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## **RECENT DEVELOPMENTS IN KNOWLEDGE OF THE HYDROGEOLOGY OF THE CLASSICAL KARST**

### **NOVA HIDROGEOLOŠKA SPOZNANJA S KRASA**

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**Izveček**

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**Franco Cucchi & Paolo Forti & Enrico Marinetti & Luca Zini: Nova hidrogeološka spoznanja s Krasa**

Razumevanje kraških pojavov in razvoj hidrogeološkega modela, ki bi bil uporaben povsod na razvitem krasu, bi bilo splošno koristno. Kras, ki je že razmeroma dobro raziskan in poznan, je lahko idelano področje za multidisciplinarne raziskave. Njegova geologija, hidrologija in zgodovina sta predmet raziskav že od 16. stoletja dalje. Dandanes kontinuirni monitoring podzemeljskih voda, digitalni model reliefa, odkritje in raziskava nekaterih novih jam je omogočilo izdelavo karte ranljivosti. Na podlagi izsledkov teh odkritij predlagajo avtorji sodelovanje evropskih raziskovalcev pri razvoju hidrodinamičnega modela najbolj znanega kraškega predela na svetu, to je klasičnega Krasa.

**Ključne besede:** zakrasevanje, hidrogeologija, ranljivost vodonosnika, Kras, Italija, Slovenija.

**Abstract**

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**Franco Cucchi & Paolo Forti & Enrico Marinetti & Luca Zini: Recent developments in knowledge of the hydrogeology of the Classical Karst**

The Classical Karst may well be the best area for polythematic researches. It would be useful to understand karst phenomena and create a hydrogeological model valid for all mature karst. The Karst area is quite well studied and known. The geology, hydrology and its history have been studied since the 16<sup>th</sup> century. Nowadays the continuous monitoring of hypogean waters, the elaboration of a Digital Elevation Model, the discovery of some new caves and their study has permitted the processing of the vulnerability map. On the basis of the results of all of these researches, we propose activating a co-operation between European researchers to develop hydrodynamic models of the most well known karst in the world: the Classical Karst.

**Key words:** karstification, hydrogeology, aquifers vulnerability, Karst, Italy, Slovenia.

## INTRODUCTION

The problem of obtaining full knowledge of a karst area and of its evolution may be solved only on the basis of interdisciplinary and polythematic studies. In fact the detailed analysis of a karst area requires the co-operation of many scientists from different fields and the acquisition of plenty of data.

Detailed knowledge of epigean and hypogean karst morphologies and their evolution in time is the single method by which karst water resources may be defined in terms of quantity and quality and how their intrinsic vulnerability may be assessed in order to plan for their correct exploitation.

Jakucs was the first to point out the complexity of karst (Jakucs, 1977), and his sketch, with several different disciplines that interfere with each other in driving the evolution of karst morphologies in a given area, is well known world-wide (Fig. 1). Even if most karst researchers are aware of Jakucs's sketch, very few apply it; in fact, most of karst research is monothematic or at least bi- or trithematic, never complex.

Absolutely rare are polythematic researches; among them are those performed in Sicily and Abruzzo by Italian researchers (Agnesi, Macaluso, 1989; Burri, 1994) and in the Slovak Ore Mountains (Western Carpathians) by Slovakian scientist (Novotný, Tulis, 1989).

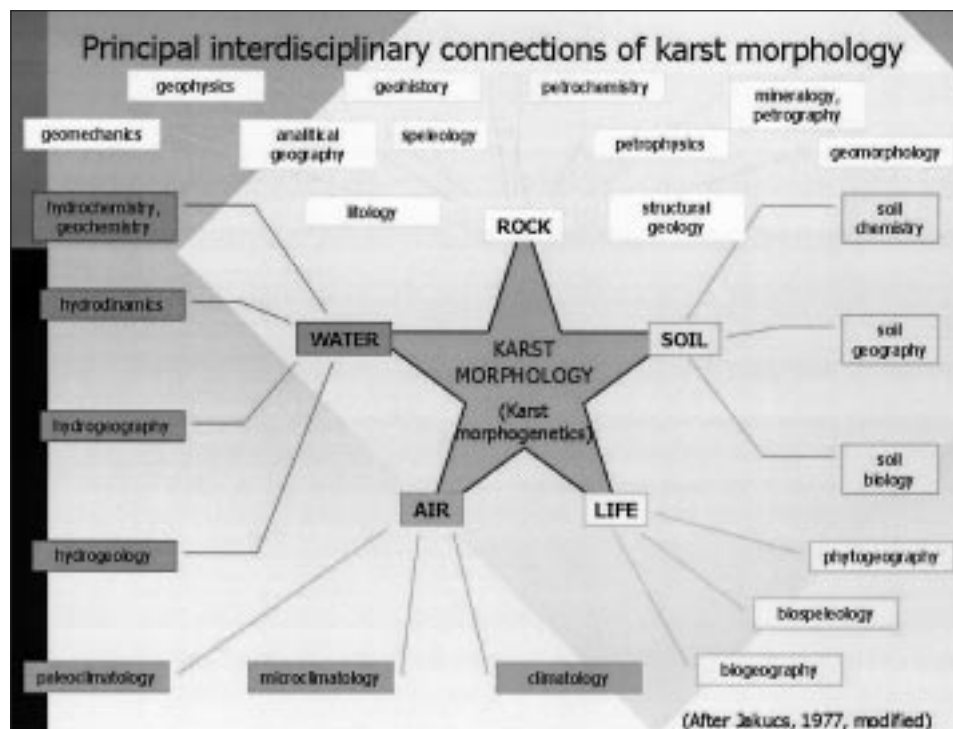


Fig. 1: Jakucs sketch (rendition): disciplines which help us to understand Karst phenomena.  
Sl. 1: Discipline, ki pripomorejo k razumevanju kraških pojavov (prerisano iz Jakucs, 1977).

This partially depends upon the attitude of cavers, who rarely have good relationships with anybody outside their communities. But the same behaviour may be observed, for example, also among biospeleologists and archaeologists, just to cite some of the scientists involved in karst; in fact, they normally are not interested in sharing their observations and findings with other scientists.

Moreover, due to its attitude and history, a “scientific school” often privileges a peculiar topic of karst research, sometimes pretending to ignore other aspects, the data of which may conflict with the presented results.

### THE CLASSICAL KARST

The Classical Karst (Fig. 2), due to its complexity, is probably the area in which co-operation between different “karst schools”, and/or research teams, may produce the best results. Most of the characteristics of the “Classical Karst” are known from the general point of view and often even in detail.

Morphologically the dimension, the form and the relief of the whole area are well known: maps at different scales exist. Adjacent morphologic units have been studied and Digital Elevation Mod-

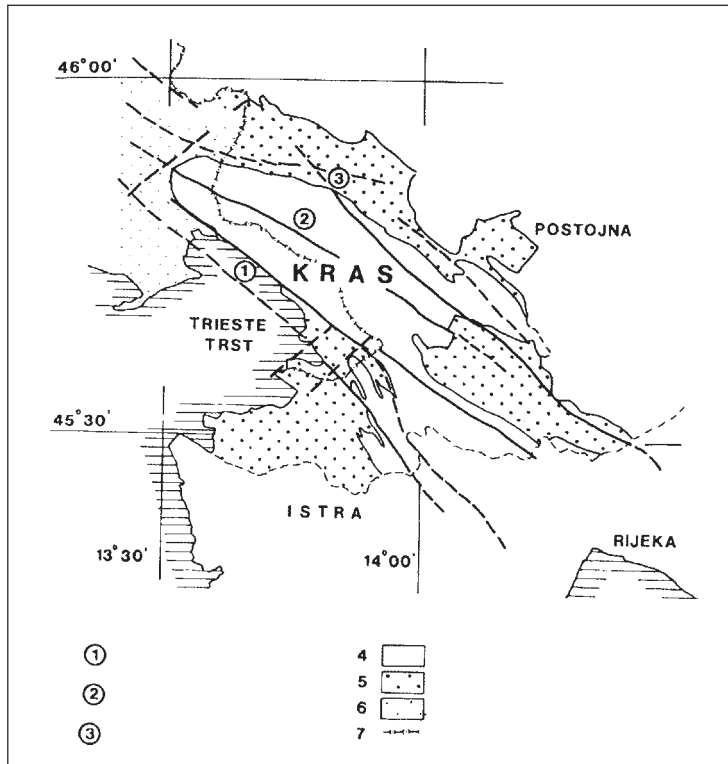


Fig. 2: The Classical Karst (After Habič, 1984):  
 1 - Trieste fault;  
 2 - Divača fault;  
 3 - Raša fault;  
 4 - Carbonate rocks;  
 5 - Flysch;  
 6 - Alluvial sediments;  
 7 - National border.  
 Sl. 2: Klasični Kras (po Habiču, 1984):  
 1 - tržaški prelom;  
 2 - divaški prelom;  
 3 - raški prelom;  
 4 - karbonatne kamnine;  
 5 - fliš;  
 6 - aluvijalni nanosi;  
 7 - državna meja.

