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Karst Hydrogeological Investigations in South-Western Slovenia

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Karst Research Institute

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The authors are fully responsible for the content and for the language of their contributions.

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1. PREFACE (A. KRANJC)

During the 6th SWT at Karlsruhe (1992) the proposal of the participants from Slovenia to organise the next, the 7th SWT in Slovenia, was generally approved. In the autumn of the same year was organised a meeting in Slovenia; a group of experts visited the karst plateau Trnovsko-Banjška Planota conducted by the Slovene specialists who provided appropriate explanations. The final decision to accept the Slovenian proposal passed in Ljubljana.

Immediately three committees were designed: the preparatory one (consisting of the members of ATH), the research council (for the research project at Trnovsko-Banjška Planota), and the organising committee. Research activities required for the symposium were carried out in the frame of the international project "Transport of pollutants in karst: tracers and models in different aquifers - field research on Trnovsko-Banjška Planota 1992-1995". Project was mainly financed by the Slovene Ministry of Science and Technology and Ministry of Environment and Physical Planning and, occasionally, by communes and water organisations in the surroundings of Trnovsko-Banjška Planota. The research work including both the field and the laboratory work of the research associates not living in Slovenia, was financed by their organisations or by themselves. More than 50 researchers of various professional profiles from 16 organisations from Austria, Germany and Slovenia co-operated at the research work of the mentioned project. Due to finances, to large number of participants, to their fluctuations, and to questions, opened during the investigations, the course of the research as well as some aims and targets had to be changed, but the essential of the initial plan was kept all the same. To minimise co-ordination questions regular "Preparatory Meetings" were held twice a year in different countries and places, where about 30 researchers gathered every time.

As the editor of Acta carsologica and as the Organising Secretary of the 7th SWT I am very glad that both the Classis IV of the Slovene Academy of Sciences and Arts with Editorial Board and the ATH decided that the results of Trnovsko-Banjška Planota investigations will be published in Acta carsologica, with special title "Karst Hydrogeological Investigations in south-western Slovenia". Due to vast number of very different researches, of large amount of data gathered, of great number of authors and of various ways and methods of data interpretation, the preparation of the material for this volume was hard and complicated. But the results prove that it was worth the work and troubles. The editor is deeply grateful, and owes a great debt of thanks to the 7th SWT Editorial Board and to the colleagues from the Karst Research Institute.

Map. 1: Visoki Kras (The High Karst) plateaux in western Slovenia (p. 12).
Map 2: Trnovsko-Banjška Planota, an overview map (Inštitut za geodezijo in fotogrametrijo FGG, Ljubljana) (p. 13).

Soča
Idrijca
Selška Sora
Poljanska Sora
Mala voda
B A N J Š I C E
T R N O V S K I G O Z D
H R U Š I C A
N A N O S
K R A S
Vipava
Bela
Unica
Nanoščica
Pivka
Reka
Merilo 1 : 450.000
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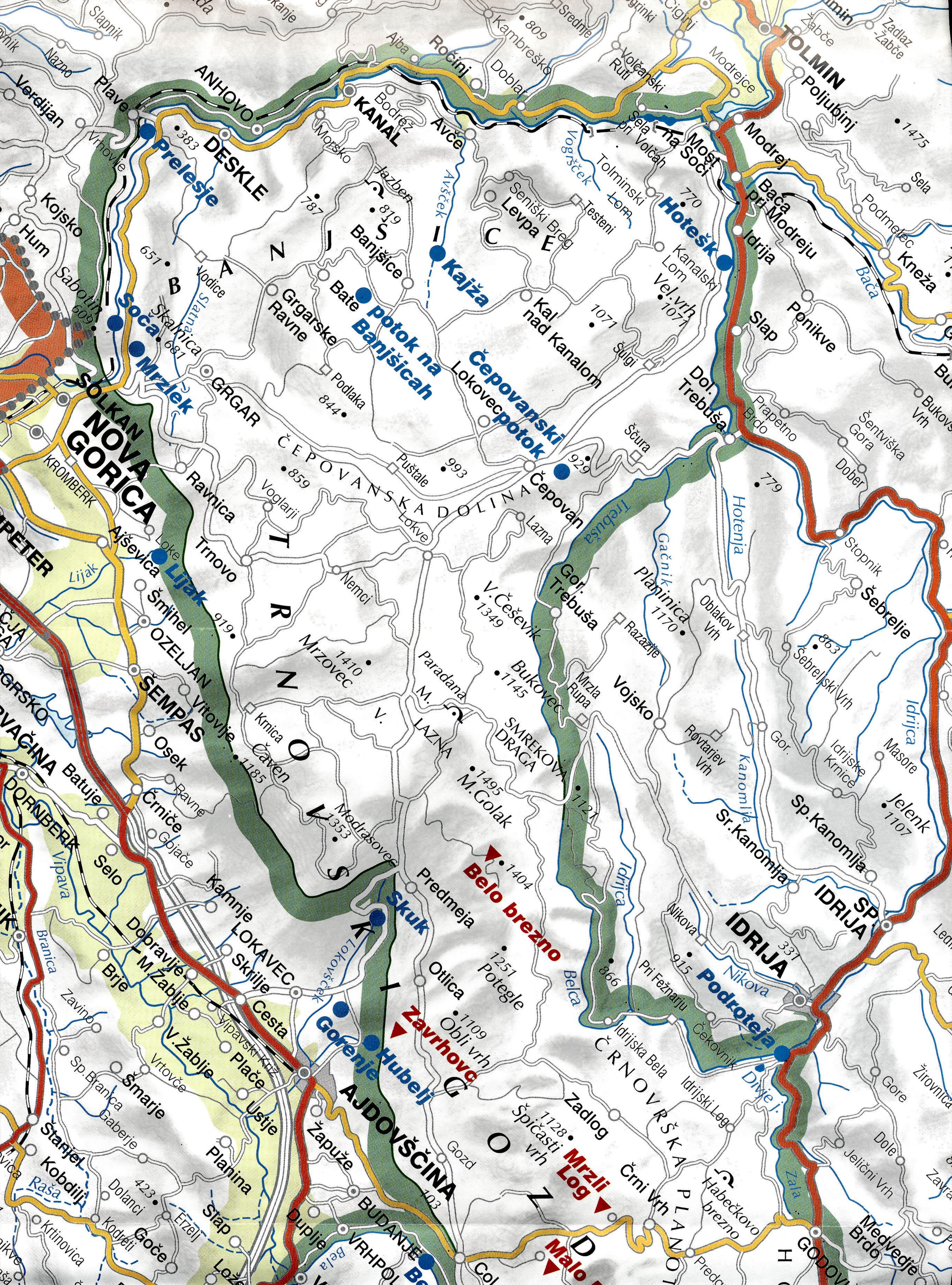

TOLMIN
Poljubinj
Modrej
Most na Soči
Sela pri Volčah
Tolminski Lom
Vogršček
Volčanski Ruti
Modrejce
Ročinj
Doblar
Kambreško
Ajba
KANAL
Bodrež
Avče
Avšček
Kajža
ANHOVO
DESKLE
Prelesje
Plave
Verdijan
Vrhovlje
Kojsko
Hum
Sabotin
Soča
Mrzlek
Solkan
NOVA GORICA
Kromberk
Ravnica
Trnovo
Lijak
Ajševica
Loke
Šmihel
Ozeljan
Šempas
Vitovlje
Osek
Batuje
Črniče
Čaven
Krnica
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Kamnje
Lokavec
Skrilje
Dobravlje
M. Žablje
V. Žablje
Cesta
Brje
Plače
Ustje
Šmarje
Vrtovče
Gaberje
Štanjel
Kobdilj
Dolanci
Planina
Slap
Goče
Erzelj
Dupije
Vrhpolje
Budanje
Žapuže
AJDOVŠČINA
Gorenje
Hubelj
Lokovšček
Skuk
Predmeja
Otlica
Potegle
Obli vrh
Zavrhovc
Belo brezno
Belca
Zadlog
Gozd
Špičasti vrh
Mrzli Log
Malo
Črni Vrh
Habečkovo brezno
ČRNOVRŠKA PLANOTA
Idrijski Log
Idrijska Bela
Čekovnik
Pri Fežnarju
Podroteja
Divje j.
Zala
IDRIJA
Nikova
Sp. Idrija
Sp. Kanomlja
Sr. Kanomlja
Kanomlja
Jelenk
Masore
Idrijske Krnice
Gor.
Rovtarjev Vrh
Vojsko
Mrzla Rupa
Bukovec
Smrekova Draga
M. Golak
Lazna
Modrasovec
Mrzovec
Paradana
V. Češevik
Nemci
Lokve
Čepovan
Čepovanska dolina
Puštale
Voglarji
Lazna
Gor. Trebuša
Trebuša
Planinica
Razažje
Gačnik
Oblakov Vrh
Šebrelje
Šebreljski Vrh
Stopnik
Hotenja
Idrijca
Dol. Trebuša
Šcura
Šentviška Gora
Prapetno Brdo
Dober
Slap
Ponikve
Idrija
Bača pri Modreju
Bača
Kneža
Podmelec
Hotešk
Kanalski Lom
Vel. vrh
Šuligi
Kal nad Kanalom
Lokovec
Čepovanski potok
potok na Banjšicah
Bate
Banjšice
Grgarske Ravne
Podlaka
GRGAR
Škalnica
Slatna
Vodice
Levpa
Seniški Breg
Testeni
Jazben
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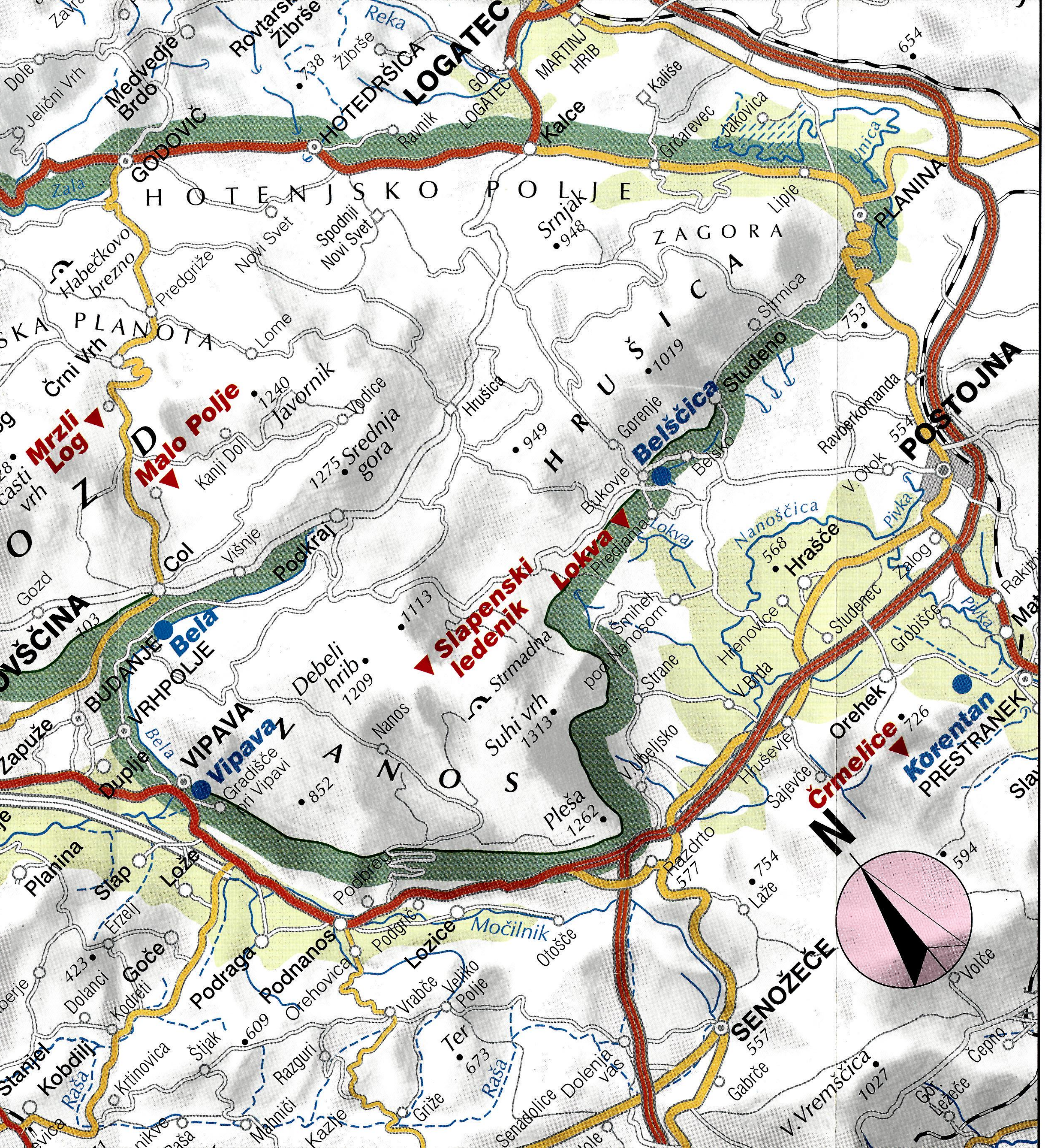

PREGLEDNA KARTA TRNOVSKO-BANJŠKE PLANOTE

GENERAL MAP OF TRNOVSKO-BANJŠKA PLANOTA

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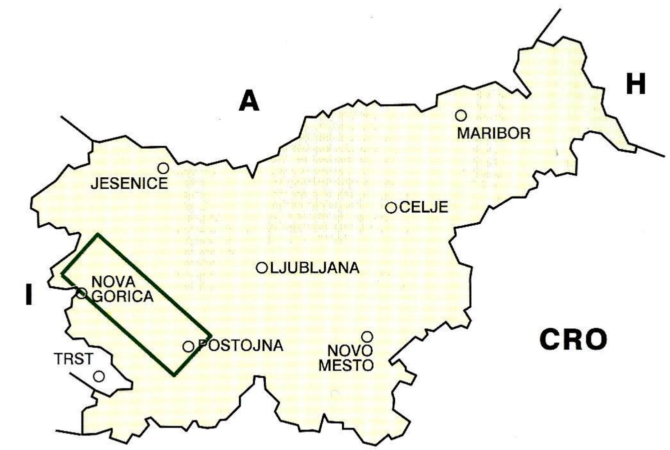
- ● MESTO VZORČENJA / SAMPLING POINT
- MEJA OBMOČJA RAZISKOVANJA / BORDER OF RESEARCH TERRITORY
- DRŽAVNA MEJA / NATIONAL BOUNDARY



Viri: Kartografska osnova: Karta Republike Slovenije - izrez v merilu 1 : 125 000. Ostali podatki: Inštitut za raziskovanje krasa ZRC SAZU, Postojna.

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2. NATURAL BACKGROUND

2.1. PHYSICAL GEOGRAPHY OF TRNOVSKO-BANJŠKA PLANOTA (P. HABIČ)

The test area of the 7th Symposium on Water Tracing includes a part of High Dinaric Karst in the western Slovenia; it is bounded by the valleys of the rivers Soča, Idrijca, Vipava and Pivka. From the Soča river in the north-west up to the sinking karst rivers Pivka and Ljubljanica in the south-east, there are, within otherwise uninterrupted landscape of the High Karst, morphologically slightly different areas as for example Banjšice, Trnovski Gozd, Črnovrška Planota, Hrušica and Nanos. This area of the High Karst is usually referred to as Trnovsko-Banjška Planota (TBP).

The belt of the High Karst between the northern border of the Adriatic Sea and eastern foot-hills of the Southern Limestone Alps narrows the most in the western Slovenia. A block of carbonate rocks belonging structurally to the Dinaric Mountains, is from 10 to 15 kilometres wide and about 50 km long, covering roughly 700 km^2 of the surface. Deeply karstified Cretaceous and Jurassic limestones and Triassic dolomites prevail; towards the north-west they underlie younger, mostly Eocene flysch rocks. Flysch encompasses karstified limestones of Trnovski Gozd and neighbouring plateaux in the southern and eastern side thus acting as a partial, hanging hydrogeological barrier. In the north the High Karst is surrounded by mostly impermeable Middle and Lower Triassic, partly also Permian and Carboniferous rocks. The valleys of the Belca, Idrijca, Trebuša, Hotenka, Kanomlja and Zala rivers are cut into these rocks. In their river basins, specially on the Vojsko Plateau, there are some sinking streams, caves and karst springs.

For several reasons this final edge of the High Dinaric Karst between the Vipava valley and the foot-hills of the Julian Alps dissected by the valleys of the Idrijca and Soča rivers was chosen as a test area of Association of Tracer Hydrology for the preparation of the 7th International Symposium on Water Tracing.

From a physiographic and hydrogeological point of view this is a relatively well-confined mountainous karst area bounded by lower, non-karstic margin regions from almost all the parts. The rainfall from this entire area sinks into deep karst aquifer feeding abundant karst springs located at its foot along the tributaries of the Idrijca, Vipava, Soča and Ljubljanica rivers. Smaller sinking streams may only be found in the western and eastern side of Trnovski Gozd. In the valleys on its border major karst springs are distributed, such as Mrzlek, Avšček, Kajža and Vogršček along the Soča; Lijak, Hubelj and Vipava along the Vipava; and Divje Jezero, Podroteja and Hotešk along the Idrijca. The rivers Idrijca, Soča and Vipava belong to the Adriatic water system, and Ljubljanica to the Black Sea basin. Thus the underground watershed between the Adriatic and Black Sea is found within the High Karst.

Karst springs in the border of the High Karst are captured for water supply of villages in Vipava valley, on Goriško and along the Soča and Idrijca. As these are the only abundant sources of drinking water in western Slovenia their karst background must be protected against pollution. Due to hydrographical complexity within this karst aquifer, it has not yet been possible to define the extent, size and capacity as well as threat to each karst spring separately. For the same reason, protection measures were not introduced separately but for the area as a whole.

Previous hydrological and geological researches indicated the main drainage directions of karst waters, but a series of unsolved hydrological questions remained. To solve these would provide better exploitation and better protection of water resources.

Intensive karstification is evidenced by solution channels, runnels and karren on bare rocky surfaces. There are numerous, karst dolines and ouvalas, more than 100 m deep, and many caves and shafts, some more than 300 m deep. In the ice-cave Velika Ledena Jama v Paradani cavers have reached a depth of almost 700 m. This external image of intensive karstification is complemented by hydrological indicators. After rainfall the discharge in springs increases rapidly and also decreases relatively fast.

Deep karstification is shown also by the location of karst springs in the bottom of the valleys and by their deep siphon outflow passages; at Mrzlek they are below the Soča riverbed, in Divje Jezero cave divers reached more than 100 m below the Idrijca valley without getting to the end of this typical Vauclusian spring.

Karst relief dominates over the entire area. Among the elevations typical cone-shaped features prevail; isolated peaks are distributed in levels over the central ridge but they appear also on lower, more flattened borders. Between the elevations there are deep dry valleys with dolines. Such a relief neutralises the superficial watershed. Deep fluvial valleys are cut on the border of the High Karst plateau only. The bottoms of river valleys are from 50 to 300 a.s.l. and this is also the altitude where are the lowest probable free surface springs.

Central karst plateaux reach altitudes from 600 to 1500 m a.s.l.; the slopes of the valleys are steep and high. The south-western edge of the High Karst from Razdrto past Vipava and Ajdovščina up to Gorica is nearly vertical and at the foot of limestone walls there are recent and fossil scree slopes above the Vipava valley.

Carbonate rubble and breccia on the flysch base represent smaller porous aquifers. Calcarenite, breccia and conglomerate inliers of carbonates in Eocene flysch along the Soča to the western border of Banjška Planota represent aquifers of karst and fissure porosity of local importance. In the eastern and western side of Trnovski Gozd, specially on Banjšice, along northern border of Nanos, near Črni Vrh and on Pivka they contribute a part of waters to the central karst aquifer which is seen also in the hydrochemical properties of related springs.

Orographic properties of the surface are controlled by geological structure and by younger tectonic movements and by geomorphologic development from the Middle Pliocene onwards. The main ridge of the High Karst trends from north-west to south-east, but it is slightly displaced towards the north-east border. The highest elevations in the central part of Trnovski Gozd are the peaks named Veliki Golak (1495 m) and Mali Golak (1480 m). On the southern and western border of the main ridge of Trnovski Gozd there are some marginal shelves preserved as remains of former, broader planations. There were found the remains of fluvial gravel deposited by waters from neighbouring Pre-alpine valleys when the rivers flowed over the actual High Karst towards the Adriatic Sea.

Transverse and also longitudinal dry valleys are downcut into an old, levelled surface. The most expressive is the valley of Čepovan, 20 km long and more than 300 m deep. It widens in its southern part and passes into a smaller karst margin polje near Grgar (280 m). The lowest exit of Grgar lies in the continuation of a dry valley on Preval, 336 m a.s.l. between Sveta Gora (681 m) and Škabrijel (546 m) which is almost 300 m above the present riverbed of the Soča near Gorica. The bottom of the dry valley reaches the highest point in the north of Čepovan, at 620 m and it lowers to 540 m in its northern border near Vrata to remain hanging in a steep edge, 270 m above the Idrijca riverbed. The valley of Čepovan is a natural border between Banjšice to the west and Trnovski Gozd to the east.

The highest main ridge of Trnovski Gozd between Paradana, Mala and Velika Lazna and Krnica is cut by a transverse dry valley. Similar are transverse valleys in the south-eastern side of Trnovski Gozd between Mala Gora and Kovk and between Črni Vrh and Col. Transverse dry valleys are important for traffic and they are used for local and forest roads. However, main traffic roads lead along the High Karst by the valleys of the Idrijca and Vipava. An important cross traffic road passes along the western border of the High Karst by the Soča valley between Gorica and Tolmin.

There is little soil on the karstified limestones of Trnovski Gozd (The Wood of Trnovo) and wood prevails there as its name indicates. The rather humid mountainous climate is favourable for fir and beech trees. These two species comprise Vast fir-beech forests. On the highest ridge of Trnovski Gozd the trees are exposed to strong wind, the bora, and therefore the trees are lower with typically shaped branches bent and blasted by the wind. The highest Golaki displays the features of upper tree limit. Instead of beech, dwarf pines appear there. This species may also be found at the bottom of deep karst dolines where cooler air accumulates. In these frost-places the vegetation belts are inversely distributed. A belt of beech is followed downwards by a belt of spruce and at the bottom of doline there is a belt of dwarf pines; in the deepest karst dolines, in particular at the entrance to ice-caves, a belt of mountainous meadows without trees may even appear. These vegetation specialities of Trnovski Gozd very early aroused the attention of experts. Forest management, that is regulation and protection of karst woods accompanied by a suitable exploitation, has a several hundred years long tradition.

From a climatic point of view the High Karst is a typical transitional area between the Mediterranean climatic influences of the Adriatic and the continental and Alpine climatic region of inner Slovenia. The high karst ridge is a sort of barrier against the frequent south-western wind that brings the humidity from Mediterranean. As humid air lifts over the first mountainous barrier it releases heavy precipitation. Thus the central part of Trnovski Gozd receives annually more than 3000 mm, and the maximal daily rainfall may even surpass 300 mm. The mean annual temperature varies from 7 to 9° C. The mean air temperature in January is about -2° C, and in July about 16° C. On Golaki where the upper tree limit is at 1440 m a.s.l. the mean air temperature in July is about 12° C. In the cold half of the year cool air from the south-eastern side frequently passes from the High Karst towards the Mediterranean; this occurs as a strong wind in gusts, called the bora, which may reach more than 200 km/h in the Vipava valley and in dry transverse valleys. Relatively early in autumn snow falls on the peaks of Trnovski Gozd and in spite of some thawing during the winter it may be found in deep dolines up to May, and in caves with large entrances throughout the summer. In many ice caves the local people used to cut out the ice and transport it to the valley and to Triest and Gorica to chill food and drink in times when electric refrigerators did not yet exist.

On the border of Trnovsko-Banjška Planota and on Nanos the trees were cut down. At first the land was used for pastures, and later permanent settlements grew. The most dense population is found on Banjšice as far as Grgar to the south and Čepovan and Lokovec to the north. On flysch rock there is more soil which favours agriculture. On Lokovec north from Čepovan and around Trnovo, Voglarji and Lokev south from the Čepovan valley there are less cultivated surfaces. Slightly more soil is provided by disintegrated

cherts that occur as lens-shaped inliers in Cretaceous and Jurassic limestones. The same may be said for the inhabited south-eastern part of Trnovski Gozd where modest farms are scattered on the border of the plateau from Predmeja, over Otlica, Kovk, Gozd and Križna Gora to Col, Podkraj and Vodice.

Some scattered farms may also be found to the north of the main ridge of the High Karst near Zadlog, Črni Vrh and Lomi. In the western border of Nanos the former Vast pastures are more and more overgrown by vegetation and only two farms remain there. Sparse population and low agricultural activity are relatively favourable to protecting the karst aquifer. But, together with endeavours to protect karst waters, there exists a wish to increase the economic development of these villages. In the past they mostly survived by cattle breeding and forestry. Later local people travelled to work in the valleys, and in factories in Gorica, Ajdovščina, Vipava and Idrija; in recent years they try to get work at home in craft and smaller industries. Former rainwater reservoirs are replaced by piped water supply; water is pumped from lower lying springs and increased quantities of waste water flow mostly untreated, underground. The economic development on Trnovsko-Banjška Planota must as soon as possible be co-ordinated with protection of this important karst aquifer which is capable of supplying the larger and more inhabited valley area of the High Karst around Vipava, Gorica and Idrija with drinking water.

2.2. HYDROLOGY (N. TRIŠIČ)

2.2.1. Basic description of the area

The area of the Trnovski Gozd, the Banjšice, the Nanos, and a part of the Hrušice plateaux hydrologically belongs to the Soča river basin extending over approx. 2000 km^2 in Slovenia, which is almost one tenth of Slovenian territory (Fig. 2.1). The river basin stretches from the central part of the Julian Alps over the pre-Alpine mountains, the territories of Cerkljansko and Idrijsko, the high karst area of the Nanos and the Trnovsko-Banjška Planota, the flysch area of the Vipavska Dolina, to the level gravel-sand accumulation of the Soča and its tributaries on Italian side. In Slovenia, the Soča river basin borders on the Upper Sava river basin, and the Ljubljanica and the Timava river basins, and on Italian side, on the Tagliamento river basin (Fig. 2.1).

The strongest tributaries of the Soča are two left tributaries, the Idrijca and the Vipava, which drain the area of Idrijsko and Cerkljansko, the high karst area of the Trnovsko-Banjška Planota, the Nanos, a part of the Hrušica, and the flysch area of the Vipavska Dolina valley. The entire area can be studied as two separate hydrological units, one of which as the catchment area of the karstic springs of the Vipava, and the other one as the catchment area of the karstic springs at the rims of the Trnovsko-Banjška Planota.

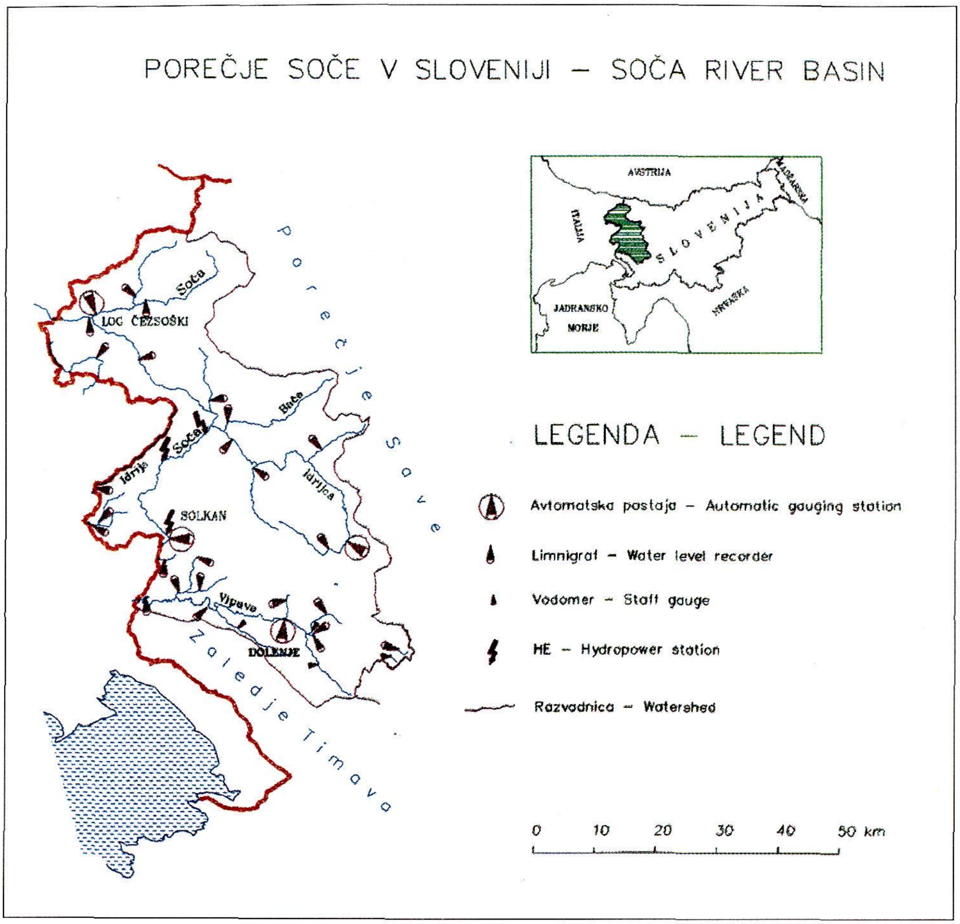


Fig. 2.1: The Soča river basin.

2.2.2. The springs of the Vipava

The karstic part of the catchment area of the Vipava springs stretches over the entire area of the Nanos and a part of the Hrušica, while the part with surface drainage stretches over the flysch river basins of the ponor streams in the basin of Postojnska Kotlina which gravitates towards the Vipava springs.

The size of the catchment area is not exactly determined due to the watershed between the Vipava and the Ljubljanica on the area of the Hrušica where it assumes the karstic features. For the river basin of the Pivka, a partial discharge of its waters to the Vipava springs has been established, which represents the bifurcation between the Adriatic and the Black sea basins

(P. HABIČ 1989). At high waters, the bifurcation was also noticed in the area of the Osojščica ponor stream (HABE 1976). A partial discharge of the Osojščica waters ends in the Belščica which runs towards the Vipava springs, and the other part of its waters drain to the Pivka, i.e. towards the Black sea. The watershed against the Trnovski Gozd is represented by the flysch part of the Bela riverbed, and also the watershed against the Močilnik is surface running and reliable. The catchment area of the Bela stretches over approx. 2 km^2. The low and medium waters of the Bela already sink in the area of Sanabor; only the high water waves run on the surface to the Vipava. The Vipava-0VP Vipava gauging station is located about 500 m downstream of the Vipava springs. This profile includes the discharges of all the permanent springs of the Vipava, and probably, also the medium and low waters of the Bela which sinks under the village Sanabor (Tab. 2.1). Only the high waters of the Bela and the discharges of periodical springs between Vipava (town) and Vrhpolje which are only active at high waters and join the Vipava river downstream from the town, are not included in the gauging profile.

