo, medtem ko izhodne sisteme predstavljajo izviri. Prisotnost vseh treh vhodnih elementov ni nujna za vsak kraški bazen, tako kot je to na primeru Baget. Manjkata lahko globoki freatični vodni sistem ali ponorna voda.

Zaradi odsotnosti sončne svetlobe v podzemeljskih ekosistemih ni fotosinteze. Vsa energija v podzemeljskih habitatih izvira s površja, z izjemo redkega števila jam in globokih intersticijskih vodonosnikov. Eden najvidnejših primerov takega vnosa je gvano, ki ga netopirji puščajo v jamah med dnevnim počitkom in nočnim izletanjem iz jam, ko iščejo hrano. Taka odvisnost od zunanjih (alohtonih) virov energije običajno pomeni, da sta količina in pestrost hranilnih snovi v podzemeljskih habitatih nizka. V površinskih habitatih se žuželke lahko specializirajo na prehranjevanje z določeno rastlinsko vrsto, medtem ko se v podzemlju vse rastline razgradijo v organski produkt podobne sestave.

Poseben vir energije v podzemeljskih habitatih predstavlja energija, vezana v anorganskih kemičnih snoveh. Izrabljanje energije v kemičnih snoveh, kemoavtotrofija, se razlikuje od energije sončnega sevanja in je navzoče v redkih drugih ekstremnih habitatih, kot so npr. globokomorski jarki (*Van Dover* 2000). Kemoavtotrofi so primarni producenti, ki energijo pridobivajo iz svetlobe neodvisnih kemijskih reakcij. Najdemo jih v mnogih drugih okoljih, vendar pa pogosto prevladujejo v podzemlju, kjer ni kompeticije s fotosintetskimi organizmi (*Engel* 2005).

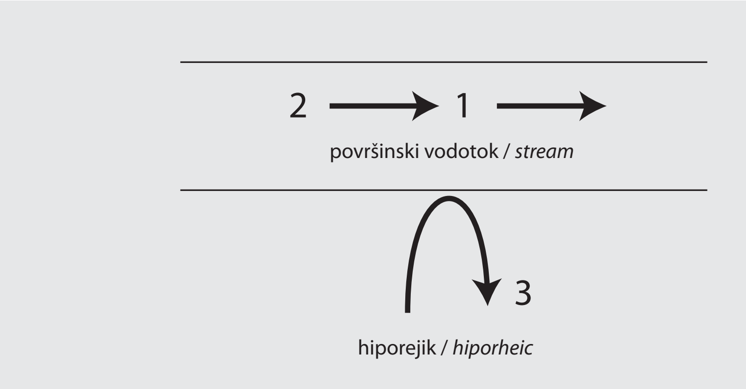
Zunanji viri energije vstopajo v podzemeljske habitate na različne načine (1). *Prenikajoča voda* (1A)

pepods were washed out of the subterranean system annually and that more than 10 million were washed into the subterranean system from surface systems, especially in times of flood (*White* et al. 1995). Taking advantage of the morphological difference between subterranean and surface harpacticoids (troglomorphy), Rouch was able to trace connections between inputs and outputs. He demonstrated that the major inputs in the system were not sinking streams but rather percolating water, especially in the epikarst zone. In a series of 20 papers on Baget, a small 11.4 $km^2$ karst basin, he defined inputs and outputs, described temporal variability and pointed out the intimate connection between surface and subsurface (*Rouch* 1968). What he did not do was to parameterize the system into units of organic carbon, nitrogen, etc. The inputs were sinking streams, percolating water and deep phreatic water, and the outputs were springs. Not all of these inputs that occur in Baget are present in every karst basin. In some there may be no input from groundwater and in some cases there may be no sinking streams.

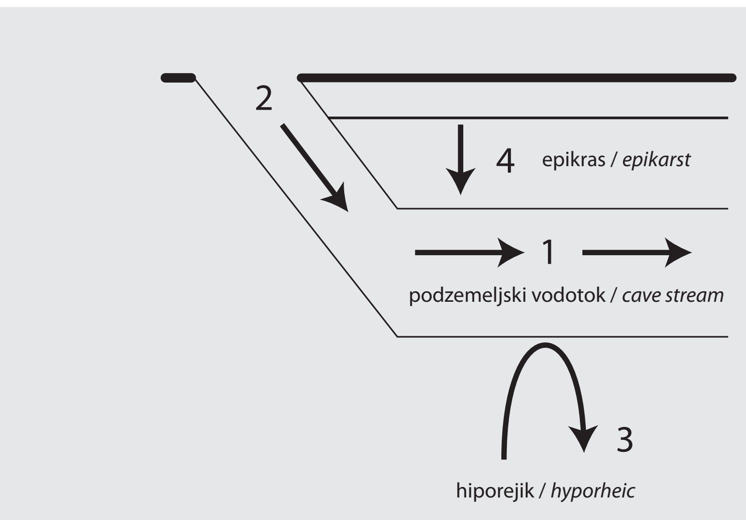
Because of absence of sunlight, there is no photosynthesis in subterranean environments. Except for a very few caves and possibly most deep interstitial aquifers, all of the energy is transferred from surface habitats to subterranean habitats. One of the most obvious examples of this transfer is guano left by bats that roost in the caves during the day and leave the caves to forage at night. This reliance on external (allochthonous) energy sources generally means that there are fewer nutrients available in subterranean habitats and that their diversity is low. In surface habitats, insects can specialize in feeding on a particular species of plant. In the subterranean realm, all plants become detritus of very similar composition.

In many ways the most interesting energy source in the subterranean realm is the energy in inorganic chemical bonds. The utilization of the energy of chemical bonds, chemoautotrophy, rather than the energy of sunlight as the basic source of energy, is common in a few other extreme environments, such as deep sea vents (*Van Dover* 2000). Chemoautotrophs, primary producers whose energy is derived from light-independent chemical reactions, are also found in nearly every environment, but it is in subterranean habitats


**1** Viri energije v podzemeljskih okoljih: (A) prenikajoča voda, (B) tekoča voda, (C) veter in težnost, (D) aktivni premiki živali, (E) korenine.
Sources of energy in subterranean environments: (A) percolating water, (B) flowing water, (C) wind and gravity, (D) active movements of animals, (E) roots.




**2** Trije viri organskega ogljika v površinskem vodotoku: (1) celokupna primarna proizvodnja v vodotoku, (2) odpadlo listje in horizontalni prenos organskega ogljika, (3) podzemeljski vir (hiporejik).
Three sources of organic carbon in a surface stream: (1) gross primary productivity in the stream itself, (2) litter fall and lateral transport of organic carbon, (3) groundwater inputs (hyporheic).

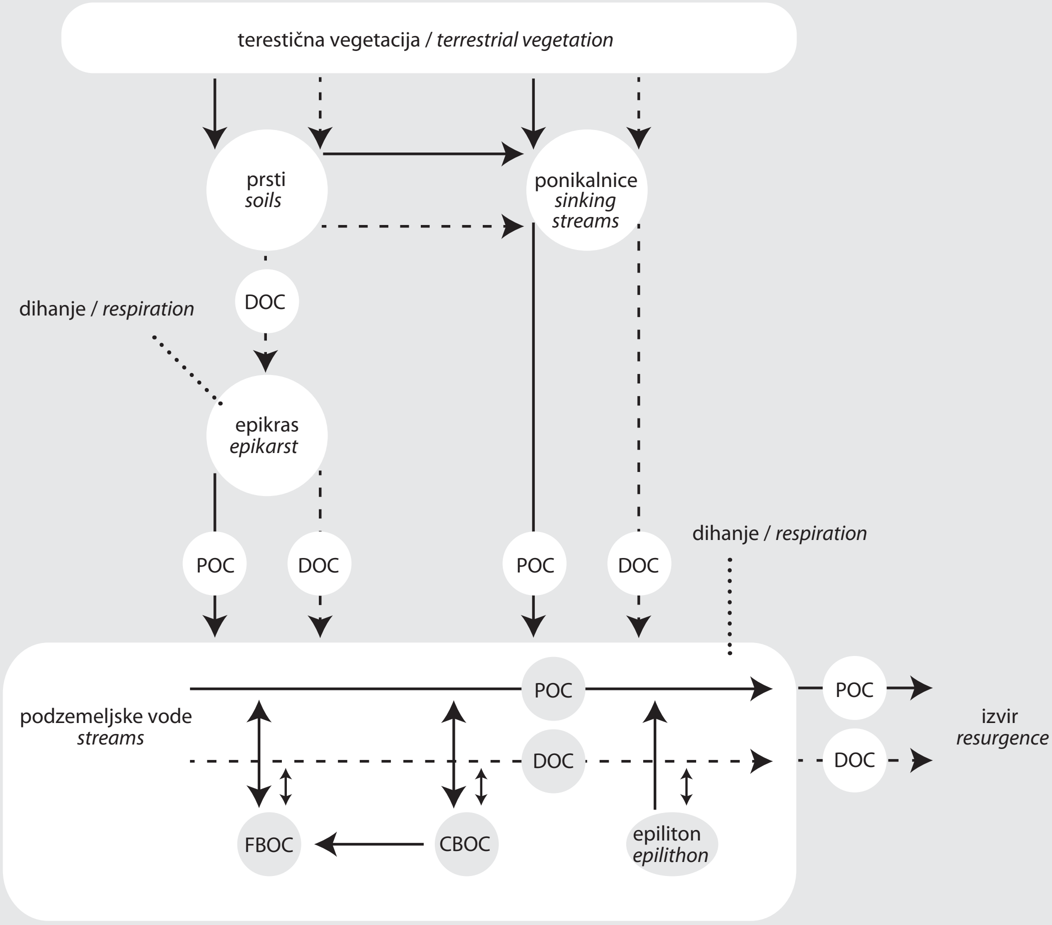



**3** Trije viri organskega ogljika v podzemeljskem vodotoku: (2) horizontalni prenos organskega ogljika, (3) podzemeljski vir (hiporejik), (4) prenos skozi epikras. Celokupne primarne proizvodnje (1, sivo obarvana) in odpadlega listja (del 2) v primerjavi s površinskim vodotokom ni.
Three sources of organic carbon in a cave stream: (2) lateral transport of organic carbon, (3) groundwater inputs (hyporheic), (4) transport through epikarst. Compared to surface streams, there is no gross primary productivity (1, shown in grey) or litter fall (part of 2).

where there is no competition with photosynthetic organisms, that chemoautotrophs sometimes prevail (*Engel* 2005).

External energy sources enter subterranean habitats in a variety of ways (1). *Percolating water* (1A) carries with it dissolved organic matter, some suspended particles of organic matter and a variety of microbes and minute invertebrates. This seemingly unimportant source of nutrients is actually the most important one in many situations. *Flowing water* (1B), especially streams entering caves, carries with it not only dissolved organic material, but also particulate organic material, in some cases up the size of logs. Flowing water provides nutrients not only to aquatic communities in caves but also to terrestrial communities that live alongside cave streams (riparian communities). *Wind* and *gravity* (1C) bring nutrients into caves when organic material comes into an entrance. Examples include falling leaves as well as animals that fall or wander into a cave, cannot exit and die. The hallmark of this food source is its unpredictability. *Active movements of animals* (1D) are in some caves a major source of nutrients, especially in terrestrial cave habitats. The most notable examples of this food source are bats, and in fact distinct communities of organisms specialize on the bat guano of caves (*Gnaspini* and *Trajano* 2000). Finally, *roots* (1E) penetrate into some shallow caves, especially lava tubes, and animals utilize the roots as a food source. Characteristics of these six types of nutrients are summarized in table 1. Of these food sources only percolating water is universal, or nearly so.

Aquatic shallow subterranean habitats share with caves the absence of light and usually the absence of any autochthonous organic production, except in those relatively rare cases of chemoautotrophy (*Engel* 2005). Shallow subterranean habitats (SSHs) differ from caves in that SSHs have close connectivity with the surface and relatively strong annual and in some cases, daily environmental cycles of environmental factors (*Culver* and *Pipan* 2009). Because of their close proximity to and connection with the surface, the amount of organic carbon entering SSHs is likely high compared to caves. Of the six types of nutrients that enter caves, only percolating water—and active




**4** Konceptualni model pretoka energije v krasu. POC = suspendirani organski ogljik, DOC = raztopljeni organski ogljik, FBOC = droben bentični organski ogljik in CBOC = zrnat bentični organski ogljik (prirejeno po Simon et al. 2007).
Conceptual model of energy flux in karst. POC = particulate organic carbon, DOC = dissolved organic carbon, FBOC = fine benthic organic carbon, and CBOC = coarse benthic organic carbon (adapted from Simon et al. 2007).

nosi s seboj raztopljeno organsko snov, druge suspendirane organske delce, različne mikrobe in majhne nevretenčarje. Ta navidezno nepomemben vir hranil je pravzaprav v mnogih primerih zelo pomemben. *Tekoča voda* (1B), predvsem tista, ki ponika v jame, prenaša s sabo raztopljeno in neraztopljeno organsko snov, včasih velikostnega razreda drevesnih debel. Tekoča voda oskrbuje s hranili tako vodne kot kopenske organizme, ki živijo ob strugi v jami (obrežne združbe). *Veter* in *težnost* (1C) prinašata hranila v vhodne dele jam. Tak primer so odpadlo listje ali živali, ki tam poginejo, ker padejo v brezno ali se v jami izgubijo in ne najdejo izhoda. Lastnost tega vira hrane je v tem,

flow in some cases—is important in aquatic shallow subterranean habitats, although wind and gravity as well as the active movement of animals may be more important in terrestrial shallow subterranean habitats.

In a surface stream there are three sources of organic carbon (2):

- gross primary productivity in the stream itself,
- litter fall and lateral transport of organic carbon,
- groundwater inputs.

In a cave stream, there is no primary productivity and no litter fall. However, in addition to lateral transport of organic carbon and groundwater inputs, there is transport through the epikarst (3).

| Vir energije<br>*Energy source* | Izvor energije<br>*Origin of energy* | Tip habitata<br>*Destination* | Podzemeljski habitati<br>*Subterranean habitats* |
|---|---|---|---|
| Kemoavtotrofija<br>*Chemoautotrophy* | Avtohton (vodni)<br>*Autochthonous (aquatic)* | Vodni in občasno terestični<br>*Aquatic and occasionally terrestrial* | Globoki intersticij in nekaj jam<br>*Deep interstitial and a few caves* |
| Prenikajoča voda<br>*Percolating water* | Alohton (vodni)<br>*Allochthonous (aquatic)* | Vodni<br>*Aquatic* | Jame, intersticijski in plitvi podzemeljski habitati<br>*Caves, interstitial, and shallow subterranean habitats* |
| Tekoča voda<br>*Flowing water* | Alohton (vodni)<br>*Allochthonous (aquatic)* | Vodni in terestični<br>*Aquatic and terrestrial* | Jame in hiporejik<br>*Caves and hyporheic* |
| Veter in težnost<br>*Wind and gravity* | Alohton (terestični)<br>*Allochthonous (terrestrial)* | Terestični<br>*Terrestrial* | Jame in plitvi podzemeljski habitati<br>*Caves and shallow subterranean habitats* |
| Aktivni premiki živali<br>*Active movements of animals* | Alohton (terestični)<br>*Allochthonous (terrestrial)* | Terestični<br>*Terrestrial* | Jame<br>*Caves* |
| Korenine<br>*Roots* | Alohton (terestični)<br>*Allochthonous (terrestrial)* | Terestični<br>*Terrestrial* | Jame in nekateri plitvi podzemeljski habitati<br>*Caves and some shallow subterranean habitats* |

**Tabela 1** Opis virov energije, njen izvor in pojavnost v podzemeljskih okoljih.
**Table 1** Classification of sources and origins of energy and their destinations in subterranean environments.

**5** Močila (hipotelminorejik) na Nanosu v Sloveniji.
Hypotelminorheic site on Mount Nanos in Slovenia.

da je povsem nepredvidljiv. *Aktivni premiki živali* (1D) so zlasti v terestičnih jamskih habitatih glavni vir hranil. Očiten primer so netopirji in posebne združbe organizmov, ki so pri prehranjevanju vezani na gvano v jamah (*Gnaspini* in *Trajano* 2000). *Korenine* (1E), ki prodirajo v nekatere plitve jame, predvsem jame v lavi, organizmi uporabljajo kot vir hrane. Značilnosti vseh šestih tipov hranil so povzete v tabeli 1. Splošno razširjena in navzoča skoraj v vseh tipih podzemeljskih habitatov je prenikajoča voda.

Vodni plitvi podzemeljski habitati so prav tako kot jame brez svetlobe in običajno brez avtohtone organske produkcije, z izjemo redkih primerov kemoavtotrofije (*Engel* 2005). Plitvi podzemeljski habitati (PPH) pa se od jam razlikujejo predvsem po tesni povezanosti s površjem ter z relativno močnimi letnimi in občasnimi dnevnimi cikli okoljskih dejavnikov (*Culver* in *Pipan* 2009). Zaradi neposredne bližine in tesne povezanosti s površjem je količina organskega ogljika, ki vstopa v PPH, višja v primerjavi z jamami. Med navedenimi šestimi viri hranil, ki vstopajo v jamo, je samo prenikajoča voda – v nekaterih primerih še horizontalni tok v jami – pomembna v vodnih plitvih podzemeljskih habitatih. Veter, težnost in aktivno gibanje živali so pomembnejši viri v kopenskih plitvih podzemeljskih habitatih.

V površinskem vodotoku so navzoči trije viri organskega ogljika (2):

- celokupna primarna proizvodnja v vodotoku,
- odpadlo listje in horizontalni prenos organskega ogljika,
- podzemeljski vir.

Primarne proizvodnje in odpadlega listja kot virov hranil v podzemeljskem vodotoku ni. Dodaten vir, poleg horizontalnega prenosa organskega ogljika in vira iz podzemeljske vode, je še prenos skozi epikras (3).

Tok skozi epikras zavzema običajno širše območje od horizontalnega prenosa organskega ogljika oz. podzemeljskega vodotoka. Pretok energije skozi epikras je navzoč tudi v jamah brez horizontalnega vodotoka. Konceptualni model pretoka energije v jamah je prikazan na sliki 4. Ogljik vstopa v sistem s ponornimi vodami (tj. horizontalni tok), s prenikajočo vodo skozi prst v epikras in predvidoma v jame.

Vsaj tri tipe vodnih PPH lahko primerjamo z jamami. Epikras je pomemben habitat, ki ga naseljujejo

Epikarst flow is also more widely distributed than either lateral transport of organic carbon or cave streams themselves. Energy flow from epikarst can take place in caves where there is no stream. Conceptual model of energy flux in caves is shown in figure 4. Carbon enters the system through sinking streams (i.e. lateral flow) and through water percolating through soils into epikarst, and eventually into caves.

There are at least three types of aquatic SSHs which can be compared with caves. The epikarst itself is an important habitat and often has more subterranean-limited species (stygobionts) than the cave stream itself (*Pipan* 2005). The physical structure of epikarst typically consists of small solution pockets integrated to varying degrees both horizontally and vertically (*Jones* et al. 2004).

In a general sense, the epikarst is like the cave system below, except:

- it is miniaturized,
- the density of spaces is higher (i.e. secondary porosity is higher),
- it is much more connected to the surface water.

As with caves, there can be both vertical and horizontal transport of organic carbon, so the model in figure 4 roughly holds for epikarst.

A second type of aquatic SSH is a seepage spring, or more properly, a shallow, tiny aquifer that is drained by the seepage spring (5). These shallow aquatic subterranean habitats have been given a series of names, none of them entirely satisfactory, and this has resulted in continuing confusion. Perhaps the earliest name used was 'seep' but this word, in U.S. usage at least, often refers to petroleum oozing out of the ground. Less confusing is the term 'seepage spring'. According to Kresic (2010), a seepage spring is a diffuse discharge of water, when the flow cannot be immediately observed but the land surface is wet compared to the surrounding area. This captures the essence of many of these wet spots in the woods. Seepage springs are gravity fed and situated in sediment. Kresic points out that variability of discharge is an important hydrological (and ecological) parameter, and indicates that if the ratio of the maximum to minimum discharge is greater than 10, then the spring can be considered highly variable. Because many seepage springs have little or no flow organizmi različnih, na podzemeljske razmere prilagojenih vrst (stigobionti). Njihovo število je lahko celo večje kot v jamskem vodotoku (*Pipan* 2005). Epikras je značilno sestavljen iz manjših, med seboj bolj ali manj horizontalno in vertikalno povezanih žepov, nastalih z raztapljanjem osnovne kamnine (*Jones* idr. 2004).

Na splošno je epikras podoben jamskemu sistemu pod njim, le da je:

- manjši,
- gostota prostorov je večja (tj. večja je sekundarna poroznost),
- neposredno je povezan s površinsko vodo.

Transport organskega ogljika v epikrasu poteka, enako kot v primeru jam, v vertikalni in horizontalni smeri, tako da model na sliki 4 delno ustreza tudi epikrasu.

Drugi tip vodnega PPH so močila (v angleščini *seepage springs*) oz. plitvi in neznatni vodonosnik, ki ga napaja podzemeljski izvir (5). Ta tip plitvega vodnega podzemeljskega habitata je bil večkrat različno, a vsakič neustrezno poimenovan, kar se kaže v kakofoniji izrazov. Eden izmed najzgodnejših izrazov, s katerim so poimenovali tovrstni habitat, je bil angleško *seep*, vendar ta beseda, zlasti v ZDA, pogosto označuje podzemeljske izvire fosilnih goriv. Bolj ustrezen angleški izraz je *seepage spring*, ki ga je Kresic (2010) definiral kot razpršen tok vode, katerega niti nujno ne opazimo, je pa območje v primerjavi z okolico namočeno. Ta definicija – mokra področja v gozdu – ustreza habitatu. Močila so tako v sedimentu razvit in s podzemeljsko vodo napajan habitat. Kresic poudarja, da je variabilnost pretoka pomemben hidrološki (in ekološki) parameter, ki v primeru, da je razmerje med največjim in najmanjšim pretokom večje od 10, označuje veliko variabilnost izvira. Tok v močilih je v vročih in sušnih obdobjih neznaten ali ga sploh ni, potemtakem so močila zelo spremenljiv habitat.

Meštrov (1962) je plitve vodne podzemeljske habitate, ki so vertikalno izolirani od podtalne vode ter jih »gradi humusna prst v goratih predelih, so bogati z organsko snovjo in prepredeni s curki mezeče vode«, poimenoval hipotelminorejik (v angleščini *hypotelminorheic*). Ta tip podzemeljskega habitata je bil v seznamih podzemeljskih habitatov običajno spregledan, čeprav ga je Juberthie (2000) vključil v razpravo o

during hot, dry periods, they would be classified as highly variable habitats.