els have been prepared (Fig. 3). The structural settlement, the outcropping formations and their lithology have been investigated in detail. Many of the old and new studies should be reinterpreted



*Fig. 3: Digital Elevation Model of the Karst of Trieste elaborated with IDRISI using 1:5.000 maps. In white we have drawn some lineaments and linear features which we observed after analyzing aerial photos.*

*Sl. 3: Digitalni model reliefa Tržaškega krasa izdelan s pomočjo paketa IDRISI na osnovi kart 1:5000. Belo so vrisani prelomi in linearne oblike, določene s pomočjo zračnih posnetkov.*

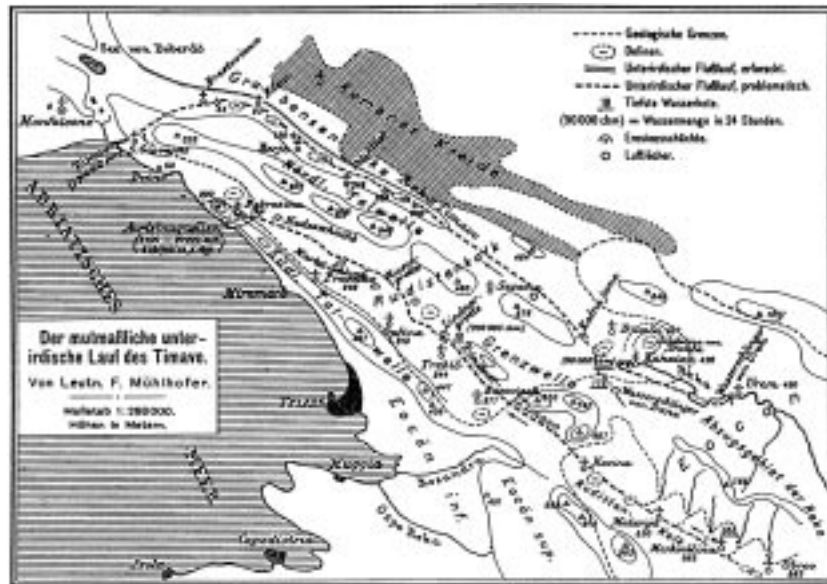


Fig. 4: Geomorphological map from the early 20<sup>th</sup> century (After Mühlhofer, 1907).  
 Sl. 4: Geomorfološka karta z začetka 20. stoletja (po Mühlhoferju, 1907).

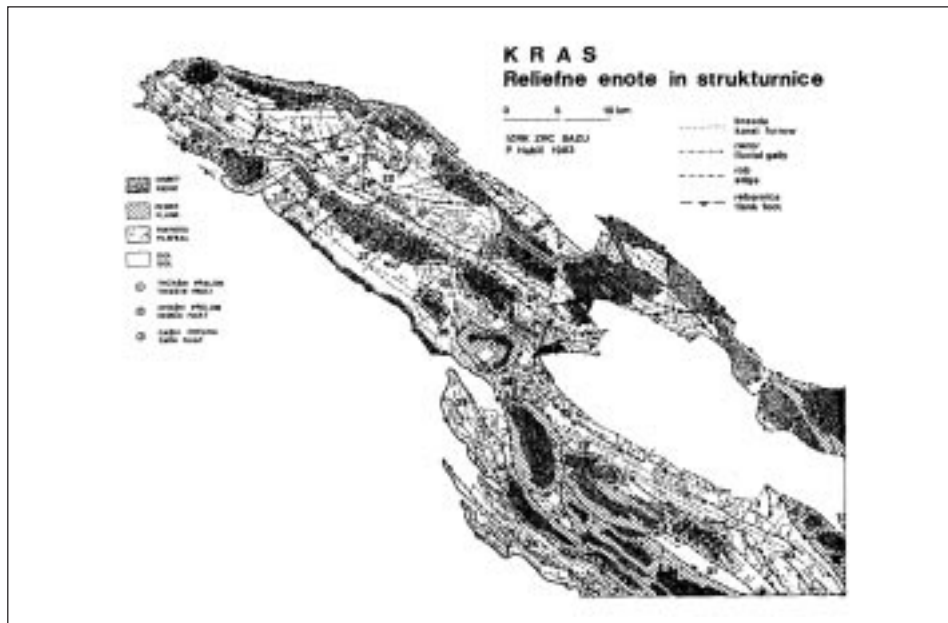


Fig. 5: Relief units and structural lines (After Habič, 1984).  
 Sl. 5: Reliefne in "strukturnice" (po Habiču, 1984).

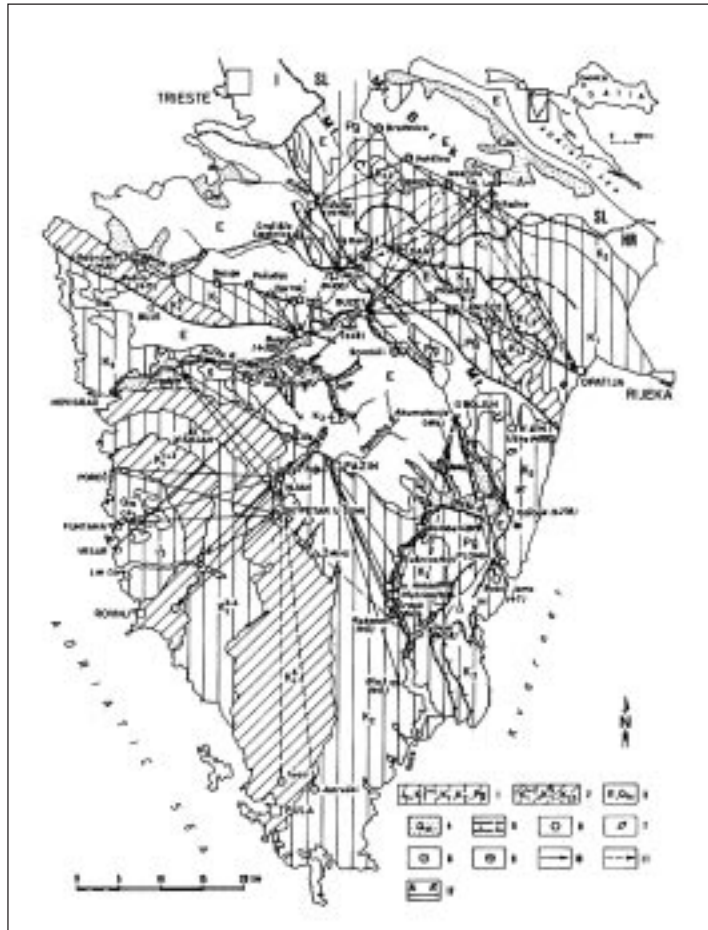


Fig. 6: Hydrogeological map of Istria: 1 - limestones (very permeable); 2-Interbedded limestones and dolomites, marly limestones and lime (partly less permeable); 3 - Flysch and terra rossa (impermeable deposits); 4 - sands, gravels and clays (variations of vertical and lateral permeability); 5 - normal and reverse fault; 6 - karst spring; 7 - coastal spring; 8 - well; 9 - sink-hole; 10 - proved underground connection; 11 - assumed underground connection; 12 - line of cross-section; (After Urumović et al., 1997).  
 Sl. 6: Hidrogeološka karta Istre: 1 - apnenci (zelo prepustni); 2 - menjavanje apnencev in dolomitov, lapornih apnencev in krede (deloma slabše prepustne); 3 - fliš in terra rosa (neprepustni nanosi); 4 - peski, prod in gline (vertikalno in lateralno spremenljiva prepustnost); 5 - normalni in reverzni prelom; 6 - kraški izvir; 7 - priobalni izvir; 8 - vodnjak; 9 - vrtača; 10 - dokazane podzemne povezave; 11 - predpostavljene podzemne povezave; 12 - prerez (po Urumoviću s sod., 1997).

to obtain an exhaustive and modern geomorphological overview of the region, while dating of the geomorphic events are still few or lacking (Figs. 4, 5).