Tab. 2.1: The Vipava-LP Vipava: the 1961-90 characteristic discharges and their ratio (m^3/sec).

Q_{min}	Q_{mean}	Q_{max}	Q_{min} : Q_{mean} : Q_{max}
0.727	6.78	70.0	1 : 9 : 96

Tab. 2.2: The average annual precipitation heights in the catchment area of the Vipava springs (mm).

Nanos-Ravnik	Podkraj	Hrušica	Razdrto	Slap p. Vipavi
1834	2179	2088	1678	1513

The total size of 125.25 km^2 of the catchment area of the Vipava springs also includes about 2 km^2 large catchment area of the Bela. Yet, the data on discharges at the gauging station do not comprise the discharges of the Bela. Since also the springs between Vipava (town) and Vrhpolje are active during the high water situation, the datum on the maximum discharge of the Vipava must be slightly higher than the quoted 70 m^3/sec. Besides, the quoted datum on the size of the catchment area of the Vipava springs is - considering the data on precipitation heights (Tab. 2.2) and runoff - also too small (Tab. 2.3).

Tab. 2.3: The 1961-90 data for the Vipava-LP Vipava profile.

F km^2	Precipitation Q (m^3/sec)	Evaporation (m^3/sec)	Precip. Runoff (m^3/sec)	Q_s (m^3/sec)	difference (m^3/sec)
125.25	7.98	2.51	5.47	6.78	+1.3

Three sides of the catchment area of the Vipava springs border on flysch layers (i.e. the areas of the Močilnik, the Pivka and the Bela), therefore, the only possible way of the catchment area expansion is the area of the Hrušica, at the cost of the catchment area of the Ljubljanica. Mathematically, the catchment area of approx. 150 km^2 would correspond with the data on precipitation (2024 mm) and discharge (6.78 m^3/sec).

A time distribution of the mean monthly discharges shows that two annual maximums occur, the first in April and the second in November, while the lowest mean discharges occur in July and August (Fig. 2.2 and Fig. 2.3). The first maximum of the monthly mean discharges occurs in April and it is higher than that of November, in spite of the fact that precipitation are more abundant in autumn; this is the result of snow melting in the spring months.

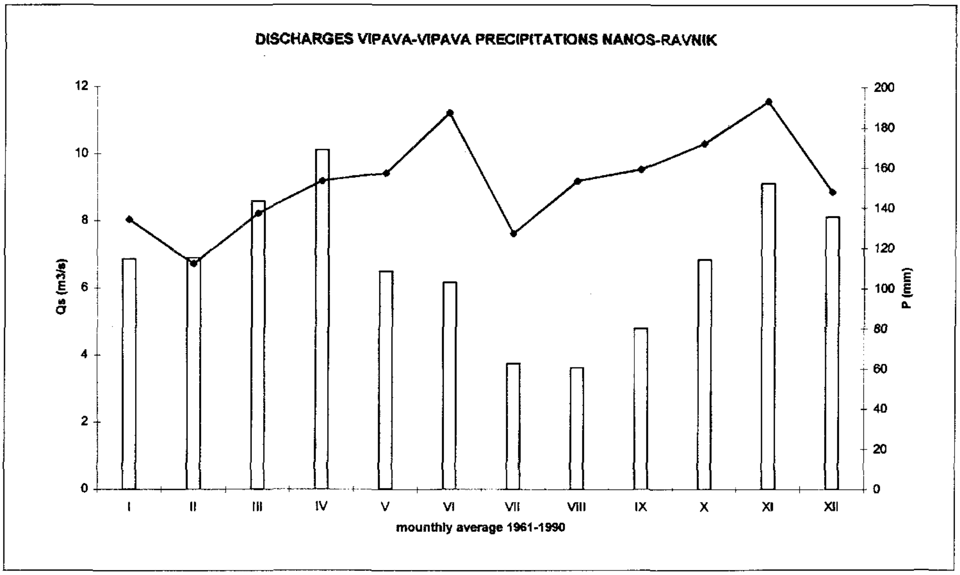


Fig. 2.2: The Vipava monthly mean discharges and monthly mean precipitation in the recharge area (1961-1990).

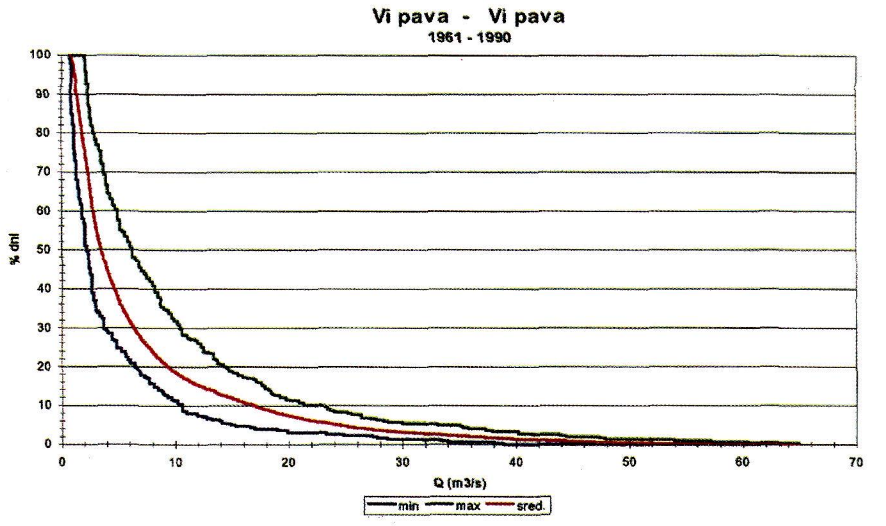


Fig. 2.3: The lines of the 1961-90 discharge duration of the Vipava at the gauging station Vipava.

2.2.3. The area of the Trnovsko-Banjška Planota

The area of the Trnovsko-Banjška Planota which can roughly be limited with the Hrušica area in the east, the Soča river in the west, the Vipavska Dolina in the south, and the valley of the rivers Trebuša, Belca and the Upper Idrijca in the north, stretches over approx. 490 km^2 of the territory. The area is bordered, except for the Hrušica area, with the steep and precipitous slopes. A permanent surface hydrographical network is only developed in the western part of the Banjšice which drains towards the Soča. This area of the so-called hanging barrier stretches over approx. 90 km^2 (see Chapter 2.6) The remaining central part consists of the high karst plateau where the precipitation immediately enter the unsaturated part of the karstic system where the vertical component of percolation prevails. Without the surface part of the catchment area of the Idrijca and the Trebuša, the area of the high karst plateau of the Trnovski Gozd, the Banjšice, the Črnovrška Planota, and a part of the territory towards Hotedrščica, stretches over approx. 350 km^2. The foregoing karstic areas drain entirely into the karstic springs which are arranged at the rims of these plateaux. The largest water quantities are drained by the springs Divje Jezero, Podroteja, Mrzlek, Lijak and Hubelj, and a minor share by the spring Hotešk ob Idrijci and the springs in the Soča valley (Vogršček) and the Avšček valley (Bolterjev Zdenc and Kajža).

The gauging profiles for the registration of discharges from the karstic part of the plateau are fixed at the following locations:

Idrijca - Podroteja
Lijak - Šmihel
Hubelj - Ajdovščina

Idrijca - LP Podroteja

The Idrijca - Podroteja gauging profile comprises the discharges as from the springs Divje Jezero and Podroteja, as from the surface part of the catchment area of the Idrijca and the Belca (Fig. 2.4 and 2.5). The surface part of the catchment area stretches over approx. 50 km^2 and exerts impact on the water regime at the gauging profile to such an extent that the karstic regime of drainage is obliterated. The size of the catchment area of 112.84 km^2 taken into account for the gauging profile, is also mathematically too small (Tab. 2.4, 2.5 and 2.6). The karstic part of the catchment area spreads towards the area of Hotedrščica where bifurcation with the Ljubljanica was established (3.SUWT), and also in the Trnovski Gozd massif, the watershed cannot be determined since the bifurcations were established in the areas of Vodice and also of Črni Vrh (HABIČ 1987).

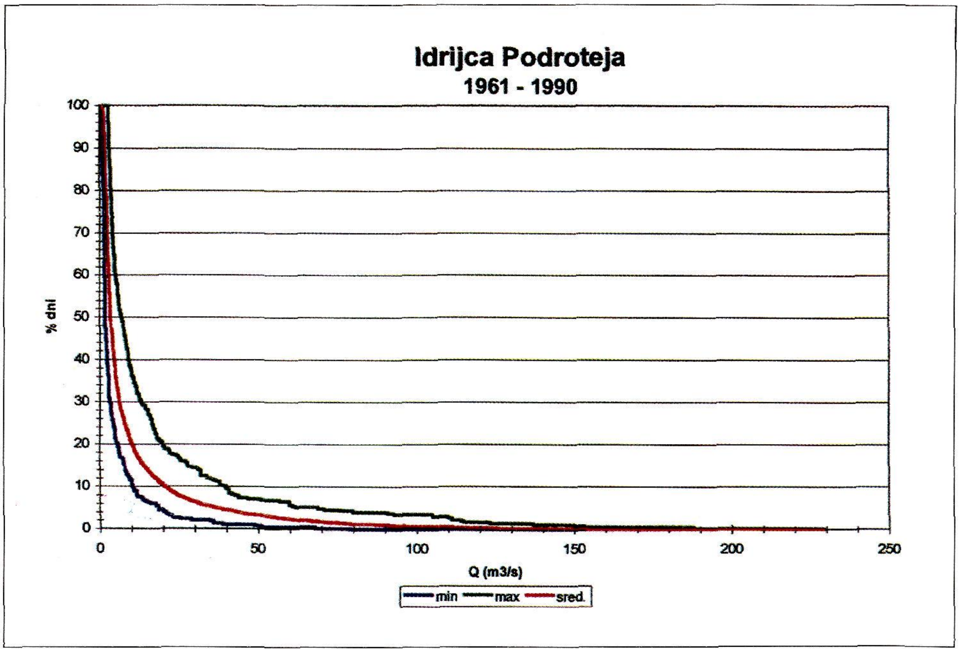


Fig. 2.4: The lines of the 1961-90 discharge duration of the Idrijca at the LP Podroteja gauging profile.

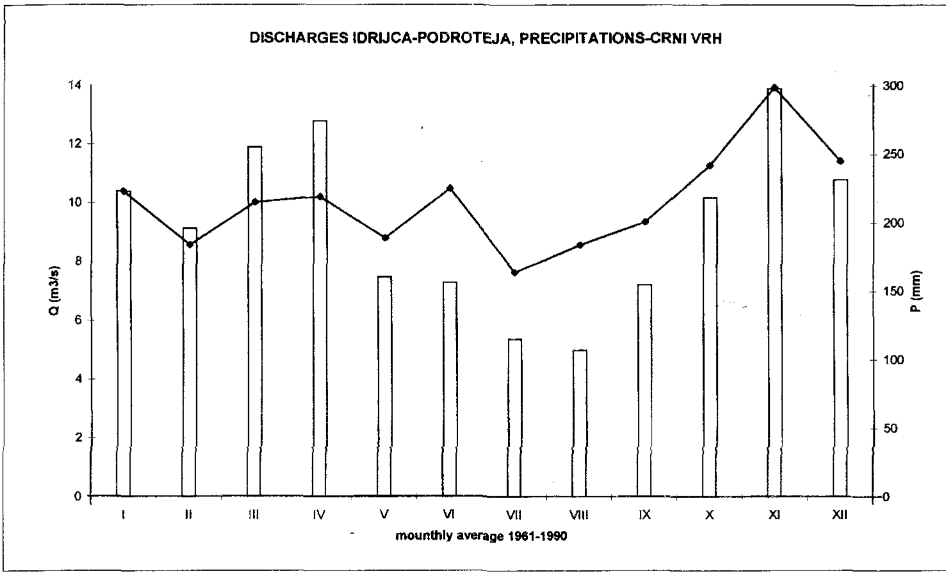


Fig. 2.5: The average monthly precipitation in the catchment area of the Idrijca and the mean monthly discharges (1961-1990).

Tab. 2.4: The 1961-90 data for the Idrijca - LP Podroteja profile.

F km^2	Precipitation Q (m^3/sec)	Evaporation (m^3/sec)	Precipit. runoff (m^3/sec)	Q_s (m^3/sec)	difference (m^3/sec)
112.84	9.20	2.21	6.99	9.75	+2.3

Tab. 2.5: The characteristic discharges of the 1961-90 period at the Idrijca-Podroteja, and their ratio (m^3/sec).

Q_{min}	Q_{mean}	Q_{max}	Q_{min} : Q_{mean} : Q_{max}
0.84	9.29	306	1 : 11 : 364

The ratio between the maximum and the minimum discharges of the Idrijca at the LP Podroteja gauging profile is so high exactly due to the surface part of the catchment area (Tab. 2.5).

Tab. 2.6: The average annual precipitation in the catchment area of the Idrijca (mm).

Črni Vrh	Idrijska Bela	Mrzla Rupa	Vojsko
2589	2623	2784	2450

Lijak - Šmihel

In the gauging profile at the Lijak - Šmihel station discharges are registered of the periodically active springs, which are only an overflow of high waters from the catchment area of the Mrzlek spring. The hydraulic link between these two springs has been confirmed. At low waters, the water level of the Lijak oscillates parallel to the oscillation of the water level in the Solkan hydropower-plant reservoir, and the gradient towards the Soča is minimal. When the spring Lijak is active, the water table in its karstic catchment area rises even more than by 40 m. There were no continuous observations of the spring in the 1961-90 period, therefore, the characteristic data for that period are missing. The highest registered discharge is 32.6 m^3/sec, but a greater part of a year the spring is dry.

The catchment area of the Lijak can also be considered as a bifurcation area since the high waters of the spring also gravitate towards the Vipava, and when the spring is not active, all the waters from the catchment area gravitate towards the spring Mrzlek, i.e., to the Soča. The regime of the Lijak spring demands a special interpretation of water balance, since the high water waves exert impacts on the discharge regime of the lower section of the Vipava, but the size of its belonging catchment area cannot be defined. The correlation with the Hubelj spring was studied for the Lijak spring; it shows a strong dependence between the regimes of both springs (MUŽIČ 1986).

Hubelj - Ajdovščina

The gauging station is located less than 2 km downstream of the Hubelj spring. At the spring itself, water is tapped for the water supply, which reduces the volume by 50 to 150 l/sec.

The orographically determined size of the catchment area (F = 85.25 km^2) for the gauging station on the Hubelj is too big, therefore the calculation of water balance gives so great a difference between the calculated and the gauged runoffs (Tab. 2.7). The theoretically calculated size of the belonging catchment area measures approx. 50 km^2 (STAHL 1994).

Tab. 2.7: The 1961-90 data for the Hubelj - VP Ajdovščina profile.

F km^2	Precipitation Q (m^3/sec)	Evaporation (m^3/sec)	Precip. runoff (m^3/sec)	Q_s (m^3/sec)	difference (m^3/sec)
85.25	6.64	1.76	4.89	3.03	-1.9

Tab. 2.8: The characteristic discharges of the 1961-90 period at the Hubelj - VP Ajdovščina, and their ratio (m^3/sec).

Q_{min}	Q_{mean}	Q_{max}	$Q_{min} : Q_{mean} : Q_{max}$
0.185	3.03	59.5	1 : 16 : 322

The Q_{max}/Q_{min} coefficient is high and speaks in favour of the fact that in the case of the Hubelj spring its maximum discharge is not suppressed (Tab. 2.8).

Tab. 2.9: The average annual precipitation heights in the catchment area of the Hubelj (mm).

Ajdovščina	Lokve	Otlica	Podkraj
1553	2381	2409	2179

The largest quantity of precipitation in the catchment area of the Hubelj spring falls in November, on average, while the mean monthly discharges of the Hubelj are the highest in April when snow begins to melt (Fig. 2.6 and 2.7, and Tab. 2.9).

The distribution of the maximum discharges in all three discussed gauging profiles do not offer any law; but from the distribution of the minimum discharges, the influence is clearly visible of the water reserves from the snow cover, even on the minimum discharges in the summer months. The minimum discharges of the Hubelj and the Vipava occur in February, and in September or October, and they are practically equal, while the autumn minimum discharges of the Idrijca are essentially lower than those in February (Fig. 2.8).

The quoted basic hydrological conditions of the discussed area and the springs already represent the hydrological problems which are typical of the karstic hydrological systems (Fig. 2.9). Besides the inaccurately determined sizes of the catchment areas and the directions of water streams in the system, an additional uncertainty occurs in the area of the Trnovski Gozd and the

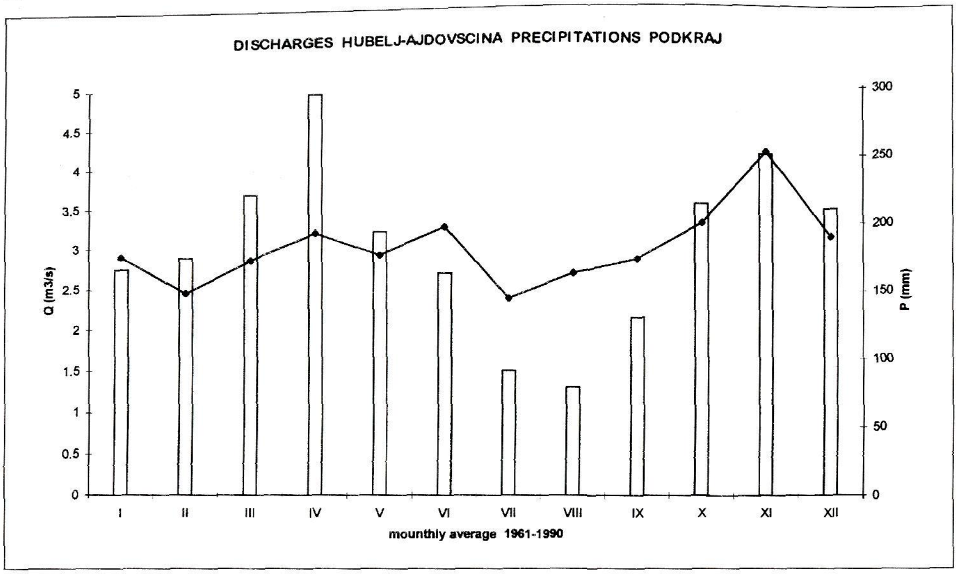


Fig. 2.6: Mean monthly discharges of the Hubelj and mean monthly precipitation in the 1961-90 period.

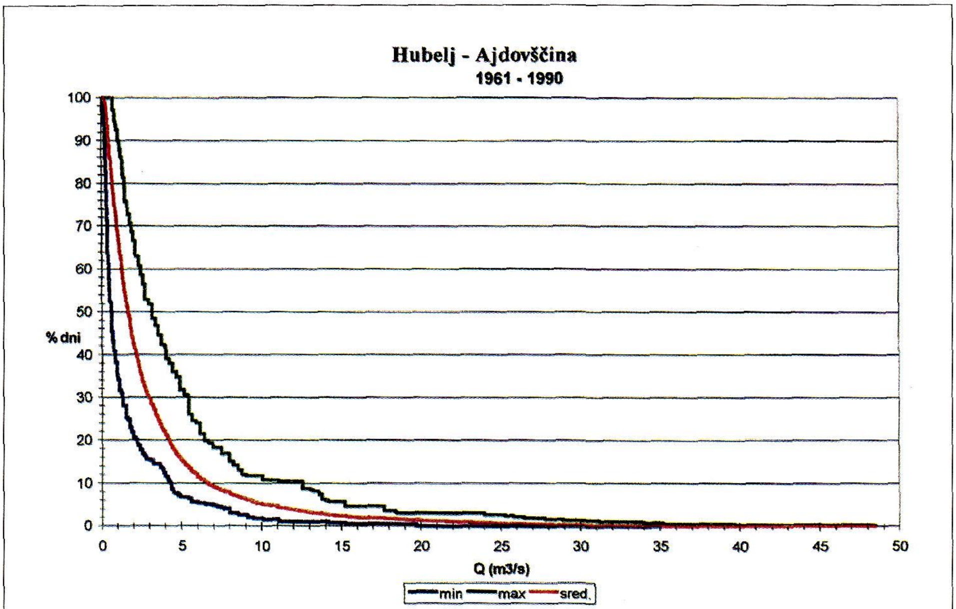


Fig. 2.7: The lines of the 1961-90 discharge duration of the Hubelj at the VP Ajdovščina gauging station.

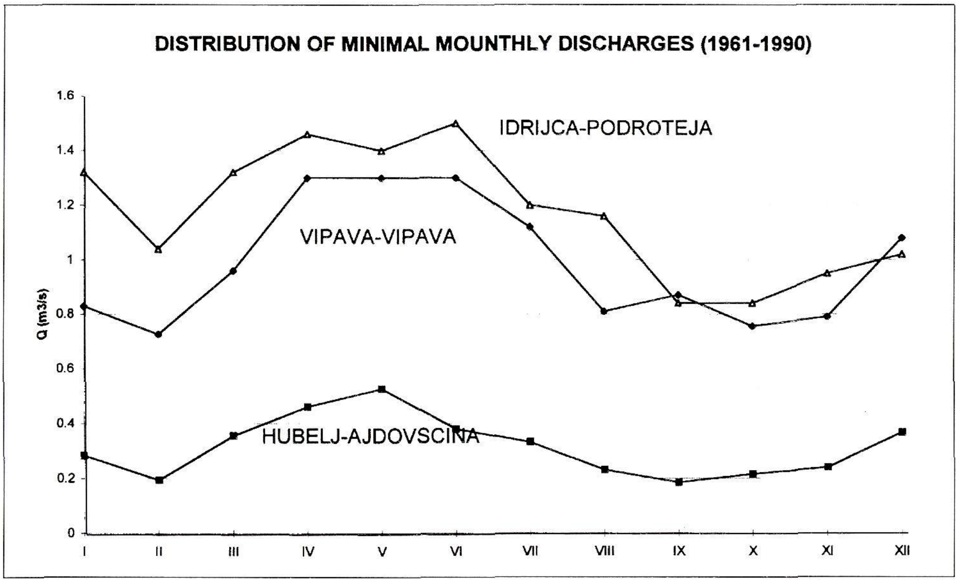


Fig. 2.8: The distribution of the minimum monthly discharges in the 1961-90 period.

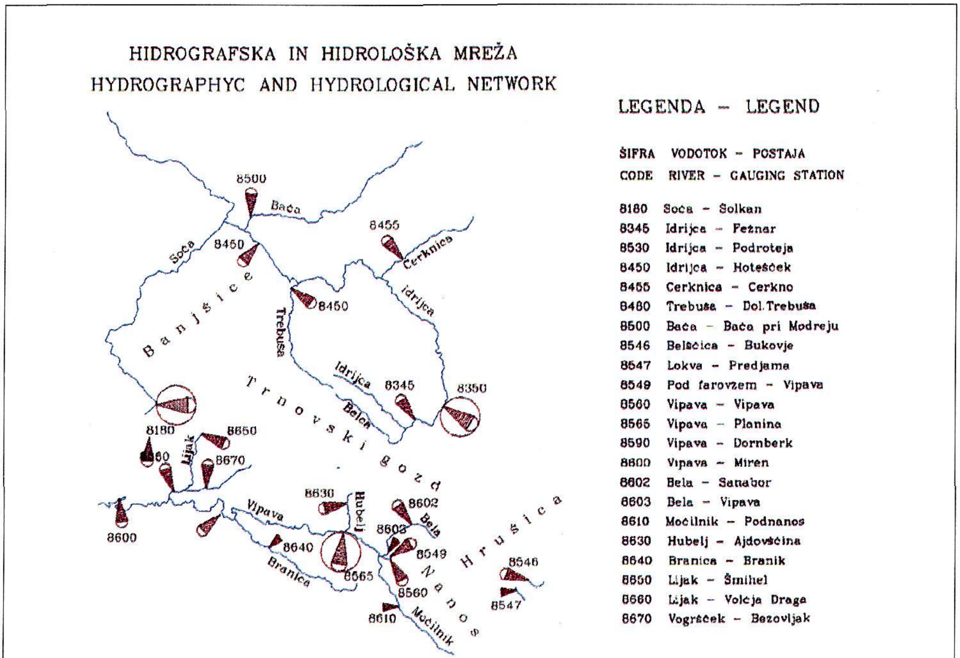


Fig. 2.9: Hydrographic and hydrological network.

Banjšice, which further aggravates the comprehension of hydrological conditions. These are the unspecified discharges of the Mrzlek spring which flows into the Soča in the area of the Solkan HPP reservoir and, thus, cannot be directly gauged.

2.3. THE CLIMATE OF THE TRNOVSKO-BANJŠKA PLANOTA (J. PRISTOV)

2.3.1. Meteorological conditions

The Trnovski Gozd, the Banjšice and the Nanos are the first mountain barrier (the altitudes of peaks between 1000 and 1500 m above sea level) on the way from the Mediterranean, or the Northern Adriatic, towards the north and the north-east. Naturally, there is the Kras plateau before it, yet, it mainly does not exceed the altitude of 600 m. Therefore, the orographic precipitation are modest on the Kras, but they already become rather abundant at the barrier running from the Banjšice to the Nanos, and they are the most abundant at the southern part of the Julian Alps. There, the altitudes of the peaks already reach approximately 2000 m, and the average annual precipitation already amounts to 4000 mm, which is the highest value in the Alps. This barrier represents a divide between the Mediterranean and the Alpine climates. The Vipavska Dolina and Goriško region, both located at the southern rims of the Trnovski Gozd, are under the intense influence of the Mediterranean climate. Yet, the Trnovski Gozd, the Banjšice and the Nanos already have the real Alpine climate with the abundant snow during the rather cold winters.

The precipitation are abundant all year round, with the explicit maximum in October and November. In the heart of the Trnovski Gozd, i.e. the area of Golaki, they exceed the precipitation average over the period of 30-years, which is 3000 mm, and also the entire area of the Banjšice, the Trnovski Gozd and the Nanos, annually receives over 2000 mm of precipitation, on the average.

The most intense precipitation very often occur in October, up to 900 mm (Vojsko 888 mm; Mrzla Rupa 855 mm; Otlica 702 mm), but on the average, October is not the wettest month. Namely, oscillations of precipitation quantity are extremely sharp in this month: on the one hand, the monthly precipitation extremes occur with heavy precipitation, and on the other, this month often receives the minimum precipitation and sometimes - although it happens rarely - they do not fall at all (in 1965). November is the month with the largest average quantity of precipitation, yet the oscillations are not as sharp as in October, and therefore, the annual extremes do not occur in this month. Although rarely, but very heavy precipitation also occur in the month of September.

It is typical of autumn precipitation that they are very intense in shorter periods, and they are often unevenly distributed over the discussed area. It happens that the intensity of precipitation in individual areas differs a lot (the ratio of 1:5), which is not the case with the convective precipitation, but with the orographic precipitation related to the front system. For determining the quantities of precipitation by individual precipitation situations, a rather dense network of precipitation gauging stations would be necessary, or, great errors could occur due to the intensely agitated precipitation area.

The Trnovski Gozd receives the majority of precipitation in autumn, when the sea is still rather warm, and the very warm and humid air, driven by the SW winds, flows in from above the Mediterranean. When on its way during the precipitation situation this air reaches the first higher mountain barrier, it must ascend to pass it, which results in the orographic precipitation. Such situations often occur during the generation of secondary cyclones in the Genoa bay or above the Northern Adriatic. It is in autumn and spring when the secondary cyclones are most frequent, only that the warm air in autumn contains quite a lot of humidity. The humidity of air is considerably lower in spring due to the cooler northern Mediterranean, and therefore, the orographic precipitation are not so abundant.

The monthly quantity of precipitation considerably exceeds the evaporation. July is the least wet month, and even then, more than 160 mm of precipitation fall; concurrently, it is also the month with the most intense evaporation, when the potential evapotranspiration (ETP) on the Nanos amounts to 130 mm, and at Čepovan, to 122 mm (Fig. 2.10 and 2.11). Since the monthly precipitation, on the average, always exceed the ETP, it is assumed that the actual evapo-

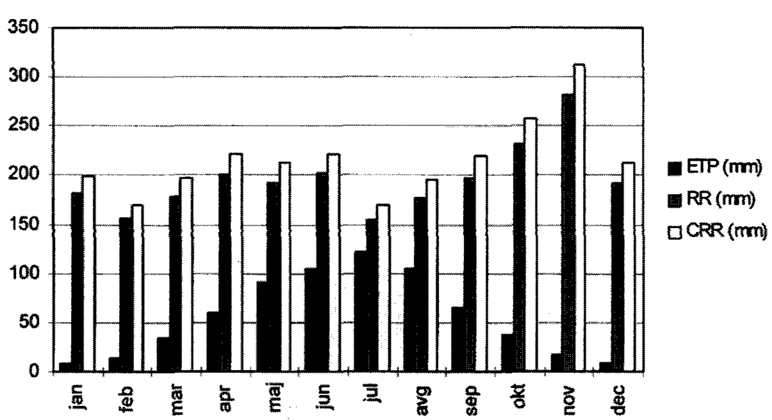


Fig. 2.10: Mean monthly values of potential evapotranspiration (ETP), precipitation (RR) and corrected precipitation (CRR) on the station Čepovan.

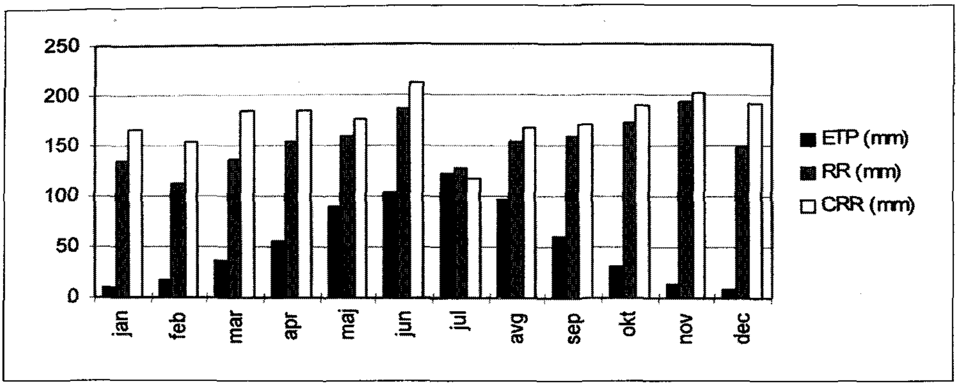


Fig. 2.11: Mean monthly values of potential evapotranspiration (ETP), precipitation(RR) and corrected precipitation (CRR) on the station Nanos-Ravnik.

transpiration (ET) equals to the potential evapotranspiration (ETP); therefore, in the continuation of this paper, only the term evaporation is used and is equalised with the ETP. On the average, more than 300 mm of precipitation fall in November at Vojsko and Mrzla Rupa, but only 15 mm evaporate. In October, the same area receives more than 250 mm of precipitation, but only about 35 mm evaporate.