Meštrov (1962) gave the name 'hypotelminorheic' to shallow groundwater habitats that were vertically isolated from the water table and were »constituted of humid soils in the mountains, rich in organic matter and traversed by moving water«. This groundwater habitat has usually been ignored in overall groundwater classification schemes, but Juberthie (2000) included it in his discussion of subterranean habitats, but more as a special case than an integral part of the subterranean realm. Based on Meštrov's definition, Culver et al. (2006) proposed that the term 'hypotelminorheic' could be used to describe habitats with the following major features (see also *Culver* and *Pipan* 2008):

- a perched aquifer fed by subsurface water that creates a persistent wet spot;
- underlain by a clay or other impermeble layer typically 5–50 cm below the surface;
- rich in organic matter compared with other aquatic subterranean habitats.

They also indicated that the drainage area of a seepage spring is typically less than 10,000 m², that it is in a shallow depression, and the fallen leaves are characteristically blackened and usually not skeletonized. Without a clay layer, water should tend to move vertically, and there would be no persistent water.

A third type of aquatic SSH is underflow of rivers and streams, the hyporheic. This is an interstitial habitat where the pore size of sediment is smaller than either epikarst or the hypotelminorheic. The hyporheic is the best studied of aquatic SSHs. Typically it consists of a series of up- and downwellings that connect the surface stream with the underlying groundwater. A detailed description of the hyporheic can be found in Malard *et al.* (2000).

In this contribution, we consider the amount of organic carbon in water entering caves and shallow subterranean habitats, in flowing water and percolating water, and review some of the emerging patterns.

## 9.1 Methods and materials

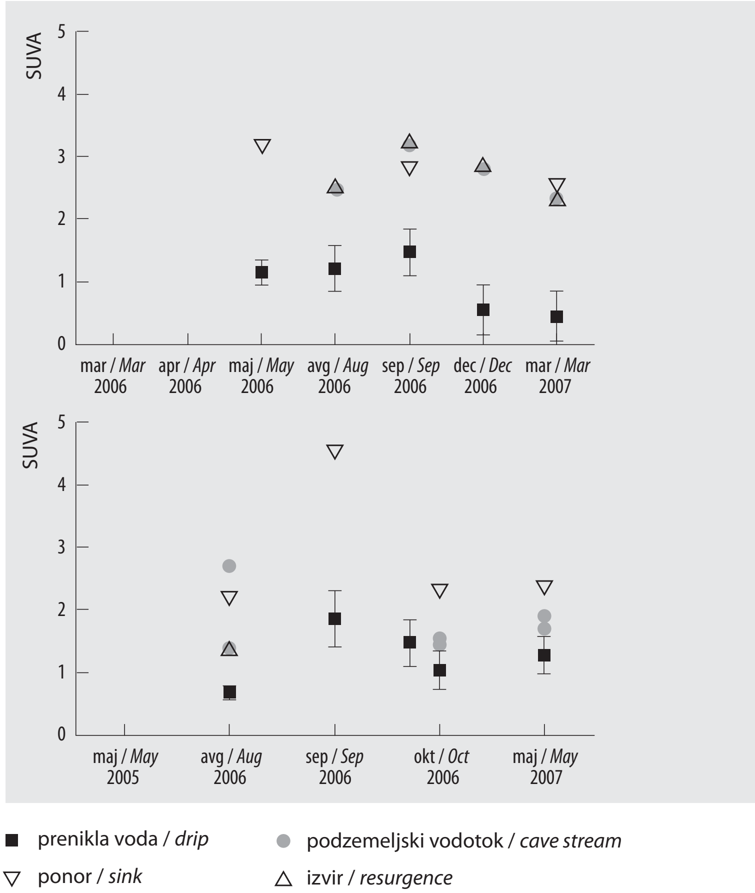
We measured the concentration of organic carbon in water samples from the Organ cave, West Virginia, podzemeljskih habitatih, toda le kot poseben primer in ne enakovreden del podzemeljskega kraljestva. Temelječ na Meštrovi definiciji, je Culver s sodelavci (*Culver* idr. 2006) predlagal, da bi izraz hipotelminorejik uporabili za opis habitatov z naslednjimi značilnostmi (glej tudi *Culver* in *Pipan* 2008):

- vodonosnik, ki je dvignjen nad nivo talne vode in ga napaja podzemeljska voda, ki oblikuje močila (stalno mokra področja);
- ilovica ali drug neprepustni material, tipično ležeč 5–50 cm pod površjem;
- je bogatejši z organskimi snovmi v primerjavi z drugimi vodnimi podzemeljskimi habitati.

Dodal je še, da je območje, ki napaja močila, značilno manjše od 10.000 m², se nahaja v plitvi depresiji, odpadlo listje pa je počrnelo in običajno nerazgrajeno. Brez plasti ilovice bi voda pronicala vertikalno in področje bi postalo stalno izsušeno.

Tretji tip vodnega PPH je podtalni tok v rekah in potokih, hiporejik. To je intersticijski habitat, kjer je velikost prostorov med zrnci sedimenta manjša kot v epikrasu ali hipotelminorejiku. Hiporejik je kot habitat med vsemi vodnimi plitvimi podzemeljskimi habitati najbolje raziskan. Niz navzgor in navzdol potekajočih tokov povezuje površinsko vodo s podzemeljsko. Natančen opis hiporejika navajajo Malard idr. (2000).

V pričujočem prispevku so podani splošna opažanja, ugotovitve in ocena o količini organskega ogljika v vodi, ki ponika v jame in druge plitve podzemeljske habitate, v ponikalnici in prenikli vodi.




**6** SUVA vrednosti za Postojnsko-Planinski jamski sistem (zgornji diagram) in jamo Organ (spodnji diagram). Prirejeno po *Simon* idr. (2010).
SUVA values for Postojna-Planina cave system (upper panel) and for the Organ cave (lower panel). Adapted from *Simon* et al. (2010).

## 9.1 Metode in materiali

Koncentracijo organskega ogljika smo merili v vzorcih iz jame Organ v Zahodni Virginiji, ZDA, iz Postojnsko-Planinskega jamskega sistema (PPJS) v Sloveniji ter iz močil in sosednjih hiporejičnih mest na Nanosu v Sloveniji. PPJS sestavlja približno 23 km raziskanih rovov (17 v Postojnski jami in 6 v Planinski jami, povezanih s poplavnimi rovi dolžine 2 km). Jamski sistem je razvit v gornjekrednih apnencih in na površju porasel pretežno z mešanim gozdom. V sistemu se združita dve ponikalnici, ki se pojavita na vhodu Planinske jame kot izvir Unice. Prva ponikalnica je reka Pivka, ki zbira vodo s približno 230 km²

U.S.A., the Postojna-Planina cave system (PPCS), Slovenia, and from seepage springs and associated watercourses on Mount Nanos, Slovenia. The PPCS has approximately 23 km of surveyed passages (17 in the Postojna cave and 6 in the Planina cave connected by 2 km of flooded passages) developed in Upper Cretaceous carbonate rocks and overlain mostly by forested land. There are two main cave streams in PPCS which join and eventually resurge to the surface through the Planina cave entrance as the Unica river. One cave stream is fed by the Pivka river, a moderate-sized river draining approximately 230 km² of carbonate and flysch which sinks near the Postojna cave entrance. The other, smaller cave stream (Rak) is fed by multiple velikega karbonatnega in flišnega območja in ponikne v Postojnsko jamo. Druga, manjša ponikalnica je Rak, ki ga tvori več ponikajočih potokov in podzemeljska voda s karbonatnega in flišnega področja, velikega približno 27 $km^2$. Vzorčenje prenikle vode iz epikrasa smo opravili v 28 curkih v Postojnski jami (za lokacije glej *Pipan* 2005) in v 5 curkih v Planinski jami (*Pipan*, neobjavljeno), ki obsegajo celokupno območje 5 $km^2$. Vzorci so bili odvzeti tudi na ponoru reke Pivke, na razdalji 2,4 km od ponora v jami, v reki Rak v Planinski jami in na izviru Unice, kjer se podzemeljska voda s celotnega zalednega področja vrne na površje.

Organ je velik, pretežno horizontalen jamski sistem s preko 60 km raziskanih rovov v provinci Greenbrier v ZDA. Vode, ki se zbirajo v jami, se stekajo s področja, velikega 8,2 $km^2$, katerega 70 % gradijo apnenci misisipijske starosti, preostalo so misisipijski peščenjaki in skrilavci. Niz manjših jamskih rečic, nekaterih preniklih s površja, drugih nastalih s preniklo epikraško vodo, se združi v enotno reko, ki izvira na robu pritoka reke Greenbrier, Second Creek. Več manjših površinskih rečic, večina sezonske narave, izvira na nekarbonatnih predelih in ponikne v bližini devetih vhodov v jamski sistem. Površje nad njim je kmetijsko, predvsem pašniki. Vzorci vode so bili odvzeti v enem izmed potokov, ki ponikne v bližini glavnega vhoda v jamo Organ, v treh manjših rečicah v jami (Lipps, Sively No. 2, in Sively No. 3), ki jih polnita prenikla voda in površinski tok, odvisen od padavin, v 13 curkih (za lokacije glej *Pipan* in *Culver* 2005), ki se zbirajo v treh zgoraj omenjenih rečicah in na izviru Second Creek.

V vznožju gore Nanos smo odvzeli vzorce na treh mestih, kjer so oblikovana močila, v bližnjem hiporejiku na nadmorski višini 750 m, v dveh manjših izvirih in površinskem toku na približno 600 m nadmorske višine in okrog 500 m linearne razdalje od najvišjega vzorčnega mesta. Vsa mesta so v gozdu, v bližini vasi Razdrto.

Vzorce vode smo odvzeli s 60-ml brizgalko in jih prefiltrirali skozi 0,45-µm filter (Gelman GF/F). Vzorce smo ob dodatku kapljice koncentrirane HCl (do končnega pH < 2) shranili v 50-ml plastenke. Koncentracija raztopljenega organskega ogljika (DOC) je bila določena s persulfatno metodo (APHA 1995)

sinking streams and groundwater that drains approximately 27 $km^2$ of carbonate and flysch. We sampled water dripping into the cave from the epikarst at 28 drips in the Postojna cave (see *Pipan* 2005 for locations) and 5 drips in the Planina cave (*Pipan*, unpublished) spanning an area of approximately 5 $km^2$. We also collected samples from the Pivka river where it enters the cave and 2.4 km away inside the cave, from the Rak cave stream, and at the resurgence spring of the Unica river where groundwater from the entire basin returns to the surface.

The Organ cave is a large, mostly horizontal cave system with over 60 km of surveyed passages located in Greenbrier County, U.S.A. Organ cave drains an 8.2 $km^2$ basin, 70 % of which is underlain by Mississippian limestone and the rest by Mississippian sandstone and shale. A series of small cave streams, some fed by sinks and others fed by epikarst water, eventually coalesce in a single stream that emerges at a spring on the edge of Second Creek, a tributary of the Greenbrier river. Several small surface streams, most of them seasonal, originate in a non-carbonate part of the basin and sink at or near some of the nine entrances to the cave system. Most of the land in the basin is agricultural, especially pastures. Water samples were taken at one stream that sinks into the cave near the Organ cave main entrance, three small streams in the cave (Lipps, Sively No. 2, and Sively No. 3) that are fed by percolating water and surface overflow depending on precipitation, 13 epikarst drips (see *Pipan* and *Culver* 2005 for locations) that drain into the three streams, and at the spring of the Second Creek.

On Mount Nanos samples were taken at three seepage springs and a nearby hyporheic habitat in a small stream at approximately 750 m a.s.l., two small springs and a surface stream at an elevation of approximately 600 m a.s.l., and about 500 m linear distance from the upper site. All of the sites are forested and lie near Razdrto village.

Water was aspirated into a 60-ml syringe and passed through a pre-combusted 0.45-µm filter (Gelman GF/F) into a 50-ml plastic bottle and preserved to pH < 2 with a drop of concentrated HCl. The water samples were analysed for DOC concentration using the persulfate digestion method (APHA 1995) on an na analizatorju OI Analytical Total Organic Carbon Analyser Model 1010 za jamske vzorce in na analizatorju EST THERMO HiPerTM TOC Analyser za vzorce z Nanosa.

Specifična UV absorpcija (SUVA), indikator vsebnosti aromatičnega ogljika, je bila določena za vsak jamski vzorec kot koeficient med absorpcijo vzorca pri 254 nm in DOC koncentracijo vzorca. Absorpcija je bila izmerjena z uporabo spektrofotometra Thermo

OI Analytical Total Organic Carbon Analyser Model 1010 for the cave samples and an EST THERMO HiPerTM TOC Analyser for samples from Mount Nanos.

Specific UV absorbance (SUVA), an indicator of the aromatic C content, was calculated for each cave sample by dividing absorbance of the sample at 254 nm by the DOC concentration of the sample. Absorbance was measured using a Thermo Electron Aquamate UV-vis spectrophotometer. The samples were sup-

| Jamski pritoki<br>*Cave inflows* | Jama Organ<br>*Organ cave* | | | Postojnsko-Planinski jamski sistem<br>*Postojna-Planina cave system* | | |
|---|---|---|---|---|---|---|
| | Št. / *n* | Srednja vrednost (mg/l)<br>*Mean value (mg/l)* | S.N.<br>*S.E.* | Št. / *n* | Srednja vrednost (mg/l)<br>*Mean value (mg/l)* | S.N.<br>*S.E.* |
| Ponikalnice<br>*Sinking streams* | 3 | 7.67 | 1.03 | 2 | 4.36 | 0.46 |
| Epikraški curki<br>*Epikarst drips* | 20 | 1.10 | 0.15 | 99 | 0.70 | 0.04 |
| Jamski potoki<br>*Cave streams* | 6 | 1.08 | 0.32 | 3 | 4.75 | 1.57 |
| Izvir<br>*Resurgence* | 3 | 0.90 | 0.17 | 2 | 2.67 | 0.80 |

**Tabela 2** Količina raztopljenega organskega ogljika (mg/l) v vodah v jami Organ, ZDA, in v Postojnsko-Planinskem jamskem sistemu, Slovenija.
**Table 2** Amount of dissolved organic carbon (mg/l) in waters in the Organ cave, U.S.A., and Postojna-Planina cave system, Slovenia.

| | Št. / *n* | Srednja vrednost (mg/l)<br>*Mean value* (mg/l) | S.N.<br>*S.E.* |
|---|---|---|---|
| Močila<br>*Seepage springs* | 5 | 2.88 | 0.28 |
| Hiporejik<br>*Hyporheic* | 1 | 1.32 | |
| Izviri<br>*Springs* | 2 | 4,11 | 1.34 |
| Potok<br>*Stream* | 1 | 12.66 | |

**Tabela 3** Količina raztopljenega organskega ogljika (mg/l) na izvirih, v potoku, hiporejiku in močilih na Nanosu, Slovenija.
**Table 3** Amount of dissolved organic carbon (mg/l) in springs, stream, hyporheic, and seepage springs on Mount Nanos, Slovenia.

Electron Aquamate UV-vis. Dodatno smo izmerili DOC koncentracijo v vzorcih prsti iz bližine jame Organ in PPJS. Raztopino iz 5 g prsti in 25 ml deionizirane vode smo stresali 15 minut pri sobni temperaturi.

## 9.2 Rezultati

Koncentracije raztopljenega organskega ogljika (DOC) za obe jami so povzete v tabeli 2. V obeh jamah, Organ in PPJS, je bila najvišja koncentracija DOC izmerjena na ponoru, v povprečju več kot 7 mg/l v Organ in več kot 4 mg/l v PPJS. Višja vrednost v jami Organ je posledica razlik v rabi zemlje, saj je nad površjem jame razvito intenzivno pašništvo. Najbolj intenzivno smo vzorčili epikraško vodo, pri kateri so koncentracije nihale malo nad 1 mg/l v Organ in 0,7 mg/l v PPJS. DOC vrednost v ponikalnici, kombinaciji prenikle vode s površja in epikraških curkov, je ustrezala vrednosti epikraške vode v jami Organ in ponorni vodi v PPJS. Razlika je posledica relativne velikosti ponornih vod v obeh jamah. Koncentracija DOC na izviru jame Organ je znašala okrog 0,9 mg/l, kar je blizu koncentracijam v epikrasu in ponikalnici v jami. V PPJS je bila vrednost na izviru nižja kot v jami, v povprečju 2,7 mg/l. Nižja DOC koncentracija na izviru v primerjavi z jamsko vodo je verjetno posledica združenja reke Pivke z reko Rak, ki ima predvidoma nižjo vsebnost DOC.

Koncentracije raztopljenega organskega ogljika (DOC) za vsa merjena mesta na Nanosu so prikazane v tabeli 3. Čeprav obstaja za močila manjša podatkovna baza kot v primeru jam, je opaziti splošen trend. V močilih je bila DOC koncentracija skoraj 3 mg/l, kar je trikrat več kot v epikraških curkih, drugem tipu PPH, katerega vode smo vzorčili. Voda iz hiporejika je imela nižjo DOC vrednost, okrog 1,3 mg/l. Izvira v nižinskem predelu sta imela relativno visoko koncentracijo DOC, okrog 4 mg/l. Vrednosti se ujemajo z rezultati na izviru v PPJS, ki je podoben, a večji habitat. Površinski potok je imel visoke DOC vrednosti, preko 12 mg/l, kar kaže na koncentriran vir organske snovi.

V PPJS so bile vrednosti SUVA v epikraških curkih vedno nizke (obseg = 0,0–2,4 (l/mgCm)) v primerjavi z vrednostmi v rekah in na izviru (obseg = 2,5–3,2 l/(mgCm)), kjer so si bile med seboj podobne v celo-

plemented with soil samples near the Organ cave and PPCS. Soil extracts were created by shaking 5 g (wet mass) of soil in 25 ml of de-ionized water for 15 minutes at room temperature.

## 9.2 Results

Dissolved organic carbon (DOC) concentrations for the two caves are summarized in table 2. In both the Organ cave and the PPCS the highest DOC concentrations were in sinking streams, averaging over 7 mg/l in the Organ cave and over 4 mg/l in PPCS. The higher values in the Organ cave are a reflection of differences in land use, especially extensive pastures over the cave. Epikarst drip water, the most extensively sampled water, averaged slightly over 1 mg/l in the Organ cave and 0.7 mg/l in PPCS. Water in cave streams, a mixture of water derived from sinking streams and epikarst drips, was close to the epikarst concentration in the Organ cave and closer to the sinking stream concentration in the PPCS. This reflects the relative size of the sinking streams in the two caves. The resurgence water in the Organ cave was close to the epikarst and cave stream average, approximately 0.9 mg/l. In the PPCS, DOC at the resurgence was lower than the cave stream and averaged approximately 2.7 mg/l. The lower value at the resurgence compared to the measured cave stream is probably because water at the resurgence is a mixture of water from the measured Pivka river and the unmeasured Rak river, with a presumably lower DOC concentration.

DOC concentrations for the measuring sites on Mount Nanos are summarized in table 3. While much less extensive than the cave data, patterns are beginning to emerge. DOC concentrations in seeps were nearly 3 mg/l, three times more than it was found in epikarst drips, the other SSH water sampled. Hyporheic water had lower DOC concentrations, about 1.3 mg/l. The lower springs had relatively high DOC concentrations, averaging 4 mg/l. It is interesting to note that these values are very similar to those found in the resurgence of the PPCS, a similar but larger habitat. The surface stream had very high values of DOC, over 12 mg/l. These values suggest a concentrated source of organic material.

tnem časovnem razponu. Take vrednosti so tipične za površinske vode (npr. *Weishaar* idr. 2003; 0,6–5,3 l/(mgCm)). V jami Organ je bila prostorska razporeditev SUVA vrednosti manj izražena, z relativno visokimi vrednostmi na ponorih (obseg = 2,3–4,5 l/(mgCm)), v primerjavi z epikraškimi curki, jamskimi rečicami in izvirom, kjer so si bile vrednosti podobne in nizke (obseg = 0,6–2,7 l/(mgCm)). Zanimiva ugotovitev iz obeh jam je ta, da so bile vrednosti SUVA v epikraški vodi nižje od vseh drugih tipov voda in prsti (6). Simon s sodelavci (2010) navaja, da so bile prostorsko bolj usklajene kot DOC vrednosti in da so običajno višje v pomladnem času.

## Sklep

Od predstavitve konceptov ekosistema o podzemeljski biologiji v literaturi, ki so jo podali Rouch (1968, 1977) ter Stanford in Gaufin (1974), so le biologi, ki so raziskovali hiporejik, uporabili koncepte ekosistema in vključili hiporejik v ekosistemske modele površinskih vodotokov. Zanimanje za ekosistemske koncepte jam in kraškega sistema kot celote je bilo obujeno v zadnjih petih letih, oboje v delih Simona in kolegov (npr. *Simon* idr. 2007a), in povečalo se je zanimanje za usodo organskega ogljika v podzemeljskih habitatih, kar je vodilo do monitoringa podzemeljskega organskega ogljika (npr. *Ban* idr. 2008; *Emblanch* idr. 1998). Podzemeljski habitati obljubljajo z ekosistemskega vidika mnoga presenečenja. Celo s trenutne začetne stopnje njegovega razumevanja je očitno, da so procesne aktivnosti dokaj visoke (npr. *Simon* in *Benfield* 2002) in je kakovost ogljika, v smislu njegove sposobnosti razgradnje, veliko večja, kot bi pričakovali (*Simon* idr. 2010).

Padavinska voda, ki pade na kraška tla, se zaradi gravitacije pretaka skozi prst v omrežje majhnih razpok tik pod plastjo prsti oz. hitro ponikne skozi relativno velike odprtine, npr. na ponorih. Meja med prstjo in osnovno kamnino je epikras, edinstven ekosistem, ki ga tvori heterogeno omrežje prepletenih in med seboj povezanih majhnih špranj in razpok, ki so vedno ali le občasno zapolnjene z vodo oz. so nekatere vedno suhe. Čeprav predstavljata epikras in ponorna voda mejni ekosistem ali ekoton, se v sposobnosti pre-

In the PPCS, SUVA values were consistently low in epikarst drips (range = 0.0–2.4 l/(mgCm)) relative to the streams and the resurgence (range = 2.5–3.2 l/(mgCm)), which were quite similar to one another over time. These SUVA values fall within a range typical of surface waters (*e.g. Weishaar* et al. 2003: 0.6–5.3 l/(mgCm)). In the Organ cave, the spatial pattern of SUVA was less distinct, with relatively high SUVA (range = 2.3–4.5 l/(mgCm)) only in the sinking stream as compared to the epikarst drip, cave stream and resurgence waters which had lower and generally similar SUVA values (range = 0.6–2.7 l/(mgCm)). In both caves, the most striking pattern is that SUVA values for epikarst were lower than for any other types of water and in the soil (6). Simon *et al.* (2010) report that SUVA values were quite consistent spatially, more than DOC values. SUVA values tended to be higher in the spring compared to other seasons.