Speleological explorations over the last two centuries have supplied a lot of cave surveys (2000 in Italy and even more in Slovenia) - even if the accuracy differs between them - but plenty of deep karst phenomena are still left to be discovered and explored. Moreover, almost none of the explored caves have been studied from the geological, geomorphological and sedimentological point of view (Lazzaro Jerko Cave, Trebiciano Abyss, Padriciano Cave - in Italy -, Postojna Cave, Kacna Jama Cave, Skocjanske Cave - in Slovenja).

On the other hand the climate is well known thanks to several active meteorological stations inside and outside the caves since dec-

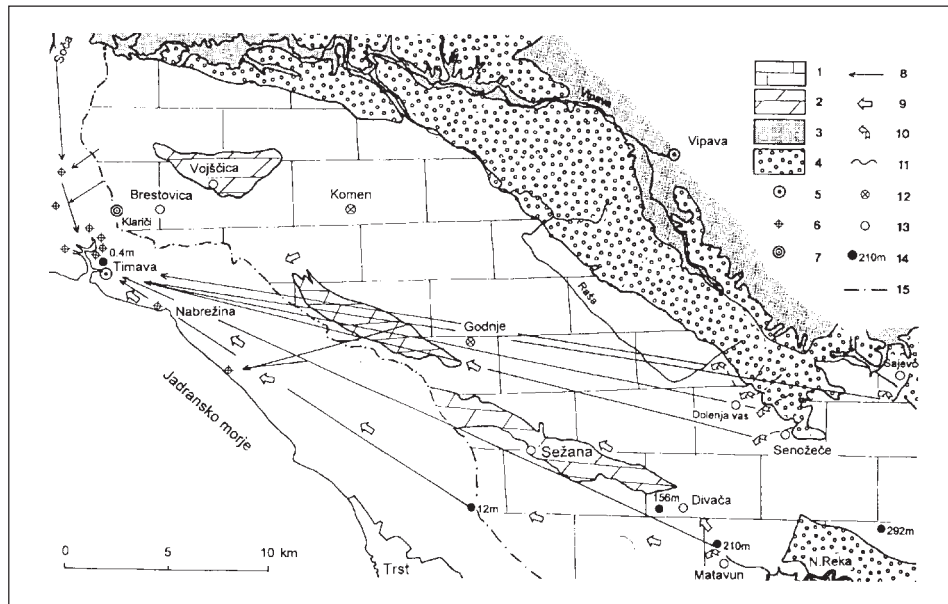


Fig. 7: A comprehensive hydrogeological map of Karst (After Novak 1993): 1 - karst fissure aquifer; 2 - less permeable dolomite; 3 - intergranular aquifer; 4 - impermeable beds; 5 - spring; 6 - smaller spring; 7 - pumping station; 8 - underground connection determined by water tracing test; 9 - presumed underground flow of the Notranjska Reka; 10 - sinking stream; 11 - superficial stream; 12 - place with precipitation station; 13 - settlement; 14 - cave with permanent stream; 15 - state border.

Sl. 7: Podrobna hidrogeološka karta Krasa (po Novaku, 1993): 1 - kraški razpoklinski vodonosnik; 2 - manj prepustni dolomit; 3 - intergranularni vodonosnik; 4 - neprepustne plasti; 5 - izvir; 6 - manjši izvir; 7 - črpalna postaja; 8 - podzemna povezava določena s sledilnim poskusom; 9 - predpostavljene podzemni tok Notranjske Reke; 10 - ponikalnica; 11 - površinski tok; 12 - padavinska postaja; 13 - naselje; 14 - jama s stalnim vodotokom; 15 - državna meja.

ades ago. The actual knowledge of pedology and vegetation are good even if the available thematic maps are normally extremely simplified. Only those related to "terra rossa" and/or other paleokarst deposits are recent and very well detailed (Lenaz et al., 1996; Zupan Hajna, 1992).

From the hydrogeological point of view the surface hydrographic network, the flow regime and the chemical behaviour of the rivers and springs are sufficiently known (Figs. 6, 7, 8), sometimes even from continuous monitoring (Kranjc, 1997; Reichert et al., 1997; Urumović et al., 1997).



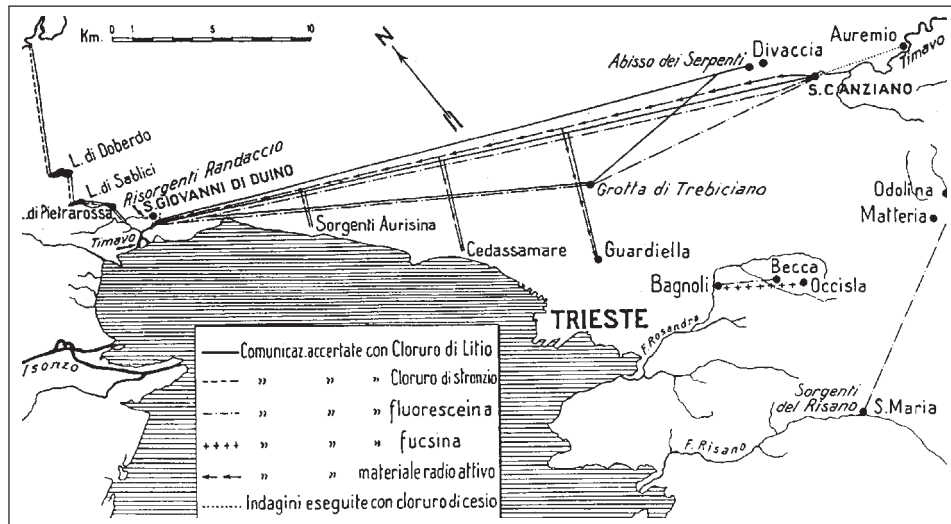


Fig. 8: Assumed underground connection of Karst aquifer (After Timeus, 1928).

Sl. 8: Predpostavljene podzemne povezave v vodonosniku Krasa (po Timeusu, 1928).

## PRESENT DAY STUDIES

Perhaps today it is easier to prepare a hydrogeological model for the Classical Karst: plenty of research and studies are now available, to be used as a starting point to work out such a synthesis. Among them are the several studies on speleogenesis and hypogean hydrology performed by scientists from Trieste (Boegan, 1938; Civita et al., 1993; Forti et al., 1978), as well as those carried out by Slovenian and Croatian researchers on geology and geomorphology of the superficial cavities and on hydrogeology (Bonacci, 1997; Habič, 1984; Habič et al., 1989; Mihevc et al., 1998; Jurkovšek et al., 1996; Placer, 1981; Slabe, 1996).

The geological knowledge of the Trieste Karst from the lithological (Cucchi et al., 1987; Cucchi et al., 1989; Ulcigrai, 1977) and structural (Carulli, Cucchi, 1981) point of view has been largely improved in order to define the local preferential trends for cave development. Several evidences of recent movements and structural evolution have been observed (Carulli et al., 1981; Cucchi et al., 1979).

The different "geological" geometries (lithology, structural settlement, degree of rock mass fracturation) have been compared with the "speleological" ones (direction, slope, morphology of the hypogean voids). In particular, a very large number of experimental measurements of the intensity and the geometry of the rock discontinuities have been carried out (Figs. 9, 10).

Starting from aerial and satellite images and utilising the information tools now available a Digital Elevation geo-referenced Model for the whole area has been produced (Fig. 3). Most of the natural cavities known in the area have been analysed from the point of view of the geometry and

morphology of their voids, to obtain the preferential directions for their development both in the early stage and the mature one (Cucchi, 1975). In fact it must be stressed here that the Classical Karst developed over the last 8-10 millions years, and it is still developing.