On the average, the greatest discharges occur in October, although the greatest quantity of precipitation fall in November. The air in the inland of Slovenia is already so cold in this month that the higher altitudes of the Trnovski Gozd are already covered with snow, which is immediately manifested in the reduced discharges. The secondary maximum of discharges occurs in the spring months when the snow cover is melting.

As it has already been mentioned, the Trnovski Gozd and Nanos represent the divide between the Mediterranean and the Alpine climates. When the inland of Slovenia is filled with the cold air from the north or the Northeast, great temperature differences originate at the foregoing barrier, as well as great pressure gradients. When the air descends from above the Trnovski Gozd and the Nanos towards the Vipavska Dolina and the Kras, it is adiabatically warmed, yet, it is still cooler than the air above the northern Adriatic. The result of this temperature difference is that the cold air cascades down the slopes, and reaches great velocities, while due to the agitated landforms, violent turbulences are generated. This strong wind is known under the name of bora, and reaches the velocities of up to 200 km/h with individual gusts. Relatively frequent occurrence of the bora, of smaller velocity of course, is also the cause that the air above the Kras and the Vipavska Dolina is dryer than the air above the other regions of Slovenia. Such relatively dry atmosphere provides for the natural drying of ham which is famous as a speciality under the name *kraški pršut* (i.e. the karstic crude ham).

2.3.2. The water balance

The equation of water balance

$$P = Q + E + N^* + R \quad (1)$$

expresses that in a specified area the precipitation, P, equal the sum of water discharges, Q, evaporation, E, the changes in water reserve, N*, and the water captured for the biological and industrial consumption, which is pumped from the studied area, R. In our case, the amount of the pumped water is small in comparison to the possible errors at precipitation gauging and making the precipitation maps, and therefore, it is not directly taken into consideration.

For the longer periods it can be assumed that the changes in water reserves in an average year are negligible, and the equation is reduced to the following items only:

$$P = Q + E \quad (2)$$

which means that the precipitation in a specified area equal the sum of discharges and evaporation.

For the needs of evaluating tracing experiments we wished to obtain water balance for the short periods, i.e., for the individual precipitation situations, or, at least for the periods of several months during which the individual tracing experiments were performed.

The results of water balance for the shorter periods were not encouraging although we tried to do our best when making the basic maps.

For the precipitation map of wider area of the Nanos and the Trnovsko-Banjška Planota, the data were made use of from 40 precipitation stations where daily precipitation were gauged at 7 hrs (Archives of the Hydrometeorological Institute, Slovenia).

In individual precipitation situations, very explicit minor precipitation cells occurred, which were impossible to be correctly presented through such low density of precipitation gauging station network.

During the relatively stationary precipitation situations, the differences of precipitation between individual areas (from the north towards the south, or, from the west towards the east), even reached the ratio of 10:1. At such sharp precipitation changes, errors occur in the making of precipitation maps, especially at the determining of precipitation for the relatively small contributing areas, particularly if the watersheds are not strictly defined.

The equation of water balance in which the precipitation are equal to the sum of water runoff and evaporation, apply only in case when the changes in the water reserve N* are negligible, which is almost impossible to expect at precipitation situations. With heavy precipitation the water reserve in the ground considerably increases. In the late autumn months, the higher altitudes

of the Trnovski Gozd are already under the snow cover which can contain quite large water quantities.

To avoid all these troubles, the 30-year water balance was taken as a basis. Let it be assumed in this case, that the water reserve at the end of the period equals to that at the beginning, since the difference in an average year is minimal in so long a period, thus, it means $N^* = 0$.

Also at the gauging of precipitation, the casual errors are eliminated by averaging; however, the systematic errors remain, which can be considerably reduced by applying supplementary procedures (precipitation correction due to wind, etc.).

Due to the considerable oscillation of annual precipitation in the 30-year period, the water balances were determined also for the 5-year and the 2-year periods, and it was also assumed that N^* was negligible. Although this is a rough premise, yet, it is acceptable were the accuracy taken into consideration, of the precipitation gauging, which is particularly problematic at the higher altitudes due to wind, while the terrain configuration does not allow that the vertical precipitation gradients be directly applied.

Precipitation determining

Precipitation are gauged with a gauge of Hellmann type which collects too little precipitation in windy weather. The experiments proved that, at wind speed of more than 5 m/sec, only 22 % of the actual snow precipitation are gauged, and 87 % of the actual rain precipitation (YANG et al. 1994). Experiments on precipitation gauging in wind conditions were not carried out in Slovenia; therefore, we assumed the WMO intercomparison results.

For the stations registering wind observations, force of wind was reduced for each precipitation day, to the altitude of Hellmann's gauge, and then, the adequate coefficient or the anticipated precipitation quantity was calculated. On the basis of gauge locations and direct obstacles, the precipitation stations were ranked into classes. For each class, the monthly and annual coefficients for the correction of precipitation were specified, on the basis of data from the stations with wind observations. By means of these coefficients, the quantities of precipitation were also corrected for the stations without wind observations.

Because the precipitation in Slovenia are heavier than in the places where the experiments were performed, it is assumed that also the rain drops and the snow flakes, on average, are slightly greater and heavier, respectively. Therefore, we reduced the corrective coefficients by 20 % for the places at the altitudes between 1000 m and 1500 m, and by 35 % for the places lying higher than 1500 m. Thus, the corrective coefficients amount to between 1.01 and 1.05; for the very exposed locations only, between 1.05 and 1.08; for the exposed locations above 1000 m in the area of the Nanos and the Trnovsko-Banjška Planota, up to 1.14.

Besides the increase of precipitation due to wind, we also took into account the increase of precipitation due to the gauge moistening. Whenever the gauge is emptied, a slight amount of water remains on the bottom and the sides of container. Following the results of laboratory testing, we took for the precipitation days with more than 1 mm of precipitation, the correction of 0.3 mm for a rainy day, and the correction of 0.15 mm for a day with snow precipitation. For all the precipitation maps, the corrected precipitation data were made use of.

In the making of precipitation maps (Fig. 2.12), the vertical precipitation gradients were not taken into account (a rather even increase of precipitation with the altitude), but the distribution was assessed subjectively, depending on the terrain configuration and precipitation data. Namely, it turned out that certain lower-lying places had received more precipitation than the higher-lying ones (Mrzla Rupa, 930 m above sea level - 2940 mm; Vojsko, 1070 m above sea level - 2800 mm; similar situation occurs in some other stations).

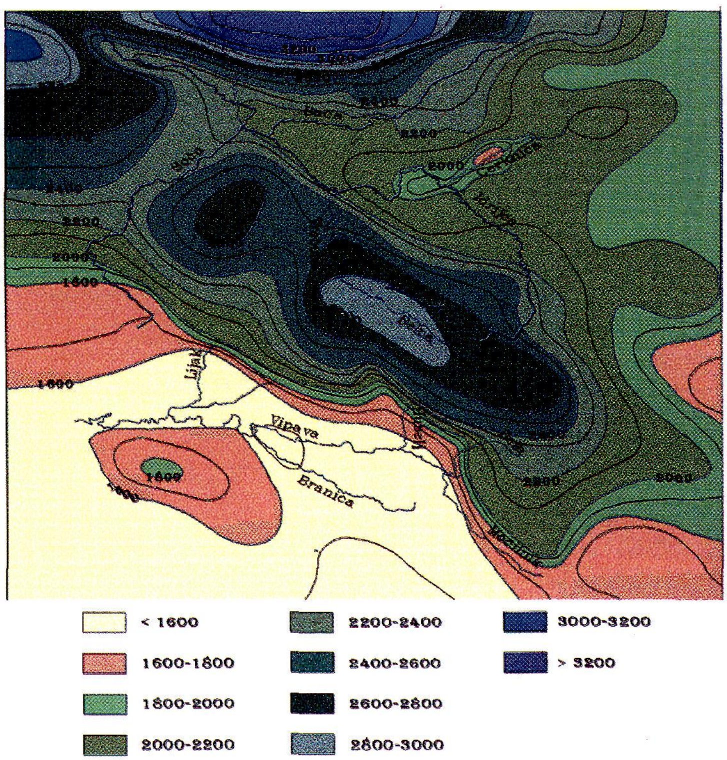


Fig. 2.12: The 1961-90 period precipitation map (mm).

The quantity of precipitation depends on the location of the valleys and mountain ridges. Certain laws were taken into consideration which, however, are based on the physics related explanation (the narrow valleys lying perpendicular to the direction of SW winds receive abundant precipitation, much more than the valleys lying in the direction of SW winds, especially if these valleys are located in the lee of mountain ridges, etc.).

Evaporation

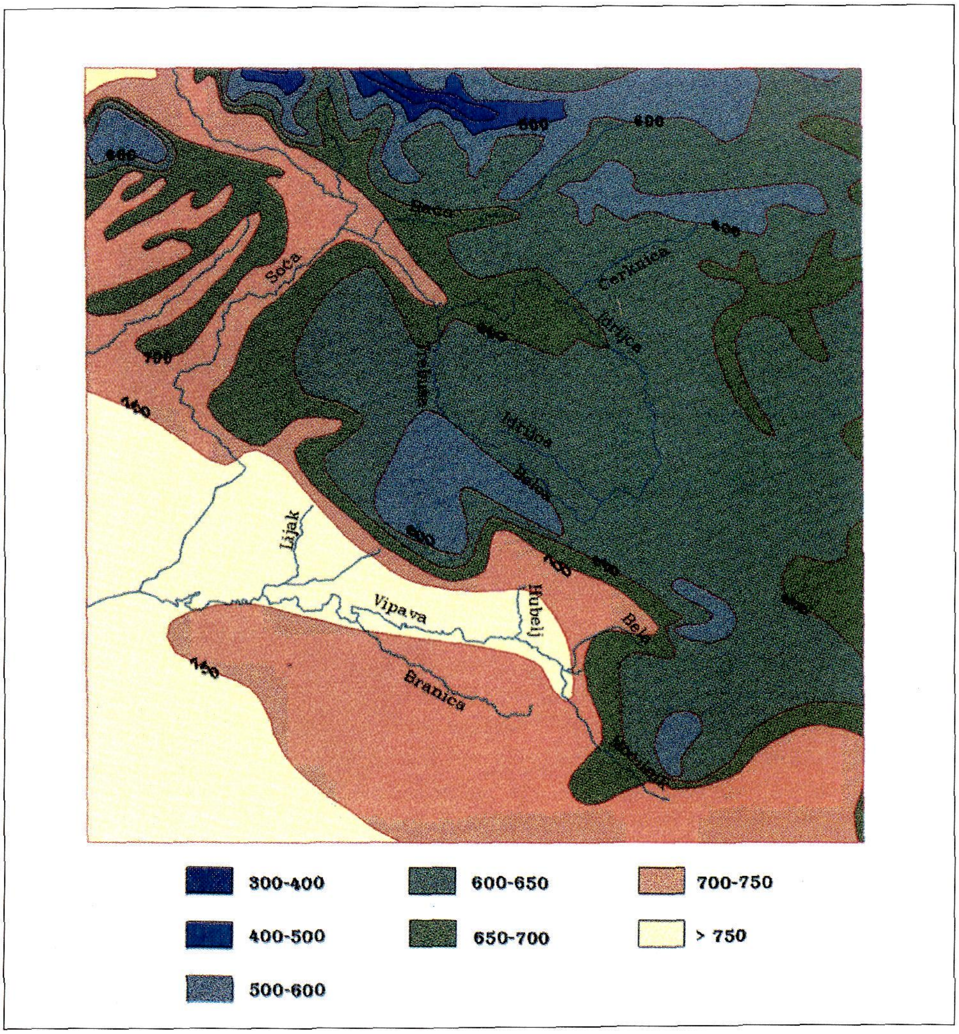


Fig. 2.13: The 1961-90 period evaporation map (mm).

For the calculation of runoffs on the basis of precipitation and evaporation, an evaporation map is indispensable. Since the precipitation in our case are much more abundant than the evaporation, considerable simplifications are applied to the evaporation data; yet, approximately equal accuracy is obtained with both maps. Calculated for the climatological stations was the potential evapotranspiration (ETP), following the corrected Penman method, by making use of the daily values of four weather parameters: air temperature, relative humidity of air, wind, and insulation (DOORENBOS et al. 1986). Since the monthly precipitation above the discussed area are always greater than the calculated ETP, we assumed that the evaporation is equal to the ETP, only for the lower-lying Kras plateau where the stone surface dries fast, we reduced the ETP by 10-15 % to obtain the evaporation.

The annual quantity of precipitation on the Trnovski Gozd is often greater than the evaporation. If the accuracy of precipitation gauging and simplification are taken into consideration, the accuracy of evaporation data is soon satisfactory. For the areas where not enough data were available, we applied the vertical gradients of evaporation which had been calculated on the basis of data from this area.

The difference between the actual surface area and its horizontal projection which is presented on the maps is taken into account in such a way that the calculated evaporation is being evenly increased with the altitude, and at the altitude of 1500 m, the addition amounts to approx. 10 %; on the plateaux, this increase is not taken into account (Fig. 2.13).

Runoff

The precipitation map (Fig. 2.12) and the evaporation map (Fig. 2.13) were digitised and then, the evaporation field was deduced from the precipitation field. Thus, we obtained a runoff map, specified in mm. Since all the maps were made for an average year in the thirty-, five-, and two-year periods, the values presented in mm also represent the annual runoff in litres per square meter (Fig. 2.14). This map has similar deficiencies as the precipitation map, because the values of precipitation are much greater than the values of evaporation. The calculated discharges for various gauging profiles are obtained from the runoff map by means of planimeter on the basis of hypothetical watersheds. The comparison of the gauged discharges with the calculated discharges and their deviations are a warning signal for the problems of watersheds and the deficiencies in the analysis of individual parameters. Usually, the greatest relative deviations occur at very small river basins, while at larger river basins, the relative correspondence is much better.

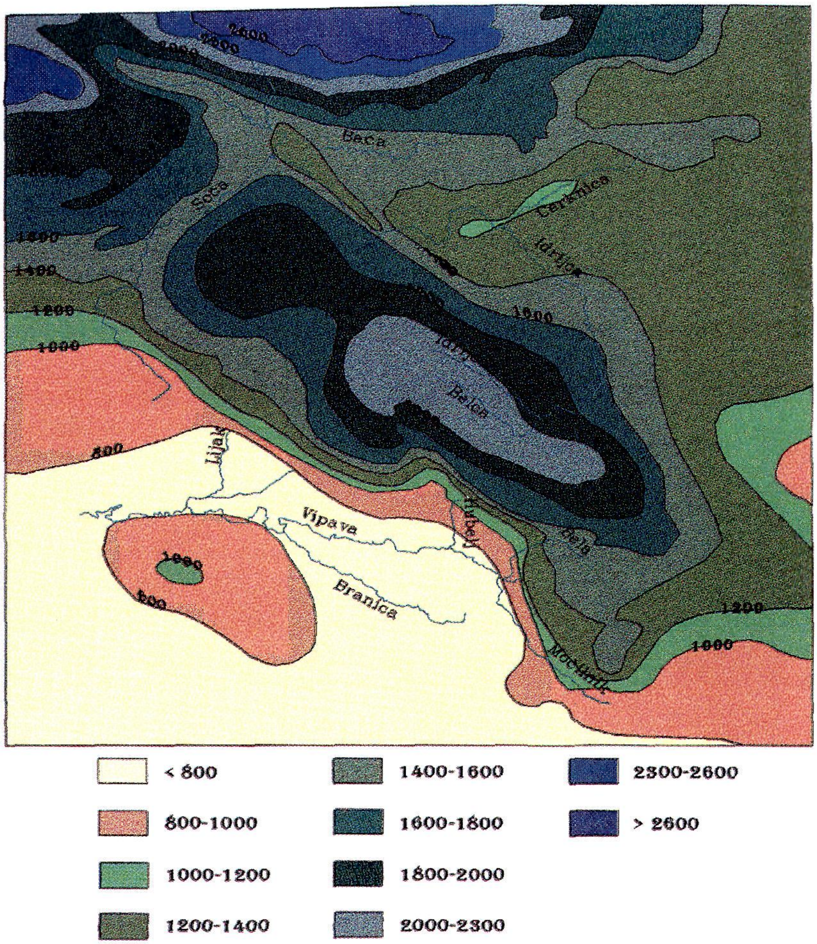


Fig. 2.14: The 1961-90 period discharge map (mm).

2.4. GEOMORPHOLOGIC REVIEW OF TRNOVSKO-BANJŠKA PLANOTA (P. HABIČ)

2.4.1. General orographic-hypsographic properties

Among the valleys of the Soča, Idrijca, Pivka and Vipava rivers in western Slovenia lies a mountain ridge of the High Karst, called Trnovsko-Banjška

Planota and sometimes Trnovski Gozd for short. The north-western part of the High Karst comprises a series of morphologically rounded units called, from the Soča valley towards Pivka or Postojna basin in the south-east, as Banjšice, Trnovski Gozd, Križna Gora, Javornik, Črnovška Planota, Hrušica and Nanos. Most of this entirely karst surface reaches altitudes between 800 to 1200 m; there are some dry valley incised in it and also some wider depressions, and at its border the surface is slightly lower. Only single peaks in a central ridge of Trnovski Gozd reach more than 1200 m a.s.l.; the highest of these is Veliki Golak (1495 m), in Javornik the highest is Srednja Gora (1275 m) and on Nanos it is Suhi Vrh (1313 m); the Črnovrška Planota lies mostly at altitudes between 600 and 800 m, and the same may be said for the western border of Banjšice; the lowest is its southern border where the bottom of a margin karst polje near Grgar lies between 285 to 300 m a.s.l (Fig. 2.4.1).

On the border of the High Karst the relatively narrow Soča valley is cut the deepest; near Gorica where it broadens to the Gorica Plain it lies at about 50 m a.s.l., but only 30 km upstream at the confluence with the Idrijca near

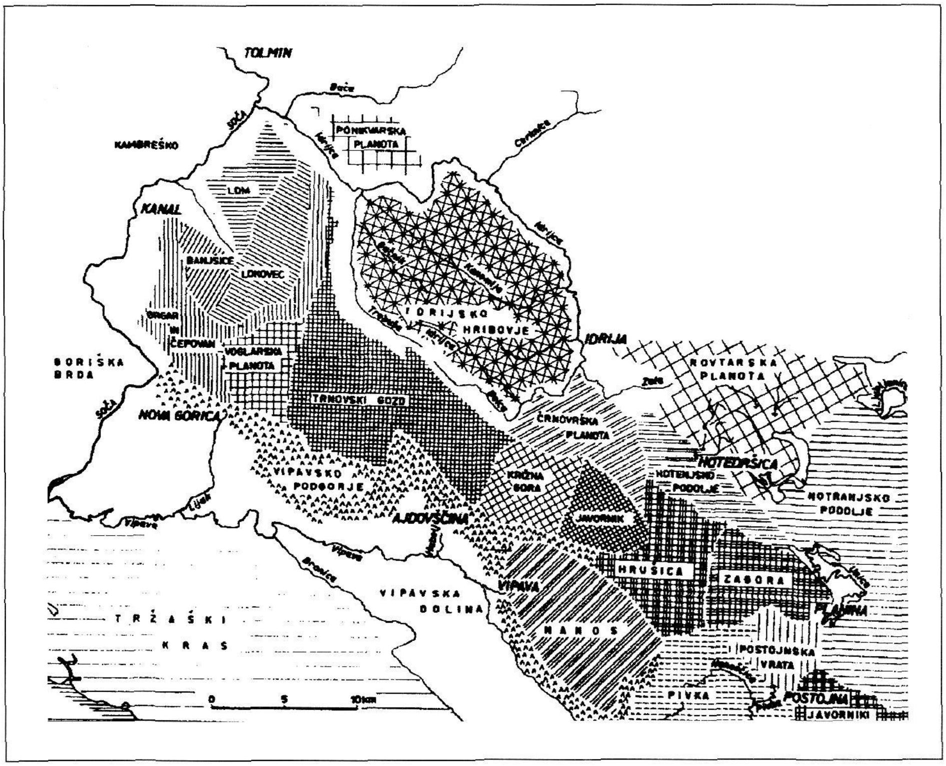


Fig. 2.4.1: The orographic units of the High Karst in western Slovenia.

Most na Soči it is 150 m a.s.l. The Idrijca valley rises for about 400 m up to the confluence with the Belca which is deeply cut in the northern border of Trnovski Gozd. The watershed between the valleys of the Belca and Trebuša, in the NE side of Trnovski Gozd lies about 1050 m high; the Trebuša flows into the Idrijca at 190 m a.s.l. Both valleys are relatively narrow, the slopes in the southern side of the highest part of Trnovski Gozd being higher and steeper, sometimes even vertical. Even more deeply downcut is the Vipava valley on the southern side which rises from its confluence with the Soča at 30 m a.s.l. up to the Vipava spring below the western slopes of Nanos at only 100 m a.s.l.; along its tributary Močivnik the watershed with the Pivka near Razdrto lies at 595 m a.s.l.

The valley of Vipava is in fact a low undulating surface on Eocene flysch between the Trieste-Komen Karst in the south and the High Karst in the north. Its valley bottom is relatively narrow, except between Vipava and Ajdovščina.

The contrast between the low flysch hills in the north and the steep and sometimes even subvertical slopes of the High Karst is a remarkable sight. Limestone overthrusted on flysch is exposed to intensive mechanical weathering and breakdown; therefore tectonic breccias, debris and breakdown blocks are accumulated at the foot.

The south-eastern karst border of the western High Karst comprises the valleys of the Nanoščica in a flysch part of the Postojna basin, from 510 to 600 m high, and a gap (Postojnska Vrata) between Hrušica and the Javorniki - Snežnik Mountains, between 600 and 750 m a.s.l.; further on there is the karst polje of Planina and a part of Notranjsko, or Hotenjsko Podolje between Logaško Polje and the valley of the Zala stream which flows near Podroteja into the Idrijca. Notranjsko Podolje at Planinsko Polje lies at about 450 m, but elsewhere the elevations between 500 and 650 m prevail. In the region between Kalce, Hotedršica and Godovič there is a karst plain up to two km wide in the Idrija fault zone. On its southern side it is bounded by the 300 m high steep edge of Hrušica and Javornik and on its northern side by Rovtarsko Žibrška Planota. To the east of Trnovski Gozd and Križna Gora the High Karst abruptly lowers to Črnovško Zadlaška Planota, up to 5 km wide, which forms the higher and broader part of Hotenjsko Podolje.

The studied part of the High Karst is composed of Cretaceous and Jurassic limestones and Upper Triassic dolomites that belong to the Trnovsko Hrušiški nappe within a thrust structure of western Slovenia. The carbonate rocks are thrust over the layers of Eocene flysch and over-thrusted blocks are fractured and tectonically displaced along longitudinal Dinaric and transverse faults (see chapter 2.6). The western part of the High Karst in the region between the Idrijca and Vipava rivers is from 10 to 15 km wide as an uniform block of karstified limestones and dolomites; between the Soča and Pivka rivers it is about 50 km long and covers roughly 700 km^2 of karst surface which is prac-

tically from all the sides bounded by lower fluvial areas. Flysch rocks encompass karstified limestones as a partial or complete hydrogeological barrier on the west, south and east. On Banjšice to the west of the High Karst flysch is preserved as a thin cover over karstified limestones and in some places the karstified base outcrops; however it mostly acts as a hanging hydrogeological barrier underlain by a typical karst circulation. In the north the High Karst is surrounded by impermeable Middle and Lower Triassic but also Permian and Carboniferous rocks. The river Idrijca and its tributaries the Belca, Zala, Kanomlja, Hotenja and Trebuša incised their superficial beds in them.

Taking into account the trend of the Idrijca headwater valleys and also corresponding hypsographic conditions we may assume that the Idrijca, Belca, Nikova and Kanomlja once flowed towards the south-east over Črnovrška Planota and by Hotenjsko Podolje into the formerly superficial Ljubljanica (MELIK 1963). It is supposed that river piracy in impermeable rocks around Idrija and karstification in the Ljubljanica riverbed contributed to diversion of the Idrijca headwaters into the Soča.

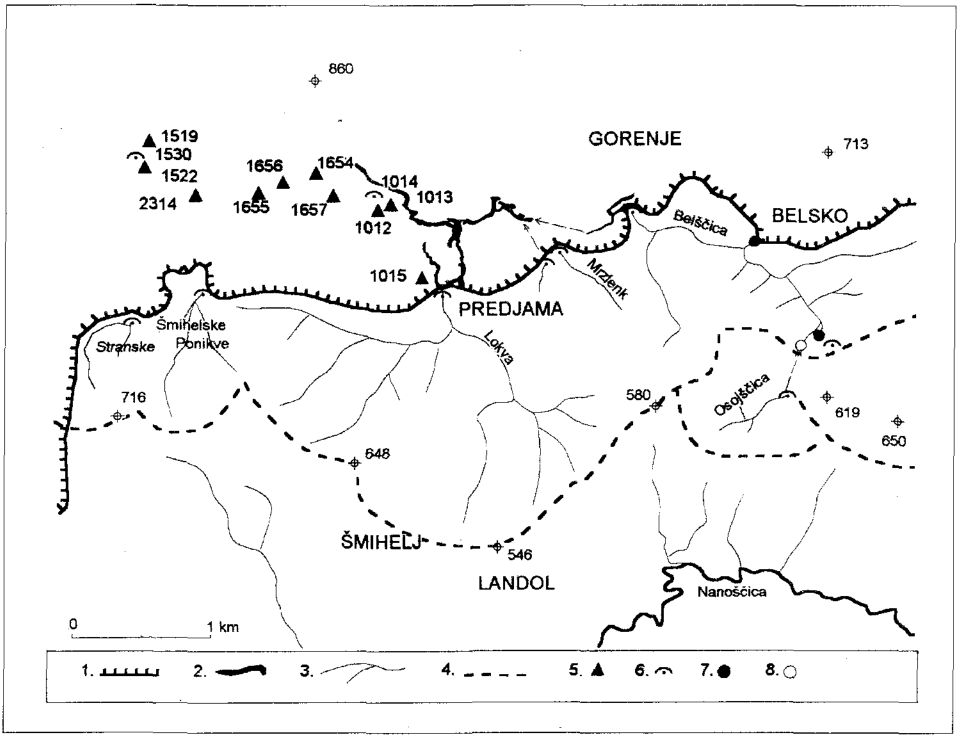


Fig. 2.4.2: The sinking streams and caves near Predjama.
Legend: 1 - overthrust, 2 - cave passage, 3 - sinking stream, 4 - Adriatic-Black Sea watershed, 5 - shaft, 6 - cave, 7 - karst spring, 8 - periodic spring.

In the Postojna basin to the east of the High Karst the deepest cut valley is that of Lokva which sinks near Predjama at 462 m a.s.l. and belongs to the Adriatic water basin together with nearby sinking streams called the Belščica, Mrzlek and Ribnik to the east and Šmihelske and Stranske Ponikve to the west of Predjama; the Pivka with its tributaries drains into the Black Sea, the watershed between the Black Sea and Adriatic passes over flysch ridges in the Postojna basin between Razdrto and Studeno at about 600 m a.s.l. Karstified Cretaceous limestones underlying the Eocene flysch enable karst bifurcation on Pivka; this is why the watershed is apparent just there. Karst bifurcation was proved also at the watershed between the Ljubljanica and Idrijca (HÖTZL et al. 1976) and it is supposed to be in Hrušica between the Ljubljanica and Vipava rivers (Fig. 2.4.2).

2.4.2. Geomorphology of single orographic units

2.4.2.1. Banjšice between the middle Soča valley and dry Čepovan valley

The central ridge of Trnovski Gozd passes towards the west into a lower plateau-like surface on both sides of the dry Čepovan valley, more than 300 m deep. Although this valley is the most impressive geomorphologic border between Trnovski Gozd in narrow sense of meaning and Banjšice, the karst surface of Voglarska Planota between Trnovo and Lokve in the south as well as Lokovec in the north of the valley display similar relief features. Obviously they were controlled by similar and interrelated morphological conditions. Major relief difference on both sides of the Čepovan valley occurred later when the impact of a different geological base had been felt and when the former Čepovan river was captured and the valley of the Soča between Tolmin and Gorica deepened.

Such geomorphologic changes were controlled by tectonic uplifting of the area in the entire region of Posočje on the northern side of Adriatic and the extreme end of the Julian Alps. Previous studies indicate that radial tectonics in the area of the Julian Alps and Dinarids was renewed in the Upper Pliocene and lasted during the whole Quaternary (HERAK 1991). Neotectonic activity was specially efficient along older Dinaric trended faults with right wrench-faults and by different uplifting of single parts of Posteocene thrusts and nappes (PLACER & ČAR 1974; PLACER 1981, 1982; ČAR & JANEŽ 1996).

Important morphological and hydrographical changes occurring in Posočje due to differentiated tectonic movements after a general levelling in the Tertiary are evidenced by meandering river valleys and by remains of the older surface between the Julian Alps and Adriatic. An accelerated karstification of

carbonate rocks took place, while in impermeable flysch rocks the valleys were erosionally deepened. Considerable erosion at the extreme end of the Julian Alps reveals complicated geological structure at the contact of the Southern Alps and the Inner and Outer Dinarids (HERAK 1991).

According to MELIK (1956) the superficial flows were in the Pliocene convergently directed from the region of the Julian Alps towards the northern Adriatic. He deduced this idea from the direction of the headwater valleys in upper and middle Posočje and also from single valleys and passes in their continuation towards the south-west. One of such flows is supposed to be the Čepovan River with headwater at upper Bača, Koritnica and Kneža. He supposed the former Tolminka with Zadlaščica somewhat parallel to the direction of the present Soča valley between Tolmin and Plave and over the present pass Vrhovlje into Goriška Brda. Relative stagnation of Banjška Planota, specially of its elevated part which is Trnovski Gozd, decisively influenced the morphological and hydrographical development of the central Posočje. The superficial waters in the present Idrijca river basin deepened their riverbeds along the Dinaric-trended faults of the Idrija fault zone. From the most uplifted area around Vojsko the rivers Trebuša, Gačnik and Hotenja flow directly towards the north-west, while the Belca, Idrijca, Nikova and Kanomlja flow at first towards the south-east and then they sharply turn towards the north-east to finish, together with the Zala, towards the north-west. The central confluence of all the waters occurred in the north of Trnovski Gozd near Tolmin where also the waters from Upper Posočje flow. Obviously the forerunner of the Tolminka succeeded in deepening the through valley in the western border of Banjšice towards the south-west. Thus the superficial rivers evaded the whole western border of the High Karst while in its central carbonate part the underground karst drainage prevailed completely with deeply etched karst at the surface.