## Conclusion

Since the introduction of ecosystem concepts in the literature of subterranean biology by Rouch (1968, 1977) and Stanford and Gaufin (1974), only biologists studying hyporheic have utilized ecosystem concepts in a major way, and they have largely incorporated the hyporheic into ecosystem models of surface streams. In the last five years, there has been a reawakening of interest in ecosystem concepts in caves and karst systems in general, both through the work of Simon and colleagues (e.g. *Simon* et al. 2007a) and through increased interest in the fate of organic carbon in subterranean habitats resulting in increased monitoring of subterranean organic carbon (e.g. *Ban* et al. 2008; *Emblanch* et al. 1998). Subterranean habitats promise many surprises from an ecosystem perspective. Even at this preliminary stage of understanding, processing rates can be surprisingly high (e.g. *Simon* and *Benfield* 2002), and carbon quality, in terms of its ability to be broken down, is much higher than initially expected (*Simon* et al. 2010).

Rainwater that falls on the surface of karst landscape follows gravity, percolating through soils and into a network of small fractures just below the soil surface or sinking rapidly through relatively large nosa energije in snovi v podzemlje dramatično razlikujeta. Skozi manjše, heterogene razpoke v epikrasu se voda počasi pretaka in omogoča, da majhni delčki ali raztopljena snov potujejo s površja v podzemlje. V nasprotju z epikrasom ponorne vode, ponikalnice, potujejo skozi večje rove, njihov tok je močnejši in bolj variabilen ter prenašajo s površja v podzemlje večje delčke snovi in organizme. Kljub temu so manj pogoste in v kraškem bazenu predstavljajo majhno območje, medtem ko epikras zavzema veliko področje v kraškem bazenu. Izsledki naše raziskave nakazujejo, da je količina ogljika, v tem primeru raztopljenega ogljika, v epikrasu majhna (tabela 2). Nizke SUVA vrednosti (nižja frakcija aromatičnih ogljikovih sestavin) pomenijo, da je organski ogljik v epikrasu bolj labilen. To mikroorganizmom v prsti omogoča, da s svojimi procesi lahko odstranjujejo labilnejše sestavine. Čeprav je realno stanje bolj kompleksno in je razmerje organskega ogljika nezadostno prikazano kot preprosto razmerje aromatičnega in celokupnega ogljika, pa so nekatere druge analize o kakovosti ogljika prinesle podobne rezultate (*Simon* idr. 2010). Dejstvo pa je, da so raziskave o kakovosti ogljika v kraških vodah šele na začetni stopnji (*Birdwell* in *Engel* 2010).

Opisana in druge objavljene raziskave (*Emblanch* idr. 1998; *Simon* idr. 2007b; *Ban* idr. 2008) poročajo o očitni prostorski in časovni heterogenosti organskega ogljika. Ban in sodelavci ugotavljajo, da je količina raztopljenega organskega ogljika zelo variabilna in da se ob močnih padavinah sprosti voda, bogata z organskim ogljikom, v epikraške curke, medtem ko Simon s kolegi navaja preliminarne podatke o povezanosti bogate epikraške združbe (zlasti ceponožcev) s količino organskega ogljika. Očitni so večkratni, mnogovrstni, kompleksni vnosi s površja v epikras.

Hipotelminorejični habitat je manj raziskan, čeprav nekatere predhodne izsledke lahko podamo. Ker je to izredna površinska oblika habitata, je povezava med površjem in hipotelminorejikom skorajda zvezna, kjer sta oba habitata ločena le z 1–2 m debelo plastjo prsti in listnega odpada. Ta bariera domnevno deluje kot filter in organski ogljik s površja je kljub majhni razdalji lahko mikrobno procesiran. Morda bi bilo takšne habitate smiselno poimenovati vodni edafski habitati, nakazujoč njihovo tesno povezanost s prstjo.

openings as sinking streams. The zone of the contact between soils and bedrock, the epikarst, is a unique environment comprised of a heterogeneous network of small fissures that are intermittently wetted with some spaces permanently wetted while others are sometimes or always dry. While epikarst and sinking streams are both interfaces, or ecotones, with the surface, they differ dramatically in the capacity to deliver energy and matter to the subsurface. The small, heterogeneous fractures in the epikarst result in relatively slow water flow rates and permit only very small particles or dissolved material to pass from the surface to the subsurface. In contrast, the much larger conduit openings for sinking streams can support much higher and more variable flow and pass larger particles and organisms from the surface to the subsurface. But they are much fewer in number and represent a small area within a basin while epikarst represents a large area of interface within the basin. Our work suggests that the amount of carbon, and in this case dissolved carbon, is lower in the epikarst (table 2). The low SUVA values (a lower fraction of aromatic carbon compounds) indicates that the organic carbon in drips is more labile. This result is somewhat surprising because the microbial processing that occurs in the soil might remove the more labile compounds. The actual situation is more complex and of course the range of organic carbon is inadequately expressed by a simple ratio of aromatic carbon to total carbon. Nevertheless, other analyses of carbon quality yielded similar results (*Simon* et al. 2010). The study of carbon quality in karst waters is just beginning, and there are many complexities just beginning to be unraveled (*Birdwell* and *Engel* 2010).

This and other studies (*Emblanch* et al. 1998; *Simon* et al. 2007b; *Ban* et al. 2008), all report considerable spatial and temporal heterogeneity of organic carbon. Ban *et al.* (2008) report that levels of dissolved organic carbon vary more than three-fold and that significant precipitation events typically release organic carbon rich water into epikarst drips. Simon *et al.* (2007b) report on preliminary data that suggest that richness of the resident epikarst community (especially copepods) is correlated with levels of organic carbon. It is clear that there are multiple, complex inputs to the epikarst from the surface.

Znanje o organskem ogljiku v hipotelminorejiku izhaja le iz njegovega izviranja na površju (*seepage springs*, tabela 3). Domnevamo, da tudi v tem primeru obstaja znatna časovna in prostorska heterogenost.

Količina raztopljenega organskega ogljika v plitvih podzemeljskih habitatih znatno niha, vendar manj, kot je to značilno za površinske vode. Iz raziskav v epikraških curkih (*Ban* idr. 2008) ugotavljamo, da znaša količina organskega ogljika okrog 1 mg/l, z določenimi viški po močnejših padavinah. Količina organskega ogljika v močilih je večja, okrog 4 mg/l (tabela 3), kar je tretjina vrednosti v bližnji površinski vodi. Ne nazadnje, hipotelminorejik je habitat, ki je v primerjavi z drugimi globljimi podzemeljskimi habitati, celo epikrasom, relativno bogat z organskim ogljikom. Opravljene so bile mnoge študije podtalnega toka v rekah in potokih (npr. *Marmonier* idr. 2000) in izmerjene vrednosti organskega ogljika v 40 cm globokem kanalu Vanoise, pritoku reke Rhône, znašajo 1,8 mg/l in 3 mg/l v podobnem habitatu v glavni strugi.

Z opisanimi raziskavami ugotavljamo, da ekosistemski način pri preučevanju podzemeljskih habitatov, še posebej osredotočenje na organski ogljik, pomembno prispeva k njihovemu razumevanju.

Hypotelminorheic habitats are less well understood but some preliminary observations can be made. Because it is an extremely superficial feature of the landscape, the connection between the surface and the hypotelminorheic must be nearly continuous, with the two habitats separated only by 1–2 m of soil and leaf litter. Presumably this barrier acts as a filter, and organic carbon from the surface is likely processed by microbial communities, even over this short distance. It is perhaps useful to think of these habitats as aquatic edaphic habitats, signaling their close connection with the soil. What little is known about organic carbon in the *hypotelminorheos* is about their exit to the surface (seepage springs, table 3). It is likely, but not demonstrated, that a considerable temporal and spatial variation exists.

Finally, the amount of dissolved organic carbon in shallow subterranean habitats varies considerably, but typically less than in surface waters. Other studies of epikarst drips, especially Ban *et al.* (2008), report the organic carbon content of epikarst drip waters averages around 1 mg/l, although with spikes after precipitation events. Organic carbon in seepage springs is higher, around 4 mg/l (table 3), but this was about one third of the value of nearby surface waters. Nevertheless, the hipotelminorheic is relatively rich in organic carbon, compared to deeper subterranean habitats, even epikarst. Numerous studies of the underflow of streams have been conducted (e.g. *Marmonier* et al. 2000), and they report values of organic carbon 40 cm deep in the Vanoise channel, a tributary of the Rhône river, averaging 1.8 mg/l, and values of approximately 3 mg/l in similar habitats in the main channel.

An ecosystem approach to subterranean habitats, especially with a focus on organic carbon, thus shows a considerable promise.

# 10

# PERSPEKTIVE JAMSKE MIKROBIOLOGIJE V SLOVENIJI

# PERSPECTIVES OF CAVE MICROBIOLOGY IN SLOVENIA

Odkritje jamskega hroščka drobnovratnika *Leptodirus hochenwartii* leta 1832 v Postojnski jami pomeni začetek speleobiološkega raziskovanja (*Polak* 2005). Od tega dogodka naprej je bil napravljen velik korak pri preučevanju pestrosti jamske favne, evolucijskih odnosov in ekoloških interakcij. Vendar je naše védenje o tem, v primerjavi z bolj elementarnimi oblikami življenja v jamah, ki ga predstavljajo mikroorganizmi, še vedno precej borno. Razvoj sodobnih molekularnih orodij in splošni napredek v naravoslovju je v 90. letih 20. stoletja in pozneje botroval temu, da se je vedno večje število raziskav o mikroorganizmih začelo navezovati na podzemlje. Kakor drugod po svetu, tudi v Sloveniji jamska mikrobiologija še nima raziskovalne tradicije.

Jamska mikrobiologija je bila nedavno utemeljena kot novo interdisciplinarno področje mikrobiologije, geologije in kemije, ki preučuje mikroskopske oblike življenja v jamah in njihove vplive na tamkajšnje naravne procese. Pregled svetovne literature kaže, da se v laboratorijih, kjer raziskujejo jamske mikroorganizme, ne ukvarjajo izključno le z mikrobi iz jam. Jamska mikrobiologija v Sloveniji je danes še vedno na ravni identifikacije in diverzitetnih študij različnih mikrobnih skupin, precej manj pa je bilo narejenega v smislu raziskovanja geomikrobioloških procesov v podzemlju in kompleksnih ekoloških interakcij. Mikroorganizmi v jamah so vpleteni tako v litogene procese, na primer odlaganje sige (*Engel* 2007), kot v litolitične procese. S človekovega vidika so slednji še posebej nezaželeni v jamah s prazgodovinskimi poslikavami, kakršna je npr. jama Lascaux v Franciji (*Ciferri* 1999).

## 10.1 Kje je danes jamska mikrobiologija v Sloveniji?

Identifikacija bakterijske združbe iz organskih prevlek na stenah v Planinski jami je dala enega prvih vpogledov v jamske mikrobe v Sloveniji (*Megušar* in *Sket* 1977). Precej bolj nazaj, leta 1878, je Joseph opisal najdbo praživali *Peridinium stygium* in *Gymnodimium* sp. v Pivki jami (*Gittleson* in *Hoover* 1969). Iz slovenskih jam so opisani primeri identifikacije že vseh mikrobnih skupin: bakterij, cianobakterij in mikroalg, gliv in praživali (*Mulec* 2008). V tem preglednem član-

Discovery of the cave beetle *Leptodirus hochenwartii* in 1832 in the Postojna cave, Slovenia, represents the start of research in speleobiology (*Polak* 2005). Since then a great step towards understanding diversity of cave fauna, its evolutionary perspective and ecological interactions has been accomplished. However, regarding more elementary forms of life in caves, microorganisms, knowledge remains rather poor. Because of development of modern molecular techniques and general progress in the natural sciences, more studies on microorganisms linked to the underground have started to appear since the 1990's. As elsewhere in the world, Slovenia has no tradition of cave microbiology research yet.

Cave microbiology has recently been established as a new interdisciplinary field of microbiology, geology and chemistry dealing with microscopic life that resides in caves and influences natural cave processes. Bibliographic search reveals that generally laboratories dealing with cave microbes are not exclusively dedicated to study of cave microorganisms. However, cave microbiology in Slovenia is nowadays conducted mostly on the level of identification and diversity studies of different microbial groups, and much less is being done in respect to geomicrobiological processes in the underground and complex ecological interactions. Microorganisms in caves are involved in lithogenic processes, e.g. speleothem deposition (*Engel* 2007), and litholytic processes. The latter are sometimes completely undesirable from the human perspective, for example in caves with prehistoric paintings as in Lascaux cave, France (*Ciferri* 1999).

## 10.1 Where is cave microbiology in Slovenia today?

One of the first insights into cave microbes in Slovenia was made with identification of the bacterial community of organic covers from walls in the Planina cave/Planinska jama (*Megušar* and *Sket* 1977). Much earlier, in 1878, Joseph reported on finding protozoans *Peridinium stygium* and *Gymnodimium* sp. in the Pivka cave/Pivka jama (*Gittleson* and *Hoover* 1969). From Slovenian caves all microbial groups have been ku z naslovom »Mikroorganizmi podzemlja: primeri iz slovenskih kraških jam« je navedenih tudi 16 različnih znanstvenih del, ki vsebujejo uporabne informacije o mikroorganizmih in njihovi pestrosti v slovenskih jamah. K seznamu je treba dodati še vsaj tri pomembne poznejše publikacije v zvezi z mikrobno pestrostjo podzemlja slovenskih jam: o mikrobnih združbah v sedimenih iz Postojnske jame (*Zakotnik* 2011), analizi pestrosti bakterij na osnovi 16S rDNA iz organskega biofilma v Pajsarjevi jami (*Pašić* idr. 2010) in sestavi mikrobne združbe v prebavilih človeške ribice *Proteus anguinus* (*Avguštin* idr. 2010). V slednji je bilo ugotovljeno, da v prebavilih te troglobiontske živali prevladujejo bakterije iz debla Firmicutes. S to in podobnimi študijami se porajajo številna nova vprašanja in raziskovalni izzivi.

Biotehnološki in bioremediacijski potencial mikroorganizmov, ki naseljujejo jame v Sloveniji, še vedno nista dovolj raziskana. Zanimiv primer sta bila odkritje in izolacija novih vrst mikroorganizmov iz jame Carlsbad cavern (ZDA), ki lahko razgrajujejo kompleksne aromatske spojine, kot sta benzentiazol in benzensulfonska kislina. Te snovi, sestavine za proizvodnjo plastike, lahko mikrobi uporabljajo kot vir energije za svojo rast (*Barton* 2006). Slovenske kraške jame ponujajo v številnih pogledih izjemen potencial za jamsko mikrobiologijo. Prihodnje raziskave bi morale preseči trenutne taksonomske preglede in se bolj osredotočiti na razumevanje vloge mikrobov v različnih procesih. Velja poudariti, da morajo raziskovalci razlikovati med mikrobi, ki so v podzemlju avtohtoni, in tistimi, ki so v podzemlje vneseni po naravni poti ali s pomočjo človekovih aktivnosti. In smo ponovno pri izhodiščni ugotovitvi: potrebujemo več bazičnih raziskav, da sploh lahko dobimo osnovno idejo, kaj naj v podzemlju na tako imenovanem mikronivoju pričakujemo.

## 10.2 Aplikacije jamske mikrobiologije

Mikroorganizmi so dobri pokazatelji dejanskega stanja v habitatih. Indikatorski organizmi so v okoljski mikrobiologiji merilo za kakovost voda in obenem opozarjajo na možne kontaminacije. Za ugotavljanje mikrobiološkega tveganja za vode uporabljamo na-

already reported: bacteria, cyanobacteria and microalgae, fungi and protozoa (*Mulec* 2008). In that review on microorganisms in hypogeon from the Slovenian karst caves 16 different scientific publications were cited containing useful data on microorganisms and their diversity in the Slovenian caves. In addition to this list, at least three important publications have been recently published on underground microbial diversity from the Slovenian caves: about microbial communities in sediments from the Postojna cave (*Zakotnik* 2011), 16S rDNA diversity of bacteria from organic biofilm in the cave Pajsarjeva jama (*Pašić* et al. 2010) and microbial community of hind gut of the olm *Proteus anguinus* (*Avguštin* et al. 2010). The latter revealed the prevalence of bacteria from the phylum Firmicutes as the main component of gut bacteria in this troglobitic animal. With this and other studies many new questions have arisen and new horizons for research have been opened.

The biotechnological and bioremediation potential of cave inhabiting microorganisms in Slovenia are still not exploited enough. For example in the Carlsbad cavern (U.S.A) novel species of microorganisms that can degrade complex hazardous aromatic compounds, such as benzothiazole and benzenesulfonic acid, were isolated. Microbes can use these compounds involved in the manufacture of plastics as an energy source for their growth (*Barton* 2006). Slovenian karst caves offer great potential in many respects for cave microbiology. Future studies should go beyond the present taxonomical survey, in a direction of understanding the role of microbes in different processes. And here, the researchers should distinguish between microbes autochthonous for the underground, and alien microbiota which are naturally or artificially introduced into the underground. This point returns us to the initial observation: more basic studies are still needed to get a general idea of what can be expected in the underground on a microscale.

## 10.2 Applications of cave microbiology

Microorganisms are good indicators of the state of habitats. Environmental microbiology uses indislednje mikrobne skupine: vse koliforme (te bakterije navadno uvrščamo med indikatorje fekalne kontaminacije, čeprav nekateri njihovi predstavniki izhajajo iz naravnega okolja, ki niso prebavila), fekalne koliforme (termotolerantni coliformi, zlasti *Escherichia coli*), fekalne streptokoke, enterokoke in sulfitreducirajoče klostridije (*Pseudomonas* spp.) ter štetje celokupnih heterotrofnih bakterij na ploščah, ki nakazujejo splošno mikrobiološko stanje v nekem sistemu (*Toranzos* in *McFeters* 1997). Visoko število fekalnih koliformov (> 200 zraslih kolonij CFU/100 ml; CFU = *colony forming units*) v reki ali potoku nakazuje visoko verjetnost, da so navzoči tudi patogeni mikrobi. Čeprav so mikrobiološki pokazatelji v veliko pomoč pri določanju ravni onesnaženja, so popolnoma izključeni iz zakonodaje (glej evropsko direktivo o varstvu podzemne vode – *Directive 2006/118/EC*).

Transport in rokovanje z raziskovalno opremo za opravljanje mikrobiološkega monitoringa sta med ekspedicijami v podzemlje v veliko primerih neprikladna. Za ugotavljanje mikrobnega vpliva je pomembno uporabljati dovolj občutljiv postopek in robustne materiale. Celotni postopek naj bi vključeval ustrezne mikrobne indikatorske skupine, biti mora relativno preprost, da se lahko hitro in enostavno ponovi, in cenovno ugoden (*Mulec* 2010). Eden takšnih bioloških kitov (kompletov, ki vsebuje vse potrebno za izvedbo določene analize) je bil že uspešno testiran v slovenskih in slovaških jamah (*Mulec* idr. 2010, 2012). Čeprav je specifičnost tovrstnih komercialnih kitov zelo dobra, njihova občutljivost še vedno zahteva določen razmislek. Zaradi tega so taki kompleti uporabni le v jamah z visokim vnosom organskih snovi, bodisi s potoki, turisti, kolonijami netopirjev ali kakršnimkoli drugim vnosom iz jamske okolice.

Druga pomembna aplikacija jamske mikrobiologije je zelo pomembna za upravitelje turističnih jam. Dandanes si je masovni turizem v jamah praktično nemogoče predstavljati brez osvetljevanja kapnikov in drugih podzemeljskih zanimivosti. Kot rezultat osvetljevanja pa se okoli svetil v jamah razvije združba fototrofnih organizmov. Ta kompleksna združba, ki jo imenujemo lampenflora, se razvije na mestih, kjer se v normalnih okoliščinah drugače ne bi. Lampenflora je običajno močno pritrjena na substrat in je posledično

cator organisms as a criterion for water quality and as a warning of possible contamination. The following microbial groups are used to determine the microbiological safety of water: total coliforms (these bacteria are classically used as indicators of faecal contamination although some members of this group can originate from nonenteric environments), faecal coliforms (thermotolerant coliforms, particularly *Escherichia coli*), faecal streptococci and enterococci, sulphite-reducing clostridia (*Pseudomonas* spp.), and heterotrophic plate counts that indicate the overall microbiological status of the system (*Toranzos* and *McFeters* 1997). A high number of faecal coliforms (> 200 colony forming units, CFU/100 ml; in a river or stream indicates a high probability of the presence of pathogenic microbes. Although microbiological indicators are a great help to determine the level of pollution, they are completely excluded from legislation (see the European groundwater directive—*Directive 2006/118 EC*).

Transport and handling of the research equipment during expeditions to monitor microbiological conditions in the underground is many times inconvenient. For microbial impact assessment it is important to adopt a sensitive procedure and robust materials. The procedure should include appropriate microbial indicator groups, and it should be fast and easy, reproducible and cost-efficient (*Mulec* 2010). One such microbiological kit has been already tested in the Slovenian and Slovakian caves (*Mulec* et al. 2010, 2012). Although specificity of such commercial kits is very good, sensitivity is still an important issue; that is why such kits can be effectively used only in caves which have high organic input from water streams, tourists, roosting bat colonies or terrestrial surroundings.

Another important application of cave microbiology is extremely important for managers of show caves. Mass tourism in caves today is impossible without illumination of cave formations and other underground phenomena. As a result of lighting around lamps in caves a community of phototrophs develops. This complex community, named lampenflora, grows at sites where under natural circumstances it would not appear. Lampenflora are usually strongly adhered to the substratum and are consequently responsible for tudi odgovorna za njegovo propadanje (*Cañaveras* idr. 2001; *Mulec* in *Kosi* 2009). Čeprav lampenfloro v nekaterih jamah predstavljajo kot turistično atrakcijo, npr. v jami Natural Bridge caverns (Teksas, ZDA), je treba poudariti, da je ta združba organizmov rezultat svetlobne evtrofikacije podzemlja in razlog biološkega propadanja različnih substratov v podzemlju. Ta problematika je še zlasti aktualna v jamah s prazgodovinskimi poslikavami in zgodovinskimi podpisi. Jamski mikrobiologi lahko v takšnih primerih upraviteljem jam ponudijo izdatno pomoč in podporo.