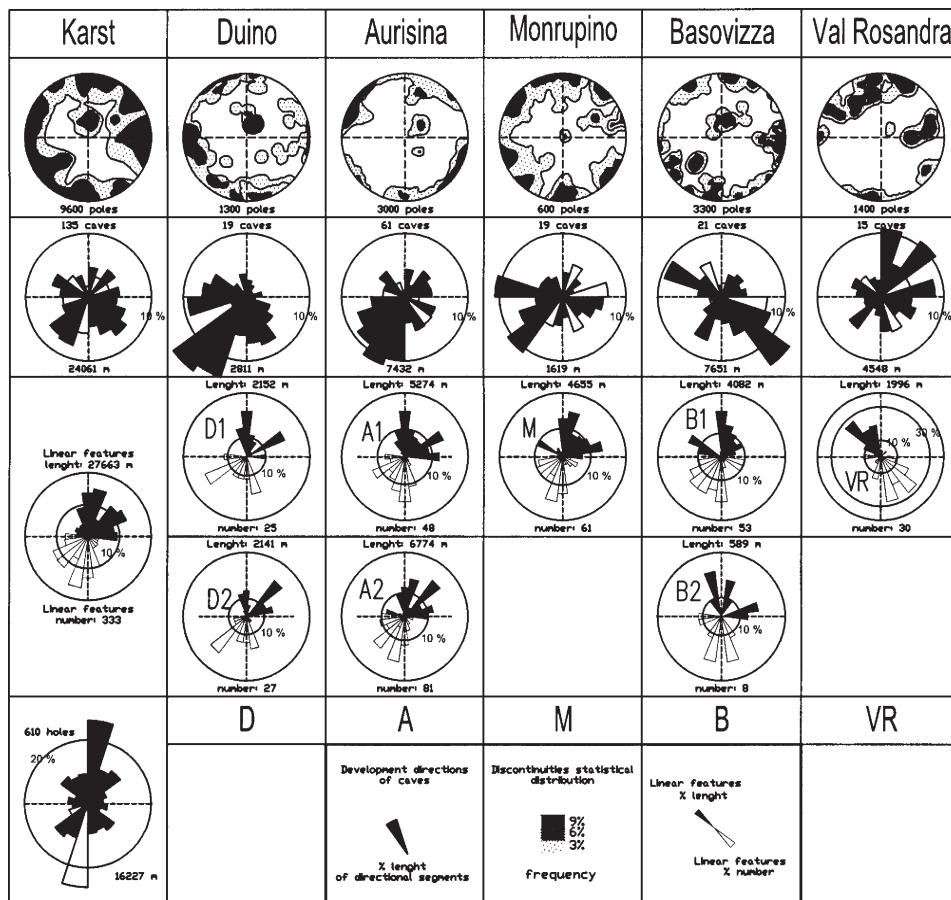
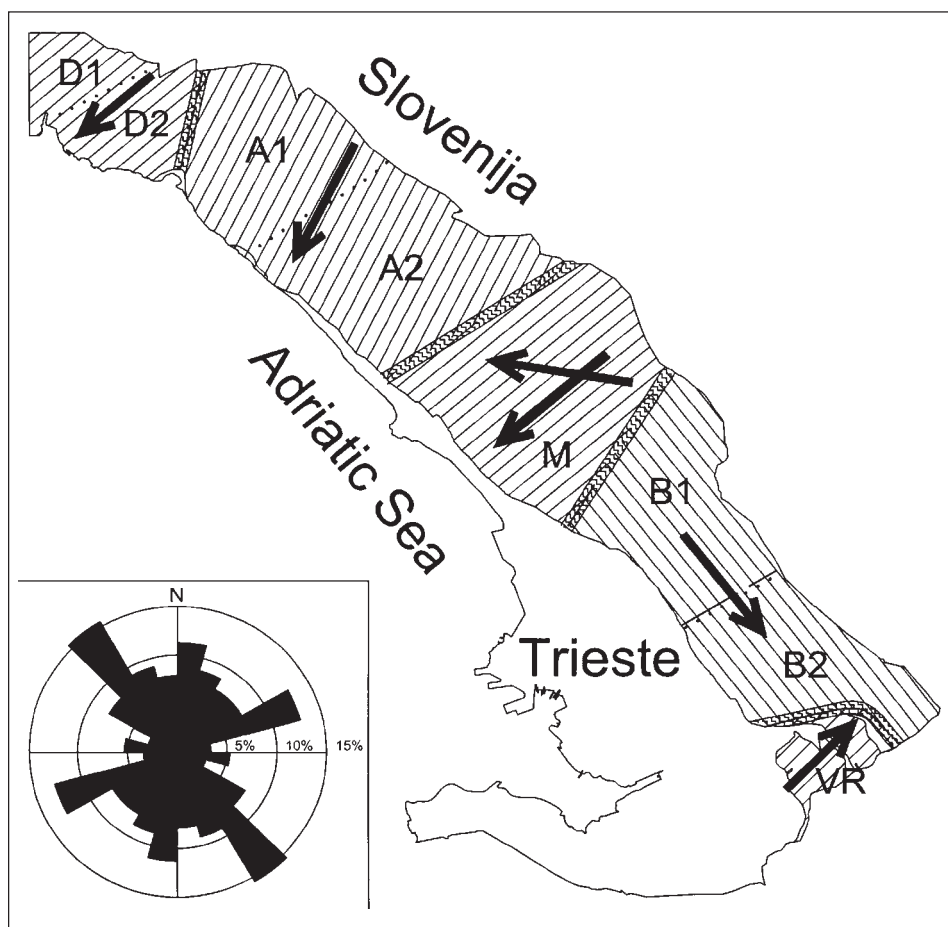


Fig. 9: From the structural point of view and from karst landforms (holes, caves, dolines, etc.), the Karst of Trieste can be divided into several different areas: first row - distribution of discontinuities; second row - preferential directions of cave development; third and fourth rows - direction, length and number of linear features (by aerial photos); fifth row - vertical planes conditioning holes (See also Fig. 10).

Sl. 9: S strukturnega in stališča kraških površinskih oblik (luknje, jame, vrtače, itd.) lahko Tržaški Kras razdelimo na več območij: prva vrsta - porazdelitev diskontinuitet; druga vrsta - preferenčna smer razvoja jam; tretja in četrta vrsta - smer, dolžina in število linearnih struktur (iz zračnih posnetkov); peta vrsta - navpične ploskve, ki omogočajo nastanek lukenj (glej tudi Sl. 10).

Using the “flow direction prediction” method by Eraso (Eraso, 1986; Eraso, Cucchi et al., 1995) the theoretical water flow on the basis of a structural model was found but this does not fit with the real situation. The speleological model also does not respect the general water flow which is from SE to NW, e. g. from Škocjan to the spring area (Fig. 10).



*Fig. 10: The recognized different areas: D - Duino area; A - Aurisna area; M - Monrupino area; B - Basovizza area; VR - Rosandra Valley area. Left corner: flow direction prediction rose diagram drawn from “tectoglyphs” - stylolites, veins, faults - following “Eraso method” (Rendition, taken from Eraso et al., 1995).*

*Sl. 10: Razpoznavna področja: D - devinsko; A - nabrežinsko; M - repenjsko; B - bazoviško; VR - dolina Glinščice. Levi vogal: diagram predvidenih smeri toka na podlagi “tektoglifov” - stilolitov, žil, prelomov po Erasovi metodi (iz Eraso et al., 1995).*

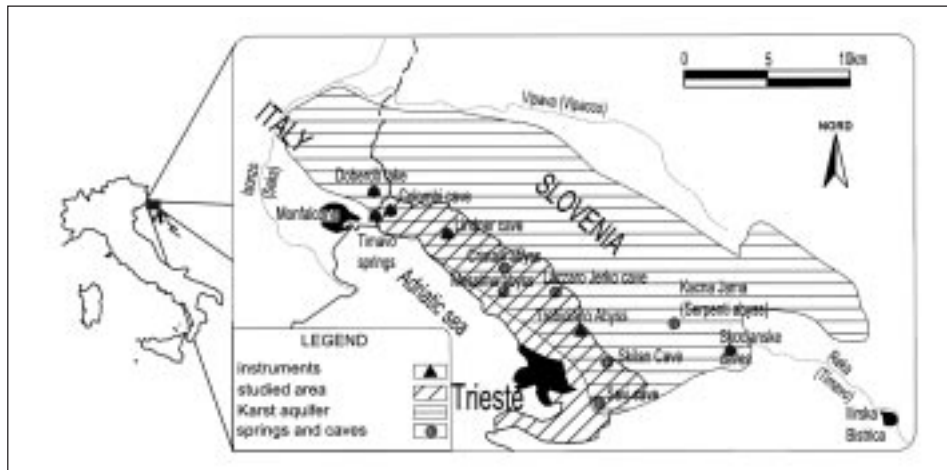


Fig 11: Classical Karst: studied and monitored caves.  
 Sl. 11: Kras: raziskane jame in jame z monitoringom.

Thanks to all these studies it has been proven that the geologic structural characteristics are the main controlling factors in the evolution of the Karst of Trieste: in all the sectors in which the karst area may be subdivided, the maximum strata dip and the main subvertical discontinuities are the preferential directions for the development of the cave galleries.

The caves which are still affected by active flows (Škocjanske Cave, Kačna Cave, Trebiciano Abyss, Lazzaro Jerko Cave - just discovered -, Timavo Springs), have flow directions in contrast with the general (regional) flow (Figs. 11, 12, 13).