The cross valley of the Soča between Tolmin and Plave is downcut into mostly impermeable flysch rocks, but in some places it reaches the limestones within a flysch basement. This occurs near Vogrščck and Avče where there are seasonal karst springs. The central valley of the Soča in flysch is relatively wide; much more narrow is a canyon section of the Soča valley which is running between Plave and Solkan towards the south-east. There the Soča deepened its riverbed in the anticline folded Cretaceous limestones of Sabotin and Sveta Gora and thus brought Mrzlek, the lowest drainage of the High Karst underground waters, into a superficial riverbed.

Between the valleys of the Idrijca, Soča and Čepovan the uninterrupted high karst plateau is preserved only in its central highest part on Lokovec and also partly on Banjšice in its narrowest part between Trušnje, Sveto, Lohke and Podlaka. To the west and to the south where there is more flysch in the basement, the surface is deeply etched. In the western side the valley of Avšček, which flows into the Soča near Avče, is the deepest along the Dinaric

Avče fault. In the north on Lome, Levpa and Kal the fluviokarst relief predominates, with superficial gullies and dales which are more gentle towards headwater side; closer to the Soča they become steeper and are mostly karstified, or at least, lacking permanent superficial streams. There are no remarkable sinking streams in this part but they prevail in the western part of Banjšice, near Bate, Kanalski Vrh, Ravne, Ravnica and Grgar. At swallow-holes of small streams shallow karst depressions occur, a sort of ouvalas; the depression near Grgar bears all the traces of a karst margin polje. A fossil blind valley Dol near Grgar is also interesting; it is downcut into a continuation of the Čepovan valley and into a narrow pass called Preval between Škabrijel and Sveta Gora close to the Soča meander above Solkan. An upward step valley between Kanalski Vrh, Banjšice and Grgar with interlying treads, ouvalas and sinking streams near Bate, Dragovica and Ravne shows that waters from this part of Banjšice formerly flowed superficially towards the south and joined the Čepovan river near Grgar. When this one was captured due to the tectonic uplifting of Banjšice, the Grgar basin was deepened by local tributaries from the flysch until the uniform water network disintegrated to single sinking streams. At present all the waters from Banjšice, both those from flysch and from the karstified part, drain into the Soča subterraneously, in particular into the Mrzlek and Bokalci spring to the south; these two springs are drowned in the dammed Soča riverbed for the hydro-power station at Solkan. Exceptionally a part of Banjšice waters flows towards the west into the Avšček which reaches the Soča during the higher waters only; in dry periods it disappears in its own riverbed in front of Avče. It is not yet known where the Avšček water reach the Soča at times of low flow. The Vogršček is similar, for it drains out of the cave Babja Jama into the Soča above Doblar at high water flow and its low water outflow is not yet known. The only permanent spring in the northern border of Banjšice is Hotešk near Slap ob Idrijci which is, during high waters, at least, fed by a sinking stream in Čepovan and by part of Zgornji Lokovec (HABIČ 1982).

In terms of shape and size the Čepovan valley is without doubt the largest morphological feature in the western border of the High Karst. It crosses it at its widest part, a distance of almost 20 km. Undissected steep slopes descend from the plateau surface to the karstified bottom for 300 m. The bottom itself has an unusual shape as it is convex in its central part at altitudes between 650 and 670 m. From there the valley descends on both sides. Towards the north it descends for an additional 100 m and remains hanging at 550 m a.s.l., or 270 m above the present superficial riverbed of the Idrijca; to the south it descends for 200 m and close to Grgar it is at 450 m a.s.l.; on Preval above Dol, south of Grgar, it is 330 m a.s.l. or 190 m above the Soča riverbed near Solkan. This convex shape of a dry valley was perhaps caused by younger tectonic movements and it corresponds to the highest central ridge of Trnovski Gozd as supposed by WINKLER (1957); maybe its deepening on both sides

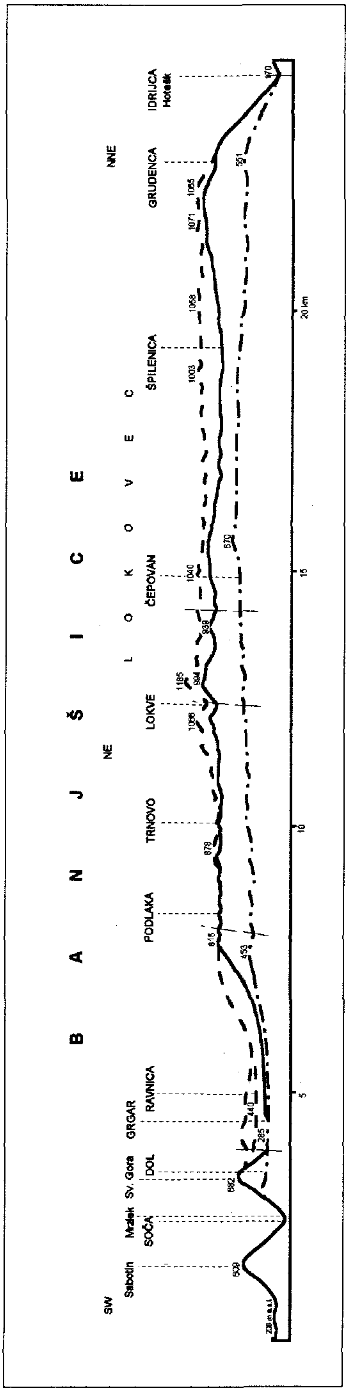


Fig. 2.4.3: The morphographic section of the Banjšice plateau and Čepovan dry valley.

was caused by local superficial waters after the Čepovan river was captured. Superficial waters were partly preserved on the less permeable dolomite where small permanent springs are still available for water supply. They also feed the sinking stream that disappears immediately when it reaches the limestones and its Quaternary sediments are already accumulated more than a kilometre over the valley. Dammed waters on the border of the Grgar basin probably also contributed to deepening of the dry valley (Fig. 2.4.3).

The higher border in the northern part of the Čepovan valley is interesting from a morphogenetical point of view. To the east just a narrow ridge of Kobilica and Vrše (909 m) are preserved above the deep valley of Trebuša; to the west there is close to the steep edge on Zgornji Lokovec a morphological karstified terrace between 850 to 900 m a.s.l. where there are remains of sediments, sand and gravel of the former Čepovan river. Even older fluvial gravel is preserved on the highest crest of Lokovec between 900 and 1000 m a.s.l. (HABIČ 1968; 1982). The Čepovan river started entrenchment into a wide gravel covered plain; its remains are found today on the border above the Idrijca valley, slightly over 1000 m high and to the south on the border above the Grgar basin about 800 m high, up to the steep edge above the Vipava Valley where near Lijak it diminished in down-bending folds to 600 to 700 m. Along wide the levelled surface of Banjšice, which reaches Voglarska Planota between Trnovo and Lokve in a form of an alluvial fan, the central ridge of Trnovski Gozd had existed before the deepening of the Čepovan valley. In fact it preserved its orographic properties at a time when Banjšice had been already exposed to fluviokarstic dissection.

2.4.2.2. Trnovski Gozd, Križna Gora, Javornik, Zadlog and Črni Vrh

We examined the morphological properties of Banjšice in detail as they are important to the understanding of the morphology and morphogenesis of Trnovski Gozd and its continuation over Križna Gora and Javornik to Hrušica. In morphological terms this is a rather confined unit of the High Karst bounded on the north and the south by steep, even precipitous slopes and deeply downcut valleys. The plateau karst surface between the Idrijca and Vipava has preserved some differences, in spite of the considerable distance from morphogenetical influences at its border due to tectonic isolation and prevailing karst transformation, which were enhanced by later endogenic and exogenic processes.

Our interest is focused on longitudinal and transverse ridges and dales which allow the morphographic classification of Trnovski Gozd into smaller units. Without doubt the central Dinarically trended ridge of Golaki is outstanding within the karst relief by its altitudes from 1400 to 1495 m, which is dome-like at the highest peaks and lowering towards the north-west over Bukovec (1445 m) to Veliki Češevik (1349 m) and Škol (1182 m) above Lokve but also towards the south-east over Javorški Vrh (1404 m) and Potegla (1251 m) to Vrh Hoje (1105 m) (Photo 1). Between conical-shaped hills, deep karst

Photo 1: The summits of Golaki in the central part of Trnovski Gozd, Julian Alps in the background (Photo by P. Habič).

dolines (also called "Kontas") are distributed and there are ouvalas like Mrzla, Mojska and Smrekova Draga at the border above Trebuša. Glacial debris is preserved in them from the last Glacial when the highest summits of Trnovski Gozd were ice-capped. The melting of ice without doubt had a decisive influence on the deepening of dolines and ouvalas and also on the formation of cirque-headed glacial valleys above the Trebuša valley.

Along the central ridge narrow ledges with lower conical-shaped summits are distributed on both sides. At the foot a wider ledge is preserved as a part of former border planation that had developed before the uplifting of the entire High Karst and accelerated erosional deepening of the flysch Vipava valley. The morphological equivalent of Voglarska Planota on the western side of Trnovski Gozd is Otliška Planota to south of Golaki between Predmeja, Kovk and Col. A corresponding border ledge on Čaven between Rijavci and Predmeja is not preserved so the rocky edges and slopes of Čaven between Ajdovščina and Šempas are the highest; at their foot there are immense breakdowns. A part of them slide down the flysch base to the bottom of the Vipava valley.

The central highest ridge of Trnovski Gozd is cut by transverse and longitudinal dry valleys and thus it is divided into four orographic units. To the west of the transverse valley there is Bukovec (1445 m) and in the south of the longitudinal one is Mrzovec (1410 m); to the east there is Golaki on the northern side and Čaven with Modrasovec and Praprot (1374 m) on the southern side of the longitudinal valley. The transverse gap lies near Paradana between Bukovec and Golaki, about 200 m deep. At its bottom opens the ice cave Velika Ledena Jama, more than 700 m deep. The dry valley continues over the ouvalas of Mala and Velika Lazna, Smrečje and Krnica and remains hanging in a steep slope above Vitovlje.

Mala Lazna in the middle of the transverse valley is etched also by a longitudinal valley that developed along a major Dinaric fault between Lokve and Predmeja. This fault, called the Avški or Predjamski fault, we already met near Avče and in the Avšček valley. On Lokovec the northern part is more raised than the southern one; on Lokve a dry valley developed which is suspended high on the margin above the Čepovan Valley and its start reaches the edges of Mala Lazna. From the pass near Strgarija a level dry valley continues to the other side towards Predmeja. There it is downcut by a steep edge; from Predmeja towards Col the precipice edge of Otliška Planota passes along the Avče fault. Between Podkraj and Predjama the Avče-Predjama fault divides the lower Hrušica from the higher Nanos. This typical Dinaric fault thus varies from a morphological point of view.

The Otlica border edge is displaced near Predmeja closely below the southern footslope of Golaki. It narrows most in its middle part near Otlica due to the slightly wider lowered surface of the central ridge between Obli Vrh (1109 m), Hoje (1105 m) and Marni Vrh (1080 m). On the hanging ledge

Photo 2: View over Otlica and eastern part of Trnovski Gozd (Photo by P. Habič).

of the Otliška Planota there are several lower conical summits and interlying hanging vales and smaller ouvalas. The highest isolated peak is Sinji Vrh (1002 m) with 200 m of relative height. At its eastern foot lies the transverse valley between Mala Gora and Kovk which represents the morphological border between Golaki and Križna Gora. Elongated ouvalas developed in the narrow bottom and along them is a broader ledge at altitudes between 800 and 900 m, extending from the southern to the northern border of the plateau. Karst dissection of the Otlica ledge is controlled by the structure of the rock basement (Photo 2). From a morphological and physiographic point of view Jurassic flat limestones with nodules and sheets of cherts are important. During weathering a thick, mostly silicate coating remains on them and thus more fertile soil is preserved above. Torrential waters transport debris from steep slopes over the surface and sculpture a sort of fluviokarstic gullies; finally they deposit the debris and fill up shallow ouvalas, dry valleys and dolines.

From a morphological point of view Križna Gora represents a special unit of Trnovski Gozd. Like the transverse valley in the western side between Kovk and Mala Gora, Križna Gora also is bounded on its northern side by a transverse dry valley which remains hanging in the northern side 200 m above Črni Vrh and in the southern side near Col in the slope above the Vipava valley. There are two larger ouvalas in it; closer to Črni Vrh is Mrzli Log with

partially filled up and partially doline-like bottom at altitudes between 790 to 800 m; closer to Col is the half open ouvala Malo Polje with a filled up bottom about 640 m a.s.l. The karst border is the lowest near Col; a dry valley from the slopes of Križna Gora on one side and those from Vodice and Javornik on the other proves that in this part of Trnovski Gozd fluviokarstic deepening lasted much longer than in the central, the most elevated part. It corresponds to the tectonic situation also, as in whole Dinaric ridge between Golaki and Javornik just the ridge of Križna Gora is the least uplifted. The highest peaks reach slightly more than 1000 m, and only the Špičasti Vrh (1128 m) near the southern border of Zadlog is a good 50 m higher than the others. Between conical peaks there are several shallow dry valleys and ouvalas; their bottoms are considerably higher than the bottoms in transverse valleys to the east and west.

Javornik with Kanji Dol and Vodice slightly differs from the morphological point of view from other units of Trnovski Gozd. According to its structure it belongs to the south-eastern part of the Trnovski nappe which is the most uplifted and where at the surface are exposed such units, as for example Čekovnik and Koševnik imbricate structure overlaid to the Hrušica nappe. Thus the relief indicates the transition from Trnovski Gozd to Hrušica. Near Col the Eocene flysch basement is almost at 600 m, near Podkraj it is already near to 900 m and below Streliški Vrh (1265 m) it reaches more than 1000 m; then it steeply descends to Vodice on one side and to Lome, to the east from Črni Vrh, on the other. As the flysch belt in the east of Col between Nanos and Javornik is relatively narrow and shallow except in the narrow valley of the Bela and on Vodice and Lome, it is not specially remarkable. Without doubt it is more important from the hydrogeological point of view as it directs the underground drainage from Javornik into Divje Jezero and Podroteja (HABIČ 1987).

The conical summits on Javornik (1240 m) are 100 m higher than those on Križna Gora. They are distributed in the northern, eastern and southern borders, in the central part there is a deep relief gap which starts at Vodice with a small margin karst polje, continues with elongated ouvala Široka Dolina and ends in the ouvala of Kanji Dol. A dry valley up to 300 m deep with local karst depressions, on Vodice at about 920 m and in Široka Dolina and Kanji Dol about 880 m a.s.l., winds from the east to the north. In a continuation there is above Kanji Dol a narrow pass, slightly above 1000 m, and to the west of Široka Dolina there is a pass at 960 m a.s.l.; from there towards Col a steep dry valley hangs up to the border ledge, about 650 m high. Considerable altitude differences between the elevations and valleys on Javornik are obviously due to abundant fluvio-denudation and karst dissection of the extreme eastern part of Trnovski Gozd. This was probably controlled by higher proportion of dolomite and fractured and broken rock within the markedly thrust structure. The deeply etched surface of Javornik essentially differs from the

levelled surface of Črnovrška Planota and also from evenly karst dissected Hrušica (Fig. 2.4.4).

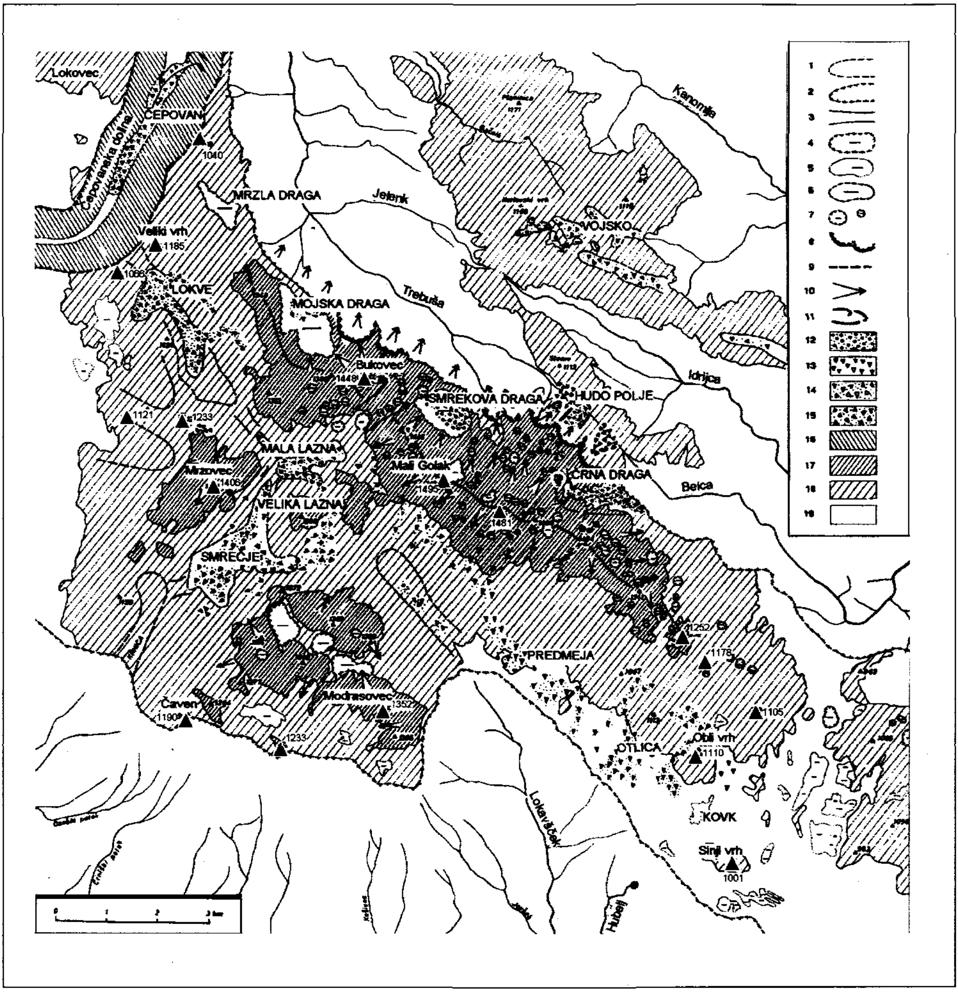


Fig. 2.4.4: The traces of glaciation in the area of Trnovski Gozd.
Legend: 1 - hanging dry valley, 2 - steep edge of High Karst, 3 - the transverse dry valley Paradana, 4 - deep karst depression, 5 - uvala, 6 - karst depression with rubble, 7 - glaciokarstic depression, 8 - glacial cirque, 9 - the central ridge of Golaki, 10 - the Pleistocene snow and ice flow direction, 11 - end moraine ridge, 12 - moraine scree material, 13 - carbonate scree and fossil talus, 14 - alluvial dolomitic scree and loam, 15 - silicate - chert scree and loam, 16 - steep slope of Čepovan dry valley, 17 - extension of Würm glaciation, 18 - periglacial area, 19 - karst plain (800 - 900 m).

2.4.2.3. Črnovrška Planota, Zadlog, Idrijski Log, Predgriže and Lome

The steep northern border of Križna Gora and Javornik descends from the altitudes between 1100 to 1240 m to a wide levelled ledge from 700 to 800 m high. A steep, mostly Dinarically verging slope is a remarkable boundary between the central ridge of the High Karst and Črnovrška Planota, about 5 to 6 km wide and 10 km long. According to the geological setting it belongs to Čekovnik and Koševnik imbricate structure and to Hrušica nappe in its base; hence this is a relief near Trnovo nappe and Idrija fault zone. A major part of Črnovrška Planota consists of Triassic dolomite which is overlain on the Cretaceous limestones in a layer some 100 m thick. The dolomite along the thrust planes is obviously very fractured and may retain the water on the surface, thus diminishing the role of karstified basement in respect to relief. It stands specially for Zadlog which is a peculiar karst polje having a seasonally flooded rocky plain from 2 to 3 km wide covered by a thin layer of dolomite debris and soil. The polje is bordered by dolomite ridges, up to 100 m high, which are on the external side downcut by streams; these flows sink in indistinct blind valleys at the contact of Triassic dolomites and Cretaceous limestones around Zadlog from Idrijski Log, Predgriže to Črni Vrh. As at Zadlog the bottoms of these valleys are also covered by a thin layer of dolomite debris. The superficial streams disappear somewhere in alluvium or in small swallow-holes; in nearby limestones there are many shafts sculptured by sinking streams. The most interesting among them is Habečkovo Brezno near Predgriže, 353 m deep (HABE et al. 1955).

In the south-eastern part of Črnovrška Planota a peculiar morphological unit, Lome, developed in a belt of Eocene flysch overlying the Hrušica nappe

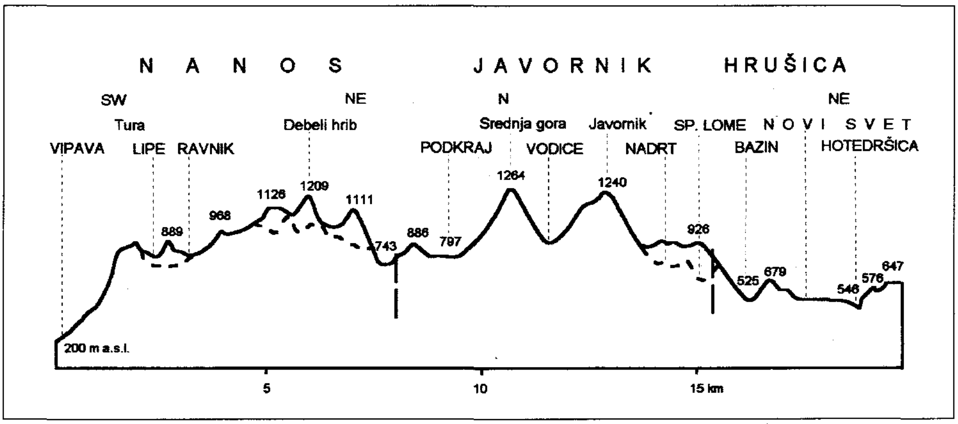


Fig. 2.4.5: Morphographic section through High Karst between Vipava valley and vale of Hotedrščica.

ı the base of Trnovo nappe. Smaller karst depressions developed in three hort belts in Gornje and Dolnje Lome and near Podjesen where the superfiial waters from nearby flysch disappear. In older phases the flysch waters ontributed to the formation of the karst plain in limestones at the border of olomite. But karstified limestones in a flysch basement shortened their uperficial flow. The north-eastern part of Črnovrška Planota is formed in Cretaceous limestones as a doline-like plain. The superficial waters from the resent Idrijca and Belca headwaters probably contributed to its former lanation when they had flowed superficially south-eastwards and helped to evelop Hotenjsko Podolje in the Idrija fault zone along the northern border f Hrušica (Fig. 2.4.5).

.4.2.4. Nanos with Hrušica and Zagora and the northern border of he Pivka basin

In the series of the High Karst morphological units of western Slovenia; Ianos Mt. takes a special place due to its wide ridge and background deep in Irušica and Zagora. This speciality derives from its geological structure with ıick beds of carbonate rocks, in particular Cretaceous and Jurassic limestones f the Hrušica nappe. On the southern side they are over-thrusted to the

hoto 3: Mt. Nanos above the village of Razdrto (Photo by P. Habič).

Javornik-Snežnik thrust sheet; from the northern side they are underlain by Trnovo nappe and interjacent slices (PLACER 1981). In its structure and at the surface also a recumbent fold thrust over flysch is well seen; it is jagged by the Idrija and Predjama fault zones and also by interjacent faults and it is differently tectonically displaced along them.

From northern, western and southern side Nanos Mt. (Photo 3) is bounded by flysch with deeply downcut superficial flows. These streams have contributed to an important exposure of the more resistant carbonate rocks and consequently to more abundant karstification. The High karst border of Nanos between Vipava and Pivka does not essentially differ from a similar one on Trnovski Gozd, but more important morphological differences appear in southern and eastern border. Nanos itself is about 12 km long and about 7 km wide, and forms together with Hrušica, the uninterrupted karst plateau between Vipavska Dolina and Hotenjsko Podolje of more than 15 km.

Nanos is highest on the north-eastern side, where its peak Suhi Vrh reaches 1313 m. It is relatively high on the eastern side also; Debeli Hrib is 1209 m high and in-between is a sort of plain with cones and valleys between 1000 and 1100 m a.s.l. The distribution of cones, dry valleys and ouvalas in this part of Nanos is controlled by the structure of the rock basement and also by long-lasting karstification which is typical of the highest parts of Trnovski Gozd, Nanos and Hrušica. In this part there are most caves and shafts, among them Slapenski Ledenik and Strmadna (HABIČ 1963). Westwards Nanos lowers in relief steps to a margin ledge similar to the one met at Voglarska Planota and Otlica; this one on Nanos is also between 800 to 900 m. This ledge is cut by a precipitous edge above Vipavska Dolina; parallel to it two dry valleys developed, called Ravnik and Lipe. The last one is deepened in its

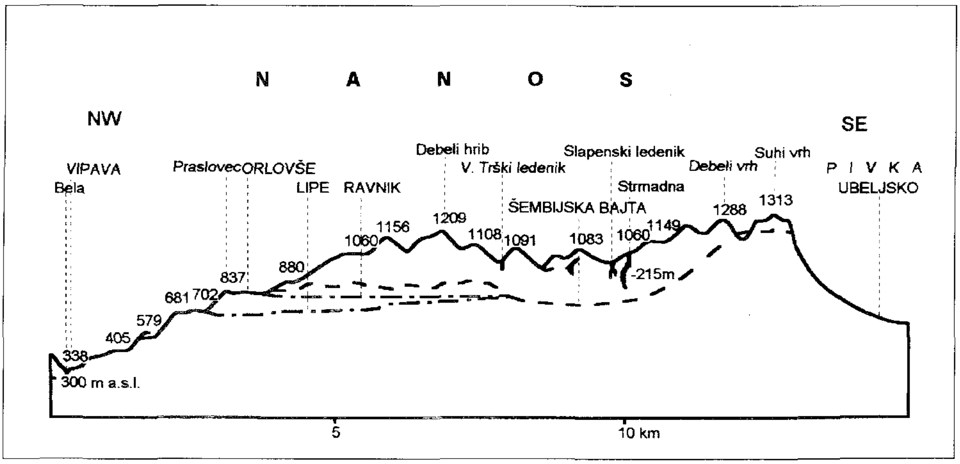


Fig. 2.4.6: Longitudinal section of the Nanos plateau.

upper part by the elongated ouvala of Šembije; towards the north-west it remains hanging, as at Ravnik, above the semi-circular border between the Vipava and Bela valley near Vrhpolje. The ledges on this slope of Nanos are structurally controlled and partly associated with gradual downcutting of the Bela stream into flysch between Vipava and Col. The intensive entrenchment of the Bela valley was enabled by tectonic subsidence of Vipavska Dolina between Vipava and Ajdovščina. Near Vipava the flysch barrier at the foot of Nanos had been eroded below the present valley's bottom. The subsided part of the valley was partly filled up by Quaternary sediments which dammed the runoff of karst waters from Nanos and thus caused the delta-like distribution of the Vipava springs (Fig. 2.4.6).

The flysch cover of Nanos extends in the western, southern and south-eastern part from Vipava, where it is below 100 m, to the border below Pleša (1262 m) where it reaches near Razdrto the height of about 800 m and near Sv. Bric below Suhi Vrh 1000 m. Below the precipitous wall called Rjava Stena above Strane it lowers to about 800 m and still more in a direction towards Stranske Ponikve and further on towards Predjama. In this part a flysch base is relatively lower, concordantly to Hrušica in the east from the Predjama fault. Also the steep eastern slope of Nanos corresponds to tectonically relatively uplifted block.

Thus Hrušica starts on the western side by Črnjavsko Podolje which is deepened at the foot of uplifted Nanos in the Predjama fault zone and remains hanging from a pass above the recent valley of the Bela near Podkraj towards Pivka basin. There the plain opens widely into a margin karst ledge called Podgora between Šmihel, Predjama and Studeno at the altitudes from 600 to 650 m. In fact it is a pediment shelf in the southern thrust edge of Hrušica. Above Predjama and Bukovje the steep slope of Hrušica reaches the altitudes slightly above 800 m, above Studeno and Strmica up to 1000 m. The higher eastern part belongs to tectonically uplifted Planinska Gora and Zagora which are separated from the lower Hrušica by a dry valley between Gorenje near Bukovje and Laniše near Kalce. To the south and east Zagora is bounded by a steep slope above Planinsko Polje and plain between Grčarevec and Kalce. Hrušica in a narrow sense of meaning is a sort of triangular inlier of karst surface between southern border of Trnovski Gozd and the northern part of the Pivka basin. To the east of Streliški Vrh (1265 m) and Javornik (1240 m) there is a karst ledge overlying the limestones of Hrušica nappe at about 1100 m; the next, lower, step surrounds Javornik from Nadrti above Hotenjsko Podolje to Podkraj above the Bela valley, about 900 m high. South from the road Kalce - Podkraj the lower, central, part of Hrušica continues along 150 m high slope in a south-west - north-east direction at altitudes from 800 to 900 m (Fig. 2.4.7).

On the extreme southern border of Hrušica at the contact with flysch the Pivka basin is located. This part of the basin is an morphologically and

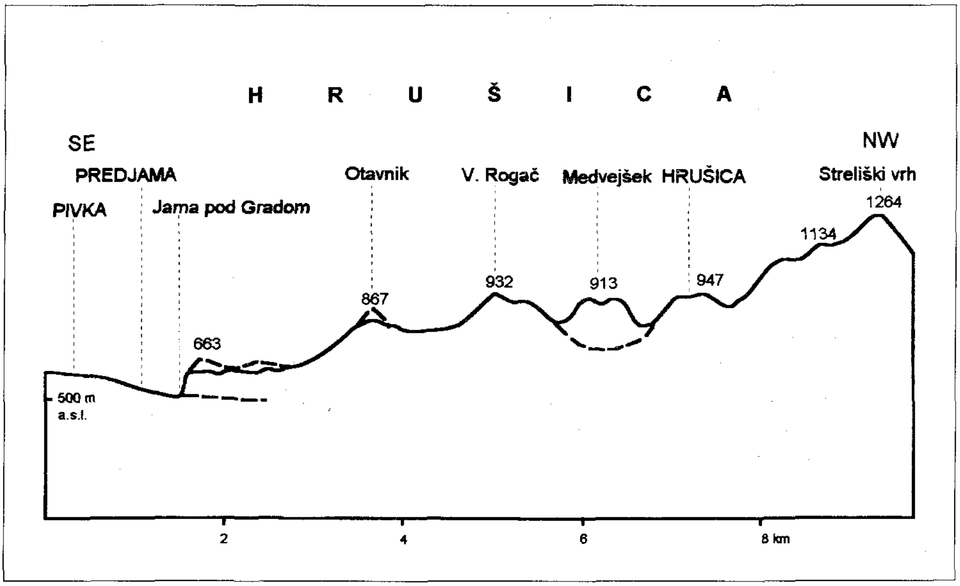


Fig. 2.4.7: The morphographic section through the Hrušica plateau.

hydrographically interesting area with small sinking flows, from the Stranske to Šmihelske Ponikve, Lokve, Ribnik, Mrzlek and Belščica, and also the Osojščica near Belska Žaga and five swallow-holes south of Studeno. Here lies the bifurcation watershed between the Vipava and the Pivka, between the Adriatic and the Black Sea. Blind valleys of sinking streams end with limestone walls where active influent caves developed at several levels. The largest is Jama pod Predjamskim Gradom (HABE 1970) which consists of underground passages that even reach Vipavska Jama and karst springs of the Vipava on the other side of Nanos.