Za upravitelje jam so zelo pomembne naslednje smernice za omejevanje rasti lampenflore: ustrezna namestitev svetil, napeljav in ohišij ter način osvetljevanja, čim krajši čas osvetljevanja posameznih sektorjev v jami, izogibanje osvetljevanju vlažnih površin ter površin, ki so prekrite s sedimenti in lahko dostopne turistom, ali območij v jamah z izrazitim prepihom, kapljajočo in mezečo vodo (*Mulec* in *Kosi* 2009). Poleg tega naj bi bili upravitelji jam seznanjeni z ekologijo organizmov lampenflore, kako jih ustrezno odstraniti iz jame in obenem ohraniti jamsko okolje neokrnjeno. Za uničevanje lampenflore in odstranitev zelene patine, ki jo daje obraslim površinam v jami, so pogosto v rabi belilna sredstva (npr. varekina) ali še bolj toksične kemične snovi. V Postojnski jami je bila za zatiranje lampenflore poskusno uporabljena 15-odstotna raztopina vodikovega peroksida (1). Predhodni rezultati govorijo v prid rabi te raztopine v jamah zaradi številnih razlogov (*Mulec* in *Glažar* 2011).

## 10.3 Vodni podzemeljski habitati

V podzemlju so različna vodna telesa, ki so zanimiva za mikrobiološke raziskave (*Mulec* idr. 2002; *Gerič Stare* idr. 2004). Nekatera izmed njih, npr. podzemeljske reke, nam lahko služijo za ugotovitev ravni onesnaženja oz. trofičnosti. V okviru dveletnega monitoringa, na primer, je pri nizkem pretoku (~ 0.6 $m^3/s$) na razdalji 9-kilometrskega podzemeljskega vodotoka skozi Postojnsko jamo med ponorom in izvirom delež koliformnih bakterij glede na celokupno število bakterij padel z razmerja 0,80 na 0,20 (*Mulec* idr. 2012). Seveda pa absolutne vrednosti

substratum deterioration (*Cañaveras* et al. 2001; *Mulec* and *Kosi* 2009). Although sometimes lampenflora is preserved as a tourist attraction, for example in Natural Bridge caverns (Texas, USA), it has to be stressed that this community is a result of light eutrophication and is a causative reason for biodeterioration of various types of substrata in the underground. This issue is extremely urgent in caves with prehistoric paintings or historic inscriptions. In these cases cave microbiologists can offer great help and support for cave management.

The following guidelines are important for cave management regarding restriction of lampenflora growth: appropriate installation of lamps, housings and modes of illumination; short-time lighting of individual sectors; avoidance of damp surfaces, places covered with sediments and areas easily accessible for tourists, as well as places with air currents, dripping and seeping water (*Mulec* and *Kosi* 2009). Besides they need to know the ecology of lampenflora organisms and how to remove it from caves in order to preserve the integrity of the underground environment. Many times bleach or even more toxic chemicals have been used to kill lampenflora and to remove the greenish patina from cave formations. Preliminary results in the Postojna cave showed using a 15 % solution of hydrogen peroxide to remove lampenflora (1) to be advantageous in many aspects (*Mulec* and *Glažar* 2011).

## 10.3 Water underground habitats

In the underground there are different water bodies which are interesting for microbiological studies (*Mulec* et al. 2002; *Gerič Stare* et al. 2004), and some of them, such as underground rivers, can serve also for determination of the level of pollution or trophic levels. For example, during the two-year monitoring period in the Postojna cave the ratio of coliform bacteria to total bacterial counts dropped from 0.80 to 0.20 at low discharge (~ 0.6 $m^3/s$) over the nine kilometres of the underground flow between the ponor and the spring (*Mulec* et al. 2012). Absolute numbers of microbial concentrations and comparisons between microbial groups are not only important to assess water mikrobnih koncentracij in primerjave med posameznimi mikrobnimi skupinami niso pomembne le za ugotavljanje kakovosti vode (*Toranzos* in *McFeters* 1997), marveč omogočajo tudi vpogled v ekološke interakcije vzdolž gradienta podzemeljskega toka reke.

V popolni temi so kompleksni ekosistemi osnovani tudi na energiji in hranilih, ki jih zagotavljajo mikrobi v kemosinteznih reakcijah. Več teh ekosistemov temelji na energijskih pretvorbah žveplovih molekul, ki so v podzemeljski vodi lahko v visokih koncentracijah. Veliko podzemeljskih habitatov je zaradi popolne teme, omejenosti hranil ipd. precej stresno okolje za organizme. V primeru žveplenih habitatov morajo organizmi tolerirati in se prilagoditi še na dodaten stres, ki ga predstavljajo toksične koncentracije plinov, izredno nizka koncentracija kisika ali celo njegova popolna odsotnost (*Engel* 2007).

Za boljše razumevanje vloge mikrobov in tudi višje razvitih organizmov v vodonosniku potrebujemo več podatkov. Ena izmed posledic primarne produkcije, temelječe na kemolitoavtotrofiji v žveplenih (sulphidic) okoljih, je povišanje organskega ogljika, tako v kvalitativnem kot kvantitativnem smislu. Ta izdatni vir prehrane bi lahko imel značilen vpliv na biodiverziteto (*Engel* 2007). Idealno okno za vpogled v tovrstne habitate predstavljajo na krasu žvepleni izviri.

quality (*Toranzos* and *McFeters* 1997) but also to get an insight into ecological interactions along the gradient of the underground river flow.

In complete darkness, complex ecosystems can be sustained by energy and nutrients provided by chemosynthetic microbes. Many of these ecosystems result from microbial manipulation of energy-rich sulphur compounds that can be found in high concentrations in groundwater. Subsurface environments in general can be highly stressful habitats for organisms because of, for example, darkness and limited food, but in the case of sulphidic groundwater habitats, organisms must also tolerate and adapt to different stresses, such as toxic levels of gases or extremely low concentrations of oxygen or its absence (*Engel* 2007).

Nevertheless, more data are needed to understand the roles of both karst aquifer microbes and higher organisms. One of the consequences of chemolithoautotrophic primary productivity in sulphidic systems is an increase in the quality and quantity of organic carbon. This rich food source may have a significant impact on biodiversity (*Engel* 2007). An ideal window into such habitats are terrestrial sulphidic springs in karst areas.

In Slovenia, the sulphidic spring Žveplenica in Dolenja Trebuša is an ideal site to investigate biological diversity (2). The dominant groups in the spring are


**1** Odstranjevanje lampenflore v Postojnski jami: A – pred aplikacijo vodikovega peroksida v Lepih jamah, B – po aplikaciji vodikovega peroksida (foto S. Glažar).
Removal of lampenflora in Postojna cave: A – before application of hydrogen peroxide solution in the section named Lepe jame, B – after application of hydrogen peroxide (photo S. Glažar).

**2** Vzorčenje vode neposredno iz odprtine žveplenega izvira v dolini Trebuščice za analizo koncentracije vodikovega sulfida (foto J. Turk).
Sampling of water directly from the orifice for analysing the concentration of hydrogen sulphide from a sulphidic spring in the Trebuščica valley (photo J. Turk).

**3** Glive iz zraka Postojnske jame (Rdeča dvorana, 6. septembra 2009) na gojišču DRBC (dikloran-rozbengal kloramfenikol) po inokulaciji (impakciji) 1 $m^3$ zraka.
Airborne fungi on DRBC (Dichloran Rose-Bengal Chloramphenicol) agar after impaction of 1 $m^3$ of air in the Postojna cave (Rdeča dvorana, 6 September 2009).

V Sloveniji je v Dolenji Trebuši žvepleni izvir Žveplenica idealen kraj za preučevanje biološke pestrosti (2). Prevladujoča skupina v izviru so gamaproteobakterije, natančneje rod *Thiothrix* spp. Manj številčne bakterijske skupine so bolj raznovrstne, vendar večinoma pripadajo Epsilon- in Deltaproteobakterijam, Firmicutes in Bacteroidetes. Poleg mikrobne diverzitete velja omeniti tudi navzočnost petih različnih taksonomskih skupin nevretenčarjev v izviru in lužici v neposredni bližini izvira. Te skupine so: Annelida-Oligochaeta, Mollusca-Gastropoda, Crustacea-Copepoda, Crustacea-Brachiopoda in Insecta-Trichoptera. Kopepodi so bili najbolj množična skupina v izviru, saj so sestavljali kar 84 % vseh osebkov (*Oarga* idr. 2010).

## 10.4 Aerobiologija v jamah

Zrak je pomemben habitat za mikroorganizme, vmesna stopnja pri njihovem širjenju in razmnoževanju. Preučevanje mikrobov v zraku in vpliva atmosferskih parametrov na njihovo porazdelitev, sezonsko variabilnost in koncentracijo lahko študiramo tudi v jamah. Poleg tega bi lahko jame predstavljale 'modelno okolje' za študij tovrstnih interakcij.

Vpliv bioloških delcev v jamskem zraku, ki so posledica masovnega turizma, še ni bil dovolj natančno opredeljen. Preučevanje zraka v Postojnski jami je vključevalo naslednje parametre: merjenje temperature, relativne vlažnosti, $CO_2$, zračnega pritiska, koncentracije celokupnega prahu in koncentracije DNA, poleg tega pa še gojenje atmosferskih mikrobov na specifičnih gojiščih za bakterije, glive, alge in amebe (3). Največjo variabilnost atmosferskih parametrov v jamskem zraku lahko pripišemo $CO_2$ in prahu, in sicer trikrat oziroma dvakrat višjo koncentracijo v poletnem obdobju glede na zimski čas. V primerjavi s številom gliv v zraku (40–195 CFU/m$^3$) je bilo v jamskem sistemu celotno število bakterij v zraku bolj stabilno skozi vse leto (34–41 CFU/m$^3$).

Postojnska jama je svetovno znana turistična jama (~ 500.000 obiskovalcev letno). V delu, ki je najbolj obremenjen s turističnim obiskom, turisti pustijo svoj 'odtis', ki se kaže v relativno višjih koncentracijah celokupnih bakterij v zraku, v primerjavi s podobnimi neturističnimi deli jame (*Mulec* in *Walochnik* 2010).

affiliated with the Gammaproteobacteria, specifically *Thiothrix* spp. Minor bacterial groups are highly diverse, but predominantly associated with Epsilon- and Deltaproteobacteria, Firmicutes, and Bacteroidetes. Beside microbial diversity, five different invertebrate taxonomic groups were identified from the spring and a pool in the immediate vicinity of the spring orifice. These groups are: Annelida-Oligochaeta, Mollusca-Gastropoda, Crustacea-Copepoda, Crustacea-Brachiopoda, and Insecta-Trichoptera. Copepods were the most abundant group recovered from the spring discharge representing 84 % of the total number of individuals (*Oarga* et al. 2010).

## 10.4 Aerobiology in caves

Air represents an important habitat and intermediate stage in propagation and distribution of microorganisms. Airborne microbes and influences of atmospheric parameters on their distribution, seasonal variability and counts can be studied in caves. Furthermore, caves may even represent a 'model environment' to study these interactions.

The influence of airborne biological particles introduced into a cave as a consequence of mass tourism has not been studied enough in detail. The study of cave air in the Postojna cave included measurement of temperature, relative humidity, $CO_2$, air pressure, total dust concentration, DNA concentration, and cultivation of airborne microbes (3) on group-specific media (bacteria, fungi, algae, amoebae). In the cave atmosphere, the highest variations in atmospheric parameters were observed for $CO_2$ and dust concentrations, three times and two times higher in the summer than in the winter period, respectively. Inside the cave system bacterial viable counts were more stable throughout the year (34–41 CFU/m$^3$) compared to airborne fungi (40–195 CFU/m$^3$).

As the Postojna cave is famous for mass cave tourism (~ 500,000 tourists annually), in the part which is most affected by tourism, tourists leave their 'print' by relatively higher bacterial counts compared to other similar but non-tourist parts of the cave (*Mulec* and *Walochnik* 2010). In smaller wild caves with little or no air mixing weak negative correlations ($0.05 < p < 0.1$)

V manjših, neturističnih jamah, kjer znotraj njih le delno prihaja do mešanja zračnih mas ali pa sploh ne, smo zabeležili šibko negativno korelacijo ($0,05 < p < 0,1$) med številom mikrobov v zraku in temperaturo (*Mulec* idr. 2010).

Zaradi navzočnosti patogenih mikroorganizmov predstavlja zrak v jamah včasih določeno tveganje za ljudi. Najbolj znan in najnevarnejši mikrob, ki se prenaša preko zraka v jamah, je gliva *Histoplasma capsulatum* (*Richardson* in *Warnock* 2003). Precejšnje tveganje za okužbo z njo pomeni zadrževanje v endemskem področju. Na splošno so jame zmernega klimatskega pasu v Evropi varne za jamarje in raziskovalce, vendar je izolacija omenjene glive iz jame Topolniţa v Romuniji z zmerno jamsko temperaturo (*Alteras* 1966) odprla možnost, da lahko nanjo naletimo tudi v drugih jamah v regiji. Na žalost pa od takrat dalje v zvezi s pojavom te glive v jamah še ni bila izpeljana nobena izčrpna študija na panevropski ravni. Prav zaradi tega ostaja vprašanje o popolni biološki varnosti za jamarje z vidika histoplazme v Evropi še vedno odprto (*Borda* idr. 2010).

## 10.5 Jamski sedimenti

Sedimenti iz slovenskih jam vsebujejo številne uporabne informacije o preteklih klimatskih, paleogeografskih in tektonskih spremembah ali za rekonstrukcijo evolucije krasa (*Zupan Hajna* idr. 2008). Rov v Postojnski jami, imenovan Spodnji Tartarus, povezuje zgornjo jamsko z aktivno spodaj ležečo etažo. Tla so v spodnji etaži prekrita z mlajšimi sivimi fluvialnimi sedimeti in občasno poplavljena. Sedimenti v stranskem rovu Spodnjega Tartarusa, imenovanem Rov koalicije, so bili deloma izprani, vendar je v osrednjem delu tega rova kljub temu ostala 13-metrska kopa sedimentov (*Zupan Hajna* idr. 2008). S te kope je bilo v vertikalni razdalji 11 m opravljeno vzorčenje za mikrobiološke analize. Rezultati kažejo visoko konsistenco in kompleksno strukturirane mikrobne združbe v sedimentih različnih starosti. Prevladujoče skupine bakterij so pripadale deblu Proteobacteria, ostale manj številčne pa so: Acidobacteria, Actinobacteria, Planctomycetes, Chloroflexi, Firmicutes, Bacteroidetes, Verrucomicrobia, Gemmatimonadetes in Nitrospira. S staranjem

were observed between airborne microbial count and temperature (*Mulec* et al. 2010).

Sometimes air in caves is hazardous for humans because of the presence of pathogenic microorganisms. The most known and very dangerous air-transmitted microbe in caves is the fungus *Histoplasma capsulatum* (*Richardson* and *Warnock* 2003) which represents a reasonable risk when venturing into endemic areas. Generally, European temperate caves have been considered safe for caving and exploration; on the other side, isolation of this fungus from bat guano from the Topolniţa cave in Romania (*Alteras* 1966) with a moderate cave climate opened the potential to find this fungus also in other caves in the region. Unfortunately, since then no comprehensive study on a pan-European level has been conducted on occurrence of histoplasma which is why the question on complete biosafety of caving in Europe remains open (*Borda* et al. 2010).

## 10.5 Cave sediments

Sediments from the Slovenian caves contain much useful information on past climatic, paleogeographic and tectonic changes and for reconstruction of evolution of karst (*Zupan Hajna* et al. 2008). In the Postojna cave the passage named Spodnji Tartarus connects the upper cave level to the lower active one. In the lower part its floor is covered with young grey fluvial sediments and is intermittently flooded. The sediments in the side passage of Spodnji Tartarus, named Rov koalicije, were partly washed out, leaving a 13 m long pile of sediments in the central part of the passage (*Zupan Hajna* et al. 2008). From this pile of cave sediments over a vertical distance of 11 m the sediments were sampled for microbiological analyses. The results show highly consistent but complex microbial community structure in the sediments of varying age. The dominant bacterial groups were affiliated with Proteobacteria and minor groups with Acidobacteria, Actinobacteria, Planctomycetes, Chloroflexi, Firmicutes, Bacteroidetes, Verrucomicrobia, Gemmatimonadetes and Nitrospira. A highly sedimentage related decrease in microbial activity was observed (*Zakotnik* 2011; *Zakotnik* et al. 2010).

**4** Kup gvana v Škocjanskih jamah (Tiha jama, 23. junija 2009). Zaradi namestitve osvetlitve v sezoni 1975/76 so netopirji na tem mestu prenehali tvoriti kolonijo (foto B. Peric).
Guano heap in the Škocjan caves (Tiha jama, 23 June 2009). Due to installation of lighting in that part of the cave in the season 1975/76 bats stopped roosting at that site (photo B. Peric).

sedimenta prihaja namreč do upada mikrobne aktivnosti (*Zakotnik* 2011; *Zakotnik* idr. 2010).

## 10.6 Gvano netopirjev

Ogljik se s površja vnaša v jame raztopljen v kapljajoči vodi, poplavnih pulzih, potokih, z zračnimi tokovi in gravitacijsko ter z vstopanjem površinskih živali (*Culver* in *Pipan* 2009). V nekaterih jamah so navzoči številni netopirji, ki vnašajo velike količine organskih snovi tudi s svojimi iztrebki.

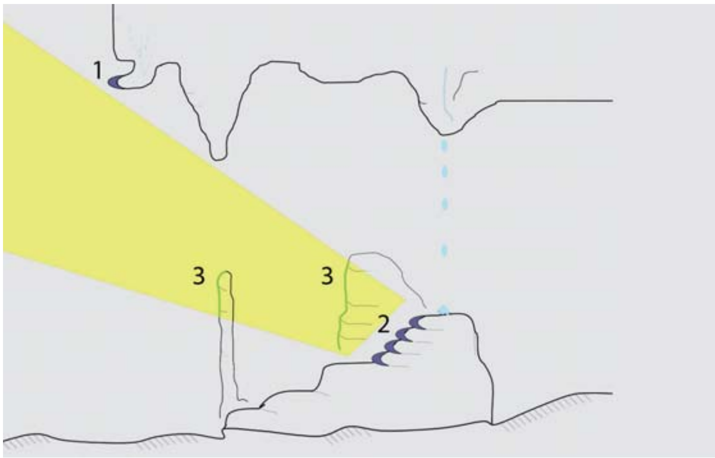
Gvano netopirjev je poseben terestični habitat in eden najpomembnejših virov hranil za jamske nevretenčarje. O njegovi ekologiji in mineralizaciji imamo še vedno precej malo podatkov. Nedavne raziskave Inštituta za biologijo tal Akademije znanosti Češke republike so pokazale, da ima gvano iz jame Domica na Slovaškem pestro združbo, je zelo kisel (pH ~ 3.0), poleg tega vsebuje tudi visoke koncentracije težkih kovin. Ker gvano vsebuje tudi veliko ohranjenega organskega materiala, bi lahko pomagal pri rekonstrukciji preteklega stanja v okolju (*Chroňáková* idr. 2009; *Krištůfek* idr. 2008; *Krištůfek* idr. 2010). Gvano netopirjev iz dveh slovenskih jam, Škocjanskih jam in Predjame

## 10.6 Bat guano

Carbon enters caves from the surface along with percolating water, flooding, streams, air currents and gravitation and with the active visits of epigean animals (*Culver* and *Pipan* 2009). Some caves are populated by large numbers of bats, providing a great amount of organic matter through their droppings.

Bat guano is a special terrestrial habitat and one of the most important sources of nutrients for cave invertebrates; however, the data on its ecology and mineralization are still poor. Recent studies from the Institute of Soil Biology of the Academy of Sciences of the Czech Republic showed that bat guano from their research site in the Domica cave (Slovakia) contained a diverse archaeal community, was highly acidic (pH ~ 3.0), contained high concentrations of heavy metals, and due to preserved organic material could be used to reconstruct past environment (*Chroňáková* et al. 2009; *Krištůfek* et al. 2008, 2010). Bat guano from two Slovenian caves, Škocjan caves/Škocjanske jame and Predjama cave (4), was used as reference material for guano from the Domica cave. Concentrations of some heavy metals in guano samples from Slovenia

**5** Shematska predstavitev epilitskih fototrofov v Schmidlovi dvorani v Škocjanskih jamah. Prim. med biogenimi karbonatnimi strukturami (vijolično) v obliki stalaktitov (1) in stromatolitnih stalagmitov (2) ter epilitsko obrastjo (zeleno) fototrofov (3).
Schematic representation of epilithic phototrophs in the Škocjan caves, Schmidlova dvorana. Note the difference between biogenic carbonate deposits (purple) as stalactitic tufa (1) or stromatolitic stalagmites (2) and epilithic growth (green) of phototrophs (3).




(4), smo uporabili kot referenčni material za gvano iz jame Domica. Koncentracije nekaterih težkih kovin v gvanu slovenskih jam so presegale mejne vrednosti, ki so v EU dovoljene za kmetijske površine (*Directive 86/278 EEC*), in sicer kadmij tri- do štirikrat, baker dva- do šestkrat in cink štirikrat (*Krištůfek* idr. 2010).

## 10.7 Lehnjakovi depoziti

Siga in kapniki so najbolj razširjene in značilne jamske oblike in za večino od njih velja, da so anorganskega nastanka. Veliko karbonatnih tvorb je tesno povezanih z živimi organizmi, njihovo navzočnostjo ali biokemijsko aktivnostjo: nekatere sigove tvorbe in kapniki, določene podvodne strukture, druge pastozne strukture (npr. jamsko mleko), kalcificirane korenine, kalcificirani mahovi in druge rastline, stalaktitni lehnjaki, stromatolitni kapniki in serpulidne tvorbe (*Taboroši* 2006).

Ena najbolj zanimivih karbonatnih struktur, katere nastanek je povezan z biološko aktivnostjo, so stromatolitni stalagmiti v vhodih jam, ki jih osvetljuje sončna svetloba. Njihova površina je prekrita s slojem cianobakterij. Mehanizem nastanka teh nenavadnih struktur vključuje rast cianobakterij, ki iz kapljajoče podzemeljske vode fiksirajo ogljikov dioksid, in odlaganje eolskega sedimenta (*Cox* idr. 1989; *James* idr. 1994). V Sloveniji lahko stromatolitne stalagmite najlepše opazujemo v vhodnem delu Škocjanskih jam, imenovanem Schmidlova dvorana (5). V združbi alg stromatolitnih stalagmitov smo identificirali 35

exceeded EU limits for agricultural soils (Directive on sewage sludge—*Directive 86/278 EEC*): Cd 3–4 times; Cu 2–6 times; and Zn 4 times (*Krištůfek* et al. 2010).

## 10.7 Tufaceous deposits

Carbonate speleothems are the most widespread and typical cave deposits, and most of them are considered to be of inorganic origin. However, many carbonate formations are linked to living organisms, their presence or biochemical activity: certain dripstones and flowstones, certain subaqueous speleothems, pasty speleothems (e.g. moonmilk), calcified roots, calcified mosses and plants, stalactitic tufa, stromatolitic speleothems, and serpulid speleothems (*Taboroši* 2006).