Sinkholes and pits (always subvertical and extremely abundant in the area) are all normally controlled by a single well-defined discontinuity with a structural axis between N-S and NNE-SSW, and their genesis is by far younger than that of the draining network of phreatic tubes.

Geomorphologic surveys have shown that no surface evidence exists for faults which controlled the evolution of some caves; moreover, several collapse dolines show a far wider vertical dimension (even if sometimes masked by subsequent collapses and infillings) than spatial (the depth to width ratio often being 10:1).

In order to reconstruct the groundwater dynamics plenty of hydrochemical and geochemical analyses have been performed and recently several data loggers have been placed in the area in order to have a continuous record for the chemistry and the hydrodynamics of the karst waters (Figs. 14, 15). These data can be easily compared with rainfall, with flow regimes of the rivers (Reka, Vipava/Vipacco, Soča/Isonzo) which feed the karst aquifer, and with the discharge of the spring complex (Cucchi et al., 1997; Flora et al., 1990; Gemiti, 1994; Gemiti, Licciardello, 1977; Krivic, 1982).

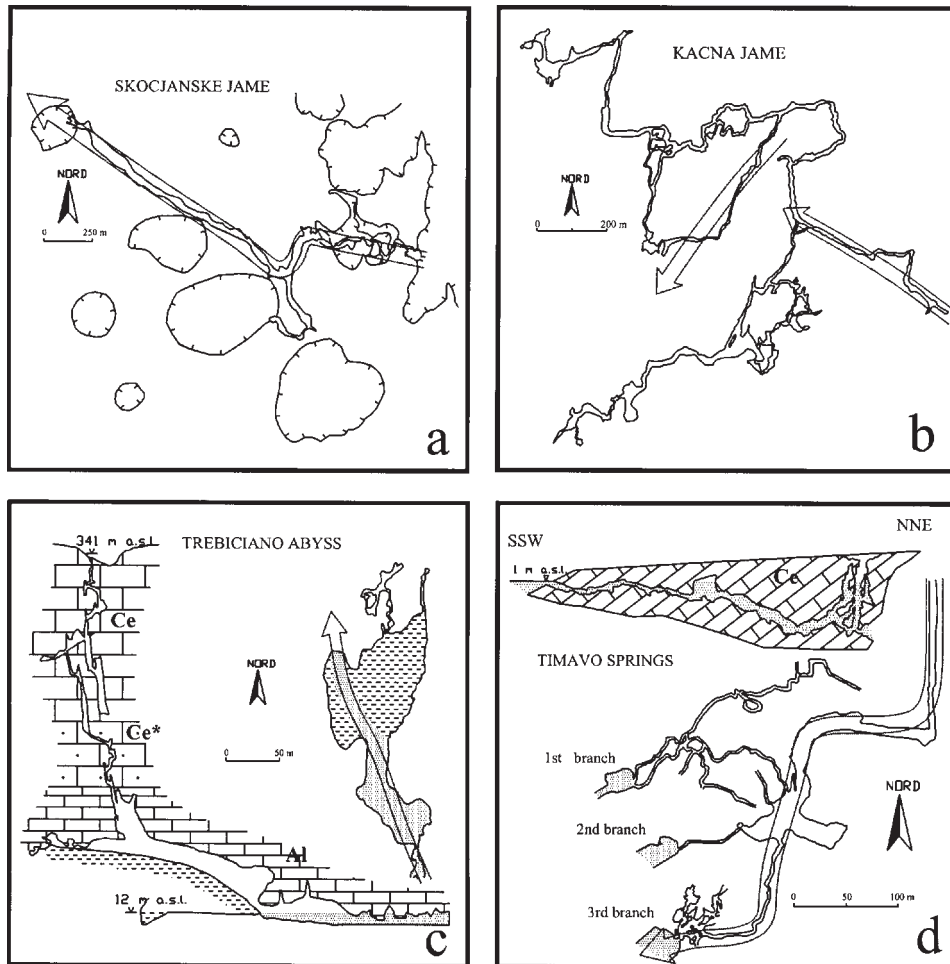


Fig. 12: a) in the Škocjanske Cave water flows to the North-West; b) the gallery network in Kačna Cave influences the variability of the drainage direction: resultant is East to West; c) in the Trebiciano Abyss inside the horizontal deep gallery (Ce: Cenomanian Rudist limestone, Ce\*: Cenomanian limestone, Al: Albian-Cenomanian dolostone) the Timavo river flows from South to North; d) in the flooded hypogean network of the Timavo springs the water flows from North to SSW (Ce: Cenomanian limestone).

Sl. 12: a) skozi Škocjanske jame teče voda proti SZ; b) mreža rogov v Kačni jami vpliva na spreminjanje smeri odtoka: rezultanta je smer V - Z; c) skozi Labodnico teče Timava po globokem vodoravnem rovu od J proti S (Ce: cenomanijski rudistni apnenec, Ce\*: cenomanijski apnenec, Al; albijsko - cenomanijski dolomit) d) skozi potopljeno podzemno mrežo izvirov Timave teče voda od S proti JJZ (Ce: cenomanijski apnenec).

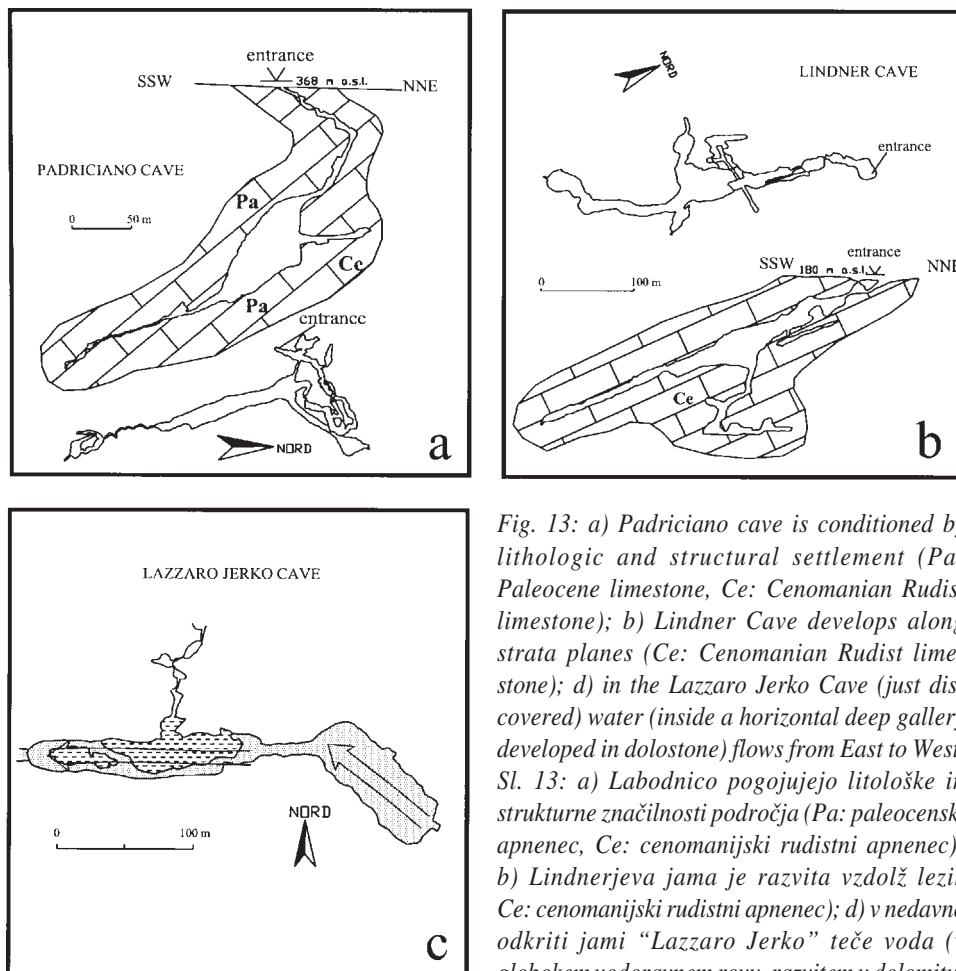


Fig. 13: a) Padriciano cave is conditioned by lithologic and structural settlement (Pa: Paleocene limestone, Ce: Cenomanian Rudist limestone); b) Lindner Cave develops along strata planes (Ce: Cenomanian Rudist limestone); d) in the Lazzaro Jerko Cave (just discovered) water (inside a horizontal deep gallery developed in dolomite) flows from East to West. Sl. 13: a) Labodnico pogojujejo litološke in strukturne značilnosti področja (Pa: paleocenski apnenec, Ce: cenomanijski rudistni apnenec); b) Lindnerjeva jama je razvita vzdolž ležik Ce: cenomanijski rudistni apnenec); d) v nedavno odkriti jami "Lazzaro Jerko" teče voda (v globokem vodoravnem rovu, razvitem v dolomitu) v smeri V - Z.