2.4.3. Geomorphological Processes and Development

While reviewing the relief properties of single orographic units we noticed the differences in shape and development of surface that are supposedly due to differences in exogenic, climatic and lithologically controlled geomorphological processes in impermeable rocks with prevailing fluvio-denudation transformation on one hand and on the other hand by karstification of limestones and dolomites. An essential difference between erosional dissection and lowering of the surface on impermeable rocks and in preservation of older relief forms at the karstified surface was shown. During long-lasting geomorphological devel-

opment from the Upper Tertiary onwards, the geological setting became more and more important but so also did the differentiated tectonic dynamics. An older, levelled surface had been partly covered by fluvial sediments and later exposed by gradual tectonic uplifting to more differentiated erosional and corrosional factors. Important changes occurred in the fluvial net and also in the direction of superficial waters. On one hand the previous river net disintegrated due to karstification, and on the other hand the superficial flows changed their directions due to tectonic uplifting or relative stagnation of single parts. All these processes occurred in the active geotectonic area between the Adriatic and Southern Alps. From the hydrographic point of view the biggest changes occurred at the Adriatic-Black Sea divide.

From the climatic point of view the conditions at the passage between Submediterranean and Alpine continental climate were decisive. Climatic influences were particularly strong during the Pleistocene when warmer and cooler, more dry or more humid periods alternated. The traces of glaciation in the highest parts of Trnovski Gozd are preserved, and the Soča valley glacier reached down to confluence of the Soča and Idrijca. In cool periods a major part of the High Karst was exposed to typical periglacial processes. In that time also karstified limestones and dolomites suffered intensive mechanical weathering. This is evidenced by huge scree cones remaining, now covered by vegetation, at the foot of the karst border above Vipavska Dolina and also in headwater gullies and gorges in the northern side of Trnovski Gozd.

Periglacial and glacial debris had also been deposited in dolines and ouvalas on the whole plateau, especially over the less resistant flat limestones. In thick-bedded limestones corrosional deepening of dolines and ouvalas prevailed, giving them a shape of larger gently sloping dolines. These features are more frequent at altitudes above 1200 m; in lower-lying areas karstification is better expressed in fractured and broken fault zones. These features are connected by several deep shafts but also caves where snow and ice now remain during the whole year. The considerable vertical permeability of the karst underground is due to karstification in cold periods when solution reached deeper than in warmer periods when corrosion was more intensive on the surface itself.

The mostly bare rocky surface on the higher parts of Trnovski Gozd (Photo 4) shows the properties of high mountainous karst. Solution flutes and karren are in some places slightly changed and weathered, but some features remained that had already developed above the upper tree limit. In the cold period this limit was at about 600 m a.s.l. and the limit of permanent glaciation reached somewhere to altitudes between 1250 to 1300 m. When the climate warmed, climatic and vegetation belts rose and the present-day tree limit is at about 1450 m which is relatively low yet it is controlled by the isolation and exposure of the highest parts of Trnovski Gozd. A large amount of precipitation contributes to the intensity of recent erosion and dissolution processes in particular, as it occurs mostly in the winter half of the year and

Photo 4: Karren surface round Otlica (Trnovski Gozd) (Photo by P. Habič).

during the frequent summer storms with heavy rain. Intensive karstification and modest soil cover on the limestones enable the precipitation to drain underground quickly and feed abundant karst springs at the border of the High Karst.

Geomorphological processes and karst and other geomorphologic features are studied in detail in geomorphologic and speleological treatises by MELIK (1959, 1963), RADINJA (1972), GAMS (1974), HABIČ (1968, 1974, 1992) and others.

2.5. SPELEOLOGICAL PROPERTIES OF THE AREA

(A. MIHEVC)

There are 489 caves known and registered on the area of Trnovski Gozd and Banjšice plateau. The longest cave is the Predjama cave, the 7571 m long ponor cave of Lokva stream. The deepest caves are Velika Ledena Jama v Paradani, Jazben, Habečkov Brezen and Strmadna on Nanos plateau. There are 17 caves longer than 200 m and 18 deeper than 100 m.

The majority of the pothole entrances lies at 800 m a.s.l. where the average annual temperature is about 4° - 6° C. Frequently, the entrance parts of the potholes compared to the interior parts are widened. Numerous potholes are blocked by ice, snow or break-down blocks. The basic shapes of the potholes not yet spoiled by the superficial influence may be observed in inner avens only. The accessible caves are of different types: simple potholes or shafts of different depths systems of shafts and inclined or horizontal passages, ponor caves on the contact limestone with flysch or dolomite on the plateau and spring caves of different types on its foot. Most of the caves, about 70% are simple potholes and other smaller corrosive caverns formed by rain and snow waters. Most of caves are not very deep, 262 less than 20 m and only 7 are deeper than 200 m.

Depth and number of caves

more than 300 m	3
200 - 299 m	4
100 - 199 m	10
50 - 99 m	49
20 - 94 m	119
1 - 19 m	262

The following caves, briefly described, partly with a cave plan, are assumed as the important caves of the area under investigations:

Vipavska jama

Situated at the foot of Nanos at the springs of Vipava, the cave consists until recently of an artificial tunnel, which reached two natural cavities, so it acts as a spring during high discharge of the Vipava. Recently, through one of the cavities cavers entered in a about 1 km long maize of epiphreatic galleries developed along fractures. The survey is in progress but a plan doesn't exists yet. There are great discharges through some of the galleries, and water oscillates, according to sediments for about 25 m only 400 m inside the Nanos karst massif.

Veliki Hubelj

The cave entrance is in an altitude of 249 m, and forms the high water spring of the Hubelj river. The cave is 440 m long and is about 50 m above the permanent spring which is 219 m a.s.l. The cave is a maze of passages developed along joints and fractures in non bedded limestone. A cave plan is given in Fig. 2.15.

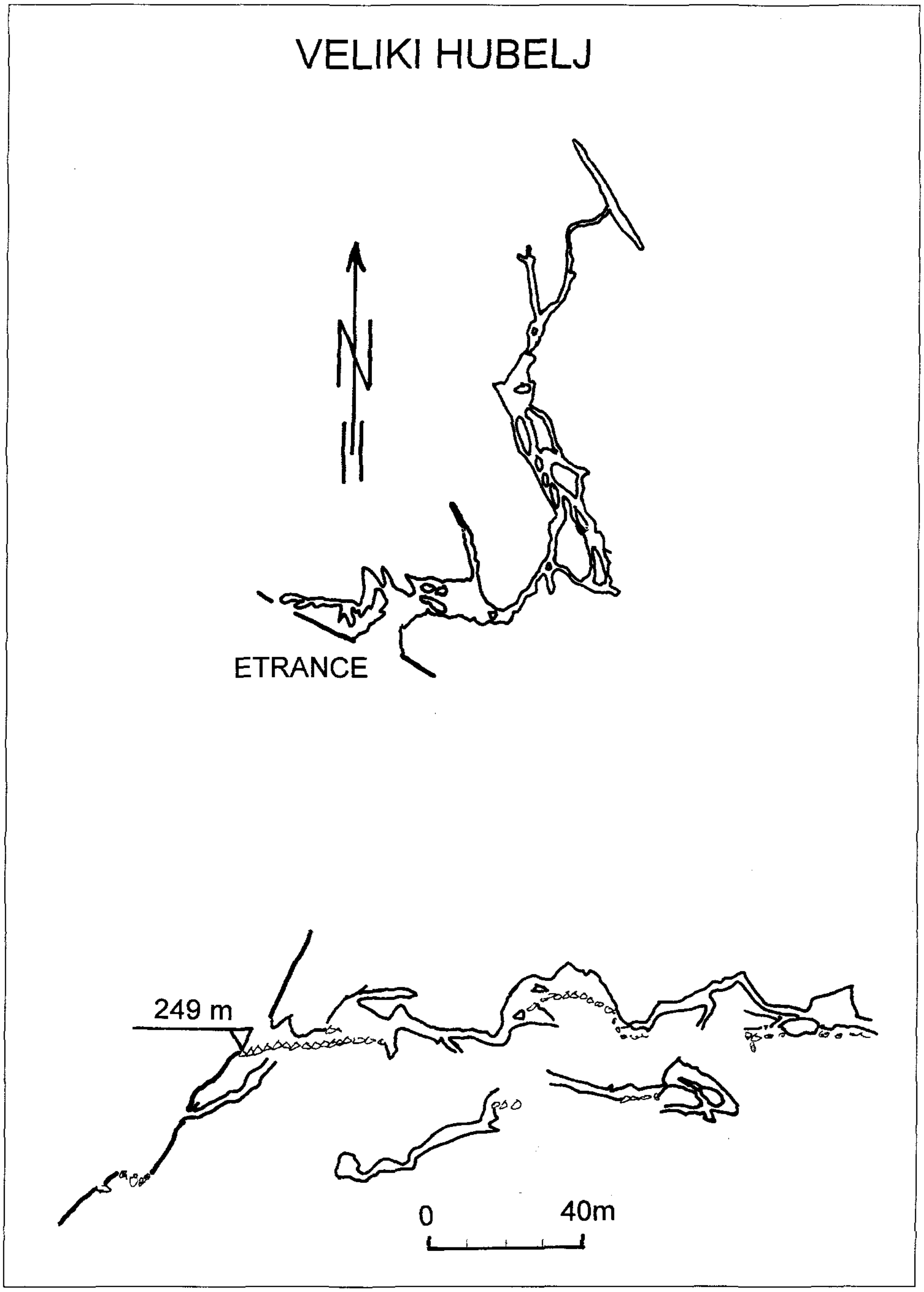


Fig. 2.15: Cave plan of the Veliki Hubelj.

Ledenica na Dolu

With an entrance in 995 m a.s.l., a length of 50 m and a depth of 80 m, this cave is developed in Jurassic limestones (Fig. 2.16). In the bottom part percolating water can be observed with a discharge up to 30 l/s after heavy rain. Its big entrance allows cooling of the cave during winter, but winter ice melts later in the year.

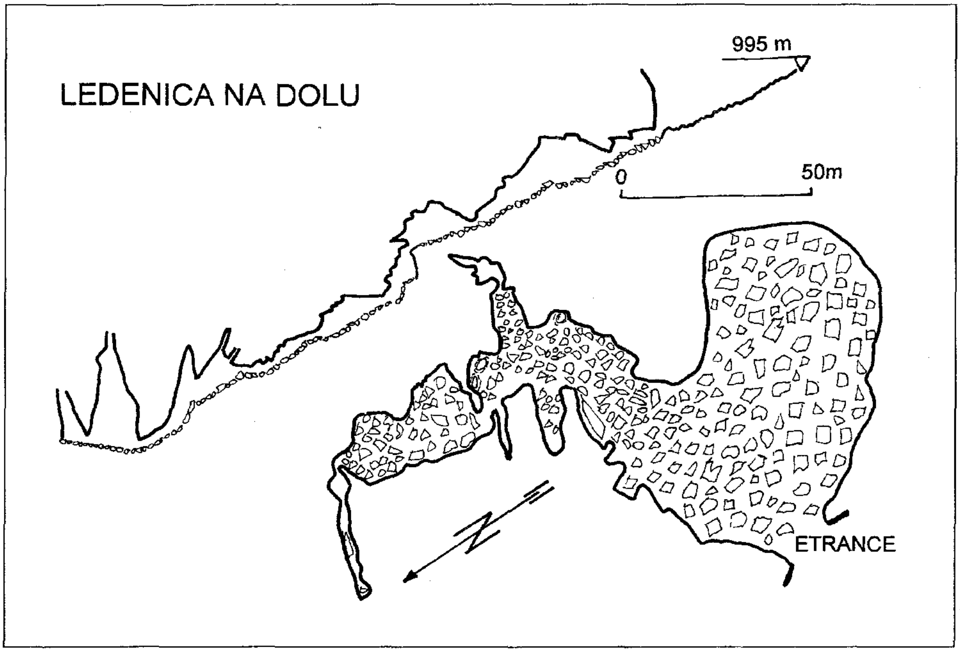


Fig. 2.16: Cave plan of the Ledenica Na Dolu.

Belo Brezno

The entrance to this simple 40 m deep shaft is in an altitude of 1240 m. The cave consists of vertical shaft which is filled with rocks and snow in the depth of about 35 m (Fig. 2.17). Short narrow rift continues to depth of about 40 m, where further passage is blocked by gravel. The cave Belo Brezno was one of the main injection points for the tracing experiments carried out in the framework of the project (compare Chapter 6).

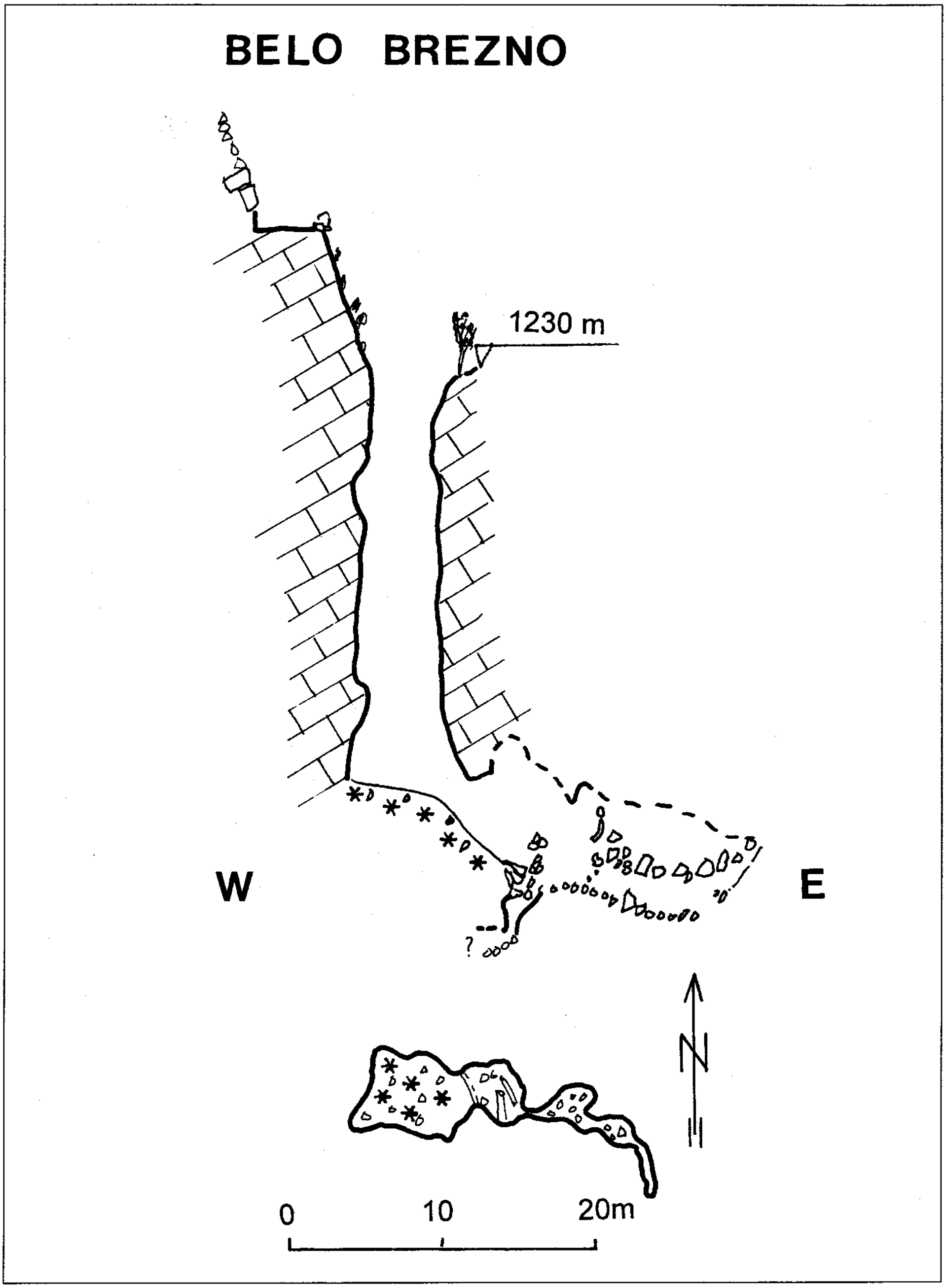


Fig. 2.17: Cave plan of the Belo Brezno, injection place for the repeated tracer injections in 1993, 1994, 1995 (see Chapter 6).

Ledenica V Kozji steni

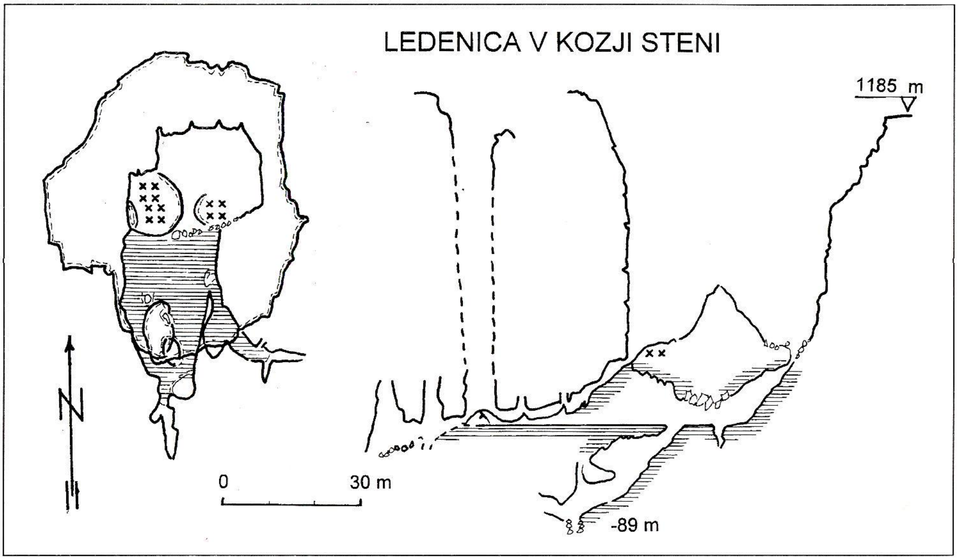


Fig. 2.18: Cave plan of the Ledenica V Kozji Steni.

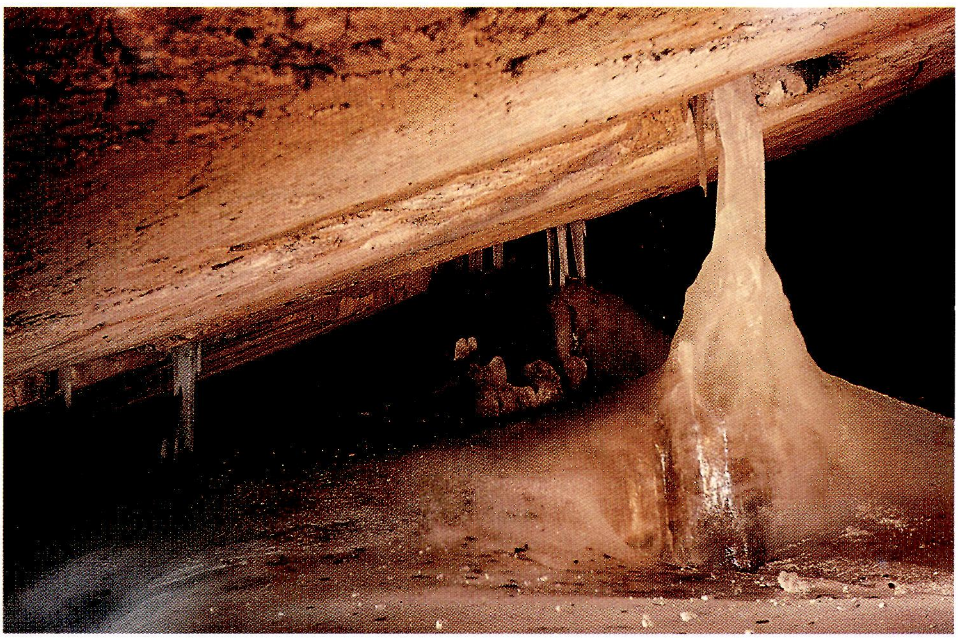


Photo 5: Ice cave Ledenica V Kozji Steni (Photo by A. Mihevc).

This ice cave in Kozja Stena is a 89 m deep pothole with a large permanent cave glacier and resembles regarding its shape and dimensions to a large collapse doline (Fig. 2.18, Photo 5). The entrance lies in an altitude of 1200 m. The 60 m deep entrance vertical drop having the dimensions at the top of 50 x 60 m, about 50 m deep the pothole narrows to 30 x 25 m. The bottom of the entrance pitch has a double depression leading downwards into common chamber where a large ice lake closes the cave continuation. The entrance pitch is developed in Jurassic limestone and dolomitic limestone in a strong fissure zone in N-S direction. By linkage of parallel potholes developed within this zone an ice volume of about 86.000 m^3 can be assumed.

Velika Ledena Jama V Paradani

Velika Ledena Jama V Paradani (Great ice cave in Paradana) is the deepest and also one of the biggest ice caves of the whole karst plateau (Fig. 2.19). It consists of series of shafts, connected by short fossil or active meanders or collapsed rooms. The depth of its surveyed part is 385 m, but in August 1996 new parts were discovered. The cave is estimated to be about 700 m deep now, but no plan of newly discovered parts exist yet, as explorations are still in progress. The cave is developed in stratified Triassic limestone and dolomitic limestone. Entrance of the cave is situated in altitude 1100 m a. s. l., in the bottom of larger, 60 m deep closed depression. This enables cold air to descent and flow into the cave during the cold period of year, forming ice to depth of about 200 m. At the bottom, even in summer, temperature does not exceed + 3° C.

The entrance part consists of three halls with permanent ice, it quantity estimated to 3000 m3 and was used as a natural source of ice. The volume of ice oscillates due to climatic changes and self controlling mechanism of filling in and reopening the narrowness at the entrance. This permits the cooling of the inner parts of the cave and so freezing the percolating water. Permanent ice is situated in the entrance part of the cave (Photo 6), in parallel shafts and in some chambers. This are three separated ice bodies, which are formed by freezing of percolated water in cooled cave. Ice level or better quantity is changing, records exist for last 25 years. In dry winters of the past years only little new ice was formed.

The inner part of the cave consists of short galleries and shafts, all situated on a very small area of 150 x 150 m. There are 38 inner avens within the cave. The deepest is 240 m deep followed by 98, 55, 40 and 35 m deep avens, the others are smaller, all together about 2000 m, and thus they represent the main building element of the cave, which was formed by percolating water. Three morphological different types of shafts are evident in the cave:

- shafts developed in steep meanders following the dip
- shafts developed in fissured zones. They originate along vertical joints one

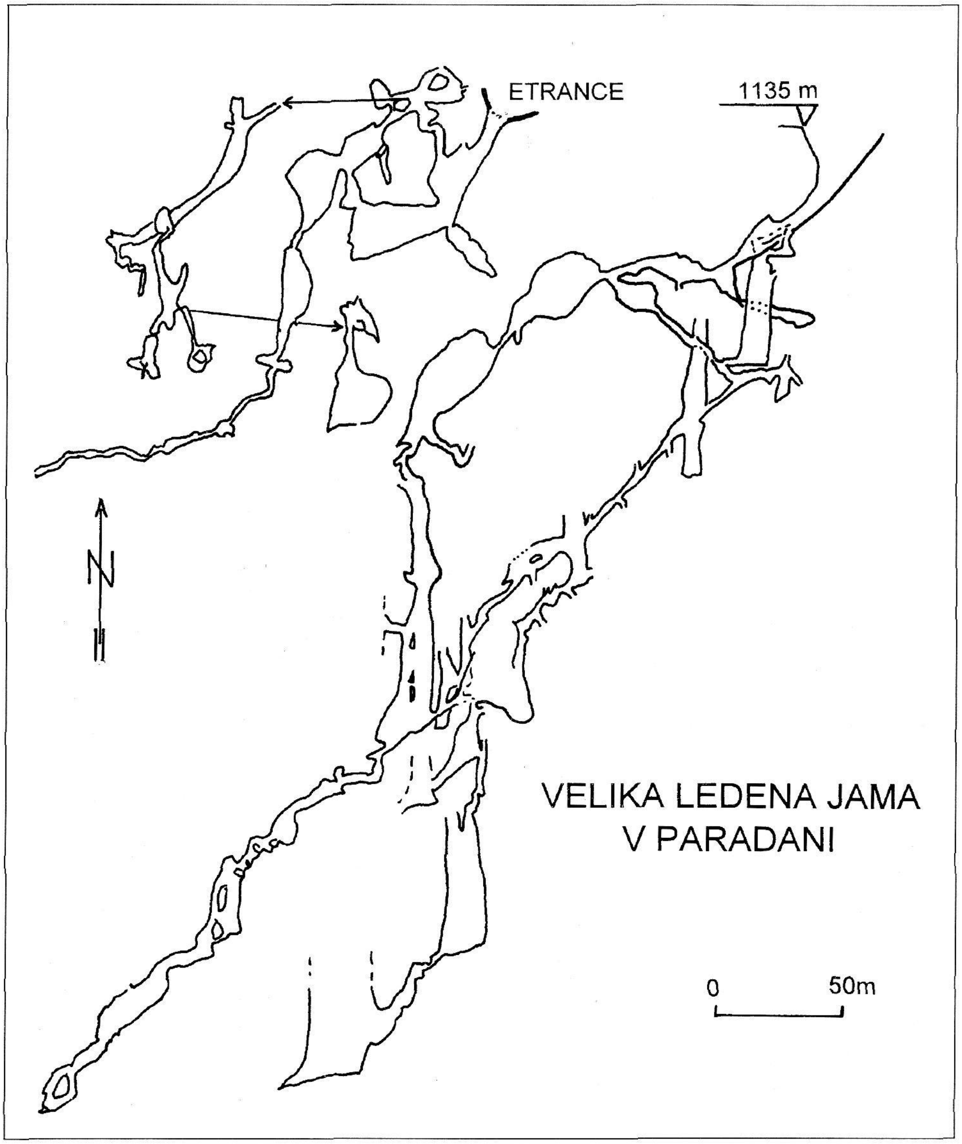


Fig. 2.19: Cave plan of the Velika Ledena Jama V Paradani.

above another, or are parallel, formed along one or along parallel joints

- third type doesn't follow the structure. In parts, which are accessible they just drill their way down, having a stable point recharge and well drained bottom.

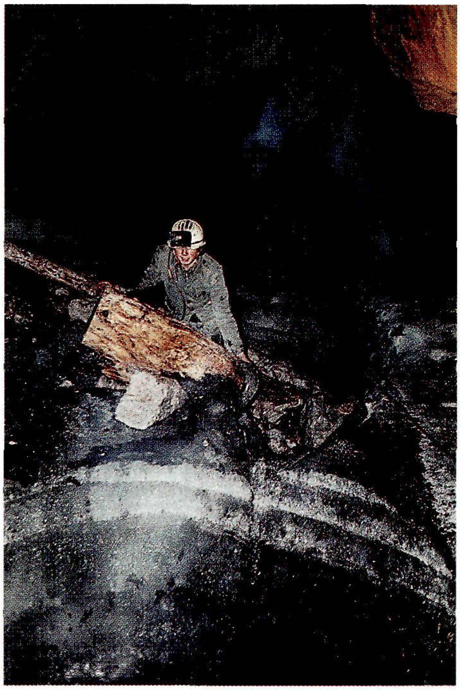


Photo 6: The cave Velika Ledena Jama V Paradani (Photo by A. Mihevc).

All three morphological types may also mean three different types of water percolation trough the vadose zone of karst.

Jazben

Entrance to cave Jazben is situated near Kanalski Vrh village in 574 m a.s.l. The cave is 334 m deep, formed near the contact of permeable upper Cretaceous limestone and flysch marls. The cave consists mostly of a series of shafts. Entrance part of a cave is dry, but in depth of about 120 m water appears. The cave than follows a NW - SE fault, along which it cascades to depth about 300 m. This part is developed in massive limestone. Below that point cave changes into a narrow meander which follows the dip of marly, thin bedded limestone with chert.

Habečkov brezen

The 336 m deep cave is developed near the contact of Triassic dolomite and Cretaceous limestone. It consist of series of potholes, which can be followed to a narrow rift at the bottom part and which terminates in a sump

at elevation of 332 m. This sump is only 3,6 km apart from the springs of Divje Jezero at the Idrijca river.

Divje Jezero spring

Divje Jezero is a karst spring of Vauclusian type. The level of the lake in which the water flows is in altitude 320 m. The submerged gallery that supply it with water is explored to the depth of 122 m (Fig. 2.20). The first part of cave to depth about 95 m is steep and reaches with a lower angle the terminal depth. Beyond the gallery it still continues.

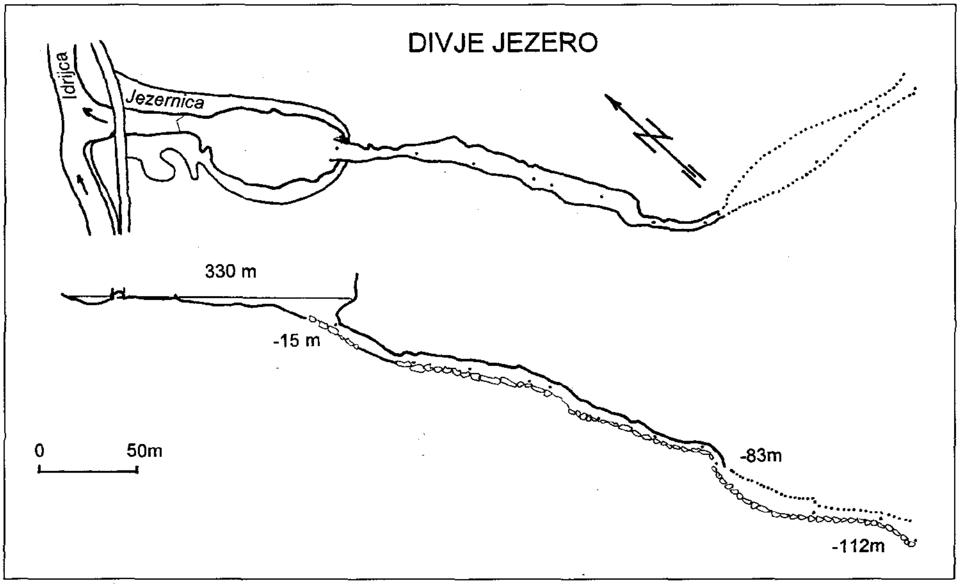


Fig. 2.20: Cave plan of the Divje Jezero.