One of the most interesting biologically-induced carbonate speleothems are stromatolitic stalagmites in cave entrances illuminated by sunlight. They are covered by superficial coatings of cyanobacteria. Cyanobacterial growth and their removal of carbon dioxide from dripping groundwater combined with eolian detritus have been demonstrated to be a mechanism for growth of these unusual speleothems (*Cox* et al. 1989; *James* et al. 1994). In Slovenia stromatolitic stalagmites can be best observed in the entrance part of the Škocjan caves, in Schmidlova dvorana (5). In the algal community of these stromatolitic stalagmites 35 taxa were identified with a low portion of coccoid cyanobacteria and taxa such as *Calothrix* sp., *Homoeothrix* sp. and *Schizothrix* sp. (*Mulec* et al. 2007). In this complex community of phototrophic organisms taksonov z nizkim deležem kokoidnih cianobakterij in taksone, kot so *Calothrix* sp., *Homoeothrix* sp. in *Schizothrix* sp. (*Mulec* idr. 2007). V tej kompleksni združbi fototrofnih organizmov je bila prvič opisana tudi vahlkampfiidska ameba *Allovahlkampfia spelaea* gen. nov., sp. nov. Prostoživeče amebe so pogoste tudi v drugih habitatih v kraških jamah, kjer prihaja do odlaganja karbonata (*Walochnik* in *Mulec* 2009).

## Sklep

V tem prispevku so povzeti rezultati številnih projektov, ki obravnavajo jamske mikroorganizme ter so bili večinoma opravljeni na Inštitutu za raziskovanje krasa ZRC SAZU in z zunanjimi sodelavci. Kot je razvidno, je v podzemlju več ekološko zanimivih niš, ki jih kolonizirajo različni mikroorganizmi. Ta 'inventarizacijski pregled' je pravzaprav šele začetek poglobljenih raziskav s področja jamske mikrobiologije v Sloveniji, ki naj bi se v prihodnosti usmerile v biogeokemijske cikle, pretok energije, nastajanje mineralov in interakcije mikroorganizmov z ostalimi elementi ekosistema. Na drugi strani pa mikrobni indikatorji kažejo na človekov vpliv, ki se zrcali v podzemlju. S tega vidika je pomembno, da okoljsko mikrobiologijo z vsemi njenimi aspekti aktivneje vključimo v upravljanje jam, ugotavljanje kvalitete voda in ne nazadnje v celostno varovanje krasa.

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a new vahlkampfiid amoeba *Allovahlkampfia spelaea* gen. nov., sp. nov. was described. Furthermore, free-living amoebae were frequently identified in various carbonate precipitating habitats in karst caves (*Walochnik* and *Mulec* 2009).

## Conclusion

In this review various projects dealing with cave microorganisms are summarized, which were mostly accomplished at the Karst Research Institute at ZRC SAZU in collaboration with external partners. As one can see, in the hypogeon there are many interesting ecological niches colonized by various microorganisms. This 'inventory review' is a starting point to go deeper into the research of cave microbiology in Slovenia, aspects of which should include biogeochemical cycles, energy fluxes, mineral formations and interactions with other elements of the ecosystem. On the other hand, microbial indicators show human impact in the karst underground, which is why it is important to include environmental microbiology with all its aspects for cave management, water quality assessment and karst protection.

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# ZAŠČITA POVRŠJA IN PODZEMLJA

# SURFACE AND UNDERGROUND PROTECTION

# 11

# ZAŠČITA KRASA

# KARST PROTECTION

Kraške pokrajine so manj primerne za človekovo poselitev (*Gams* 2004). Zaradi neugodnih naravnih razmer (razgiban relief, plitva prst, odsotnost vodotokov) so možnosti za poljedelstvo slabe. Zato so z izjemo matičnega Krasa in Suhe krajine kraške planote redko naseljene, gozdnate, a gosto prepredene s pomembnimi prometnimi potmi. Prebivalstvo je zgoščeno na dnu kraških polj in dolin, kjer so možnosti poljedelstva nekoliko boljše, vendar so obdelovalne površine izpostavljene poplavam. Kljub poplavni ogroženosti na dnu kraških polj in dolin ter na območjih kontaktnega krasa prihaja tam do zgostitve ekstenzivnih agrarnih in industrijskih dejavnosti. Poleg tega je kras s svojimi posebnostmi privlačen tudi za turiste.

V zadnjih letih pa različne dejavnosti kot posledica vsestranskega ekonomskega in urbanega razvoja povečujejo pritiske na kraške pokrajine. Na nekaterih območjih industrijska dejavnost, nekontrolirana poselitev in širjenje infrastrukture, razvoj turizma in intenzivna kmetijska raba vse bolj ogrožajo tako kraško površje kot podzemlje, čeprav je po drugi strani na krasu marsikje še vedno prisotno tudi opuščanje rabe kmetijskih zemljišč.

## 11.1 Zakonodajni okviri

Okoljevarstveni ukrepi za ohranitev kraške pokrajine in njenih elementov so skopi. Krovni zakon, ki je vzpostavil temelje za trajnostni razvoj v prostoru, je Zakon o varstvu okolja (*ZVO-1*, 2004) z dopolnitvami. Preprečuje pretirano obremenjevanje okolja, omogoča njegovo dolgoročno ohranjanje in ohranjanje biotske raznovrstnosti. Ne vključuje pa natančnejših določil za varovanje kraških pokrajin in kraških pojavov, čeprav je kras eden izmed najznačilnejših pokrajinskih tipov pri nas, v svetovnem merilu pa veljajo slovenske kraške pokrajine za klasične.

Z uveljavitvijo Zakona o prostorskem načrtovanju (*ZPN*, 2007) se za posege v prostor predvideva predhodno vrednotenje vplivov na okolje, ki so obvezni del okoljskih poročil. Na podlagi teh so sprejeti državni in občinski prostorski načrti, ki določajo prostorske ureditve. Po predpisih o graditvi objektov (Zakon o graditvi objektov – *ZGO-1*, 2002) je občinski prostorski

Karst landscapes are less suitable for human settlement (*Gams* 2004). Owing to unfavourable natural conditions (variegated relief, shallow soil, absence of watercourses), the prospects for agriculture are rather poor. With the exception of the Kras and Suha krajina regions, karst plateaus are scarcely populated and wooded but densely criss-crossed by major traffic routes. Densely populated settlements are found at the bottoms of karst poljes and valleys. These offer somewhat better conditions for agriculture although the arable land is exposed to flooding. Despite the flood risk, extensive agrarian and industrial activity is concentrated at the bottoms of karst poljes and valleys and in areas of contact karst. The special features of karst regions make them attractive for tourism, too.

In recent years, a variety of activities resulting from comprehensive economic and urban development have increased pressure on karst landscapes. In some areas the surface and the underground are increasingly threatened by industrial activities, uncontrolled settlement and spread of infrastructure, development of tourism, and intensive agrarian land use even though in many places agriculture continues to be abandoned on karst land.

## 11.1 Legislative framework

Environmental protection measures for preservation of karst landscapes and its elements are limited. The Environment Protection Act (*ZVO-1*, 2004) and its supplements comprise umbrella legislation that establishes foundations for sustainable development. It prevents excessive human impacts on the environment, enables its long-term preservation, and maintains biodiversity. It does not, however, include specific provisions for protection of karst phenomena, even though karst is one of the most characteristic landscape types in Slovenia and Slovenian karst landscapes are considered as being the areas of 'classical karst' around the world.

Relative to encroachments on space, implementation of the Spatial Planning Act (*ZPN*, 2007) requires advance environmental impact studies that are a compulsory part of environmental reports. National načrt osnova za pripravo projekta za pridobitev gradbenega dovoljenja. S tem sta pristojnost za določanje rabe prostora in skrb za ohranjanje narave in prepoznavnih značilnosti prostora preneseni na raven posameznih občin. Ohranjanje kraških pojavov in oblik ter varovanje podzemlja in voda tako ni več celovito, saj se mnoga kraška območja raztezajo prek več občin. Znotraj vsakih občinskih meja pa veljajo drugačna merila, saj se interesi in prioritete posameznih občin pogosto razlikujejo ter so nemalokrat podvrženi pritiskom zasebnega kapitala in županskim lobijem.

V primeru občin s kraško pokrajino je zelo pomembno načelo ohranjanje prepoznavnih značilnosti prostora in preprečevanje ekstremnih posegov v prostor (Odlok o strategiji prostorskega razvoja Slovenije – *OdSPRS*, 2004), ki je pri pripravi prostorskih načrtov le malokrat upoštevano. Poleg tega je pomembno še načelo usmerjanja prostorskega razvoja v naselja, ki usmerja novogradnje znotraj obstoječih naselij, izven pa le takrat, ko v naseljih ni več prostora. S tem se preprečujeta razpršena gradnja in uničenje kraške pokrajine. Številni primeri v praksi, ki so predstavljeni v naslednjem poglavju, pa kažejo na brezbrižnost načrtovalcev prostora do omenjenih načel.

Naravne vrednote pri nas varuje tudi Zakon o ohranjanju narave (*ZON*, 1999). Kraške reliefne oblike so z njim zavarovane le izjemoma kot naravna dediščina ali v okviru zavarovanih območij (narodnega, regijskih ali krajinskih parkov). Posamezni površinski in podzemni kraški pojavi, podzemne jame, izviri ipd. morajo za zavarovanje pridobiti status naravne vrednote, medtem ko zakon posebnih varstvenih režimov za kras kot celoto ne vključuje. Predvideva pa ohranjanje naravne pokrajine, ki je pomembna za ohranjanje biotske pestrosti.

Obsežna sklenjena območja krasa so tako zavarovana v okviru Triglavskega narodnega parka, Notranjskega in Kozjanskega regijskega parka, regijskega parka Škocjanske jame ter 21 krajinskih parkov. Skupna površina zavarovanih območij na krasu obsega 14 % krasa v Sloveniji. V okviru teh zavarovanih območij so zavarovane tudi jame in vodni viri (*Kepa* 2001; *Breg* 2007b).

Varstvo in urejanje podzemlja ureja Zakon o varstvu podzemnih jam (*ZVPJ*, 2004). Kot edinstveni

and municipal spatial plans that determine spatial arrangements are adopted on the basis of these reports. According to the provisions on building construction in the Construction Act (*ZGO-1*, 2002), the municipal spatial plans are the basis for obtaining construction permits. The competence for determining land use and responsibility for the conservation of nature and the recognizable characteristics of the space is thus transferred to the level of individual municipalities. Consequently, the preservation of karst phenomena and forms and the protection of the underground and waters are not consistent because many karst areas stretch across several municipalities. Different measures apply in different municipalities because they do not always share the same interests and priorities and are often subjected to pressures from capital and other local interest groups.

The principle of preserving recognizable spatial characteristics and preventing extreme encroachments on space—Ordinance on Spatial Planning Strategy of Slovenia (*OdSPRS*, 2004) is very important for municipalities with karst areas, but this principle is rarely considered in the preparation of spatial plans. The principle of focusing spatial development within settlements is equally important. It orients new construction inside existing settlements and outside them only when all the available space is occupied. This measure prevents the spread of construction and destruction of the karst landscape. However, a number of examples presented in the next chapter demonstrate that spatial planners are indifferent to these principles.

In Slovenia valuable natural heritage is protected by the Nature Conservation Act (*ZON*, 1999). This act only exceptionally protects karst relief forms as natural heritage or in the framework of protected areas (national, regional, or landscape parks). Protection measures apply only if individual surface and underground karst features, caves, springs, and the like acquire the status of a natural asset and the act does not include special protection regimes for karst as a whole. However, it does foresee the conservation of natural landscapes which is important for preserving biotic diversity.

Extensive contiguous karst areas are protected in the framework of the Triglav National Park, the Notranjska and Kozjansko regional parks, Škocjan zakon na svetu predvideva rabo in upravljanje jam in jamskega inventarja ter določa varstvene režime za vse jame in jamski živi svet. Vsebuje določila za vstop in obnašanje v podzemlju in za varstvo jam pri gradnji objektov. Prepovedana je tudi čezmerna obremenitev podzemlja. Žal pa je zakon na tem področju precej ohlapen in ne predpisuje dovoljenih meril obremenjevanja. Varuje le znane dele jam in ne predvideva načrtovanja rabe tal na površju nad jamo, čeprav lahko ta bistveno vpliva na ohranjanje naravnega stanja v podzemlju (primer industrijske cone Risnik pri Divači neposredno nad podzemeljskim tokom Reke).

Postopki varovanja kraške podtalnice in vodnih virov so predpisani z Zakonom o vodah (*ZV-1*, 2002) in pripadajočimi podzakonskimi akti (Pravilnik o kriterijih za določitev vodovarstvenega območja – *PrKDVO*, 2004, in drugi). Vendar pa v njih posebnosti pretakanja vode v krasu, kot so vloga zaščitnih slojev, razvitost kraške mreže, spreminjanje zaledja v različnih hidroloških razmerah ipd., niso dovolj upoštevane (več o tem v poglavju »Prilagajanje slovenske zakonodaje posebnim značilnostim kraških vodonosnikov« v prvem delu knjige). Z ustreznim varovanjem kraške podtalnice pa bi posredno varovali tako edinstvene podzemeljske ekosisteme, kot se tudi izognili številnim neprimernim posegom na kraškem površju. V Sloveniji veliko pomembnih kraških vodnih virov (npr. Malenščica, Bistrica idr.) še ni primerno zavarovanih, zato je skladno z veljavno zakonodajo prostorsko načrtovanje na teh območjih še vedno prepuščeno lokalnim oblastem, čeprav so kraški vodni viri strateški državni naravni vir in je njihovo varovanje zakonsko pod državnim okriljem (*Ravbar* in *Kovačič* 2006).

## 11.2 Onesnaževanje in spreminjanje kraške pokrajine

Kraška območja imajo velik pomen kot naravna vrednota, velik ekonomski pomen in so unikatni ekosistemi z bogato biodiverziteto ne samo pri nas, temveč povsod po svetu (*Ford* in *Williams* 2007). Mnogi kraški vodni viri so strateškega pomena za lokalno ali regionalno oskrbo z vodo in pokrivajo skoraj polovico potreb po pitni vodi pri nas (*Lah* 1998; *Ravbar* 2007).

caves Regional Park, and 21 landscape parks. The total surface of protected karst areas covers 14 % of the karst in Slovenia. Caves and water resources located in these areas are protected in the framework of protected areas (*Kepa* 2001; *Breg* 2007b).

The protection and management of the underground is regulated by the Cave Protection Act (*ZVPJ*, 2004). Worldwide this is a unique act that governs the use and management of caves and the cave inventory and determines protection regimes for all caves and cave life forms. It contains provisions regarding access and behaviour in the underground and to protect caves during the construction of buildings. Excessive burdening of the underground is prohibited by law. Unfortunately, the law in this field is quite loose and does not specify standards. It only protects the known sections of caves and does not regulate land use planning on the surface above caves, even though this can have a significant impact on the preservation of natural conditions in the underground (the Risnik industrial zone near Divača, for example, is located directly above the underground course of the Reka river).

The procedures for the protection of karst groundwater and water sources are prescribed by the Waters Act (*ZV-1*, 2002) and related regulations—Rules on criteria for the designation of a water protection zone (*PrKDVO*, 2004) and others. However, the special features of water percolation in karst, such as the role of protective layers, the development of karst networks, changes in the catchment areas under different hydrological conditions, etc., are not given sufficient consideration (more about this in chapter »Adjustment of Slovene legislation to the special characteristics of karst aquifers« in the part of this book). The proper protection of karst groundwaters would indirectly protect unique underground ecosystems and provide protection against numerous unsuitable encroachments on the karst surface. Many important karst water sources in Slovenia (the Malenščica and Bistrica springs among others) have not yet been properly protected. In accordance with existing legislation, spatial planning in these areas is still left to the local authorities even though karst water resources are a strategic national natural resource and legally their protection is the responsibility of the state (*Ravbar* and *Kovačič* 2006).

Kras je bogat z gradbenim materialom, veliko vrednost ima tudi zaradi številnih naravnih znamenitosti, kot so jame, naravni mostovi, presihajoča jezera, udornice ipd.

Zaradi specifične strukture in procesov v kraških pokrajinah so te v primerjavi z drugimi izredno občutljive za onesnaženje in druge človekove posege. Kraške reliefne oblike na površju in v podzemlju ter kraški vodni viri se le počasi in težko obnavljajo. Če želimo ohraniti njihovo naravno vrednost, moramo z njimi primerno in previdno upravljati (*Kepa* 2001).

Najpogostejši onesnaževalci kraške pokrajine in njenih voda so komunalne in gospodinjske odpadne vode, izcedne vode iz divjih odlagališč odpadkov, industrijske odpadne vode in neprečiščene meteorne vode s prometnic in pozidanih površin. Kras ogroža tudi kmetijstvo, zlasti pretirana uporaba umetnih ali naravnih gnojil in zaščitnih sredstev, neurejeno odtekanje, skladiščenje in odvajanje iz kmetijskih obratov ter spremembe v rabi tal. Velika nevarnost za kraške vode in podzemlje so razlitja večjih količin nevarnih in strupenih snovi ob nesrečah. Občutljivost podzemnih voda na krasu se poveča tudi zaradi gradbenih del (npr. prometnice, industrijske in obrtne cone, kamno-

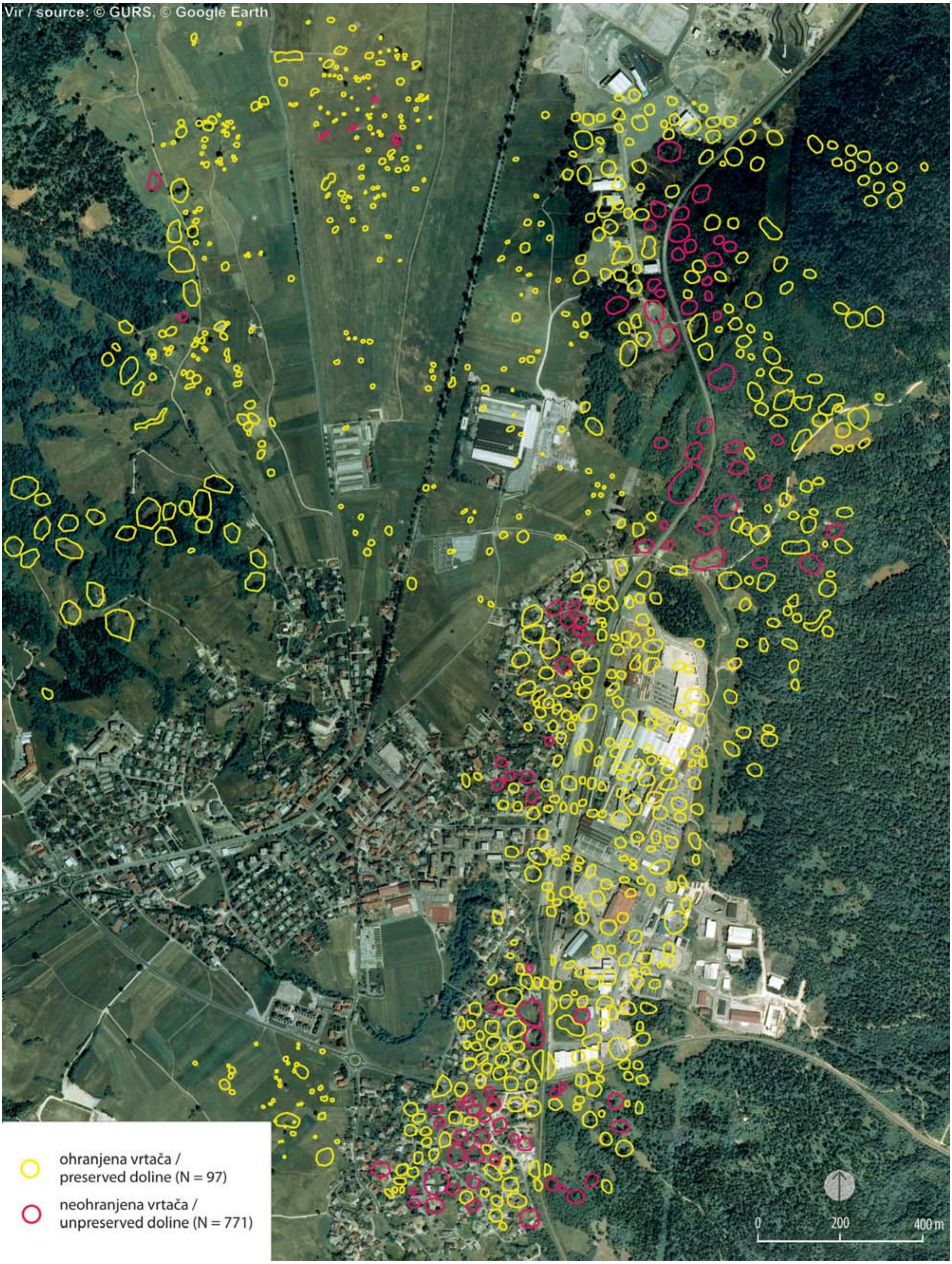
## 11.2 Pollution and changing of karst landscape

Karst areas have great importance as a natural asset, they are of major economic importance and unique ecosystems with rich biodiversity not only in Slovenia but around the world (*Ford* and *Williams* 2007). Many karst water resources are of strategic importance for local or regional water supplies and cover almost half the demand for drinking water in Slovenia (*Lah* 1998; *Ravbar* 2007). Karst areas are also rich with construction materials and have a great value as well due to their wealth of natural attractions such as caves, natural bridges, intermittent lakes, collapse dolines, etc.

Due to their specific structures and processes, karst landscapes are extremely vulnerable to pollution and other human impacts compared to other landscapes. Karst geomorphological features on the surface and underground and karst water resources take a long and difficult time to recover from damage. In order to preserve their natural value, they must be properly and carefully managed (*Kepa* 2001).

**1** Primer tradicionalne rabe tal v delani vrtači v okolici vasi Lokev na Krasu.
An example of traditional land use in a cultivated doline near the village Lokev in the Kras region.

**2** Uničene vrtače na Logaškem polju v obdobju med 1823 in 2005 (vir *Breg* 2007b).
Degradation of dolines in the Logaško polje in the period between 1823 and 2005 (source *Breg* 2007b).


Vir / source: © GURS, © Google Earth
ohranjena vrtača /
preserved doline (N = 97)
neohranjena vrtača /
unpreserved doline (N = 771)
0
200
400 m

lomi), kjer je pogosto odstranjena krovna, zaščitna plast vodonosnika. Problematično je tudi neprimerno vedenje obiskovalcev jam (npr. lomljenje kapnikov).