In fact it must be pointed out that in an area of a few square kilometers the groundwater comes out in some lakes and several springs; moreover, the base level can be reached through several natural cavities.

Continuous recording of temperature, conductivity, flow rate and base level and weekly analyses of the chemical behaviour for many waters are presently available thus allowing us to understand the hydraulic behaviours of the karst drainage and to test the hydrodynamic models proposed.

Moreover, the automatic instruments located in several points of the underground drainage in the last few years supply very useful data for the definition of the water flow inside the karst network.

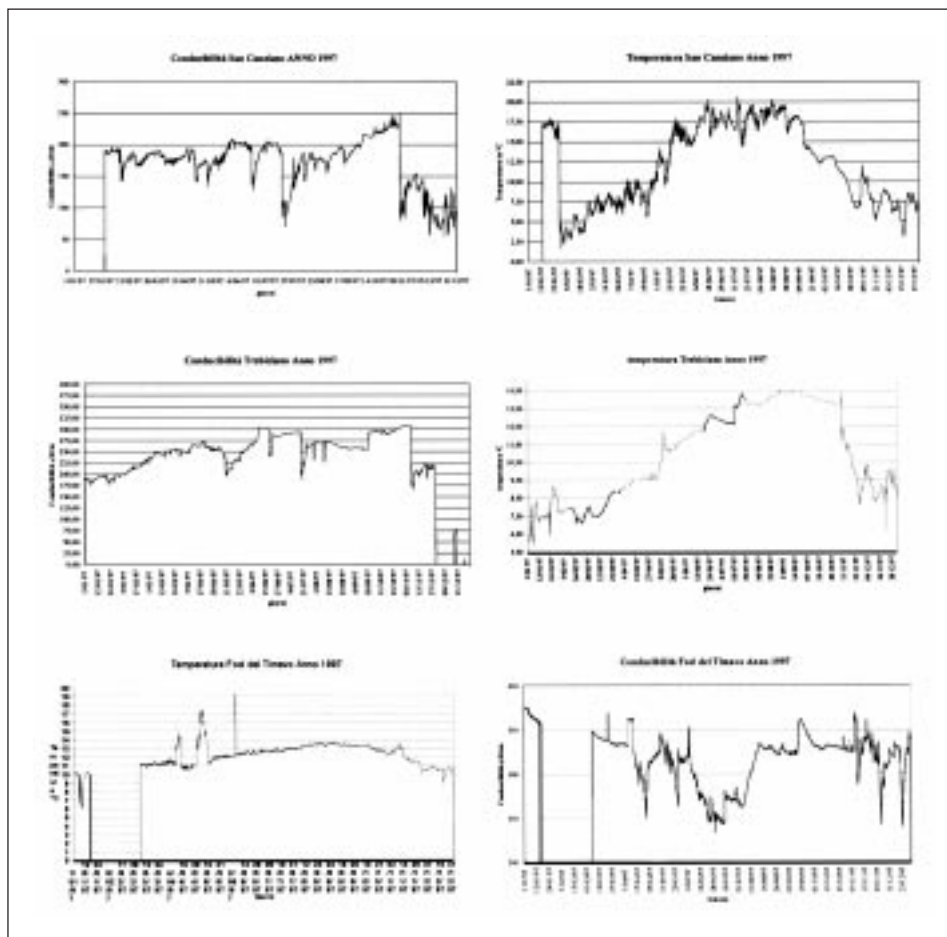


Fig. 14: Škocjanske Cave, Trebiciano Abyss, Timavo Springs: water conductivity and temperature during 1997.

Sl. 14: Škocjanske jame, Labodnica, izviri Timave: prevodnost in temperatura vode v letu 1997.

Plenty of dye tracing experiments have tested the connections between the recharge areas and the karst springs. Many other studies related to different aspects of karst hydrology and hydrogeology have been done in the last few years, however some important factors of the karst flows are still unknown. The location of real drainage flows, the volumes of preferential flows, and those of a discontinuous or diffuse nature have not yet been evaluated; the local flow directions are still undetermined and the values for the vertical and or horizontal permeability in the different hydrogeological situations are still unknown.

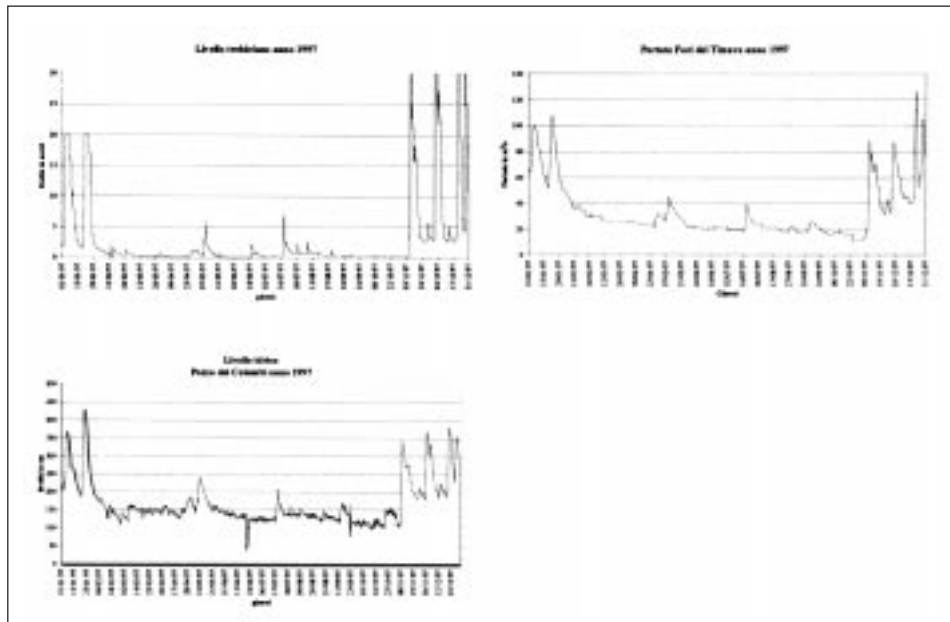


Fig. 15: Trebiciano Abyss, Colombi Cave, Timavo Springs: water level during 1997.  
 Sl. 15: Labodnica, jama "Colombi", izviri Timave; gladina vode v letu 1997.

### INTRINSIC VULNERABILITY

Recently maps of intrinsic vulnerability for the karst aquifer have been proposed. Aquifer vulnerability, intrinsic or natural, is defined as the specific susceptibility of aquifer systems, in their various parts and in their various geometric and hydrodynamic settings, to ingest and diffuse fluid or/and water-borne contaminants, the impact of which on the ground water quality is a function of space and time. The vulnerability of an underground water body is a function of a number of parameters: hydrolithology and hydrostructure of the hydrogeological system, nature of soil and overburden, recharge, ground water inflow-outflow processes, the physical and hydrogeochemical processes that produce the natural quality of water and the attenuation of the prevailing contaminants impacting the system.

In our researches, the SINTACS method to evaluate the aquifer's vulnerability to pollution is applied (Civita, De Maio; 1997). The program is based on a Parametric Point Count System model (PCSM) which has been specifically adapted to the peculiarities of karst environments and successfully tested in several of the main karst areas of Italy.

The acronym of the program comes from the initials (in Italian) of the seven parameters utilized in the computer algorithm: *Soggiacenza* (depth to groundwater), *Infiltrazione efficace* (net



recharge), *Non saturo* (unsaturated zone), *Tipo di copertura* (soil characters), *Acquifero* (aquifer types), *Conducibilita' idraulica* (hydraulic conductivity), *Superficie* (slope).

The depth of the piezometric level (both for confined or unconfined aquifers) referenced to the ground surface has a large significance on vulnerability because its absolute value together with the unsaturated zone characteristics, determine the travel time ( $\tau_{OT}$ ) of a water-borne or fluid contaminant and the duration of the attenuation process, in particular the oxidation process by atmospheric  $O_2$ .

The role that effective infiltration plays in aquifer vulnerability assessment is very significant because of the direct infiltration of pollutants on the one hand, and their dilution (first during the travel through the unsaturated zone and second within the saturated zone) on the other.