Slapenski ledenik

Slapenski ledenik ice cave is located in the bottom of a small doline in an altitude of 1010 m on the plateau of Nanos. Under the entrance, a 30 m deep shaft, a large room is developed, partly filled with ice and snow (Fig. 2.21). Both were used for water supply too. On the side of this chamber a second shaft reaches the lowest part of the cave at -112 m. During the tracing experiment in 1995 (compare chapter 6.) the tracer was injected in the first room at the depth of about 30 m in between boulders and the wall of the cave.

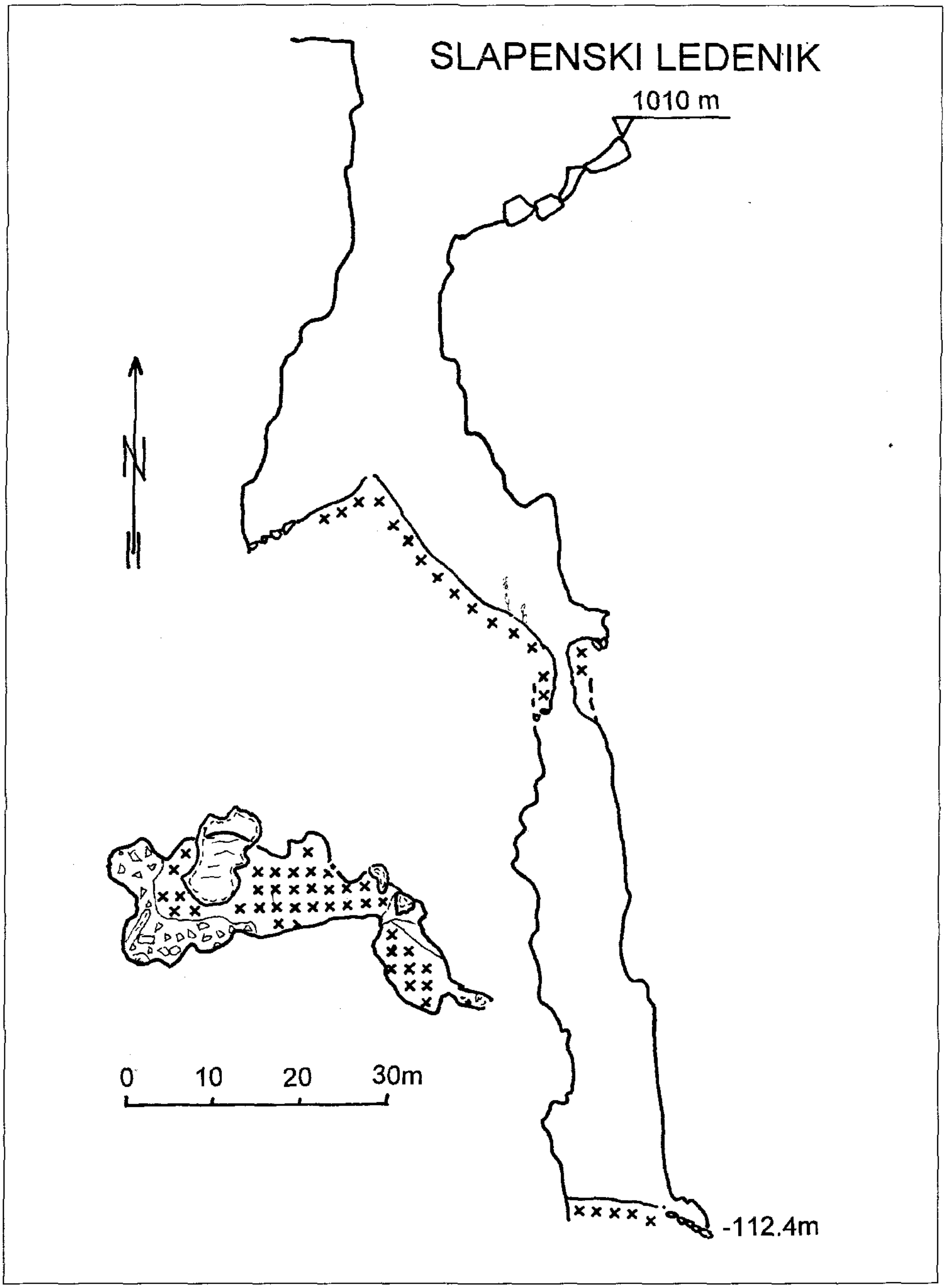


Fig. 2.21: Cave plan of the Slapenski Ledenik, injection place for the experiment in 1995 (see Chapter 6).

Strmadna

Strmadna cave is the deepest cave of the Nanos plateau. It entrance is in altitude of 1060 m a.s.l., and it is 218 m deep. The cave is a system of shafts mostly controlled by fractures in direction NW - SE.

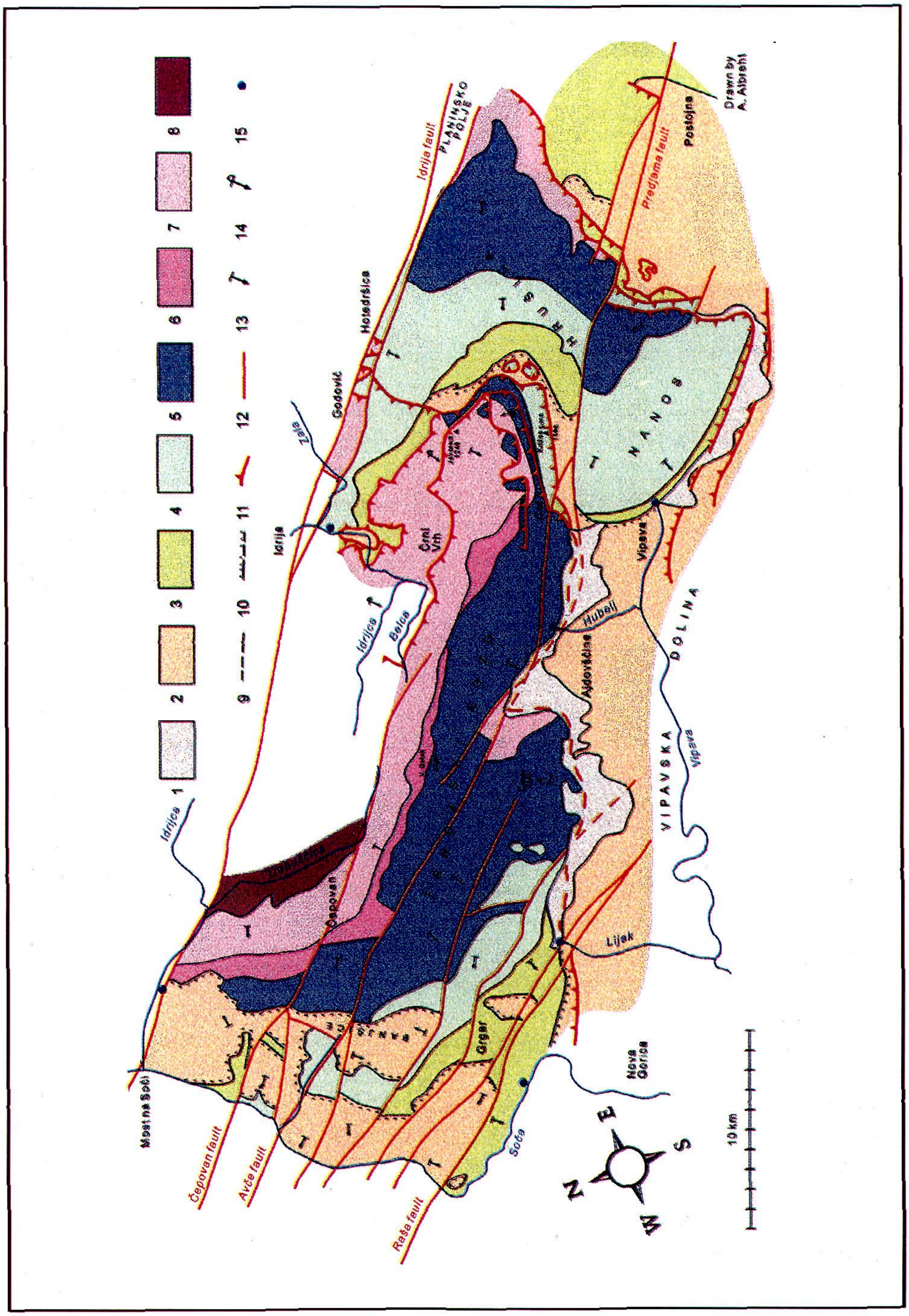
2.6. GEOLOGY AND HYDROGEOLOGY

2.6.1. Geological Description (J. ČAR)

The geological description covers the territory limited by the valleys of the Vipava, Soča, Idrijca, Trebuša, Belca and Zala rivers from the southwest, west and northeast, respectively. To the southeast the border of this territory runs along Hotenjsko podolje (Hotenja lowland) across Planinsko polje (Planina polje) through Postojnska Vrata (Postojna gate) and embraces the Pivka basin and Nanos (Mt. Nanos).

The basic data on the geological conditions on Banjška Planota (Banjščica plateau), the Trnovski Gozd (Trnovo forest), Črni Vrh plateau, Hrušica, Pivka basin and Nanos can be found on the geological maps of Gorica (BUSER 1968), Postojna (BUSER et al. 1967) and Tolmin (BUSER 1987) and in the corresponding descriptive notes and legends. More details and particularities about the geological structure of the regions may also be found in the works of BUSER (1965), MLAKAR (1969), PLACER & ČAR (1974), PLACER (1981), ČAR & GOSPODARIČ (1988) AND JANEŽ & ČAR (1990). Reviews of geological discussions of older authors are also included in the listed works. Based on the above mentioned literature, the official maps and own mapping a general geological sketchmap of the investigation area is given in Fig. 2.22.

Fig. 2.22: Geological sketchmap of Banjšice, Trnovski Gozd, Nanos and Hrušica: 1 - periglacial breccia and rubble, 2 - flysch rocks of the Upper Cretaceous, Palaeocene and Eocene age, 3 - Upper Cretaceous organogenic limestone, 4 - Lower Cretaceous bituminous limestone with inliers of dolomite, 5 - limestones and dolomites of the Jurassic age, 6 - Norian-Rhaetian limestone (Dachstein), 7 - Norian-Rhaetian dolomite, 8 - Carnian granular dolomite, alternation of silt and sandstone, 9 - normal geological boundary, 10 - erosion discordance, 11 - thrust line, 12 - fault, 13 - dip and strike of strata, 14 - dip and strike of inverse strata, 15 - karst spring.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14
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Idrija fault
Predjama fault
Čepovan fault
Avče fault
Raša fault
PLANINSKO POLJE
Postojna
Hotedršica
Godovič
Zala
Idrija
Črni Vrh
Idrijca
Belca
NANOS
HRUŠICA
Vipava
Hubelj
Ajdovščina
VIPAVSKA DOLINA
Lijak
Čepovan
Grgar
Nova Gorica
Most na Soči
Soča
N
E
S
W
10 km
Drawn by A. Albreht

2.6.1.1. Lithostratigraphic Description

Variously coloured Carboniferous (C) and Permian (P_2^2) clastic rocks, Upper Permian (P_3) bituminous dolomites and limestones, Scythian (T_1) sandy dolomites, marlstones and silts with lenses of oolitic limestone, grey dolomite and marly limestones, crushable Anisian (T_2^1) dolomites and variegated Ladinian (T_2^2) rocks represented by a dolomite-limestone conglomerate, lime sandstone varieties and pyroclastic rocks with intercalations of silicificated limestones can only be found in the upper part of the Zala torrential stream, which partly sinks directly into the basin of the springs of Podroteja. The complicated mutual relationship of the above-mentioned rocks reflect the complexity of the entire overthrust structure in the Idrija region (MLAKAR 1969).

The Upper Triassic Carnian (T_3^1) layers are relatively modest in size in the region discussed. White, grainy non-bedded Cordevolian dolomite (${}^1T_3^1$) is found in the Trebuša and Zala river valleys. The Julian-Tuvalian sandstones and siltstones and the dolomites with shale intercalations between layers build the steep slopes of the north side of the Trnovski Gozd above the Trebuša valley and smaller parts of the slopes on the right side of the Zala stream.

The Upper Triassic Norian-Rhaetian "principal" dolomite (${}^1T_3^{2+3}$) is the first extensive lithostratigraphic bed in the region discussed. A broad band of this rock begins in the Idrijca valley south of Most na Soči, builds extensive terrains all the way to Čepovanski Dol (Čepovan valley) and extends to the northern periphery of the Trnovski Gozd. It builds slopes above Trebuša and Belca river valley, partially covers the Zadlog and Črni Vrh plateaux and the ridge extending to Javornik (1240 m). Norian-Rhaetian dolomite also builds the eastern slopes of Čaven (1185 m) and the southern side of Hrušica. In stratigraphically higher parts the grey layered dolomite passes into light grey layered oroganogenic Dachstein limestone. In the continuous belt it has developed between the Čepovanski Dol (Čepovan valley) and the central part of the Trnovski Gozd. It can also be found around Križna Gora (957 m) along the southeast periphery of Javornik.

Norian-Rhaetian limestones and dolomites gradually pass into Jurassic rocks. On the Banjška Planota (Banjšica plateau), in the Trnovski Gozd, on Hrušica and on the eastern part of the Nanos range, all the Liassic (J_1), Doggerian (J_2) and Malmian (J_3) lithostratigraphic units have developed, descending toward the southwest. The lithogical and according to fossils of the Lower and Middle Jurassic layers of the Trnovo Gozd is similar those of the old rocks of Nanos and Hrušica. Lithological changes of the Malmian layers are noticeable to the east of Col.

The layers of Jurassic rocks with a thickness of 1000 to 1500 meters have primarily developed in the form of limestones and dolomites with all the characteristic mutual transitions. The variously coloured thick and oolitic

limestones alternate and transform along the edges into white, grey or even brown-coloured dolomite. The Doggerian grey limestone with chert found at Banjšice and in the west part of the Trnovski Gozd is a particularity.

In the entire region discussed, the Lower Cretaceous (K_1) rocks were deposited in the form of characteristic carbonitic facies. However, significant lithological differences already appear in the development of Upper Cretaceous (K_2) rocks. The Cretaceous rocks are about 2500 to 3000 m thick.

On the periphery of the Pivka basin, on Nanos, Hrušica and in the Trnovski Gozd the Lower Cretaceous rocks have developed in the form of brownish to light-grey limestone with intercalations of grained bituminous dolomites. These are followed by grey to orogenogenic Upper Cretaceous limestones rich in shell biostromes. The carbonate Cretaceous development ends with an erosional discordance.

Palaeocene (Pc) and then Eocene (E_1) flysch rocks are lying on the eroded Upper or Lower Cretaceous limestone on the western periphery of the region discussed, on Banjšice plateau south of the Avšček valley. Upper Cretaceous limestone breccia forms the base rock of the Palaeocene flysch on the plateau west of the Kajže spring. Even greater variations can be found in the region northeast of the Avšček valley. Here the Upper Cretaceous rocks appear in the characteristic flysch development forms and turbidite type of limestone of Volče (K_2^3). These rocks lie above eroded Norian-Rhaetian, Jurassic or Cretaceous carbonates. Different types of limestone breccia with intercalations of greenish and reddish marlstone can be observed above the thin-layered limestone of Volče with chert, followed by brown marlstones and sandstones with intercalations of breccia (scaglia, ${}_4K_2^3$).

Palaeocene rocks are found in the west part of the Trnovski Gozd, at Banjšice and in the tectonic windows in the surroundings of Idrija. Typical lithological components are reddish, purple marlstones alternating with greyish red varieties and intercalations of marly limestone. On eroded Upper Cretaceous limestones near Idrija basal block limestone conglomerates are covered with greenish-grey marlstones. In the surroundings of Grgar, at Banjšice and Kanalski Vrh, flysch rocks are deposited discordantly above the Upper and Lower Cretaceous rocks of various ages. At Lijak the Upper Cretaceous limestones gradually pass into Palaeocene flysch rocks.

Eocene flysch sediments are deposited discordantly on Upper Cretaceous limestones in the Pivka basin, in the belt between Črni Vrh, Col and the Vipava Valley and on the Vipava side of Nanos. In the vicinity of Lijak the transition from Palaeocene and Eocene rocks is gradual. The Eocene flysch consists of alternating brownish to greenish grey marlstones and quartz sandstones with intercalations of calcarenites and calci-rudites of varying particle range.

Periglacial coarse-grained block breccia with reddish flowstone cement of the Quaternary age (Q) covers the flysch rocks on the south-western slopes of

the Trnovski Gozd from Vipava on the west to the Soča Valley near Mrzlek. The breccias can also be found on the periphery of Nanos.

The Holocene (al) is characterised by loams with chert found in some levelled parts of the Trnovski Gozd and extended unconsolidated slope debris from Col on the east to the Soča Valley on the west.

2.6.1.2. Tectonics

The region discussed has a very complex tectonic structure (MLAKAR 1969; PLACER 1981). The predominant tectonic elements are the extensive and complex overthrusts which, in the past alpine tectonic phase, were cut with a dense system of subvertical faults.

Thrust structure

The overthrust structure is characterised by the repetition of Palaeocene-Eocene flysch in the overthrusted and underthrusted structural units near Gorica, in the Vipava Valley, Hruševje and in the Pivka basin, Vodice above Col and Idrija (PLACER, 1981). The above-mentioned alternation of poorly pervious flysch rocks and karstified limestones and the discordant and normally placed Palaeocene-Eocene and Cretaceous flysch on the west part of the Trnovski Gozd, Banjšice and Lom near Tolmin represent the basic structural hydrological element of the south-western part of Slovenia.

The flysch of the Pivka basin as well as of the narrow flysch belt extending past the northern periphery of Nanos into the Vipava valley belongs to the Snežnik thrust sheet. Upper Triassic, Jurassic, Cretaceous, Palaeocene and Eocene rocks of the Hrušica nappe were thrust onto it. The Hrušica nappe encompasses Hrušica, Nanos and the central and northern part of the Vipava Valley to Gorica. Between the nappes at the west periphery of the Pivka basin, the Bukovnik, Debeli Vrh and Suhi Vrh interjacent slices are developed. These interjacent slices are comprised of the same rocks as Hrušica's nappe. In the Idrija region, the Hrušica overthrust unit is covered first with Lower and Upper Cretaceous limestone of the Koševnik interjacent slice, followed by a plate of Upper Triassic dolomite and Carnian rocks of the inversely positioned Čekovnik interjacent slice. These units have built the Belca river stream, the Zadlog-Črni Vrh plateau, the Hotenje lowland and part of Javornik, Križna Gora and the territory between Križna Gora and Col. The above-mentioned overthrusts and flysch rocks of the Hrušica nappe are covered by the Trnovo nappe, built of rocks from the Carboniferous to Eocene periods. It encompasses the entire Trnovski Gozd, Banjšice, Lokovec, Čepovanski Dol and the Trebuša valley.

Strike-slip faults

The region discussed is limited on the northeast side by a 300 to 1500 m wide fault zone of the Idrija fault. Within the broader fault area numerous accompanying faults are in progress, branching from the main fault plane and repeatedly joining it. The most important accompanying fault zone is the Zala fault. In the enclosed map of the Idrija fault zone it appears between Most na Soči and Hotedrščica. A significant regional fault, which cuts across the entire region discussed, is the Avče fault, whose east past is also referred to as the Predjama fault. It extends from the Soča valley near Avče to the periphery of the Pivka basin. Between Idrija and the Avče fault an even greater number of significant tectonic zones can be observed in Banjščica and in the surroundings of Grgar. These faults undoubtedly cut across the central and southeast part of the Trnovski Gozd, but were not defined in detail by previous geological mappings.

Running along the southwest side of the region discussed is the regional Raša fault, which disappears below Lijak into the flysch rocks of the Vipava Valley. The Grgar valley on the northeast side of the Raša fault is cut by several quite extensive fault zones. At present their continuation in the direction south-east is still not known.

Tectonic lithological mapping on a scale of 1:5000 proves that the areas between the above-mentioned faults are interwoven with numerous crushed zones of varying width extending in the direction north-south, east-west or north-northwest, south-southeast. A similar structure can also be expected in Hrušica, Nanos, Pivka basin and its periphery.

2.6.2. Hydrogeology (J. JANEŽ)

2.6.2.1. The review of the previous investigation

Underground water of Nanos, Trnovski Gozd and Banjšice is the subject of hydrologic and hydrogeologic investigations for about 40 years. P. HABIČ published the largest number of works and papers (HABIČ 1968, 1981, 1983, 1985, 1987.). The same researcher was the author of many waters tracing tests in the catchment area of Mrzlek, Podroteja in Hubelj. Underground water tracing investigations in Slovenia 1972-1975 (GOSPODARIČ & HABIČ 1976) confirm important water connections in the catchment area of Podroteja and Divje Jezero. PLACER & ČAR (1974) explained the regional hydrogeological position of the karst springs. ČAR & GOSPODARIČ (1988), JANEŽ (1990) and PETRIČ (1994) wrote about the Lijak boiling spring. JANEČ & ČAR (1990) defined the geology and the catchment area of the spring Kajža.

2.6.2.2. Hydrogeological Classification

The surface of the Trnovski Gozd, Banjšice, Nanos and Hrušica covers about 700 km^2. That is 3.4 % of the total Slovenian territory respectively 7.8 % of the Slovenian karst surface. The total discharge of the karst springs in dry periods reaches more than 2 m^3/s (7 % of Slovenian karst underground water). During high water the main karst springs (Mrzlek, Lijak, Hubelj, Vipava, Podroteja, Divje Jezero, Kajža and Hotešk) drain about 280 m^3/s of water.

The whole area can be divided according to the permeability of their lithological characteristics in several hydrogeological units (compare Fig. 2.23):

- well permeable rocks - aquifer(s) with karst and fissure porosity
- well permeable rocks with intergranular porosity
- medium permeable rocks - aquifers with fissure porosity
- impermeable rocks.

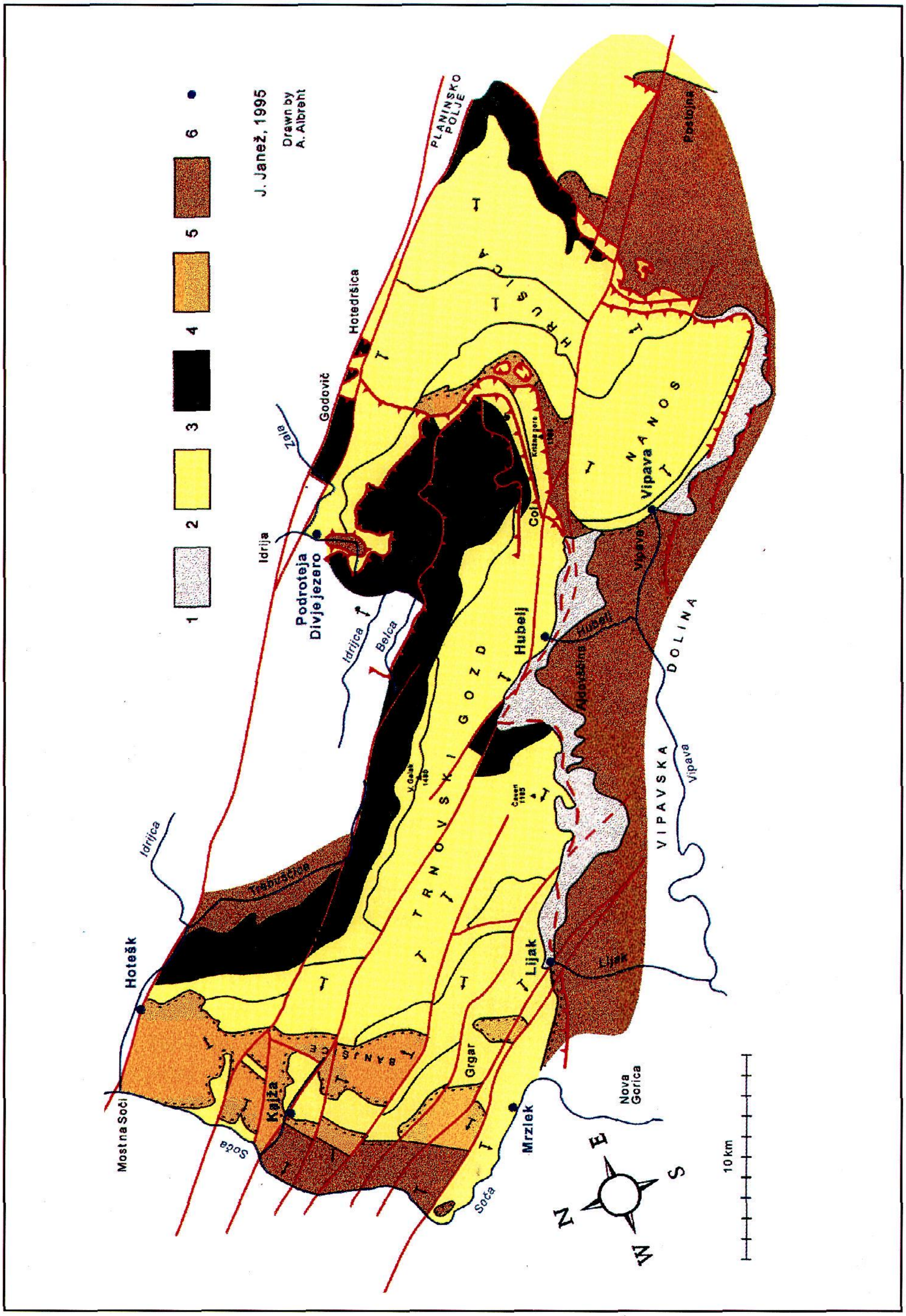
The karst porosity aquifers are formed in Upper Triassic Dachstein limestone, Liassic, Dogger and Malm limestone, Lower and Upper Cretaceous limestone and Upper Cretaceous lime breccia. The main hydrogeologic units are the karst aquifer of Hrušica, the karst aquifer of Nanos, the karst aquifer of Črni Vrh plateau, the karst aquifer in the catchment area of Hubelj and the karst aquifer of the western part of Trnovski Gozd and Banjšice. In all these cases the existence of deep karst systems is in question.

Well permeable rock with intergranular porosity are built by coarse grained to block shaped Quaternary periglacial breccias and unconsolidated Holocene slope debris. They cover big surface in form of an almost uninterrupted belt on the southern border of Trnovski Gozd and Nanos. The discharges of the slope debris springs yield up to 15 l/s.

As relative hydrogeological barriers the fissure aquifers have to be assumed. Aquifers with fissure porosity are built by dolomite of different age. The biggest extent has the Upper Triassic dolomite. It borders the karst aquifer from the northern side and partly direct the underground water runoff. The discharges of the springs in the dolomites reach up to 10 l/s.

Uncrushed Carboniferous clastic rocks, Medium Permian (Gröden) siltstone and sandstone, pure tuff beds of Ladinian age (in Idrija region), Carnian clastic rocks (impermeable footwall of the Upper Triassic dolomite in the valley of the Trebušica river) and Palaeocene and Eocene flysch marl (in the

Fig. 2.23: Hydrogeological sketchmap of Banjšice, Trnovski Gozd, Nanos and Hrušica: 1 - well permeable rocks and sediment, intergranular porosity; 2 - well permeable rocks, karst aquifer; 3 - medium permeable rocks, fissure porous aquifers; 4 - impermeable rocks, relative hanging hydrogeological barrier; 5 - impermeable rock, lateral and footwall hydrogeological barrier, 6 - karst spring.



1
2
3
4
5
6
J. Janež, 1995
Drawn by A. Albreht
PLANINSKO POLJE
Postojna
HRUŠICA
NANOS
Hotedršica
Godovič
Zala
Idrija
Podroteja
Divje jezero
Idrijca
Belca
Col
Vipava
Hubelj
TRNOVSKI GOZD
VIPAVSKA DOLINA
Trebuščica
Hotešk
Lijak
Grgar
BANJŠICE
Kajža
Most na Soči
Soča
Mrzlek
Nova Gorica
N
E
S
W
10 km

surrounding of Trnovski Gozd and Nanos) form the impermeable lithostratigraphic horizons. But due to the fact that those series are characterised by an alternating lithological setting with smaller inliers of more permeable sediments, fissured or karst aquifers between the impermeable rocks are important (Lower Schythian marly shists with lenses of oolitic limestone; Ladinian piroclastites with beds of silicified limestone; the clastites of Carnian age with various limestone inliers; flysch rocks of Palaeocene and Eocene age with calcirudite and calcarenite lenses).

The hydrogeological role of lithostratigraphic units is controlled not only by permeability but also by primary stratigraphic superposition, tectonic setting and neotectonic geomorphologic terrain development. The hydrogeological barriers (footwall and sideways), hanging hydrogeological wall and relative hydrogeological barrier are distinguished. To hanging hydrogeological barrier belongs the area between Banjšice and Idrijca river where flysch rocks are found on the karstified base. The hanging hydrogeological barrier is depending on lithological structure and thickness of flysch either locally vertically or horizontally permeable. Limestone, sandstone and breccias intercalated as lenses or beds in water tight flysch marlstone and quartz sandstone accumulate some water that reappears in feeble springs.

2.6.2.3. Karst Aquifer of Nanos and Hrušica

Nanos karst plateau is a karst fissured aquifer bordered on three sides by impermeable Eocene flysch. On the north-eastern side it continues along the Predjama fault to the karst aquifer of Hrušica. The interpretation of the geological setting (PLACER 1981) infers that flysch below the carbonate nappe of Hrušica lies higher (level about 0 m a.s.l.) than the flysch below the limestone of Nanos (in the north-western part of Nanos even up to -1300 m).

The underground water flows out across the lowest gap in the flysch border in the Vipava spring. The minimal discharge of Vipava springs yields 700 l/s, medium annual discharges are from 6 to 9 m^3/s, and the maximal about 7 m^3/s (HABIČ 1973). The catchment area is bigger than 150 km^2 and comprises the entire massif of Nanos and substantial parts of flysch and limestone surface near Postojna.

2.6.2.4. Hydrogeologic Structure of Trnovski Gozd and Banjšice Plateau

The result of the overthrust tectonic in older Tertiary and neotectonic fault displacement is the superposition of thrust sheets, nappes and smaller interjacent slices. Hydrogeological conditions of Trnovski Gozd and Banjšice depend on that geologic structure and lithology.