Zaradi nenadzorovanih človekovih posegov pa v kraških pokrajinah prihaja do vse pogostejše in obsežnejše degradacije kraških reliefnih oblik, ki je dosegla neobvladljiv razmah predvsem s tehnološkim razvojem in mehanizacijo.

Preoblikovanje in zasipavanje vrtač ter trebljenje kamenja (1), to so bile na krasu tradicionalne oblike prilagajanja pokrajine za kmetijsko rabo (*Mihevc* 2005). Mnogo vrtač pa je danes zasutih s smetmi in gradbenim materialom, kar ogroža kakovost vodnih zalog in obstoj edinstvenih habitatov. Sodobno čezmerno zasipavanje vrtač za izravnavo površja je postalo grob poseg v okolje, ki vpliva na obliko kraških pojavov in podobo pokrajine ter na intenzivnost kraških procesov (tj. korozije). Zelo nazoren primer spreminjanja tradicionalne rabe vrtač in njihove degradacije je Logaško polje (2), kjer je analiza Franciscejskega katastra iz leta 1823 in letalskih posnetkov v letih 1944 in 2000 pokazala, da je približno 89 % vrtač popolnoma izginilo zaradi zasutja z različnim materialom (*Breg* 2007a, b).

The most frequent polluters of the karst landscape and its waters are municipal and household waste water, water leaching from illegal dump sites, industrial waste waters, and untreated runoff from roads and built up areas. Karst is also threatened by agriculture, particularly by the excessive use of artificial or natural fertilizers and pesticides and unregulated runoff, storage, and dumping from agricultural activities, and changes of land use. Spills of larger amounts of hazardous and toxic substances in accidents present a great risk to karst waters and underground. Construction works in karst areas (e.g. roads, industrial zones, quarries) where the soil cover and protective layer of an aquifer is often removed increases vulnerability of groundwater. Inappropriate behaviour of cave visitors is another problem (e.g. breaking off of flowstone).

Unsupervised human encroachment on karst landscapes is causing the increasingly more frequent and more widespread degradation of karst relief forms. The intensive reshaping of the landscape has expanded beyond control largely as a result of technological development and mechanization.

**3** Primer zavarovanja na novo odkrite jame na avtocestnem odseku pri Divači.
An example of protection of a newly discovered cave at the expressway section near Divača.

**4** Gradnja dolenjske avtoceste in nove industrijske cone pri Mirni Peči (vir © *Google Earth*).
Construction of the Dolenjska highway and a new industrial zone near Mirna Peč (source © *Google Earth*).


N
2005
2010
Avtorja / authors: Kovačič & Ravbar 2011 Vir / source: © Google Earth
0 200 400 m

Med najbolj vidne posege v kraško površje v zadnjih letih sodita gradnja avtocest (3) in izgradnja industrijsko-obrtnih con. Z izkopom usekov, predorov in zasipavanjem vrtač ob gradnji avtocest prihaja do sprememb v podobi kraške pokrajine, izgradnja novih odsekov pa navadno pospeši tudi razvoj industrijsko-obrtnih con v manjših krajih. Poleg intenzivnega širjenja industrijske cone v Logatcu so bile v zadnjih letih zgrajene podobne cone še na Kozini, v Podskrajniku, Divači in pri Mirni Peči (4). Njihova postavitev na reliefno razgibanem in kamnitem kraškem površju pomeni uravnavanje površin, ki je možno le z zasipavanjem vrtač in odstranjevanjem robov med njimi ter njihovo pozidavo. Posegi bistveno spremenijo podobo pokrajine in povečajo tudi občutljivost območja na onesnaženje, čeprav so ob primerni ureditvi negativni vplivi na kakovost podzemlja (vode in ekosistemov) zelo majhni.

Izgradnja industrijske cone Risnik pri Divači in drugi posegi (npr. zidava stanovanjske soseske Risnik, vzpostavitev drugega tira železniške proge Divača–Koper), ki jih predvidevajo občinski in državni

In karst regions, cultivation of doline bottoms and clearing of stones (1) were traditional methods of adapting farming practices to the landscape (*Mihevc* 2005). Today, many dolines are filled with general and construction waste which threatens the quality of water supplies and the existence of unique habitats. The excessive modern filling of dolines for leveling purposes has become a major encroachment on the environment that has begun to affect the shape of karst features and the appearance of the landscape as well as the intensity of karst processes such as corrosion. Logaško polje is a very illustrative example of the change of traditional use of dolines and their degradation (2). An analysis of the Franciscan cadastre from 1823 and aerial photographs taken in 1944 and 2000 shows that almost 89 % of the dolines have completely disappeared due to filling with a variety of waste materials (*Breg* 2007a, b).

Among the most visible encroachments on karst surfaces in recent years is the construction of expressways (3) and industrial zones. The construction of expressways with the excavation of road cuts and tunnels and the filling of dolines result in changes to the

**5** Gradnja industrijske cone Risnik pri Divači (foto B. Peric).
Construction of the Risnik industrial zone near Divača (photo B. Peric).

**6** Prostorske spremembe pri Kozini v letih 2006 in 2009 (vira © *Geodetska uprava Republike Slovenije* 2009 in © *Google Earth*).
Spatial changes near Kozina in the years 2006 and 2009 (sources © *Surveying and Mapping Authority of the Republic of Slovenia* 2009, © *Google Earth*).


2006
2009
0
200
400 m
Avtorja / authors: Kovačič & Ravbar 2011 Vir / source: © GURS, © Google Earth

prostorski načrti, so vzorčni primeri konflikta interesov med hitrim gospodarskim in prebivalstvenim razvojem ter trajnostno ohranitvijo pokrajinskih posebnosti (5). Posegi so načrtovani v neposredni bližini Regijskega parka Škocjanske jame (uvrščenih v seznam Unescove svetovne naravne dediščine) in Kačne jame, skozi katero teče podzemeljska Reka. Uničevanje naravnega okolja z zasipanjem in neurejenim odvodnjavanjem odpadnih vod je neprimerno z geomorfološkega in speleološkega vidika (*Placer* 2009; *Kranjc* 2009). Podobne prostorske spremembe se dogajajo še v naseljih Hrpelje in Kozina (6), ki tudi doživljata intenzivno urbanizacijo. V vrtačo pri Kozini so nekaj časa vozili celo mulj iz koprskega pristanišča (*Čič* 2011).

Nekoliko drugačen primer degradacije kraške pokrajine in podzemlja je načrtovanje v zaledju kraških izvirov na Planinskem polju, Unice in Malenščice. Slednji je zajet za vodooskrbo prebivalcev občin Postojna in Pivka. Izvira se napajata iz neposeljenega območja Snežnika in Javornikov ter gosteje poseljenih območij Zgornje Pivke in kraških polj Notranjskega podolja (Babno, Loško in Cerkniško polje). Območja gostejše poselitve z neposrednim odtokom neočiščene vode v podzemlje pomenijo resno grožnjo kakovosti izvirov. Skladno z zakonodajo s področja varstva voda so lokalne skupnosti začele urejati problematiko, med drugim tudi zato, ker sta urejeno odvodnjavanje in čiščenje odpadnih voda predpogoja za gradnjo na vodovarstvenih območjih (Uredba o emisiji snovi pri odvajanju odpadne vode iz malih komunalnih čistilnih naprav – *UrES*, 2007). Tako so v nekaj letih predvidene razširitev in posodobitev kanalizacijskega omrežja ter posodobitev ali gradnja novih čistilnih naprav v večjih naseljih, kot so Cerknica, Pivka in Postojna, na katere bodo priključena tudi bližnja naselja. V načrtu je tudi izgradnja manjših čistilnih naprav v nekaterih drugih naseljih znotraj vodovarstvenega območja izvira Malenščica v občinah Cerknica, Pivka, Ilirska Bistrica in Postojna (*Trček* 2011).

Na neposeljenem območju Javornikov pa kraško površje in podtalnico ogrožajo vojaške dejavnosti na Osrednjem vadišču Slovenske vojske (OSVAD) Postojna na Počku. Območje vadišča Poček je bilo

appearance of the karst landscape, and the construction of new sections of expressways usually accelerates the development of industrial zones in smaller towns. In addition to intensive sprawl of the industrial zone in Logatec, the last few years also saw the construction of similar zones in Kozina, Podskrajnik, Divača, and Mirna Peč (4). The construction of such zones on the irregular and rocky karst surface means leveling the surface, which is only possible by filling dolines, removing the ridges between them, and building over them. Such encroachments significantly change the appearance of an area as well as increase its vulnerability to pollution, although taking appropriate measures can reduce the negative impacts on the quality of underground waters and ecosystems to a minimum.

The construction of the Risnik industrial zone near Divača and other encroachments (the Risnik residential development and the second track of the Divača–Koper railroad) envisaged by the municipality's and state's spatial plans provide a model example of the conflict of interests between rapid economic and population development and the sustainable preservation of landscape features (5). The planned encroachments are occurring in the immediate vicinity of the Škocjan caves Regional Park, a Unesco World Heritage site, and the cave Kačna jama through which the underground river Reka flows. From the geomorphological and speleological viewpoint, destruction of the natural environment by filling and the unregulated drainage of waste waters is inappropriate (*Placer* 2009; *Kranjc* 2009). Similar spatial changes are occurring in the settlements of Hrpelje and Kozina (6), which are experiencing intensive urbanization. For a while, a doline near Kozina was even used to deposit silt dredged from the Port of Koper (*Čič* 2011).

Spatial planning in the catchment area of the karst springs of the Unica and Malenščica rivers on the Planinsko polje is a somewhat different example of the degradation of karst landscape and underground. The Malenščica spring is exploited for water supply of the residents of the Postojna and Pivka municipalities. The spring is recharged from the uninhabited Snežnik and Javorniki karst plateaus as well as from more densely populated areas of Zgornja (Upper) Pivka and the karst poljes of the Notranjsko valley system (Babno polje, Loško polje and Cerkniško polje). Areas of dense popuaktivno vrsto let že v času nekdanje SFRJ. Neposredne okoljske posledice eksplozij različnih eksplozivnih sredstev, topovskih in drugih izstrelkov v obliki kraterjev so v trdni apnenčasti kamnini, v primerjavi s posledicami kemičnega onesnaženja, zanemarljive (*Zorn* in *Komac* 2009). Večje onesnaženje poleg emisij iz transportnih sredstev povzročajo snovi, ki se v obliki plinov, aerosolov in trdnih delcev sproščajo v zrak ob streljanjih, detonacijah streliva in eksplozivov, med katerimi so tudi zelo nevarne težke kovine (svinec, kadmij, cink, baker idr.). Te snovi se nato usedejo na skromno prst ter s padavinsko vodo počasi pronicajo v podzemlje in proti vodnim virom.

Država je leta 2010 pripravila Državni prostorski načrt za OSVAD Postojna, ki predvideva širitev vojaške dejavnosti na tem območju, kljub dejstvu da je bil osnutek Uredbe o vodovarstvenem območju vodonosnikov območja Postojna in Cerknica, ki bi izvir Malenščica ustrezno zavaroval, pripravljen že leta 2009. Skladno s to uredbo bi vojaško vadišče težko umestili v vodovarstveno območje kraškega izvira, saj mora vsako nadaljnje planiranje upoštevati izsledke vseh raziskav o pretakanju voda na območju. Sledilni poskus z uraninom iz vrtače na Počku (izveden junija 1997) je namreč jasno dokazal raztekanje voda s tega dela vodonosnika v izvire na Planinskem polju in v Vipavo (*Kogovšek* 1999a; *Kogovšek* idr. 1999). V izvir Malenščica je s hitrostjo 26 m/h odteklo 55 % sledila, preostanek pa s podobno hitrostjo v izvire Vipave.

Zaradi dolgoletne vojaške dejavnosti na območju OSVAD Postojna predvidevamo, da je vsebnost nevarnih snovi v tanki prsti in zgornjem sloju vodonosnika velika, nimamo pa natančnih podatkov o količinah. Po podatkih Inštituta ERICO so na območju vadišča ponekod presežene referenčne vrednosti težkih kovin, ki so zelo blizu mejnim dovoljenim dnevnim vrednostim na enoto površine (*Vrabič* idr. 2010). Izmerjene vsebnosti določenih kovin (svinca, niklja, bakra, kroma, kadmija) v odvzetih vzorcih sedimenta v izviru Malenščica so zelo verjetno posledica spiranja onesnaženih tal z območja Počka (*Kogovšek* idr. 1999).

Poleg omenjenih fizičnih posegov in neprimernih aktivnosti na površju prihaja z onesnaženo prenikajočo in ponorno vodo na krasu tudi do degradacije

lation with direct runoff of untreated water into the underground present a serious threat to the quality of springs. In accordance with the legislation in the field of water protection, local communities have agreed to address the problem, among other reasons because regulated drainage and treatment of waste waters is a precondition for construction activities in water protection areas (Decree on the emission of substances in the discharge of waste waters from small urban waste water treatment plants—*UrES*, 2007). The expansion and modernization of the sewage system or the construction of water treatment plants in major settlements such as Cerknica, Pivka, and Postojna, with connections to the near-by settlements is therefore expected in the next few years. There are plans to install smaller water treatment plants in several other settlements inside the water protection area of the Malenščica spring in the municipalities of Cerknica, Pivka, Ilirska Bistrica, and Postojna (*Trček* 2011).

In the uninhabited Javorniki plateau, the karst surface and groundwater are threatened by military activities at the Postojna Central Training Site (CTS) in the Poček area. The Poček military training site was active for many years during the time of the former Yugoslavia. The direct environmental consequences of explosions caused by a variety of explosives, artillery fire, and other missiles in the form of craters in solid limestone rock are negligible compared to the consequences of chemical pollution (*Zorn* in *Komac* 2009). Along with emissions from transport vehicles, major pollution is caused by substances released into the air during firing and detonation of munitions and explosives in the form of gas, aerosols, and solid particles that can contain very harmful heavy metals (lead, cadmium, zinc, copper, etc.). These substances settle on the thin karst soil and with precipitation percolate into underground and towards springs.

In 2010, Slovenia prepared a National Spatial Plan for the Postojna CTS that envisages an expansion of military activities in the area, even though a draft of the Regulation on the water protection area of the Postojna and Cerknica water aquifer, which would protect the Malenščica spring properly, had already been prepared in 2009. In accordance with this regulation, it would be difficult to establish a military training site in the podzemlja, podzemnih voda in biotopov. Zaradi velike prepustnosti matične kamnine, ki omogoča takojšen prodor vode v podzemlje, se odplake in izcedne vode spirajo skozi brezna, jame in manjše kraške kanale proti izvirom. Procesi samoočiščevanja so pogosto manj učinkoviti zaradi visokih hitrosti pretakanja in anaerobnih razmer v podzemlju. Na Krasu, na primer, imajo urejeno kanalizacijo s čistilno napravo samo občinska središča Sežana, Divača, Senožeče, Hrpelje in Komen (*Macarol* 2010).

Z lomljenjem kapnikov, odstranjevanjem drugih jamskih sedimentov in vandalskim obnašanjem so jame mehansko poškodovane in uničene, posledice pa so trajne. Neposreden vpliv na jame ima tudi turizem. Z neprimerno ureditvijo jame za obisk ter izdelavo vhodov in turističnih poti lahko pride do spreminjanja jamske klime, do rasti 'lampenflore' ob umetni razsvetljavi ipd. Do uničevanja jam prihaja tudi ob gradnjah (npr. avtoceste). Izgradnja čistilne naprave za odpadne vode v Postojnski jami, ki je začela obratovati leta 2011, je pozitiven primer omilitvenega ukrepa za zmanjšanje negativnih učinkov turizma na krasu.

## Sklep

Kraška območja so pokrajinsko zelo občutljiva. Med pokrajinskimi elementi so zaradi nizkih samočistilnih sposobnosti še posebno občutljivi kraška podtalnica in podzemni ekosistemi. Čeprav je človek kraški relief s preoblikovanjem in zasipavanjem vrtač, gradnjo teras in trebljenjem obdelovalnih površin spreminjal že stoletja, sodobno intenzivno preoblikovanje pokrajine zaradi potreb po širjenju cestnih povezav ter urbanih in industrijskih površin vse bolj uničuje neobnovljiv naravni vir nacionalnega pomena. Razlogi za nenadzorovano spreminjanje in onesnaževanje so tudi v neustrezni in pomanjkljivi zakonodaji.

Spreminjanje dejanske in planske rabe zemljišč je v razvitih državah praviloma nadzorovano in poteka po postopkih, določenih z zakonodajo. V Sloveniji so pristojnosti na področju urejanja prostora deljene med državno in občinsko raven, pri čemer regionalni nivo še ni vzpostavljen. Državna raven opredeljuje

water protection area of a karst spring because any new planning or construction must consider the findings of all research on water connections in the area. A tracer test with Uranine from a doline in the Poček area (conducted in June 1997) clearly indicated that the water from this part of the aquifer flows to the springs on the Planinsko polje and Vipava valley (*Kogovšek* 1999a; *Kogovšek* et al. 1999). Some 55 % of the tracer flowed to the Malenščica spring at the speed of 26 m/h, and the rest flowed to the Vipava springs at a similar speed.

Due to the long-term military activities in the Postojna CTS area, we can assume the amounts of hazardous substances in the thin soil and the upper layer of the aquifer is high, but there is no detailed data on the quantities. According to the data from the ERICO Institute, the reference values for heavy metals are exceeded in some places in the training site or are very close to the limit of permissible daily values per unit of the surface (*Vrabič* et al. 2010). The measured content of specific metals (lead, nickel, copper, chromium, cadmium) in samples of sediment collected in the Malenščica spring are very likely the result of the water leaching through the polluted ground in the Poček area (*Kogovšek* et al. 1999).

In addition to such physical encroachments and inappropriate activities on the surface, the pollution of percolating and ponor water in karst areas causes degradation of the underground, groundwater, and biotopes. Due to a great permeability of the karst bedrock which allows the immediate penetration of water into the underground sewage water and leachate are carried through shafts, caves, and smaller channels towards springs. Natural self-cleaning processes are frequently less effective due to high flow velocities and anaerobic conditions in the underground. In the Kras region, regulated sewage systems with water treatment plants are only found in the municipal centres of Sežana, Divača, Senožeče, Hrpelje, and Komen (*Macarol* 2010).

Breaking off of stalactites and stalagmites and removal of other cave sediments along with other vandalism cause physical damage and destruction in caves with permanent consequences. Tourism also has a direct impact on caves. Inappropriate management of tourist visits and construction of entrances and tourist trails can change the cave climate, and artificial illumination can encourage the growth of 'lampenflora'. Surface con-sistem prostorskega planiranja ter določa strateške cilje in usmeritve v prostoru, občinska raven oziroma lokalne skupnosti pa imajo izvirno pravico urejanja prostora na svojem območju. Z nastankom številnih novih občin je v Sloveniji opaziti, da je pritisk na odprti prostor zaradi različnih interesov močno narasel. S tem se pojavlja vprašanje o učinkovitosti kontrole spreminjanja rabe prostora.

Eden od primerov neustreznega planiranja aktivnosti je razmah gradnje v okolici Divače. Prostorski razvoj mesta in okolice je povsem prepuščen zgolj občinski oblasti, ki pa je strokovno in finančno prešibka, da bi lahko ponudila bolj trajnostno obliko izrabe prostora in ne bi bila podvržena različnim pritiskom kapitala. V takšnih in podobnih primerih bi ustrezni zakonodajni ukrepi s področja ohranjanja kraške pokrajine na državni ravni pomenili varovalo za bolj trajnostno usmerjeni razvoj.

Primer OSVAD Postojna pa kaže na neprimerno urejanje dejavnosti na krasu s strani države, in to na območju, kjer se lokalne skupnosti in prebivalstvo dobro zavedajo pomena varovanja krhke kraške pokrajine, saj so od nje življenjsko odvisni (pitna voda, turizem, gozd, paša idr.). Širitev vojaških dejavnosti je sporna predvsem zaradi neposrednega ogrožanja kraškega vodnega vira Malenščica, ki je za prebivalce občin Postojna in Pivka nenadomestljiv. Ker državni prostorski akti za načrtovane vojaške aktivnosti ne predvidevajo izdelave celovite presoje vplivov na okolje, država v primeru širitve OSVAD ni dolžna upoštevati pripomb lokalnih skupnosti in zainteresirane javnosti.

Merila in pogoji za varovanje kraških pokrajinskih značilnosti so v trenutnih zakonodajnih okvirih preohlapni oziroma so neizdelani. Predvsem ni enotnih mehanizmov za varstvo posebnih reliefnih oblik in za primerno varovanje kraških voda. Ohranjanje tipične kraške pokrajine je v pretežni meri prepuščeno lokalnim skupnostim, ki navadno nimajo potrebnih finančnih in strokovnih virov, da bi lahko ustrezno usmerjale rabo prostora. Kompleksnost krasa in njegovo ranljivost pa tisti, ki se ukvarjajo s prostorskim načrtovanjem in rabo prostora, premalo poznajo. Zato pod različnimi pritiski sprejemajo napačne odločitve. Skladnost med posebnimi na-

struction work (e.g. expressways) can also damage caves. Installation of a water purification plant in the Postojna cave which already began operating in 2011 is a positive example of a mitigation measure to reduce the negative impacts of tourism on Slovenian karst.

## Conclusion

Karst areas in general are very sensitive, and due to low self-cleaning capacities, karst groundwater and underground ecosystems are especially vulnerable to pollution. While humans have been changing the karst relief for centuries by transforming and filling dolines, constructing terraces, and clearing arable surfaces, an intensive modern reshaping of the landscape due to expansion of road systems and urban and industrial areas is accelerating destruction of this non-renewable, nationally important natural resource. The reasons for these uncontrolled changes and pollution also lie in inadequate and insufficient legislation.

As a rule, the changing of actual and planned land use in developed countries is supervised and conducted according to the procedures prescribed by legislation. In Slovenia, jurisdiction relative to spatial planning is divided between the national and municipal levels, while the regional planning level has not been established yet. The national level determines the system of spatial planning and defines strategic goals and orientation for spatial planning while municipalities or local communities have the autonomous right to manage space in their territory. The formation of numerous new municipalities in Slovenia has resulted in pressure on open spaces increasing significantly and raised questions about effective control over changing land use.

The growth of construction in the surroundings of Divača is a typical example of inappropriate planning. The spatial development of the town and its surroundings has been left entirely to the municipal authorities which are professionally and financially too weak to promote more sustainable land use or resist the various pressures of capital investment. In this and similar cases, adequate legislative measures for the preservation of the karst landscape at the national level would offer a guarantee of the more sustainability-oriented development.

ravnimi vrednotami in kulturno krajino, ki je izjemnost kraških območij v Sloveniji, je tako ogrožena. V prihodnje je zato nujna izdelava celostne strategije varstva krasa.