Inside the unsaturated zone a four dimensional process takes place in which physical and chemical processes interact to promote the contaminant attenuation. The unsaturated zone attenuation capacity is assessed starting from the hydro-lithologic features (texture, mineral composition, grain size, fracturing, karst development, etc.). A rating is assigned to the hydro-lithology of the unsaturated zone with the cell of the square grid as its base.

The type of overburden, and particularly of the soil, plays a very effective role in the attenuation process of contaminants travelling inside a hydrogeological system, and hence in aquifer vulnerability assessment and mapping. Soil is identified as an open, three-phase, accumulator and transformer of matter and energy sub-system which develops by physical, chemical and biological alteration of the bottom lithotypes and of the organic matter filling it. It is the first *defence line* of the hydrogeological system: inside the soil is where several important processes take place to enhance the attenuation capacity.

In vulnerability assessment models the aquifer characteristics describe the processes that take place below the piezometric level. Before a contaminant is mixed with groundwater it has more or less lost a relevant part of its original concentration during the travel through the soil and the unsaturated thickness. Those processes are, essentially: molecular and kinematic dispersion, dilution, sorption and chemical reactions between rock and contaminants.

Hydraulic conductivity represents the groundwater mobility capacity inside the saturated media, and thus the mobility potential of a water-borne contaminant having a density and viscosity almost the same as of groundwater. In the SINTACS assessment context, this parameter governs the hydraulic gradient and the equipotential flux across sections, the aquifer unit yield and flow velocity toward the effluences and the tapping work marking the *exposition* of risk targets.

Topographic slope is an important factor in vulnerability assessment because it governs the amount of surface runoff produced, the precipitation rate and displacement velocity of water (or a fluid and/or water-borne contaminant) over the equipotential surface. Moreover, the slope may be a genetic factor for the soil type and thickness, indirectly governing the attenuation potential of the hydrogeological system.

The SINTACS program calculates a numeric value for the intrinsic vulnerability which is then converted in % and finally subdivided into 6 vulnerability classes (Extremely High, Very High, High, Medium, Low, Very Low or Null) which are represented in a map by different colors.

We have used IDRISI for processing all the maps elaborated by SINTACS model. This GIS is very useful for the map overlaying that is essential to obtain the vulnerability maps. It does not use a square network, normally used for cartographic processing of SINTACS, but it works in pixels.

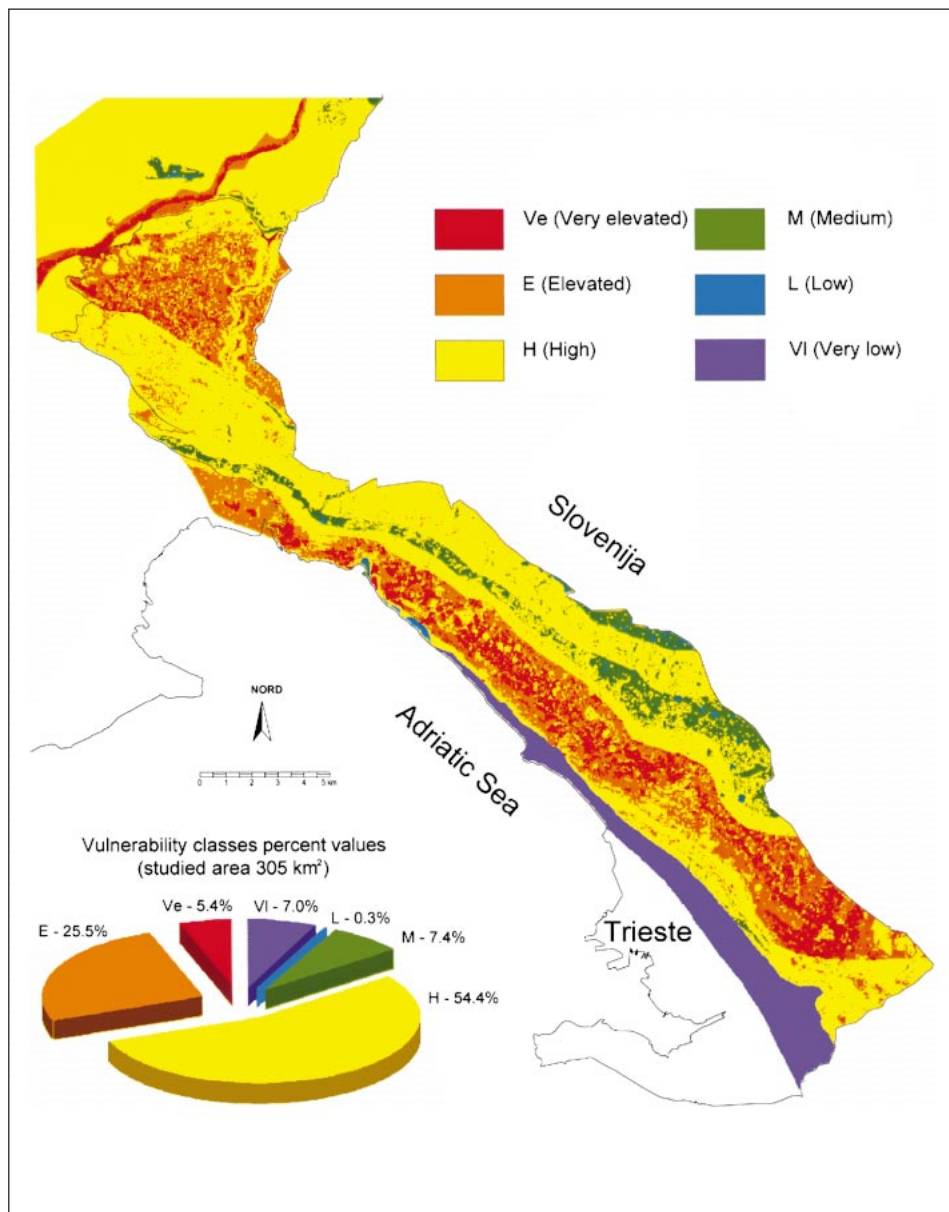


Fig. 16: The Intrinsic Vulnerability Map of the Italian part of the Classical Karst, processed with SINTACS (release 4) and IDRISI GIS, The map is georeferred on the Numerical Map 1:5.000 of Friuli-Venezia Giulia Region.

Sl. 16: Karta splošne ranljivosti italijanskega dela Krasa, izdelana s paketom SINTACS (verzija 4) in IDRISI GIS. Karta se navezuje na zemljevid 1:5.000 Furlanije - Julijske krajine.

So it is possible to choose the best definition for the final map and follow the natural borders of the studied area's limits by all parameters with more accuracy: our work has a base grid of 10 m fields (Fig. 16).

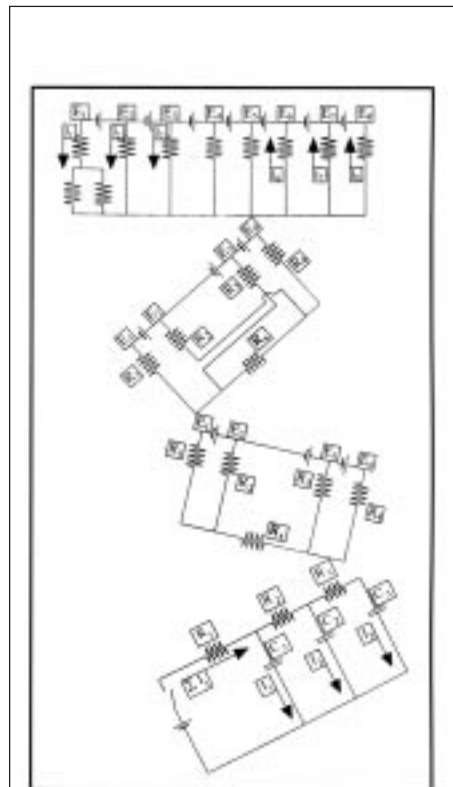
### KARST EVOLUTION MODEL

Practically, a hydrogeological model that fits all the already available data has not yet been proposed. Presently only hypotheses, or attempts of hypotheses, exist, none of which can justify the many self-contradictions resulting from a detailed analysis of the entirety of the thematic studies.