The flysch of Vipava valley belongs, according to PLACER (1981), to several tectonic units. The southern side is a part of the Komen thrust sheet. The flysch on the northern side belongs comparable to Nanos and Hrušica, to the Hrušica nappe superposed to the Snežnik nappe near Postojna. The flysch of the Hrušica nappe represents the impermeable footwall for the karst aquifer of Trnovski Gozd and Banjšice as well as the impermeable southern and south-western sideways barrier in the Vipava valley. On the East it is thinned out and exhibits a carbonatic development. Therefore it represents an only partially (locally) hydrogeological barrier. Flysch beds that are near Javornik on the 1000 m a.s.l. strike towards west. In tectonic windows near Idrija the flysch reappears on the surface at the altitude of about 300 m. Near Lijak the flysch was drilled at the altitude -16 m (ČAR & GOSPODARIČ 1988) while the boreholes at Prilesje did not reach the flysch at the depth of -220 m. The shape and the inclination of the impermeable base essentially influence on the direction of runoff of the karst underground water.

Upper Triassic, Jurassic and Cretaceous limestone rocks of the Trnovski Gozd and Banjšice belong to tectonic unit of Trnovo nappe and build the central part of the karst aquifer. The underground water lies extremely deep. Between Soča river and Lijak low waters are found at the Hill 77 m being fed by the water level of the accumulation lake on Soča (JANEŽ 1992). The underground water level is higher in the northern part of Banjšice (the Kajža spring 191 m a.s.l.; JANEŽ & ČAR 1990) and especially in the background of Hubelj (270 to 290 m a.s.l.; HABIČ 1985).

The underground water of the karst aquifers of Nanos and Trnovski Gozd (the springs of the Vipava river, Hubelj, Lijak) appear on the surface at the lowest points of the impermeable flysch border (PLACER & ČAR 1974) or on the erosion basis (Mrzlek spring near the Soča river).

The northern border of the karst aquifer is built by dolomite rocks of the Upper Triassic age outcropping along the valleys of Trebušica and Belca at the base of the impermeable Carnian clastic rocks. Upper Triassic dolomites are locally important aquifers with fissured porosity with spring yields of up to 10 l/s.

Between Hrušica and Trnovo nappe there are near Idrija two tectonic and hydrogeologic units. The Koševnik interjacent slice lying on the Hrušica nappe, flysch is built by karstified limestones of the Cretaceous age forming the central catchment area of Podroteja and Divje Jezero. The Čekovnik interjacent slice is built by the Upper Triassic dolomite in the inverse position where the underground water in the fissured aquifer is under pressure.

2.6.2.5. Important Springs

The Podroteja karst spring (329 m a.s.l.) (Photo 7) is situated on the confluence of the river Idrijca and its right tributary Zala. The famous lake Divje Jezero lies 500 m Southwest from Podroteja (330 m a.s.l.). In both

Photo 7: Podroteja springs (Photo by A. Mihevc).

springs the water flows on the surface out of dark bituminous thick bedded Lower Cretaceous limestone. The Vauclusian spring Divje Jezero has a karst channel of exceptional shape where divers have reached the deepest point in Slovenia till now, 122 m of depth. In Podroteja the underground channels are more narrow and inaccessible. The Podroteja discharge oscillates among 0,2 to some m^3/s. During low water Divje Jezero does not flow over the rim although the siphon's depression is always filled. During the high water the runoff of Divje Jezero is more than 60 m^3 per second.

Hubelj spring emerges on the highest altitude of all springs on the southern border of Trnovski Gozd. With a spring outlet at 240 m in dry periods. At high water the water table rises up 40 m higher (Photo 8). During the drought 300 to 400 l/s of water flow out of karstified limestone, but the highest discharges reach more than 40 m^3/s.

The Vipava springs emerges at the western foot of Nanos (Photos 9 - 11). The most abundant permanent springs are in the Vipava town, 98 m a.s.l. To the Northwest there are several periodical springs. The minimal discharge of Vipava springs yields 700 l/s, medium annual discharge is from 6 to 9 m^3/s, and the maximal about 70 m^3/s (HABIČ 1983). The catchment area is bigger than 150 km^2 and comprises the entire massif of Nanos and substantial part of flysch surface near Postojna.

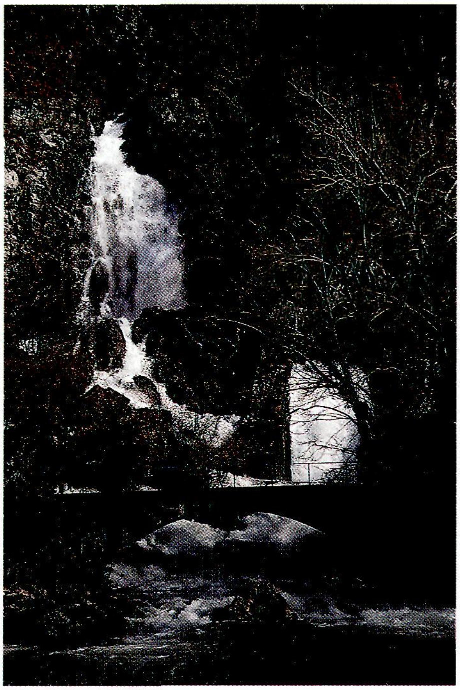


Photo 8: High discharge of the spring Hubelj in November 1996 (Photo by P. Habič).

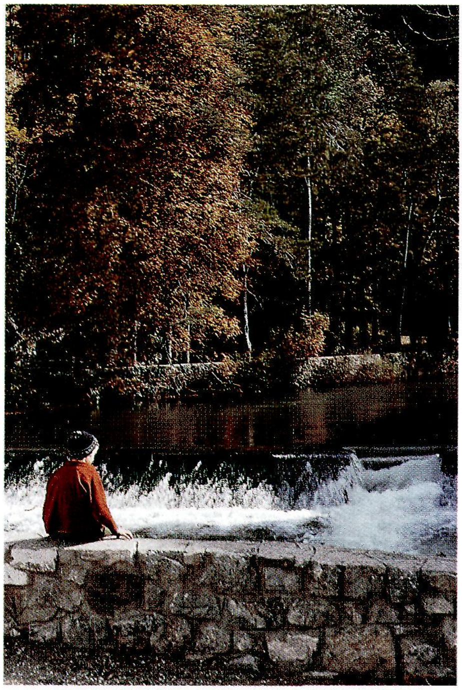


Photo 9: Karst springs of Vipava - Za Gradom (Photo by P. Habič).

Lijak, a periodical karst spring near Nova Gorica, represents a hydrological curiosity due to extremely high but short lasting discharges. The spring acts as flood overflow spring for karst underground water of Trnovski Gozd that otherwise flow north-westward to 6 km distant springs along Soča river. The limestone walls above Lijak are separated from the flysch of Vipava valley by a vertical fault. The boreholes near Lijak hitted the karst channels 90 m deep. Lijak resurgence is active seven to ten times per year. Its activity lasts from one to several days, the most up to 20 days. The biggest discharge measured since was 32,6 m^3/s. The low water level approaches to the Soča accumulation lake level (77 m a.s.l.). The artificial changes of the water level in the accumulation lake have a clear response in the limnigraphic records of the Lijak. The influences are noticeable during low and medium water tables while during higher waters the influence of precipitation is stronger (JANEŽ 1990).

The water supply of Nova Gorica is based on the karst water of the Mrzlek spring (Photo 12), emerging directly in the Soča valley. The water quantities flowing directly into the Soča river can not be directly measured. It was

Photo 10: Karst springs of Vipava - Pod Skalco (Photo by P. Habič).

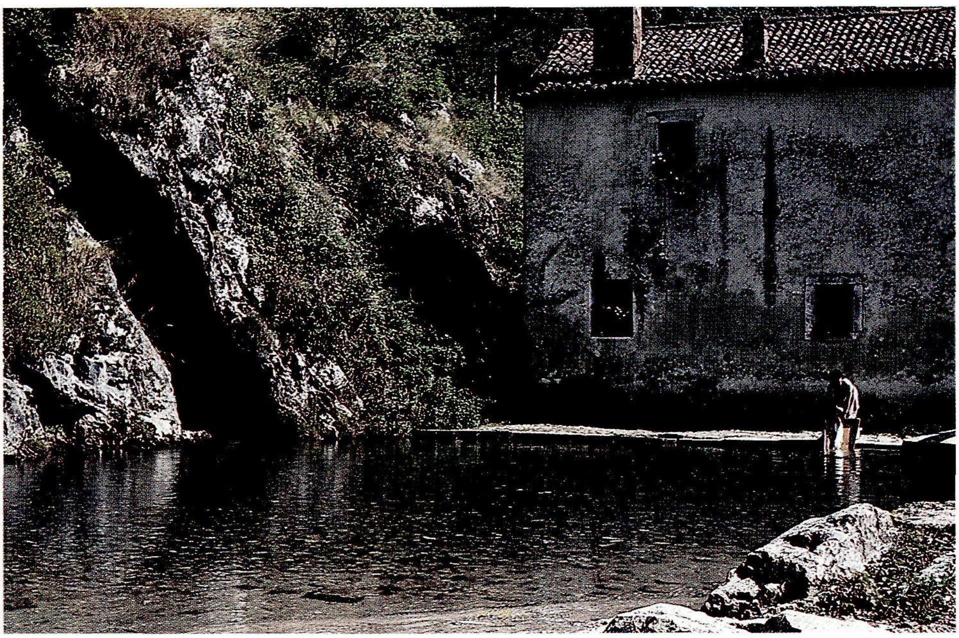


Photo 11: Karst springs of Vipava - Pod Farovžem (Photo by P. Habič).

Photo 12: Karst spring Mrzlek, mixing with the Soča river water is well visible (Photo by P. Habič).

estimated that their amount at low water is about 600 l/s and 40 m^3/s at high water (HABIČ 1982). Since the construction of the hydropower station Solkan the pumps are flooded and superficial Soča water breaks into the water supply system.

Kajža spring lies in the valley of Avšček brook at 191 m a.s.l.. Water appears on the surface at the contact of Cretaceous limestone and 20 m wide belt of strongly crushed rocks of the Avče fault. The lowest discharge of the spring is 7 l/s, t raises up to 1,5 to 2 m^3/s after heavy rain falls (JANEŽ & ČAR 1990).

Hotešk is a karst spring in the north-western part of Trnovo plateau along the Idrijca river. Water catchment area of the spring is built by Upper Cretaceous and Upper Triassic limestone. The discharge oscillates from 30 l/s at low water to 6 m^3/s at high water.

Čepovan valley is limited from the Trebušica by a ridge built of dolomites of Upper Triassic age. Most of the underground water drains towards Trebušica, smaller part only reaches the resurgence in the Čepovan valley about 610 m a.s.l.. It seems that the underground water has through flown to the Trebuša side due to dried up "Čepovan river" and deepening of the Idrijca and Trebušica valleys.

2.6.3. Geological structure and hydrogeological position of the Hubelj spring (J. JANEŽ)

First hydrological data about the Hubelj spring were published by PUTICK (1928). Much later the studies about this spring were presented by HABIČ (1970, 1985, 1987). PLACER & ČAR (1974) explained the regional hydrogeological position of the Hubelj spring.

2.6.3.1. Extent and method of mapping

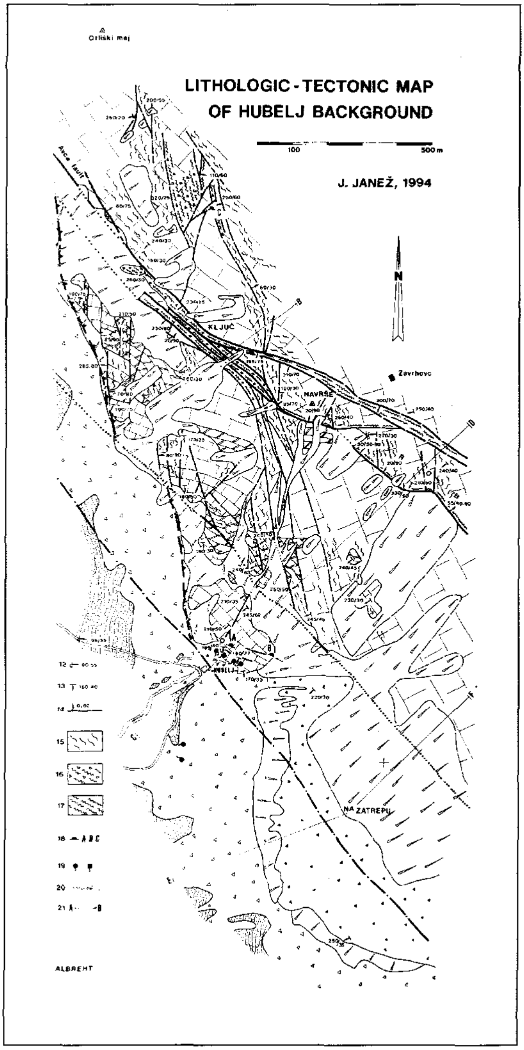


Fig. 2.24 Lithologic-tectonic map of Hubelj background: 1 - slope rubble, collapse block, screes; 2 - coarse-grained to block-like limestone slope breccia, younger, Quaternary; 3 - slope breccia, older, Quaternary; 4 - marlstone, siltstone and sandstone; flysch, Eocene; 5 - light brown limestone, usually grained, rarely thick, oolitic limestone, non-bedded, bedded to thick-bedded, Jurassic - Upper Lias and Dogger; 6 - pure grained dolomite, dolomitized oolitic limestone, bedded to thick-bedded or non-bedded - Jurassic - Upper Lias and Dogger; 7 - strong fault, visible and covered; 8 - weak fault, visible and covered; 9 - supposed fault; 10 - nappe border; 11 - lithological limit; 12 - dip and strike of inverse beds; 13 - dip and strike of normal beds; 14 - dip and strike of fault plane; 15 - fissure zone; 16 - broken zone; 17 - crushed zone; 18 - karst caves: A - Veliki Hubelj, B - Hubljeva Kuhinja, C - Otliška Jama; 19 - spring; 20 - surface water; 21 - cross-section.

Slightly more than 2 km² of the immediately background of the Hubelj spring was examined by a detailed geological mapping in 1994. The steep slope of the Trnovo plateau, including the edge of the plateau at the north-eastern side and the first outcrops of the Eocene flysch (impermeable edge of the karst aquifer) in the South and south-west were mapped (Fig. 2.24 and 2.25). The average incline of the terrain with numerous overhangs is over 45°. The altitude difference between the lowest (190 m) and the highest point (855 m) is 655 m.

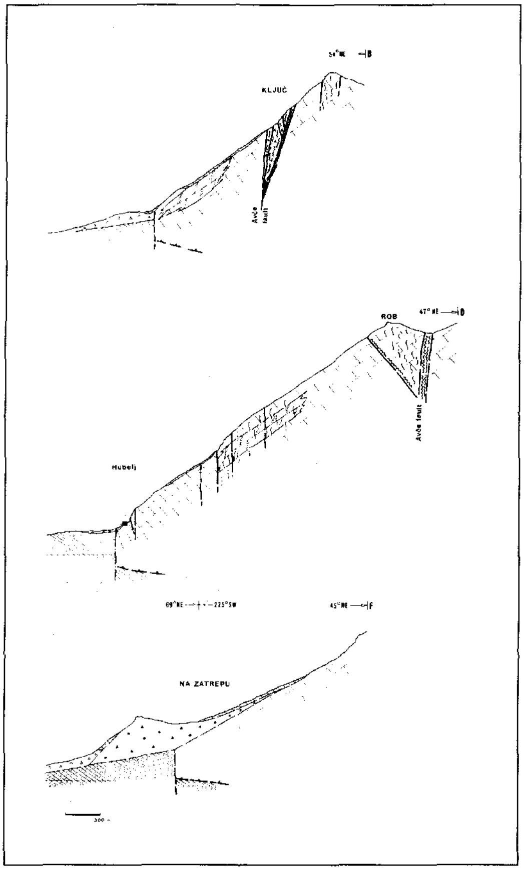


Fig. 2.25 Geological cross-sections near Hubelj.

The method of mapping of all outcrops is used. The scale of the map is 1:5000. The terrain is uncovered and the weathering zone is thin, so the identification of the bedrock is not difficult. Conditions on the flysch beds are rather different. Diluvium and weathering sediment cover the solid rocks and the outcrops are very rare. Besides, a thick layer of slope sediments - the Quaternary slope breccia, collapse blocks, slope rubbles and recent still active screes - covers a large part of Mesozoic and Tertiary bedrock and complicates the geological interpretation.

The objects of geological mapping were mainly the lithology of rocks, the character of the contact between different rock types and the tectonic conditions. The method of mapping and interpretation of the crushed zones character, introduced by PLACER (1982), was used. Further ČAR (1982) developed this method for geological mapping of karst. Crushed, broken and fissured zones can be distinguished on the base of the tectonic damage of the rock. ČAR & GOSPODARIČ (1988), JANEŽ & ČAR (1990) and ČAR & JANEŽ (1992) tested the method successfully for the explanation of geological, structural and hydrogeological position of karst springs on the edge of the Trnovo plateau and in Julian Alps. ŠEBELA & ČAR (1991) use this method to explain the evolution of some typical karst objects. It can also be applied

for definition of hydrogeological background and protecting areas of karst springs (JANEŽ 1986).

Stratigraphic definition of the mapped lithologic units in respect to their age and position is based on the relevant literature (BUSER 1968, 1973).

2.6.3.2. Geological structure near the Hubelj spring

The mapped area consists of Jurassic, Eocene and Quaternary rocks. The slope of the Trnovo plateau between Otliški Maj, Navrše, Sinji Vrh and Hubelj spring is mainly built by light brown limestone. The limestone is usually grained, rarely thick. On several places it changes continuously into oolitic limestone. The limestone on Otliški Maj, Navrše and Rob is mostly non-bedded with rarely notable beds. Lower, in the spring area of Hubelj, the limestone beds are 40 cm to 2 m thick, some of them even 10 m.

The limestone is in several places dolomitized or recrystallized into a pure grained dolomite. Often, oolitic limestone changes into the oolitic dolomite. The transition from limestone to dolomite is progressive. Same as the limestone, the dolomite is bedded to thick-bedded or non-bedded.

Following the basic geological map, sheet Gorica (BUSER 1968; 1973), the carbonate rocks above the Hubelj spring are defined as Upper Jurassic (Oxfordian and Lower Kimmeridgian, $J_3^{1,2}$), but the beds are more likely of the Upper Lias and Dogger age ($J_{1,2}$ - brown and grey oolitic limestone, thick limestone, grained dolomite), due to their obvious lithological features.

The Eocene (Ypresian and Lower Lutetian ($E_{1,2}$)) flysch in the Vipava valley consists of changeable beds of marlstone, siltstone and sandstone. The beds are 5 cm to 30 cm thick. Flysch on the mapped area has no inliers of limestone breccia and calcarenites.

Slope breccia, collapse blocks, slope rubbles and recent still active screes present the Quaternary sediments. There are two types of breccia. The older breccia builds the overhang ridge and the flattened area south-eastern from the Hubelj spring. It is partly bedded, agglutinated and has greater share of rounded clasts. The younger breccia is more chaotic, coarse-grained and block like. The unconsolidated slope sediments, collapse blocks and slope rubbles are also of different age. The youngest are recent active screes, that can be found at the foot of the rocky overhangs of today still active tectonic zones.

The most expressive tectonic deformations are the result of the young fault tectonic activity. The main tectonic line is according to the interpretation found of BUSER (1968) the obvious continuation or one of the legs of the regional Avče-Dol fault. South-west under the Otliški Maj on the altitude of 500 m the visible fault plane (45/90) confines the limestone massive. The screes and slope rubbles accumulate on the south-western side of this plane. First outcrops of flysch can be found at the distance of 120 m. On location Ključ, southern from the Otlica cave, the fault zone is 50 to 70 m wide. At

this point it divides into two legs that encircle the lens like peak of Navrše (857 m). The south-western fault plane builds the wall of Rob and the north-eastern leg represents 10 to 30 m wide broken zone. The valley southern from farm Zavrhovc was formed along this zone.

The course of the second fault line in the Dinaric direction is above the Hubelj spring at the altitude about 405 m. It is narrower, less marked and mostly covered with slope rubbles. It is displayed with a characteristic morphological step and with disposition of the connecting faults and crushed zones, those are interrupted at this line.

On the geological map (Fig. 2.24, and Fig. 2.25: geological cross sections) a supposed fault is drawn south-eastern from the springs of Hubelj. It is indicated by an outcrop of the tectonic breccia behind the abandoned army barracks near the Hubelj spring and by the geological and morphological conditions of the wider area.

Between these described tectonic lines there are the connecting crushed zones in the direction northwest-southeast. Their intensity varies from open wide fissured zones to crushed and broken zones. The broken zones are narrow and we present then on the geological map only with a line of a fault plane.

The beds of Jurassic limestone dip in general towards south-west. The dip angle changes between 30° and 60°. An evidently different dip direction can be established only at the western edge of the limestone, western and north-western above the Hubelj spring. In a narrow, up to 100 m wide belt at the contact between flysch and limestone, the dip direction turns towards south (strike 170° - 190°) and the dip angle reaches 75°. At the Hubelj spring the dip angle is a little lower (22° - 40°) and the beds dip towards south.

The character of the contact between the Mesozoic carbonate rocks of the Trnovo plateau and the flysch beds of the Vipava valley north-western from the mapped terrain is not problematic even though the contact is covered. This is undoubtedly a subvertical fault. But more unclear is the character of the contact between the carbonate rocks in the background of the Hubelj spring and the flysch beds south-western from the Avče-Dol fault on the section from Gosta Meja to the Hubelj spring, and also eastern from the Hubelj spring. On Gosta Meja location flysch undoubtedly lies under the thin layer of slope breccia at the altitude of 475 m, whereas near the Hubelj spring thus 235 m lower at the altitude of 240 m. The morphology of the terrain indicates, that towards east the upwarding of flysch is more gently. PLACER & ČAR (1974) described the structure as a depression, a synclinal bow of the Trnovo nappe thrust plane with the axis in the northeast-southwest direction. The change of a dip direction of the Jurassic beds from south-west to south and simultaneous rise of the dip angle at the contact with the flysch is also a proof for such explanation. The thrust character of the contact at the section between Gosta Meja and Hubelj spring is transformed with younger northwest-southeast and north-south oriented fault deformations.

2.6.3.3. Hydrogeological position of the Hubelj spring

It can be seen from the structural characteristics, that the Hubelj spring lies in the bottom of the expressive, narrow and deep structural depression in the thrust plane of the Trnovo nappe. Springs are situated in about 70 m wide belt at the altitudes from 240 to 265 m. Water generally comes from the bedplanes, widened by corrosion. The highest springs are in the eastern part and the altitudes of springs constantly decrease towards west. Above the permanent springs there are two caves. The "Veliki Hubelj" cave has the entrance at the altitude 280 m. Eastern from the spring there is the "Hubljeva Kuhinja" cave, which is not explored enough yet. The "Veliki Hubelj" cave is a horizontal cave - a temporary spring at high water - with permanent water inside also during draughts. The hydraulic gradient of the underground water behind the spring is very high (HABIČ 1985). The reason for such position of the water level is according to HABIČ (1970) the low permeability of the Jurassic limestone. PLACER & ČAR (1974) gave an additional interpretation on the basis of the flysch basement shape near the Hubelj spring. For the correct explanation also the influence of the neotectonic movements must be considered. The arrangement of the karst rooms and the position of the underground water indicate the neotectonic lifting of the block. The karst corrosion is slower than lifting and it is not able to fuse the underground flow. The opposite process was examined at the Lijak spring, which lies in the structural lowered block with the karst channel in the depth of 90 m (ČAR & GOSPODARIČ 1988). Naturally, there are no karst features formed above the spring Lijak because of the neotectonic lowering. In this case the term "immersed karst" has also the neotectonic meaning. Finally, the determination of the depth to the impermeable flysch basement of the karst aquifer would be very important for the final explanation of the hydrogeological structure of the Hubelj spring.

2.6.4. Geologic conditions and some hydrogeologic characteristics of the Vipava karst springs

(J. JANEŽ, J. ČAR)

2.6.4.1. The aim and method of investigation

The aim of the investigation was to explain the detailed geologic position of the Vipava karst springs. The same as in the case of the Hubelj spring we used the method of mapping of lithology and structural elements. The scale of mapping was 1:5000. The lithologic-tectonic map of the Vipava area is given in Fig. 2.26.

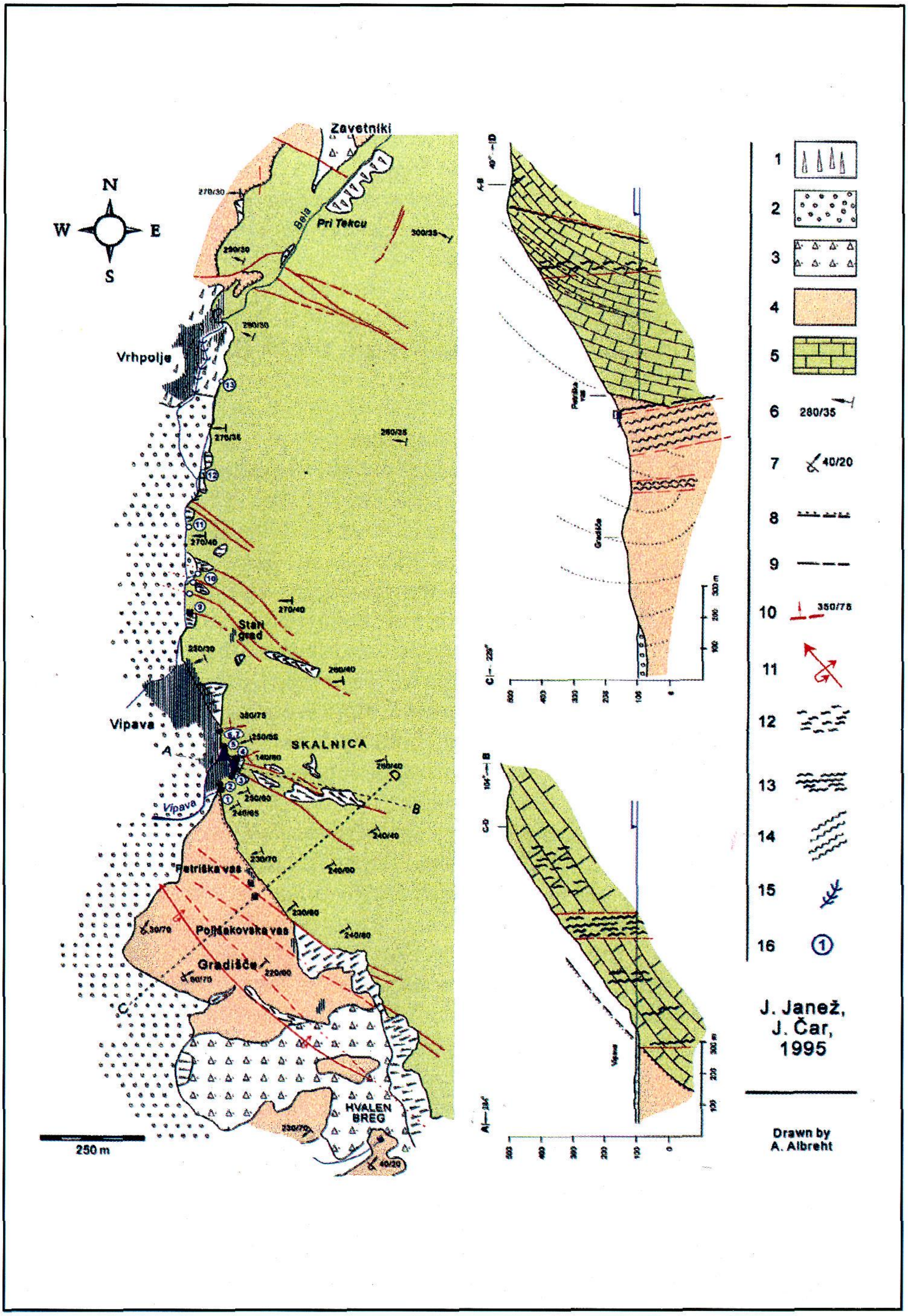

N
W
E
S
Zavetniki
Bela
Pri Tekcu
Vrhpolje
Stari grad
Vipava
SKALNICA
Vipava
Petriška vas
Poljšakovska vas
Gradišče
HVALEN BREG
250 m
A
B
C
D
1
2
3
4
5
6 280/35
7 40/20
8
9
10 350/78
11
12
13
14
15
16
J. Janež,
J. Čar,
1995
Drawn by
A. Albreht

Fig. 2.26: Geologic position of the Vipava springs. 1 - Slope rubble, scree; 2 - Alluvial deposit; 3 - Periglacial limestone breccia; 4 - Eocene flysch; 5 - Upper Cretaceous limestone; 6 - dip and strike of beds; 7 - inverse beds; 8 - erosion discordance; 9 - geologic boundary; 10 - fault; 11 - axis of an overturned fold; 12- fissure zone; 13 - broken zone; 14 - chrushed zone in flysch; 15 - the Vipava karst springs; 16 - sinking of the surface water Vipava karst springs: 1 Pri Kapelici, 2 Pod Lipco, 3 Perhavčev Mlin, 4 Vipavska Jama, 5 Za Gradom, 6,7 Pod Farovžem, 9 Črncova Jama, 10-13 periodical springs (number of springs according to P. Habič 1983).

We adopt the stratigraphic data about the age and position of the mapped lithologic units from the older geologic maps (PLENIČAR 1970; BUSER 1973).

2.6.4.2. The review of previous investigation

Nanos and the springs of the Vipava river have been the objects of geologic, geographic, geomorphologic, speleologic and hydrologic investigation for over than hundred years. We count more than 90 scientific papers and treatises, that touch directly or indirectly the hydrogeologic themes. Nanos belongs to the most investigated karst areas in Slovenia.

Hydrogeologic investigations of Nanos started more than forty years ago. MICHLER (1952), SAVNIK (1955) and HABE (1963, 1970, 1976) carried out the tracing tests of the sinking streams in Pivka basin. Later, HABIČ (1987, 1989) established the connection of the Stržen sinking stream near Postojna with the Vipava springs and possible connection of these springs with the brook at Vodice village near Col.

HABIČ investigated also the Vipava springs. He describes precisely the situation of the springs, hydrologic regime, physical, chemical and bacteriological properties of the water, the water catchment area, the threat to the karst groundwater and necessary protection measures (HABIČ 1983). The water level of the springs in Vipava oscillates for 2 m, but the position of the periodical springs near Vrhpolje is 20 meters higher. The groundwater level in the background should be much higher. There are no other data about the permanent underground accumulation of Nanos. SAVNIK (1959) and HABIČ (1983) described the Vipava cave.

2.6.4.3. Geology and morphology at the Vipava springs and their hydrogeologic consequences

Nanos is an overturned anticline. The anticline axe falls gently towards north-west. Nanos is structurally a part of the Hrušica nappe. On the north-east it borders the Predjama fault. (PLACER 1981, 1996).