Regijski parki in druge oblike zavarovanih območij (npr. Natura 2000 – *UrNat*, 2004) so dobra rešitev, saj so načrti upravljanja zasnovani naravovarstveno in razvojno hkrati, vendar je treba določene ukrepe za varstvo površja, podzemne vode in jam opredeliti tudi izven zavarovanih območij. Na primeru varovanja kraških voda ponuja ravnotežje med zaščito ter prostorskim načrtovanjem in ekonomskimi interesi Slovenski pristop, metoda za ocenjevanje ranljivosti in tveganja kraških voda za onesnaženje (*Ravbar* 2007). Po zgledu takšne metode velja razviti podobne varovalne mehanizme za preostale pokrajinske elemente in jih uzakoniti.

The Postojna CTS example reveals the inadequate management of activities on karst on the part of the state in an area where the local communities and the population are very much aware of the importance of protecting the fragile karst landscape because their lives depend on it (drinking water, tourism, forests, pastures, etc.). The expansion of military activities is controversial primarily because it presents a direct threat to the karst Malenščica spring which is irreplaceable for the inhabitants of the Postojna and Pivka municipalities. Since national spatial planning regulations for planning military activities do not require a comprehensive environmental impact study, in the case of expanding the Postojna CTS the state is not obliged to consider the objections of the local communities and the interested public.

In the current legislative framework, the standards and conditions for the protection of karst landscape characteristics are loose or not fully elaborated. Principally, there are no uniform mechanisms to protect specific relief forms or for the adequate protection of karst waters. To a large extent, the preservation of the characteristic karst landscape is left to the local communities that most often lack the necessary financial and professional resources to appropriately direct land use, and those dealing with spatial planning and land use have insufficient knowledge regarding the complexity of karst and its vulnerability. Under pressure from various sources, they consequently make wrong decisions. The harmony between special natural assets and the cultural landscape, which is an exceptional feature of karst areas in Slovenia, is thus at risk, and the future urgently calls for a comprehensive strategy to protect the karst.

Regional parks and other forms of protected areas (e.g. Natura 2000—*UrNat*, 2004) are a good solution because management plans are based simultaneously on environmental protection and development; however, it is also necessary to define measures for the protection of the surface, groundwater, and caves outside protected areas. In the case of the protection of karst waters, the Slovene approach and its method for assessing the vulnerability of karst waters and the risk of pollution offers a balance between protection, spatial planning, and economic interests (*Ravbar* 2007). Following the example of this method, similar protection mechanisms should be developed and enacted into law for other karst landscape elements.

# 12

# ZAŠČITA KRAŠKEGA PODZEMLJA TER EU PROJEKT »KARST UNDERGROUND PROTECTION« V SLOVENIJI

# PROTECTION OF THE KARST UNDERGROUND AND THE EU PROJECT "KARST UNDERGROUND PROTECTION" IN SLOVENIA

Kraško podzemlje je zaradi svojih lastnosti zelo občutljiv in ranljiv sistem, ki je močno podvržen vplivom s površja. Voda s površja hitro ponika v podzemlje, kjer se pretaka po odprtih kanalih. Stopnja samoočiščenja je tako odvisna od hitrosti pretoka in vrste onesnaženja, ki pa je na krasu nasploh zelo nizka ali pa je ni (*Kogovšek* 1999b). Negativni vplivi se tako hitro razširijo v podzemlje, kjer vplivajo na jame in razmere v njih ter tako podzemskim organizmom spreminjajo življenjsko okolje in vplivajo na vodo, ki jo lahko onesnažijo do take mere, da ni več pitna. Glede na dejstvo, da kras lahko sega tudi preko državnih meja, je nujno skupno delo ustanov, ki se ukvarjajo z zaščito okolja, krasa in jam na obeh straneh meje. Potrebno je vzpostaviti in v nadaljevanju pozitivno razvijati sodelovanje z nevladnimi združenji in organizacijami, kot so na primer jamarska društva in klubi. S poznavanjem terena in jam lahko jamarji veliko prispevajo k širjenju novih spoznanj o njih, sodelujejo pri monitoringu njihovega stanja, njihovem čiščenju in tudi zaščiti.

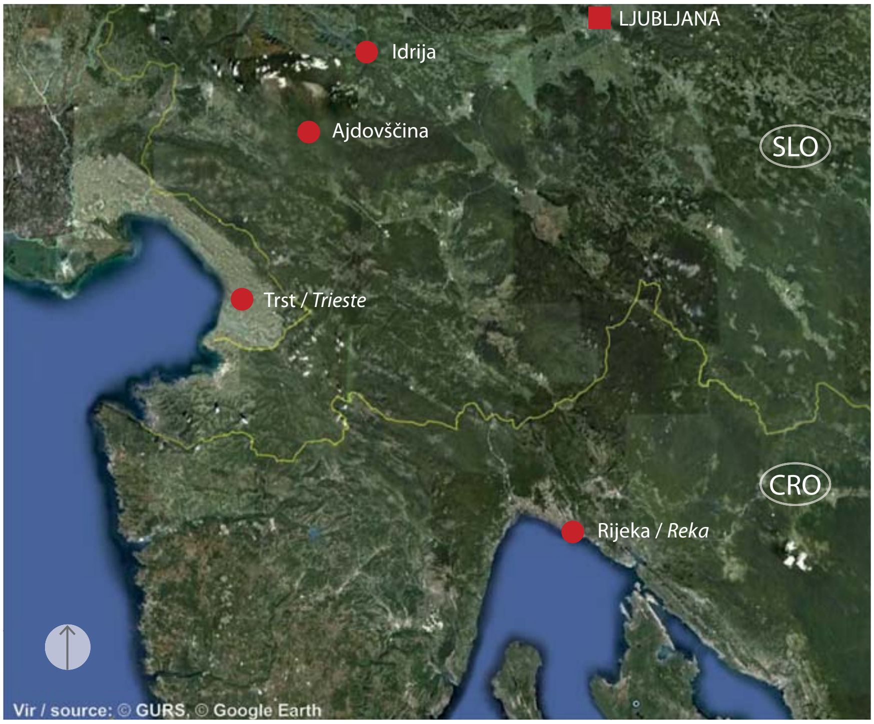
Eden od načinov varovanja in zaščite krasa na meddržavnem nivoju je tudi skupno delo na raznih projektih. Tak primer je sodelovanje Slovenije in Hrvaške v EU projektu »Zaščita kraškega podzemlja / Karst Underground Protection« s kratico KUP. Projekt deluje v okviru Operativnega programa IPA (Inštrument za predpristopno pomoč) Slovenija–Hrvaška 2007–2013. Projekt v Sloveniji financirata EU in Služba Vlade RS za lokalno samoupravo in regionalno politiko. Vodilni partner projekta je Istrska županija (Hrvaška), sodelujoča partnerja pa sta Inštitut za raziskovanje krasa ZRC SAZU (Postojna, Slovenija) in Natura Histrica (Hrvaška).

Projekt je namenjen dvigovanju zavesti o pomembnosti krasa in zaščiti kraškega podzemlja, to je jam, vode in favne na lokalnem, nacionalnem in nadnacionalnem nivoju ter sodelovanju Slovenije in Hrvaške na lokalnem in regionalnem nivoju. Ciljne skupine projekta so: a) lokalno prebivalstvo in lokalna skupnost na geografskem območju polotoka Istre (Republika Hrvaška in Republika Slovenija) in na njegovem obrobju (1) kot tudi širša družbena javnost; b) enote regionalne in lokalne samouprave ter javne ustanove; c) znanstvene ustanove in znanstveniki; d) izobraževalne ustanove

The characteristics of the karst underground make it an extremely sensitive and vulnerable system that is highly susceptible to influences from the surface. Water from the surface percolates rapidly into the underground where it flows through open conduits. The rate of self-cleaning is thus dependent on the rate of flow and the type of pollution, but in general is extremely low or almost non-existent in karst areas (*Kogovšek* 1999b). Negative impacts are therefore able to spread rapidly into the underground where they affect caves and conditions in them, altering the habitats of underground organisms, and also have an effect on water which they can pollute to such an extent that it is no longer drinkable. In view of the fact that karst areas can extend beyond national borders, the cooperation of institutions involved in the protection of the environment, karst and caves on both sides of the border is essential. It is vital to establish cooperation and, subsequently, positive collaboration with non-governmental organizations and associations such as caving clubs. With their knowledge of the terrain and caves, cavers can do a great deal to help disseminate new discoveries about caves, help monitor their status, and participate in their cleaning and protection.

One of the ways to protect and safeguard karst at the international level is through a joint work on various projects; an example of this is the cooperation between Slovenia and Croatia on the EU project »Karst Underground Protection« (KUP). The project is part of the IPA (Instrument for Pre-Accession Assistance) Operational Programme Slovenia–Croatia 2007–2013. The project is funded in Slovenia by the EU and the Government Office of the Republic of Slovenia for Local Self-Government and Regional Policy. The lead partner on the project is the Istrian Region (Croatia), while the Karst Research Institute at the Scientific Research Centre of the Slovenian Academy of Sciences and Arts (Postojna, Slovenia) and Natura Histrica (Croatia) are participating partners.

The purpose of the project is to raise awareness of the importance of the karst and to protect the karst underground, i.e. caves, waters and fauna at the local, national and supranational levels, and the cooperation of Slovenia and Croatia at the local and regional




1 Ozemlje izvajanja EU projekta »Zaščita kraškega podzemlja«.
The implementation area of the EU project »Karst Underground Protection«.

(univerze, visoke šole, srednje in osnovne šole); e) nevladna združenja (jamarji, 'zeleni' idr.); f) turistične organizacije in podjetja.

Cilji projekta so splošni in specifični, čezmejni, kot so:

- zaščita in izboljšanje stanja krasa na obmejnem območju Istre in Slovenije;
- krepitev sodelovanja in skupno delovanje regionalnih in državnih institucij na področju zaščite okolja v Sloveniji in na Hrvaškem;
- zagotavljanje prepoznavnosti območja s promocijo okoljskih in naravnih posebnosti kraškega dela Istre;
- zaščita in preprečevanje onesnaženja kraških vodnih virov;
- inventarizacija in načrtovano upravljanje z jamami na projektnem območju s ciljem zagotovitve njihove trajnosti;
- vzpostavitev speleo-hiše v Istri kot centra delovanja mednarodnega omrežja ustanov in združenj civilne družbe, ki se ukvarjajo s speleologijo, zaščito okolja in kraškimi pojavi;
- dvigovanje ravni ozaveščenosti lokalnega prebivalstva iz vseh starostnih skupin o biološki in okoljski vrednosti kraškega območja s ciljem zvišanja življenjske ravni.

levels. The target groups of the project are: a) local population and local administrative community in the geographical area of the Istrian peninsula (Republic of Croatia and Republic of Slovenia) and on its margins (1), and society in general; b) units of regional and local governmental and public institutions; c) scientific institutions and scientists; d) educational institutions (universities, colleges, secondary schools, primary schools); e) non-governmental organizations (cavers, environmentalists, etc.); and f) touristic organizations and firms.

The objectives of the project can be divided into general and specific, cross-border objectives:

- protection and improvement of the karst state in the border area of Istria and Slovenia;
- strengthening of cooperation and a joint action of the regional and national institutions in the field of the environmental protection in Slovenia and Croatia;
- ensuring recognizability of the area through promotion of the special environmental and natural features of the karst area of Istria;
- protection of karst water resources and pollution prevention;

Aktivnosti slovenskega partnerja v projektu so omejene na organizacijo dveh mednarodnih krasoslovnih šol, izvajanje biospeleoloških raziskav skupaj s Hrvati v izbranih jamah v Sloveniji in Istri, čiščenje šestih slovenskih jam v dveh letih (čiščenje jam izvajajo jamarji treh slovenskih jamarskih klubov, ki so bili izbrani na javnem razpisu) in sodelovanje pri najmanj dveh skupnih čistilnih akcijah s hrvaškimi jamarji.

## 12.1 Kraško podzemlje, njegova ranljivost in potreba po zaščiti

Kras povsod po svetu deluje na enak način. Ne glede na površinske oblike je kraško podzemlje prepleteno z jamami, kanali in razpokami, skozi katere se pretaka voda, ki nam obenem predstavlja čist ali onesnažen vodni vir. Voda in tudi onesnaževalci lahko na več načinov vstopajo v podzemlje: razpršeno skozi golo ali pokrito kraško površje s padavinami ter koncentrirano skozi ponore in zaprte depresije v obliki vodotokov in koncentriranih padavin (*Kogovšek* idr. 2008). V podzemlju se potem prosto pretakajo skozi odprte kraške kanale, kjer je stopnja samoočiščenja zelo nizka ali je sploh ni, se koncentrirajo in tečejo proti izvirom.

Kras zavzema okrog 44 % Slovenije. Njegov večji del pripada Dinarskemu krasu, na katerem trenutno poznamo več kot 10.000 jam (Kataster jam JZS in IZRK ZRC SAZU). Od tod prihaja okrog 60 % pitne vode, na krasu pa živi tudi približno tretjina prebivalcev Slovenije. Prav zato je kras dobro preučen tudi z vidika rabe in varovanja (*Ravbar* 2007; *Petrič* in *Ravbar* 2008). Na slovenskem krasu so raziskani reliefne oblike, kraški površinski in jamski sedimenti, jame in pretekli razvoj krasa (npr. *Mihevc* 2001b). Z analizo podatkov je bil rekonstruiran paleogeografski razvoj krasa za več milijonov let nazaj in z jamskimi sedimenti podrobneje določene klimatske spremembe od konca pleistocena do sedanjosti (*Zupan Hajna* idr. 2008).

Na jame vpliva vse, kar se dogaja na površju nad njimi ali v njihovem vplivnem območju. Ljudje s svojim načinom življenja in velikokrat z nepremišljenimi posegi v prostor močno ogrožamo naravo. S posegi lahko porušimo naravno ravnovesje v okolju, vpli-

- cataloguing and planned management of caves in the project area for the purpose of ensuring their sustainability;
- creation of a ‘speleo-centre’ in Istria as a centre of activity for an international network of institutions and civil society organizations involved in speleology, environmental protection and karst phenomena;
- raising awareness of the local population of all age groups about the biological and environmental value of the karst area with the aim of improving their standard of living.

The activities of the Slovenian partner in the project are limited to the organization of two International Karstological Schools, carrying out biospeleological research together with Croatian researchers in the selected caves in Slovenia and Istria, and cleaning up six caves in Slovenia over the course of two years. Cave cleanups are carried out by cavers from three Slovene caving clubs selected on the basis of a call for applications and will involve participation in at least two joint cleanup operation with Croatian cavers.

## 12.1 Karst underground, its vulnerability and need for protection

Karst functions in the same way all over the world. Whatever formations are visible on the surface, the karst underground is perforated by a network of caves, conduits and fissures through which water flows—water which at the same time represents a clean or polluted water source. Water and pollutants can enter the underground in several ways: in dispersed form through bare or covered karst surface with precipitation and in concentrated form through ponors and closed depressions in form of watercourses and concentrated precipitation (*Kogovšek* et al. 2008). Once underground, they move freely through open karst conduits where the rate of self-cleaning is very low or almost non-existent. Here they concentrate and flow towards springs.

Around 44 % of the territory of Slovenia is karst, the greater part of which belongs to the Dinaric karst in which over 10,000 caves have been identified to date. Karst aquifer is the source of approximately 60 % of the country’s drinking water, and around a third vamo na biotsko raznovrstnost ali uničimo geološke zanimivosti in informacije ter različne kraške oblike.

Skupine onesnaževalcev krasa in jam so: prebivalstvo (komunalni in gospodinjski odpadki), industrija (kemikalije, smeti, odplake itd.), kmetijstvo (fekalije, gnojenje, škropljenje itd.), promet (gradnja cest in železnic, nesreče-izlitja nafte, soljenje itd.), gradnje (izkopi, kamnolomi itd.), turizem (smeti, uničevanje naravnega okolja, turistični kompleksi nad jamami z vso infrastrukturo itd.) in vojska (vojaški poligoni, rezervoarji itd.).

Jame so zelo občutljive na človekove vplive (*Mihevc* 1995). V izoliranih prostorih so poškodbe trajne, le počasi se odstranijo ali prerastejo, še zlasti kjer ni navzoče spiranje s tekočo vodo. Odlomljen kapnik, ki je rasel tisoč ali več let, pomeni uničenje informacije o preteklih speleogenetskih in klimatskih dogajanjih. Že majhna sprememba v jamski klimi lahko ustavi izločanje sige in tudi specializirane jamske živali pred spremembami okolja nimajo kam pobegniti. Žal postajajo številne jame kljub prepovedi odlagališča odpadkov. S ciljem preprečevanja takšne prakse sta nujni njihova aktivnejša zaščita ter preudarna in nadzorovana uporaba z upoštevanjem vseh varnostnih ukrepov. Nekontrolirano obiskovanje jam pogosto pripelje do njihovega opustošenja. Sonaraven razvoj krasa je možen izključno s kontinuiranim opravljanjem znanstvenih raziskav, stalnim nadzorom in spremljanjem stanja v jamah ter s skrbjo za njihovo zaščito.

In kaj lahko storimo za ohranitev krasa? Dokumentiramo kraške pojave (jamski kataster, kataster izvirov, podzemnih vodnih povezav in specifične jamske favne), postavimo in izvajamo naravovarstvene zakone, ki omogočajo manjše onesnaževanje površja in jam, v zadostni meri informiramo ljudi o posebnostih in značilnostih kraške pokrajine ter prebivalce na krasu opozarjamo na ogrožanje naravne dediščine z njihove strani, predvsem v zvezi z večjimi tehničnimi posegi. Namen in končni cilj sta ohranjeni in nedotaknjeni kraško površje in podzemlje.

V Sloveniji kras in kraško podzemlje na območju projekta KUP že ščitijo naslednji zakoni:

- Nacionalni program varstva okolja 2005–2012 (*ReNVPVO*, 2006);
- Zakon o varstvu okolja (*ZVO-1*, 2004);

of the population of Slovenia live in the karst. It is for this reason that the karst is the subject of close scrutiny from the point of view of use and protection (*Ravbar* 2007; *Petrič* and *Ravbar* 2008). Subjects of the study include relief forms, karst sediments on the surface and in caves, caves themselves, and genesis of the karst (e.g. *Mihevc* 2001b). Analysis of data has allowed researchers to reconstruct the palaeogeographic development of the karst going back several million years and, by means of cave sediments, identify changes of climate from the end of Pleistocene to the present (*Zupan Hajna* et al. 2008).

Caves are affected by activities that happen on the surface above the cave and within its area of influence. Human beings represent a serious threat to nature through their way of life and frequently ill-considered interventions in the environment. Such interventions can destroy natural balance, affect biodiversity, and destroy interesting geological features and information and various karst formations.

Polluters of the karst and caves may be divided into: population (municipal and household waste), industry (chemicals, rubbish, waste, etc.), agriculture (faecal matter, fertilization, spraying, etc.), transport (building roads and railways, accidents-oil spillages, salting, etc.), construction (excavations, quarries, etc.), tourism (rubbish, destruction of the natural environment, tourist complexes above caves with all their infrastructure, etc.), and military (firing ranges, fuel dumps, etc.).

Caves are extremely sensitive to human influences (*Mihevc* 1995). In isolated locations damage is lasting and is only slowly eliminated or overgrown, especially where there is no washing away by running water. A broken stalactite which has been growing for a thousand years or more means the destruction of information about past speleogenetic and climatic events. Even a small change in the cave climate can halt the precipitation of calcium carbonate, and specialized cave fauna have nowhere to escape to when faced with changes to their environment. Unfortunately, many people use caves as rubbish dumps, despite the fact that this is prohibited. In order to prevent this practice, more active protection of caves is essential, along with prudent and controlled use taking into account

- Zakon o varstvu podzemnih jam (*ZVPJ*, 2004);
- Pravilnik o določitvi in varstvu naravnih vrednot (*PrDVNV*, 2004);
- Zakon o ohranjanju narave (*ZON*, 1999);
- Uredba o posebnih varstvenih območjih – območjih Natura 2000 (*UrNat, 2004*);
- Natura 2000 (*UrNat*, 2004), Matarsko podolje in Slovenska Istra: koda območja po Direktivi o pticah (SPA) SI5; koda območja po Habitatni direktivi (pSCI) SI3;
- Zakon o vodah (*ZV-1*, 2002);
- Pravilnik o kriterijih za določitev vodovarstvenega območja (*PrKDVO*, 2004);
- Direktiva o vodah (*Directive 2000/60/EC*);
- Odlok o določitvi varstvenih pasov izvira Rižane in ukrepih za zavarovanje voda (*OdDVPRiž*, 1988);
- Zakon o varstvu kulturne dediščine (*ZVKD-1*, 2008).

Zakon o varstvu podzemnih jam v Sloveniji ureja varstvo in rabo podzemnih jam, varstvene režime, ukrepe varstva in druga pravila ravnanja, vključno z obnovitvijo jam, ki so onesnažene in poškodovane. Določa tudi status podzemeljske geomorfološke naravne vrednote državnega pomena za vse jame.

## 12.2 Slovenske aktivnosti v okviru projekta

Kras je najbolj značilna oblika površja v Istri, ki se čez Čičarijo in Matarsko podolje nadaljuje v Slovenijo, kjer prihaja do stika med zakraselimi karbonatnimi kamninami in eocenskim flišem. Kraško podzemlje je tridimenzionalni splet razpok in kraških kanalov (jam), ki jih zapolnjujejo zrak, sedimenti ali voda. Pomen podzemnega krasa je mnogostranski: je vir pitne vode, uravnalec pretočnih režimov porečij, habitat podzemnim živalim, nosilec informacij o preteklem paleogeografsko-klimatskem razvoju, eden izmed najboljših virov informacij o zgodnjem razvoju človeka in med drugim tudi pomembna ekonomska kategorija (turistične jame). Jame na območju projekta so bivališča številnih endemičnih, redkih, ogroženih in zaščitenih živalskih vrst (*Proteus* sp., *Istriana mirnae*, *Chiroptera* sp. div. itd.).

all necessary safety measures. Uncontrolled visiting of caves frequently leads to their devastation. The sustainable development of the karst is only possible through continuous scientific research and constant control and monitoring of situation in the caves with a view to their protection.

What can we do to preserve the karst? We can document karst phenomena (caves register, register of springs, underground water connections and specific cave fauna). We can adopt and implement nature protection laws that help reduce pollution of the surface and of the caves. We can ensure that the population is sufficiently well-informed about the specificities and characteristics of the karst landscape. We can draw attention to a threat to the natural heritage represented by inhabitants of the karst areas, particularly through major technical interventions. The purpose and ultimate goal are a conserved and unspoilt karst surface and karst underground.