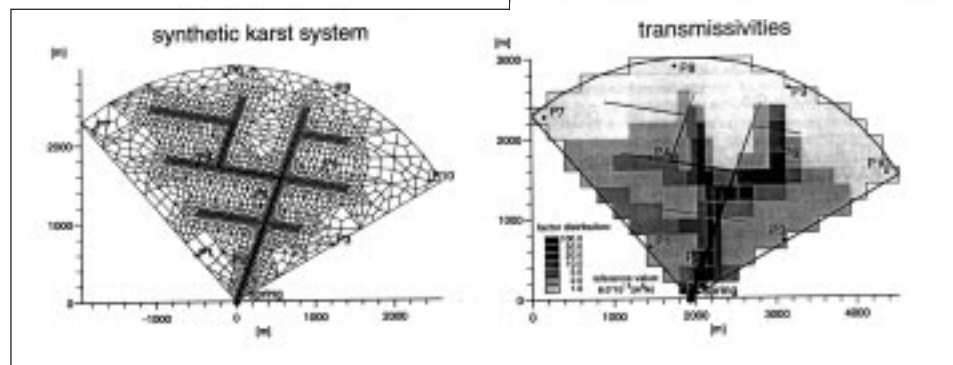
Moreover, the comparison of the mineralogical content of the "terre rosse" on the surface with the cave deposits allow us to state that the recharge came from several and not a single feeding basin.

Several are the blowing caves during the floods in the Timavo river, but they are not homogeneously distributed and they are not aligned along preferential directions.

The hydrodynamics are not unambiguous: floods derived from similar inputs may show



*Fig. 17: Examples of hydrogeologic models (After Badino, 1995 and Mohrlök et al., 1997).  
Sl. 17: Primeri hidrogeoloških modelov (po Badino, 1995, in Mohrlök et al., 1997).*



different delay times and different chemical behaviour, while identical flood diagrams may correspond to different climatic and hydrologic conditions.

There are many other incongruences which should be considered globally: a modern hydrogeological model for the Classical Karst may only result by strict cooperation between all the scientific teams presently working on it. If this will happen then the Classical Karst will become the new symbolic karst area, where scientists from all over Europe will test their hypotheses and models (Fig. 17) (Badino, 1995; Birsoy, 1997; Bodin, Razack, 1997; Dreybrodt, Siemers; 1997; Pulido-Bosch et al., 1993). It should become the first area in which a general methodology to study karst areas in a multidisciplinary manner can be defined in order to achieve hydrogeological models suitable for a safe exploitation of karst water resources.

The hydrogeological model is in fact absolutely needed not only to enhance the scientific knowledge on karst phenomena, but also to make the exploitation of hosted resources easier. However, modelling the hydrogeological behaviour of an area is extremely difficult due to the very high number of independent parameters which must be considered simultaneously. This is the challenge we have to face in Classical Karst.

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## NOVA HIDROGEOLOŠKA SPOZNANJA S KRASA

### Povzetek

Popolno razumevanje krasa in njegovega razvoja je mogoče le na osnovi inter- in multidisciplinarnega pristopa. Detajlna analiza kraškega področja je možna le ob sodelovanju raziskovalcev z različnih področij in na osnovi analize velikega števila podatkov. Kakovost in količino kraške vode ter ranljivost kraških vodonosnikov lahko definiramo le, če podrobno poznamo površinsko in podzemeljsko morfologijo kraškega področja in njegov razvoj. To je tudi osnova za pravilno izkoriščanje kraških voda.

Jakucs je prvi izpostavil kompleksnost krasa in njegov diagram prepletanja disciplin, potrebnih za študij razvoja kraške morfologije na nekem področju, je splošno poznan. Čeprav ga pozna večina krasoslovcev, ga le malokdo uporablja; še vedno je pristop k raziskavam krasa predvsem monotematski, morda bi- ali tridisciplinaren, a redko zares kompleksen. Pogosto se ne upoštevajo določeni aspekti obravnavane tematike ali podatki, ki so v nasprotju s pričakovanimi rezultati. Redke resnično politematske raziskave so bile opravljene na Siciliji, v Abruzzih in v Zahodnih Karpatih na Slovaškem.

Področje klasičnega Krasa je tisto, na katerem sodelovanje med različnimi krasoslovnimi šolami zaradi njegove kompleksnosti lahko da najboljše rezultate. V splošnem so znane vse njegove značilnosti, v precejšnji meri pa poznamo tudi detajle, npr. morfologijo, obstajajo podrobne karte področja ipd. Raziskane so tudi sosednje morfološke enote, tako da je izdelan digitalni model reliefa. Prav tako so podrobno določene strukturne enote in litologija formacij, ki izdajajo. Pri podrobnem pregledu geomorfologije so potrebne nekatere nove razlage obstoječih podatkov, medtem ko je datacija posameznih dogodkov pogosto še vedno pomanjkljiva.

V zadnjih 200 letih je bilo objavljenih preko 2000 speleoloških raziskav v Italiji in približno toliko v Sloveniji, od katerih vse morda niso zanesljive. Kljub temu pa je veliko kraških pojavov globoko pod površino še vedno neznanih oziroma neraziskanih. Le malo jam je bilo podrobno opisanih tudi z geološkega, geomorfološkega ali sedimentološkega stališča.

O Krasu je razmeroma veliko meteoroloških podatkov, zahvaljujoč gosti mreži meteoroloških opazovalnic. Tudi pedološki podatki in podatki o vegetaciji so zadovoljivi, čeprav so mnoge tematske karte precej poenostavljene. Novejše resnično detajlne karte obravnavajo terra rose in/ali druge paleokraške sedimente. Površinska hidrografska mreža, tokovni režimi in kemizem voda so dobro poznani, čeprav pogosto ni na razpolago kontinuiranega monitoringa. V zadnjih letih so na več mestih v podzemlju nameščene avtomatske merilne postaje, ki dajejo pomembne podatke za raziskave podzemnih vodnih tokov. Opravljeni so bili mnogi sledilni poskusi, s katerimi so raziskovali povezave med zbirnimi področji in kraškimi izviri. V zadnjih nekaj letih so bile opravljene tudi številne druge študije, ki so obravnavale različne aspekte krasa. Vendar so nekateri dejavniki,

pomembni za hidrologijo krasa, še vedno nedoločeni, npr. lokacija dejanske drenaže, volumen preferenčnih tokov, občasni in difuzni tok. Lokalne smeri tokov še vedno niso določene, tudi vertikalna in horizontalna prepustnost kamnin v različnih hidrogeoloških pogojih še ni znana.

V pripravi so karte splošne ranljivosti kraških vodonosnikov. Ker pa še vedno niso definirane preferenčne smeri tokov, tudi lateralna in vertikalna prevodnost nasičenih in nenasičenih con kraških vodonosnikov ni znana. Tudi praktični hidrogeološki model, ki bi upošteval vse parametre, s katerimi bi lahko zadovoljivo opisali do zdaj zbrane eksperimentalne podatke, še ni razvit. Obstajajo samo hipoteze, nobena od njih pa ne pojasnjuje nekaterih nasprotujočih si dejstev, ki izhajajo iz tematsko različnih študij. Če na primeru Škocjanskih jam uporabimo metodo "smeri razvoja jam" ali metodo "napoved smeri toka" po Erasu, dobimo povsem drugo teoretično smer toka od dejanske, ki poteka od JV proti SZ, t.j. od Škocjana proti izviru Timave.

V jamah z aktivnim tokom (Škocjanske jame, Kačna jama, Labodnica, izviri Timave) ima ta povsem drugo smer kot pa je regionalna smer tokov na tem področju. Primerjava mineralne sestave jamskih sedimentov s površinsko rdečo prstjo kaže, da se voda v jame steka z več različnih področij.

Ob naraščanju podzemeljske Reke prično delovati številni dihalniki, vendar niso enakomerno razporejeni niti niso locirani vzdolž preferenčnih smeri. Hidrodinamika ni enoznačna: visoke vode iz istega vira imajo lahko različno zakasnitev in različne kemijske značilnosti, medtem ko identični diagrami visoke vode lahko ustrezajo različnim klimatskim in hidrološkim pogojem.

Obstaja še več navideznih nasprotij, ki bi jih bilo treba obravnavati celovito: sodobni hidrogeološki model Krasa je mogoče izdelati le ob dosledni povezavi raziskovalnih skupin, ki delajo na tem področju. Če naj Kras postane modelno območje za kraške terene, na katerem bi raziskovalci iz vse Evrope testirali svoje hipoteze in modele, potem mora biti tudi prvo področje, na katerem bo definiran multidisciplinarni pristop k izdelavi hidrološkega modela, ki bo služil za varno izkoriščanje kraških vodnih zalog. Hidrogeološki model je dejansko potreben za boljše poznavanje kraških pojavov, pa tudi za lažje in boljše izkoriščanje kraških virov. Modeliranje hidrogeologije nekega področja je izjemno zahtevno zaradi velikega števila neodvisnih spremenljivk, ki jih je treba sočasno upoštevati. Prav to pa je izziv klasičnega Krasa.