In Slovenia, the karst and the karst underground in the KUP project area are already protected by the following laws and programmes:

- National Environmental Protection Programme 2005–2012 (*ReNVPVO*, 2006);
- Environment Protection Act (*ZVO-1*, 2004);
- Cave Protection Act (*ZVPJ*, 2004);
- Rules on the designation and protection of valuable natural features (PrDVNV, 2004);
- Nature Protection Act (*ZON*, 1999):
- Decree on special protection areas – Natura 2000 areas (*UrNat, 2004*);
- Natura 2000 (*UrNat*, 2004), Matarsko Podolje and Slovenska Istra: Area code under the Birds Directive (SPA) SI5; Area code under the Habitats Directive (pSCI) SI3;
- Water Act (*ZV-1*,2002);
- Rules on criteria for the designation of a water protection zone (*PrKDVO*, 2004);
- Water Directive (*Directive 2000/60/EC*);
- Ordinance on the definition of protection belts for the Rižana spring and measures for protection of the water (*OdDVPRiž*, 1988);
- Cultural Heritage Protection Act (*ZVKD-1*, 2008).

The Cave Protection Act regulates the protection

V skladu s civilizacijskim razvojem človeka na površju so opazni tudi čedalje večji vplivi v podzemlju. Dejstvo je, da se to z mnogimi neustreznimi posegi v nadzemni in podzemni kras biotsko, kulturno, znanstveno in naravno-dediščinsko siromaši. Za povrnitev v prvotno stanje je načeloma potrebno izjemno dolgo obdobje (več tisoč let) ali pa povrnitve v prvotno stanje niti ni možno več doseči. A kadar so sanacijski ukrepi možni, so praviloma tudi izjemno dragi. Zaradi ranljivosti in pomembnosti kraškega sveta se upravičeno pojavlja čedalje večja potreba po strožjem nadzoru nad posegi, ki lahko negativno vplivajo na kraško podzemlje. Tako so kraški vodonosniki še posebej varovani z vidika zagotavljanja čiste pitne vode, podzemne naravne in kulturne vrednote pa pogosto varovane na državnem nivoju.

Kras se razprostira na mejnem območju Hrvaške in Slovenije, tako da je vsa problematika v zvezi z zaščito in razvojem tega predela pomembna za obe državi. S skupnim strateškim pristopom k ohranitvi in revitalizaciji omenjenega področja bomo omogočili konstruktivno razreševanje stanja na terenu in sodelovanje z lokalnim prebivalstvom v obeh državah. Med izvajanjem projekta se bosta s čiščenjem odpadkov iz jam poskušala tako v Sloveniji kot na Hrvaškem izboljšati kakovost vode na kraških izvirih in dvigniti nivo ozaveščenosti prebivalstva o nesmiselnosti odlaganja odpadkov v jame. Kraško območje je izjemnega pomena za obe državi. Poleg socialne in splošne družbene problematike pa največji skupni izziv in interes predstavljata biološka ohranitev tega predela in njegova zaščita. Vse ekološke spremembe in različni vplivi imajo dolgoročne posledice prav zaradi njegove izredne občutljivosti. Republika Slovenija in Republika Hrvaška imata izdelan načrt in zakonski okvir za zaščito okolja, status Slovenije, članice EU in partnerja pri projektu, pa je v pomoč Hrvaški, državi kandidatki, pri implementaciji pravnega reda EU. Žal pa je bil položaj pred začetkom izvajanja projekta takšen, da je ostajala zaščita mejnega kraškega ozemlja skoraj izključno samo na deklarativni ravni. Na podlagi skupnih potreb smo si tako zamislili skupno načrtovanje in izvajanje nekaterih aktivnosti pri čiščenju jam, biološkem monitoringu v jamah ter pri izvajanju izobraževanja lokalne in širše javnosti.

and use of caves in Slovenia, setting out protection regimes, protection measures and other rules of behaviour including the renovation of caves that are polluted and damaged. The Act gives all caves the status of the underground geomorphological heritage of national importance.

## 12.2 Slovenian activities within the project

The karst is the most characteristic landform in Istria which continues into Slovenia via Čičarija and Matarsko podolje. In this part of Slovenia karstified carbonate rock comes into contact with Eocene flysch. The karst underground is a three-dimensional web of fissures and karst conduits (caves) that are filled by air, sediments or water. The importance of underground karst is manifold: it is a source of drinking water, a regulator of the flow regimes of river basins, a habitat of subterranean fauna, a bearer of information about past palaeogeographic-climatic development and one of the best sources of information about the early development of human beings. It is also an important economic category (show caves). Caves in the project area are home to numerous endemic, rare, endangered and protected animal species (*Proteus* sp., *Istriana mirnae*, *Chiroptera* sp. div., etc.).

With the development of human civilization on the surface, the impacts on the underground become increasingly evident. The fact is, many inappropriate interventions in karst areas, both above and below ground, are a cause of impoverishment in the biotic, cultural, scientific and natural heritage senses. An extremely long period (usually several thousand years) would be necessary for a return to the original state, and in many cases a return to the original state is no longer feasible. Even if remedial measures are possible, they are usually very expensive. Because of vulnerability and importance of the karst, there is an increasing need for stricter control of interventions that may have a negative impact on the karst underground. Karst aquifers, for example, are specially protected from the point of view of providing clean drinking water, while underground natural and cultural features of value are often protected at the national level.

Izvajanje projekta zahteva vrsto koordiniranih institucionalnih, strokovnih in izobraževalnih aktivnosti, usmerjenih v direktne ukrepe ohranitve biološke in krajinske pestrosti in trajnostnega gospodarjenja z naravnimi dobrinami, v skladu z družbenim razvojem in potrebami prebivalstva.

V času izvajanja projekta potekajo v Sloveniji organizacija dveh mednarodnih krasoslovnih šol, biospeleološke raziskave in čiščenje šestih jam na obravnavanem območju.

### 12.2.1 Mednarodna krasoslovna šola

Vsakoletna mednarodna krasoslovna šola »Klasični kras« se izvaja že od leta 1993 naprej in privablja raziskovalce, strokovnjake, študente in vse ostale, ki jih zanimajo kras, njegovi naravni pojavi in problematika življenja na njem. Zaradi ugleda slovenskega Krasa, njegovega zgodovinskega pomena za razvoj krasoslovja na slovenskih tleh, dobre vsakoletne organizacije in široke udeležbe jo podpirajo Slovenska nacionalna komisija za Unesco, Mednarodna speleološka zveza (UIS), Kraška komisija pri Mednarodni geografski zvezi (IGU) in Jamarska zveza Slovenije (JZS). Delo na šoli poteka v obliki uvodnih predavanj, vabljenih in

The karst extends across the border region of Croatia and Slovenia. This means that all issues relating to the protection and development of this area are significant for both countries. A strategic joint approach to the preservation and revitalization of this area will enable the constructive addressing of the situation on the ground and cooperation with the local population in both countries. During implementation of the project an attempt is made, through the cleanup of waste from caves, to improve water quality in karst springs in Slovenia and Croatia and to raise awareness among the population with regard to the dumping of waste in caves. The karst region is of enormous importance for both countries. Beside general social issues, the biggest common challenge and interest is represented by the biological conservation of this region and its protection. All ecological changes and various impacts have long-term consequences precisely because of the extreme sensitivity of this area. The Republic of Slovenia and the Republic of Croatia have a worked-out plan and legal framework for the protection of the environment, and the status of Slovenia as EU member and partner in the project is a factor which can assist Croatia, a candidate country, in the implementation of the European Union law. Unfortunately, however, the situation before implementation of the project

**2** Predstavitev posterjev v okviru 18. mednarodne krasoslovne šole »Klasični kras«.
The poster presentation during the18th International Karstological School »Classical Karst«.

krajših tematskih predavanj, predstavitve plakatov (2), okrogle mize ter ekskurzij in terenskega dela.

V prvem letu izvajanja projekta je bila izpeljana 18. mednarodna krasoslovna šola, ki je potekala v juniju 2010 in bila posvečena Dinarskemu krasu. Cilj šole je bil predstaviti Dinarski kras kot referenčni kras, ki ima tako z zgodovinskega kakor tudi s fizično-geografskega in kulturnega vidika posebno vlogo v svetovnem krasoslovju. Predstavljene so bile osnovne geološke, geomorfološke, hidrološke, speleološke, biospeleološke in zgodovinske posebnosti tega krasa ter primerjane z različnimi oblikami krasa po svetu. Posebna pozornost je bila namenjena možnostim bodoče zaščite Dinarskega krasa. Šole se je udeležilo 208 udeležencev iz 36 držav (Avstralija, Avstrija, Bolgarija, Bosna in Hercegovina, Brazilija, Češka, Črna Gora, Egipt, Estonija, Francija, Grčija, Hrvaška, Indija, Iran, Italija, Japonska, Kanada, Kuba, Madžarska, Makedonija, Mehika, Nemčija, Norveška, Nova Zelandija, Poljska, Portugalska, Romunija, Rusija, Slovaška, Slovenija, Srbija, Španija, Švica, Ukrajina, Velika Britanija, ZDA).

Leta 2011 je bila organizirana 19. mednarodna krasoslovna šola z naslovom »Varstvo kraškega podzemlja«. Cilj te šole je bil osvetliti problematiko mnogoterih pritiskov na kraško podzemlje, podati vzroke ter preventivne in sanacijske rešitve zanje, predlagati alternative marsikje neustreznemu ravnanju s podzemljem, obenem pa dvigniti zavest o pomenu podzemne naravne dediščine. Uvodna predavanja so obravnavala varstvo kraških jam in upravljanje z njimi, varstvo kraških vodonosnikov in varstvo podzemnega živalstva.

### 12.2.2 Čiščenje jam

V sklop aktivnosti projekta »Zaščita kraškega podzemlja« smo uvrstili tudi čiščenje šestih kraških jam v Sloveniji in šestih jam na Hrvaškem. Znano je namreč, da je okrog 10 % jam, zlasti v nižinskem svetu, onesnaženih z najrazličnejšimi odpadki. Čeprav je glavnina odpadkov v jamah gospodinjskega izvora (drobni in kosovni odpadki) in velikokrat ne pomeni resne grožnje za okolje, se med njimi najdejo tudi snovi, ki so toksične že v zelo majhnih koncentracijah

began was that protection of the border karst area was almost entirely limited to the level of declarations. On the basis of our common needs, we therefore came up with a joint planning and implementation of certain activities relating to the cleanup of caves, biological monitoring inside caves and education of the local population and general public. Implementation of the project requires a series of coordinated institutional, specialist and educational activities oriented towards direct measures for the conservation of biological and landscape diversity and the sustainable management of natural resources in accordance with the social development and needs of the population.

The main activities in Slovenia during the period of implementation of the project include organization of two International Karstological Schools, a biospeleological research project and a cleanup of six caves in the project area.

### 12.2.1 International Karstological School

The International Karstological School »Classical Karst« has taken place every year since 1993 and brings together researchers, experts, students and other individuals interested in karst, its natural phenomena and issues surrounding life in karst areas. Thanks to the prestige of Slovenian Karst region and its historical importance for the development of karstology in Slovenia, and thanks also to the good organization and broad participation year after year, the school is supported by the Slovenian National Commission for Unesco, the International Union of Speleology (UIS), the Commission Karst at the International Geographical Union (IGU) and the Caving Association of Slovenia (JZS). Work at the schools takes the form of keynote lectures, invited lectures and short thematic lectures, poster presentations (2), round-table sessions, excursions and fieldwork.

The 18$^{th}$ International Karstological School was held in the first year of implementation of the KUP project. It took place in June 2010 and its theme was the Dinaric Karst. The aim of this edition of the school was to present the Dinaric Karst as a reference karst which has a special role in world karstology both histor-

**3** Vlačenje smeti iz Pokčeve jame v okviru KUP projekta.
Lift of waste from the cave Pokčeva jama in the frame of the KUP project.

**4** Čiščenje Pokčeve jame v okviru KUP projekta.
Cleanup of the cave Pokčeva jama as an activity of the KUP project.

ically and from the physical-geographical and cultural points of view. The essential geological, geomorphological, hydrological, speleological, biospeleological and historical features of the Dinaric Karst were presented and compared to various forms of karst around the world. Particular attention was devoted to the possibilities of future protection of the Dinaric Karst. The school attracted 208 participants from at least 36 countries (including Australia, Austria, Bosnia and Herzegovina, Brazil, Bulgaria, Canada, Croatia, Cuba, Czech Republic, Egypt, Estonia, France, Germany, Greece, Hungary, India, Iran, Italy, Japan, Macedonia, Mexico, Montenegro, New Zealand, Norway, Poland, Portugal, Romania, Russia, Serbia, Slovakia, Spain, Switzerland, Ukraine, United Kingdom, U.S.A., and Slovenia).

The 19 $^{th}$ International Karstological School, on the theme of Karst Underground Protection, took place in 2011. The aim of this edition of the school was to shed light on issues of the multiple pressures on the underground karst, set out causes of these pressures and offer preventive and remedial solutions to them, propose alternatives to the frequently inappropriate management of the underground karst, and at the same time raise awareness of the importance of the underground natural heritage. The keynote lectures covered the themes of the protection and management of karst caves, the protection of karst aquifers, and the protection of subterranean fauna.

### 12.2.2 Cave cleanups

The activities of the Karst Underground Protection project also included the cleanup of six karst caves in Slovenia and six caves in Croatia. It is a well-known fact that approximately 10 % of caves, particularly those in lower-lying areas, are polluted by waste of various kinds. Although the bulk of waste in caves is household waste (bulky and non-bulky) and often does not represent a serious threat to the environment, it can also include substances that are toxic in very small concentrations (oils, paints, solvents, heavy metals, pharmaceuticals, pesticides), or be mixed with waste of different origin (industry, small business, agriculture) that represents a more serious threat to the environment (*Prelovšek* 2011). For this reason, every (olja, barve, topila, težke kovine, zdravila, škropiva) ali pa se gospodinjski odpadki mešajo z odpadki drugačnega izvora (industrija, obrt, kmetijstvo), ki okolju predstavljajo hujšo grožnjo (*Prelovšek* 2011). Zaradi tega je treba vsakršen pojav odpadkov v podzemlju jemati resno, dokler ne izključimo njegovega negativnega vpliva na okolje.

Za čiščenje smo na podlagi podatkov iz Katastra jam IZRK in pregleda terena izbrali šest slovenskih jam, ki ležijo v zaledju pomembnejših vodnih virov. Šimenkova jama leži na vodozbirnem območju Vira pri Stični, ki je z zgodovinskega vidika pomembno ekološko območje, saj je bil od tam prvič opisan močeril, *Proteus anguinus*. Drugih pet leži v vodozbirnem območju izvira Rižane, glavnega vira za vodooskrbo Slovenskega Primorja. Zaskrbljujoče je, da so bile nekatere jame pretirano onesnažene z odpadki in jih z razpoložljivimi sredstvi ne bi mogli očistiti (npr. Brezno pod Revo pri Kozini), druge so bile povsem zasute in njihova lega ni bila določljiva (npr. Zasuto brezno pri Polžanski pečini), pri tretjih pa je bilo tveganje pri čiščenju zaradi potencialnih bolezni preveliko (npr. Golobnica pri Prešnici). Ključni dejavnik za izbor je bil tudi dostop do jame, saj so se v minulih desetletjih poti mimo jam, od koder se je odpadke vozilo vanje, dodobra zarasle in dostop po njih do jam brez sečnje ne bi bil mogoč. Skupna količina odpadkov je bila ocenjena na 76 m³. Izvajalce čiščenja smo z javnim razpisom izbirali med jamarskimi društvi. Odzvala so se tri društva: Jamarsko društvo Rakek, ki je očistilo štiri jame ter Jamarski klub Železničar in Društvo za raziskovanje jam Luka Čeč iz Postojne s po eno jamo. Nekaj jam bo očiščenih skupaj s hrvaškimi jamarji, s čimer se krepijo tudi meddržavni stiki na področju jamarstva in varovanja okolja.

Med oktobrom 2010 in januarjem 2011 so bile na slovenskih tleh končane štiri akcije čiščenja jam, in sicer v Marnošnovi jami pri Materiji, Pokčevi jami pri Prapročah (3, 4), Šimenkovi jami nad Virom pri Stični in v jami Majekavc pri Kozini. Slednja je bila med tehnično najbolj težavnimi, saj so odpadki ležali na dnu nad 10 m širokega in 55 m globokega brezna. Količina odstranjenih odpadkov, ki so bili odloženi na komunalno deponijo oz. uporabljeni za reciklažo

occurrence of waste underground needs to be taken seriously until a negative impact on the environment can be excluded.

On the basis of data from the Caves Register of the Karst Research Institute and an inspection of the terrain, we selected six caves in Slovenia that lie in the catchment areas of important water sources. The cave Šimenkova jama lies in the catchment area of the spring at Vir pri Stični which is an important ecological area from the historical point of view because it was here that the first scientifically described olm, *Proteus anguinus*, was found. The other five caves are in the catchment area of the Rižana spring which represents a principle source of water for the Slovene coastal region. It is worrying that some caves were excessively polluted with waste and that we would be unable to clean them up with the means at our disposal (e.g. Brezno pod Revo near Kozina), while others were entirely filled up and their position was impossible to determine (e.g. Zasuto brezno near Polžanska pečina). With others again, the risk of potentially contracting diseases was too great (e.g. Golobnica near Prešnica). Another key factor in the selection process was access to the cave, because in past decades the paths leading past the caves, from where waste was transported to them, have become overgrown and access would not be possible without clearing away vegetation. The total quantity of waste was estimated at 76 m³. The cleanups were carried out by caving clubs chosen via a call for applications. Three caving clubs applied: JD Rakek (which cleaned up four caves), JK Železničar and DZRJ Luka Čeč of Postojna (one cave each). Some caves will be cleaned up in conjunction with Croatian cavers, in this way strengthening contacts between the two countries in the fields of caving and environmental protection.

Between October 2010 and January 2011 four cave cleanup operations were completed in Slovenia: in the caves Marnošnova jama near Materija, Pokčeva jama near Praproče (3, 4), Šimenkova jama above Vir pri Stični, and Majekavc near Kozina. The latter was among the technically most demanding because the waste was situated at the bottom of an above 10 m wide and 55 m deep shaft. The quantity of the removed waste deposited in the municipal landfill or used for (kovine), znaša 57 m³. Med nevarnejše odpadke lahko uvrstimo elektronske komponente televizijskih in radijskih sprejemnikov (PCB in težke kovine), ostanke embalaže z olji in lepili, avtomobilske motorje, ostanke zdravil, akumulatorje in baterije. Pri čiščenju so bila najdena tri neeksplodirana ubojna sredstva, v Pokčevi jami pa je obstajala nevarnost kontaktnih okužb z vraničnim prisadom.

Ugotavljamo, da je z zagotovitvijo finančnih sredstev, s strokovnim izborom lokacij za čiščenje, pripravljenostjo jamarskih društev za sodelovanje in z medijsko odmevnostjo čistilnih akcij cilj zdajšnjega in prihodnjega izboljšanja kakovosti bivalnega okolja za ljudi in podzemne živali ustrezno dosežen.

### 12.2.3 Biospeleološke raziskave

V okviru KUP projekta smo predvideli tudi izvedbo leto in pol trajajočih biospeleoloških raziskav v šestih izbranih jamah v Sloveniji in ravno tolikšnem številu na Hrvaškem. Za to smo se odločili predvsem zaradi dejstva, ker se lokalni prebivalci na krasu vse manj zavedajo, kako bogato okolje jih obdaja, ne nazadnje pa so podatki pomanjkljivi tudi v strokovnih evidencah. Biospeleološke raziskave bodo prinesle natančen popis in delno številčnost podzemnih živalskih vrst v izbranih jamah, izmerjeni pa bodo tudi klimatski parametri habitata v kraških jamah (temperatura, vlaga). Raziskave izvaja slovensko-hrvaška ekipa biospeleologov (Hrvaško biospeleološko društvo in Biotehniška fakulteta iz Ljubljane v sodelovanju s Slavkom Polakom, specialistom za podzemne hrošče), s čimer je še dodatno poudarjen meddržavni značaj projekta. Za prenos strokovnega znanja med lokalne prebivalce bo poskrbljeno z javnimi predavanji in dokumentarnim filmom, za prenos znanja k strokovnjakom s področja krasoslovja pa na strokovnih srečanjih, kakršna je bila na primer 19. mednarodna krasoslovna šola »Klasični kras«, posvečena varovanju podzemnega krasa.

recycling (metals) is 57 m³. Hazardous waste includes electronic components of televisions and radios (PCBs and heavy metals), the remains of oil packaging, adhesives, car engines, medicines, batteries and accumulators. During the cleanup operation three items of unexploded ordnance were discovered while in the case of Pokčeva jama there was a risk of anthrax infection.

We consider that with the provision of funding, the expert selection of the cleanup locations, the willingness of caving clubs to cooperate and the media reaction to the cave cleanup operations, the aim of present and future improvement in the quality of the living environment for people and subterranean fauna has been satisfactorily achieved.

### 12.2.3 Biospeleological research

The Karst Underground Protection project also included an 18-month biospeleological research project in six selected caves in Slovenia and the same number in Croatia. This was decided upon above all because the local population in the karst is growing progressively less aware of the richness of the environment that surrounds them. The biospeleological research project will provide an exact inventory of the animal species present in selected caves along with some information on their numbers. The climatic parameters of the karst cave habitat (temperature, humidity) will also be measured. The research is being carried out by a joint Slovenian-Croatian team of biospeleologists (from the Croatian Biospeleological Society and the Faculty of Biotechnology at the University of Ljubljana, in conjunction with Slavko Polak, a specialist in subterranean beetles), which further emphasises an international character of the project. The transfer of specialist knowledge to the local population will be provided for by means of public lectures and documentary film, while the transfer of knowledge to specialists in the field of karstology takes place at specialist events such as the 19th International Karstological School »Classical Karst« was, dedicated to the theme of the karst underground protection.

## Sklep

S financiranjem tega projekta iz sredstev Inštrumenta za predpristopno pomoč (IPA) bo zagotovljeno informiranje o pomenu krasa, očiščenih nekaj jam na obeh straneh državne meje med Republiko Slovenijo in Republiko Hrvaško, narejen popis podzemeljske favne v izbranih jamah in ugotovljeni okoljski parametri v njih. Implementacija projekta pa bo zagotovila čezmejno sodelovanje ustanov, pristojnih za preučevanje in spremljanje stanja krasa ter za njegov razvoj.

## Conclusion

Through the financing of this project with funds from the Instrument for Pre-Accession Assistance (IPA), information will be provided on the importance of karst, a number of caves will be cleaned up on both sides of the national border between the Republic of Slovenia and the Republic of Croatia, an inventory will be made of subterranean fauna in selected caves and environmental parameters in these caves will be established. The implementation of this project will ensure the cross-border cooperation of institutions responsible for studying and monitoring the state of the karst and for its progress.

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