The western slope and the belt around Nanos from Sanabor and Vrhpolje to Vipava are built of limestone of Upper Cretaceous (Senonian) age (PLENIČAR 1970; BUSER 1973). This limestone forms the nearest background for all the Vipava springs. The limestone beds are few decimetres to one meter or more thick, with partly massive occurrence. The colour of the rock is mostly light brownish or grey-brown, rarely grey, light grey or white. Grained limestone prevails over the thin grained or thick limestone. Mostly it is more or less bituminous.

North-east from Vrhpolje in the direction to Sanabor the beds of Upper Cretaceous limestone dip towards north-west (290 - 320°). The strike ranges between 25 and 40°. Near Vrhpolje the beds dip 270 - 290° towards west and the strike of the beds is the same - mostly 30°. Southern from Vrhpolje the Upper Cretaceous limestone still dips towards west, but in town Vipava the beds start to turn towards south-west. In the northern part of the town the dip is 250 - 260°, near spring Pod Skalco 235 - 250°, and further towards Petriška Vas 235 - 240°. The strike angle ranges between 30 and 50° in the northern part of the town, 45 - 55° near spring Pod Skalco and increases to 60 - 70° in the direction of Petriška Vas.

Further to south-east the dip of Senonian limestone does not change. All the way to Hvalen Breg it varies between 230 to 240°. The strike angle is about 80°, at some places also 85 - 90°. Of course, that is a sign for the nearness of the arch-bend of the Nanos anticline. In the upper part of the slope, on the location Plaz and Pri Topolih the beds strike 40 to 80° in the direction 230 - 250°. The limestone beds are thick. Also the inliers of thin bedded marl limestone can be found. On the contact with flysch we notice few decimetres of limestone conglomerate.

According to Buser (1973) the flysch beds that lie on the Upper Cretaceous limestone belong to Eocene (Upper Cuisian and Lower Lutetian). If the stratigraphic definition is correct, then there must be an erosion discordance between both lithologic units. We do not notice any angle discordance. The strike and the dip of the flysch beds and the beds of Upper Cretaceous limestone are the same.

Flysch beds are typical for the distal type of turbidites. Few centimetres or decimetres thick beds of marl and fine-grained quartz sandstone alternate in the rock. The number and the thickness of the calcrudite and calcarenite beds rise towards south-west. On location Gradišče the Baum sequences 1 to 2.5 meters thick, can be found. It is a medial type of turbidites with clear A, B, D and E horizons, while the horizon of current lamination C appears rarely.

North-eastern from Gradišče the flysch beds dip steeply towards south-west. The position of the beds is therefore normal. At Gradišče the beds are vertical, and south-east their position is inverse, dipping 50 to 80° towards north-east. The axis of the overturned anticline is therefore well defined. It crosses the Gradišče village and joins the faults that come from Vipava.

In the short section among Vrhpolje and Zavetniki the Eocene flysch is covered with Quaternary limestone slope breccia, that is typical for the southern slope of Trnovski Gozd. At Vrhpolje the flysch is covered with limestone rubble. Along the riverbed of Bela among Vrhpolje and Vipava flysch is covered with alluvial deposits, composed of clayey thick-grained limestone and flysch pebbles.

In the western part of Nanos the slope rubble and scree cover very small areas. This shows the relative tectonic inactivity of the area. The morphology of the relief confirms this supposition. Among Vipava and Vrhpolje the western slope of Nanos is monotonous. It dips slowly toward west - with the strike angle that correspond with the strike angle of the Cretaceous limestone. North-east from Vrhpolje the Bela brook forms a narrow and up to 50 meters deep gorge in the Upper Cretaceous limestone. 100 to 150 meters above the gorge, at the location Njivce, there are remains of an erosion terrace, probably an older stream of Bela. That stream had the same direction towards south-west as the recent one. In the gorge, the limestone is weekly damaged with some fault and fissured zones. The direction of the Bela brook is mainly defined with the dip and strike of the Upper Cretaceous limestone. The limestone of the western part of Nanos has no signs of the superficial karstification, except of some shallow dolines in the initial phase of evolution. It seems, that the surface was covered with flysch in the nearest past.

Several smaller depressions in relief of the western part of Nanos, which are probably the remains of old surface water streams, have the same or similar direction as the one at Njivce location. The most outstanding remains of an old surface stream at Stari Grad above the Vipava town have the transverse Dinaric direction from the north-east to south-west. The origin of the valley is not connected with transverse Dinaric tectonic zones, but with the dip of the limestone. The third "hanging dry valley" is at Pri Topolih location above the Poljšakova Vas.

A little more crushed limestone has been mapped south from Vrhpolje. In that part the Bela brook sinks. In Vipava town the limestone is again more compact. It has only some rare fissures that are later extended by corrosion. So, the springs Pod Farovžem and Za Gradom come out from the tectonic fissures, extended by corrosion. The springs Pri Kapelici, Pod Lipco and Perhavčev Mlin drain the karst water from the vertical joints.

The limestone is tectonically modified into the crushed zone in the amphitheatrical rocky indentation named Skalnica, above the spring Vipavska Jama. The direction of the indentation is from west to east or 10 to 20° towards south-east. Its south (south-west) margin, that is morphologically exposed as an 10 to 15 meters high wall, is a fault zone with elements 30/90. The northern border of the amphiteatre has also the direction west-east, just like less visible fissures in the limestone. Inside the amphitheatre of Skalnica the rock is deformed into the crushed zone and the dip and strike can be measured only at few places.

The origin of the Skalnica amphitheatre can be induced by the tectonic deformation of the limestone, but also by a strong underground water stream towards the springs. There is a small chance, that the depression is only the result of the erosion of crushed limestone. In this case the same surface forms should come into existence also on places where there are no karst springs or karst groundwater streams; but they mostly do not. Such morphologic forms are characteristic for the surroundings of karst springs. The groundwater probably could not form bigger karst objects, because in the crushed limestone the well permeable cave break down originate simultaneously. If the amphitheatre of Skalnica is induced by cave break down, this process is in the initial phase. This agrees with our earlier ascertainment, that the relief in the western part of Nanos is still young and that the limestone was in younger geologic past covered with flysch beds. In the geologic future the result of this corrosion-erosion process will be a greater and ripe morphologic depression with overhanging walls, similar to those one at Divje Jezero near Idrija or Lijak spring near Nova Gorica.

A stronger and 150 meters wide zone of Dinaric oriented faults crosses Poljšakova Vas. It seems that the strongest is the most north-eastern fault (50/80) with 50 meters wide broken zone. Parallel to the other fault planes a dense system of fissures can be found. Flysch beds in this fault zone are strongly folded. Considering secondary tectonic deformation we suppose another Dinaric oriented fault, crossing Hvalen Breg, Žgavska Vas and Gradišče. It should be mapped easier in the limestone slope of Nanos, south-east from the investigated area.

2.6.4.4. Some hydrologic data

At the entrance in the gorge under Sanabor the discharge of Bela brook was in December 1994 and in January 1995 among 70 and 100 l/s. We estimate, that in the gorge all the way to Vrhpolje the Bela brook does not sink. Obviously it sinks in the Vrhpolje village. At the end of the village the discharge was only 2 l/s and 500 metres lower the brook was dry. The village Vrhpolje strongly pollutes the karst water, but probably only the most northern permanent spring Črnceva Jama.

Among Petriška Vas and Hvalen Breg there are some weak but captured springs. Those springs drain groundwater from calcarenite layers in flysch.

2.7. WATER QUALITY

2.7.1. Long-term Quality Monitoring (M. ZUPAN)

2.7.1.1. Introduction

Long-term water quality monitoring of the springs in Slovenia has been run since 1990. Already the first results of some main springs at the foot of the Trnovo plateau reminded that some pollution sources in the catchment area exist. In the frame of the present project the monitoring program in the springs was more extensive in years 1993-96.

2.7.1.2. Sampling And Chemical Analyses Program

The samples for the water quality observations in the following sampling points were taken in 1993-1996:

The Vipava spring	15 times for basic physical, chemical and bacteriological analysis and 6 times for the analysis of heavy metals and organic micropollutants in water and sediments and saprobiological analysis
The Hubelj spring	15 times for basic physical, chemical and bacteriological analysis and 6 times for the analysis of heavy metals and organic micropollutants water and sediments and saprobiological analysis
The Lijak spring	1 time for basic physical, chemical (including heavy metals and organic micropollutants in water) and bacteriological analysis in 1993; later the sampling was impossible because the borehole was stopped
The Mrzlek spring	3 times for basic physical, chemical (including heavy metals and organic micropollutants in water) and bacteriological analysis
The Podroteja spring	14 times for basic physical, chemical and bacteriological analysis and 6 times for the analysis of heavy metals and organic micropollutants in water and sediment and saprobiological analysis.
In the catchment area	two water supply captures in Čepovan (Čepovan and Čepovan Puštale) were sampled and analysed once in 1993; physical, chemical (including heavy metals and organic micropollutants in water and sediment) and bacteriological analysis

The investigation program was run conforming to the methodology recommended by international organisations.

2.7.1.3. Analytical Methods And Water Quality Standards

Sampling was done in various seasons of the year, preferably at low to mean low discharges. Samples for all types of analyses at one location were taken simultaneously. Samples were taken at a depth of 0.5 m and as close to the spring outlet as possible. In waters less than 1 m deep, samples were taken at mid depth.

When sampling, air and water temperature, as well pH value, conductivity, free carbon dioxide and dissolved oxygen were measured. Samples for determining nitrite, chemical oxygen demand (COD), colour, and phosphates were conserved, samples for determining detergents, phenols, mineral oils, and formaldehyde were cooled.

Basic physical and chemical analyses:

In unfiltered, mixed samples, suspended solids, chemical oxygen demand (COD), biochemical oxygen demand (BOD), phenols, and detergents were determined. The unfiltered, sedimented sample was used to determine ammonium and nitrite ion, real colour, mineral oils, formaldehyde and ligninsulphonates. Other analyses were performed on samples filtered in Filtrak 388.

Samples are analysed in the shortest possible time according to the following standard analysing methods for determining the basic water-pollution parameters (3, 4, 5):

determination of free carbonic acid:	titration with NaOH
determination of dissolved oxygen:	titration acc. to Winkler and measuring by an WTW probe
determination of COD:	$K_2Cr_2O_7$ and $KMnO_4$
determination of Ca and Mg ions:	titration with NaEDTA
nitrate ions:	Na - salicylate procedure
nitrite ions:	procedure with sulfanilic acid solution
iron ions:	procedure with 1,10 - phenanthroline
SiO_2:	procedure with ammonium molybdate solution
aluminium:	procedure with alizarin
actual colour:	comparison with K_2PtCl_6 standards
anionic surfactants in detergents:	methylene-blue method
phenols:	procedure with 4-aminoantipyrine
ammonium ions:	procedure with Nessler reagent
phosphate ions:	procedure with ammonium molybdate solution

sodium and potassium:	flame AAS
sulphate ions:	titration by thorin (6)
formaldehyde:	procedure with phenilhydrazine hydrochloride (7)
mineral oils:	fluorescence measurement in hexan-extract (8)
ligninsulphonates:	fluorescence method (9)

Analyses of heavy metals and organic compounds

Sampling of water, suspended solids, and sediments for analyses of metals and organic compounds (organic micropollutants) was performed according to the sampling methods as stated by DIN 38402-T15 and ISO 5667-T6. Concentrations of individual elements were measured by analytical procedures according to the standards stated in Table 2.10.

The following organic compounds were analysed in unfiltered water by the method of gas chromatography: phenols, pesticides, polycyclic aromatic hydro-

Tab. 2.10: Analytical methods to determine the content of metals in water, suspended solids, and river sediment.

METAL	WATER		SEDIMENTS AND SUSPENDED SOLIDS	
	Regulation	Method	Regulation	Method
Copper	DIN 38406-T7	F AAS	DIN 38406-T7	F AAS
Chromium	DIN 38406-T10	ET AAS	DIN 38406-T10	F AAS
Nickel	DIN 38406-T21	F AAS	DIN 38406-T21	F AAS
Zinc	DIN 38406-T21	F AAS	DIN 38406-T21	F AAS
Lead	DIN 38406-T21	ET AAS	DIN 38406 T21	F AAS
Cadmium	DIN 38406-T19	ET AAS	DIN 38406 T19	F AAS
Mercury	DIN 38406-T12	CV AAS	DIN 38406 T12	CV AAS

Notes: F AAS Atomic absorption spectrophotometric analysis, flame AAS, instrument PE 1100B
ET AAS Atomic absorption spectrophotometric analysis, electrothermical AAS, instrument Zeeman 3030
CV AAS Atomic absorptional spectrophotometrical analysis, cold vapour AAS, instrument PE 2380 MHS 20

Tab. 2.11: Analytical methods to determine the content of organic compounds in water.

	Regulation	Method
Pesticides	EPA 608, 1982 and DIN 38407-T6 and T14	GC/MS/SIM
Phenols	EPA 604 and ref. 21	GC/MS/SIM
PAO	EPA 610	GC/MS/SIM
PCB	EPA 608, modified	GC/ECD
AOX	DIN 38409 - T14	Stroehlein Coulomet 702 CL
EOX	DIN 38414 - T17	Stroehlein Coulomet 702 CL

carbons, (PAH) and polychlorinated biphenyles (PCB). Also the adsorbed organohalogen compounds (AOX) were analysed and GC/MS screening was performed (identification of untargeted organic compounds). Analytical methods for determining concentrations of organic compounds in water are given in Table 2.11.

PCB was determined in the untreated sample of the sediment too. A GC/MS screening was made from the extract of the sediment to identify untargeted organic compounds. As well halogenated extracted organic compounds (EOX) were analysed.

Saprobiological and bacteriological analyses

For the evaluation of the quality of surface waters from the biological point of view we used the saprobic system (10 - 15) and the calculation of the value of the saprobic index of a biocoenosis (16, 17). The value of the saprobic index (SI) increases with the deterioration of the living conditions from 1 to 4. Samples were taken biannually, in the cold and in the warm season of the year at lower discharges. The biological material was sampled in the littoral of the effluent down to a depth of ca. 0.5 m, where the sampling was not hampered by either water depth or speed. Semiquantitative and qualitative samples of periphyton and macrozoobenthos were taken. Macrozoobenthos was collected in the gravel to a depth of down to 15 cm in the ground semiquantitatively by means of a standard manual net (ISO 7828(E), 1985) with 0.5 x 0.5 mm mesh.

With regard to the value of the saprobic index, the river is at a particular sampling point ranged into the corresponding quality class according to the values stated in Table 2.12.

The bacteriological conditions of surface waters are subject to change due to the nature of the rivers, therefore the results of bacteriological analyses reflect the current state, i.e. pollution. Samples for bacteriological analyses were taken simultaneously with the samples for physicochemical analyses to be analysed according to the standard methods (4). The most probable number of

Tab. 2.12: Quality classes according to the value of saprobic index.

Trophic degree	SI value	Quality class	Description of the quality of the water body
oligosaprobic	1.0 - 1.5	1	uncharged to very little charged
oligo to beta	1.51- 1.8	1 - 2	little charged
betamezosaprobic	1.81- 2.3	2	moderately charged
beta to alfa	2.31- 2.7	2 - 3	critically charged
alfamezosaprobic	2.71- 3.2	3	heavily polluted
alfa to poly	3.21- 3.5	3 - 4	very heavily polluted
polysaprobic	3.51- 4.0	4	excessively polluted

bacteria (MPN/l) was determined and the following more important groups of bacteria were qualitatively determined as well:

faecal coliforms, faecal streptococci, Proteus sp., Pseudomonas aeruginosa, sulphite-reducing clostridia and total number of aerobic mesophilic bacteria.

Standards and guidelines for water quality assessment

In general the Slovenian regulation classifies running waters with regard to their potential utilisation into four quality classes:

- **1st class:** waters which in their natural state or following disinfection may be used as drinking-water, in food-processing industry, as well as in breeding high-class fish species (Salmonidae);
- **2nd class:** waters which in their natural state may be used for bathing, water sports, breeding other species of fish (Ciprinidae), or following normal treatment (coagulation, filtration and disinfection), may be used as drinking-water or in food-processing industry;
- **3rd class:** waters which may be used in irrigation, or, following normal treatment, in industry, except in food-processing industry;
- **4th class:** waters which may be used for any purpose only following an adequate treatment.

The criteria used in ranging spring water courses into quality classes according to the contents of metals in water and suspended solids are shown in Table 2.13. Concentrations in bold type in the table make up the division between 1st-2nd and 3rd-4th quality class.

Table 2.13. lists criteria for categorising watercourses into quality classes according to the content of metals in sediments. The criteria are based on natural contents of metals in carbonate sediment rocks (18, 19), amended with the results of investigation of certain surface waters in Slovenia at their springs or in polluted sections. Values in bold indicate the division between natural

Tab. 2.13: Standards and guide-lines for classification of watercourses into quality classes according to the contents of metals in water and suspended solids.

Metal	**Classification into quality classes**			
μg/l	**1.**	**2.**	**3.**	**4.**
Cooper	< 30	100	140	> 140
Chromium	< 45	150	800	> 800
Nickel	< 15	50	140	> 140
Zinc	< 50	200	1400	> 1400
Lead	< 15	50	140	> 140
Cadmium	< 1.5	5	15	> 15
Mercury	< 0.5	1	1.4	> 1.4

Tab. 2.14: Standards and guide-lines for classification of watercourses into quality classes according to the contents of metals in river sediment

Metal	Classification into quality classes			
μg/l	1.	2.	3.	4.
Copper	< 50	**50 - 100**	100 - 340	> 340
Chromium	< 75	**75 - 150**	150 - 540	> 540
Nickel	< 50	**50 - 100**	100 - 360	> 360
Zinc	< 650	**650 -1300**	1300 - 4600	> 4600
Lead	< 80	**80 - 120**	120 - 1000	> 1000
Cadmium	< 6	**6 - 12**	12 - 40	> 40
Mercury	< 0.1	**0.1 - 0.2**	0.2 - 1	> 1

values and pollution.

Table 2.14 lists criteria for categorising into 1.-2. quality class according to the content of organic micropollutants considering EC (20,21) and WHO (22) recommendations. The AOX and EOX are used as group criteria for monitoring the pollution with chlorinated organic compounds. The value of 0.5 - 2.5 μg EOX/kg air dried sample represents the natural background, a concentration from 30 - 700 μg EOX/kg might cause the extermination of some benthos organisms (23).

The identification of organic compounds in the GC/MS screening of samples of waters and sediments shows which organic compounds are present in watercourses and makes it possible to determine the pollution caused by man. In performing and evaluating the analyses less stress is lain on the quantity. Based on GC/MS screening, watercourses were evaluated according to the following criteria (Tab. 2.15):

Tab. 2.15: Considered standards for classification of watercourses into the first(1.) and the second (2.) quality class according to the contents of organic micropollutants.

ORGANIC COMPOUND	1.-2. QUALITY CLASS
AOX - μg Cl/l	< 5
Mineral oils - mg/l	0.01
Polychlorinated biphenyles - μg/l	0.1
Phenols - μg/l	0.001
Polycyclic aromatic hydrocarbons - μg/l	0.2
Pesticides - individual - μg/l.	< 0.1
Pesticides - total - μg/l	< 0.5

1st quality class: the water shows presence of compounds of natural origin only

2nd quality class: the water shows presence of compounds which are biodegradable and may be removed from the water with simple methods used in preparation of drinking water

3rd quality class: the water shows presence of not easily destructible compounds, which when infiltrating into the groundwater remain almost unchanged or are transformed into stable metabolites

4th quality class: the water shows presence of chlorinated compounds which are typical man-caused pollutants, compounds which tend to accumulate in living beings and compounds with carcinogenic and/or mutagenic potential.

2.7.1.4. Results and water quality assessment

The pollution of the water springs, in particular of the water, was relatively slight. The chemical parameters in most water samples did not exceed the normative for drinking water. On the other hand relatively high concentrations of mercury, cadmium, lead and copper in sediment samples were measured, which means that the pollution was nevertheless present in the investigated springs (Fig. 2.27.). The phenolic compounds and polycyclic aromatic hydrocarbons (PAH) were very often present in water samples of the Vipava, Hubelj and Podroteja springs (Fig. 2.28). The number of present PAHs determined in GC/MS screening was very high in water and sediments extracts. In the all investigated springs numerous compounds which originate from different human activities, were determined in GC/MS screening of water and sediment as well.

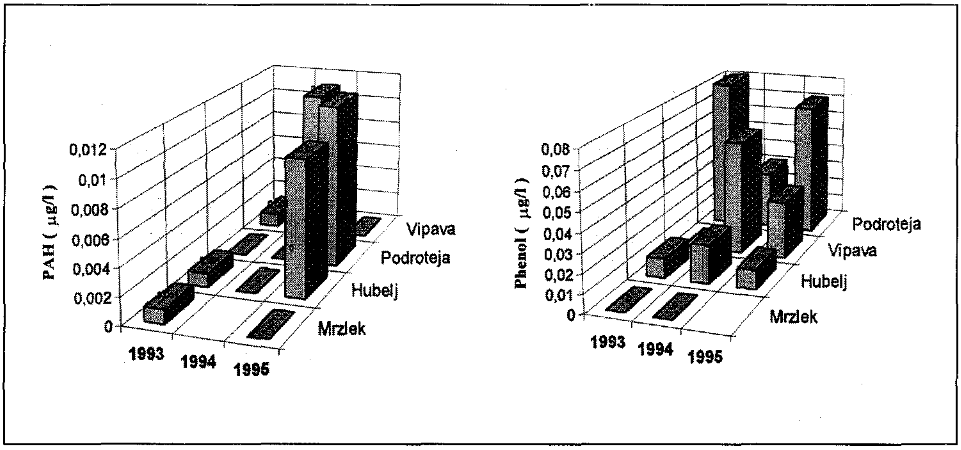


Fig. 2.28: Polycyclic aromatic hydrocarbons and phenolic compounds in the water samples of the investigated springs (maximal values).

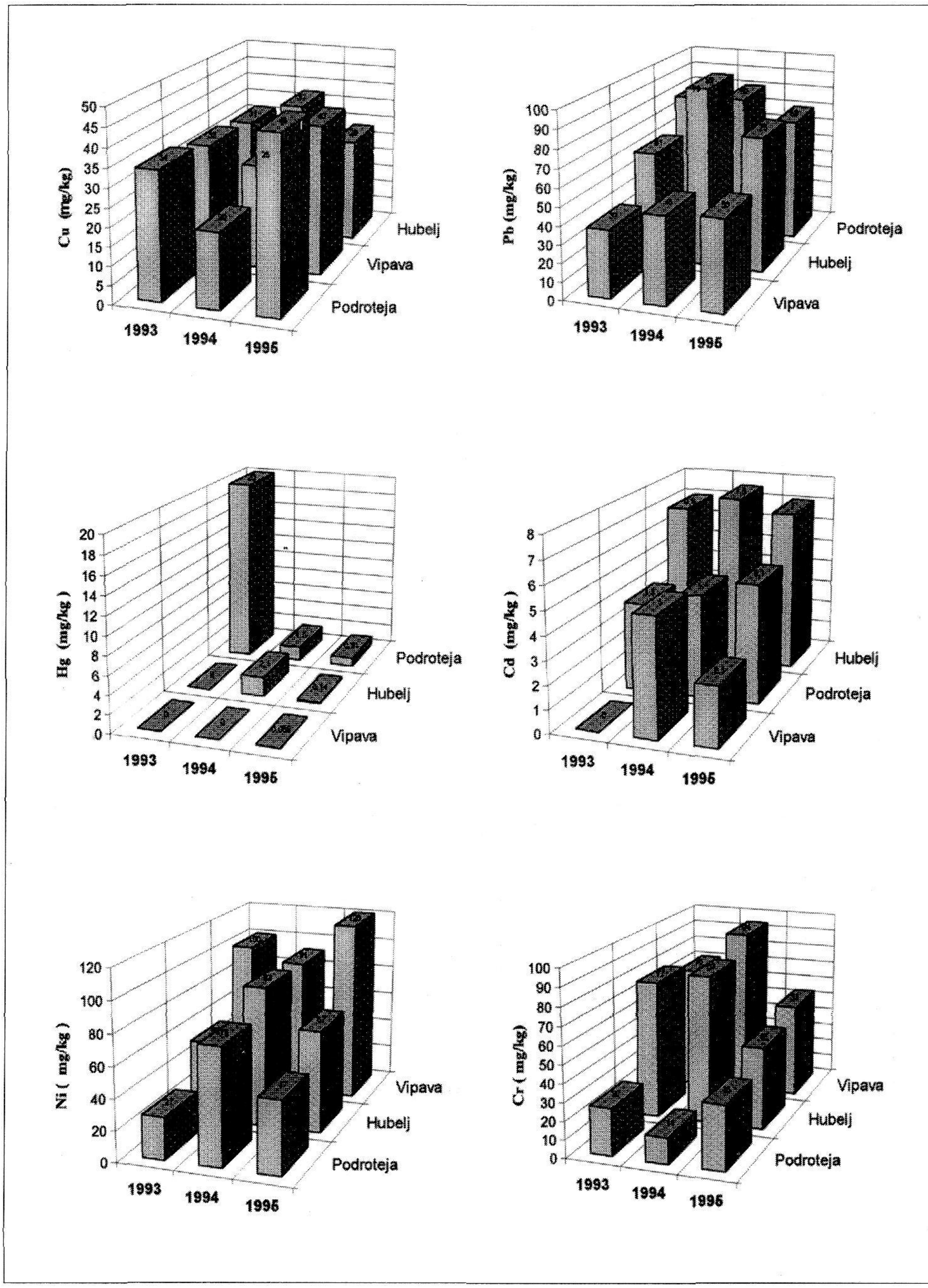


Fig. 2.27: Heavy metal levels (maximal values) in the sediment samples of the investigated springs.

Tab. 2.16: Content of heavy metals in the sediments of the two water springs in Čepovan.

Water spring	Copper mg/kg	Zinc mg/kg	Cadmium mg/kg	Chromium mg/kg	Nickel mg/kg	Lead mg/kg	Mercury mg/kg
Čepovan	58	583	4.4	81	61	<10	<0.05
Čepovan — Pultale	56	1600	6.5	37	43	228	<0.05

Tab. 2.17: Content of phtalic acid esters (sum) in the investigated springs.

	Sum of phtalic acid esters - µg/l		
	1993	1994	1995
Čepovan	0.065	-	-
Vipava	0.120	0.115	0.520
Hubelj	0.126	0.200	0.360
Mrzlek	0.175	0.234	0.420
Lijak	0.145	-	-
Podroteja	0.260	0.615	1.110

In the catchment area we analysed two springs in Čepovan, which were polluted by polycyclic aromatic hydrocarbons in water (0.009 µg/l) and sediment. The concentrations of single PAH-s were not high but they were present in great number, thirteen in each Čepovan spring. We determined high contents of heavy metals in the sediment as well (Tab. 2.16). Phtalic acid esters were determined once a year and were found in all analysed water samples. Besides we establish a trend of increasing concentration (Table 2.17).

The presence of heavy metals and many different organic compounds in water and sediment samples is pointing to a constant pollution from the hinterlands.

For the estimation of the water quality in the investigated springs all in the chapter 2.7.1.2 mentioned criteria have been taken into account and the results are shown in the Table 2.18.

WATER-COURSE	SAMPLING POINT	DATE	QUALITY EVALUATION: PHYSICO-CHEMICAL ANALYSES: Basic	Metals*	Organic compounds**	EOX	AOX	BIOLOGICAL ANALYSES: Sapro-bio-logical	Bacteriological: MPN/l	Bacteria of fecal origin***	FINAL EVALU-ATION
KRAŠKI IZVIR	Podroteja	09.06.93	2	1/3 -/Hg	1/1,1-2,1,1,1-2/2 1-2	1	1		2	++	
		19.11.93	1						1	0	2
		14..2.93	1 - (2)						1	0	
		15.03.94	2	1/1				1	1	0	
		23.06.94	(1) - 2						1	0	1 - 2
		05.07.94	2		1/1,1,1,1,1/1-2 1	1	1	1	1	0	
		13.09.94	(1) - 2					1 - 2	1	+	
		04.04.95	2					1	1	0	
		11.07.95	2 - (3)	1/2 -/Hg	1/1,1,1,1,2-3/1-(2) 2	2	1	1	1	0	2
		03.08.95	2						1	0	
		03.10.95	2						1	0	
VIPAVA	Vipava	18.03.93	2					1 - 2	1	0	
		09.06.93	2	1/1	1/1,1,1,1,2-3/2 2-1	1	1	1 - 2	1	+	
		29.07.93	2						2	+	2
		18.11.93	1 - (2)						1	0	
		16.03.94	2	1/1				1 - 2	1	0	
		23.06.94	2						2	0	2
		06.07.94	2		1/1,1,1,1,1-2/ 1-2	1	1		1	+	
		14.09.94	- 2					2	2	+	
		04.04.95	2					1	1	0	
		11.07.95	2	1/1	1/1,1,1,1,2-3/2-3 2	2	1	1 - 2	1	0	2
		02.08.95	2						1	0	
		03.10.95	2	2/1 Zn,Ni/-					1	++	
HUBELJ	spring	09.06.93	1 - 2	1/1	1/1,1,1,1,1/ 1	1	1	1 - 2	1	0	
		29.07.93	1 - 2						1	0	1 - 2
		18.11.93	1 - 2					1 - 2	1	0	
		14.12.93	1						1	0	
		16.03.94	1 - 2	1/2 -/Zn,Hg,Cd				1	1	0	
		23.06.94	1 - 2						1	0	2
		06.07.94	1 - 2		1/1,1,1,1,1/3 2-1	1	1	1	1	0	
		14.09.94	1 - 2					1 - 2	1	0	
		04.04.95	1 - 2					1 - 2	1	0	
		11.07.95	2 - (3)	1/2 -/Hg	1/4,1,1,1,(2)-3/2-3 3	1	1	1	1	0	2/3■
		02.08.95	1 - 2						1	0	
		03.10.95	1 - (2)						1	0	

Notes:
- * evaluation of metals - in water / in sediment; metals present in higher concentration in water / in sediment
- ** sequence of evaluations of organic compounds: PCB (water/sediment), phenols, pesticides, polycyclic aromatic hydrocarbons, GC/MS (water/sediment); final evaluation with regard to the present organic compounds; PCB in evaluation mark means that only polychlorinated biphenyles in water / in sediment have been analysed; EOX - extracted organohalogen compounds; AOX - adsorbed organohalogen compounds
- *** each + sign denotes one species of qualitatively determined bacteria of faecal origin
- ■ water quality after GC/MS screening of organic micropolutants.

Tab. 2.18: Evaluation of the quality of the investigated karstic springs in 1993-1995.

2.7.1.5. Contour diagrams of fluorescence intensity

We used the excitation-emission matrix (EEM) method as pattern recognition technique and as semi-quantitative technique to follow the transport of natural and anthropogenic pollution in hydrologic system (WOLFBEISS 1993).

We scanned the 3D spectra in all background samples. Emission spectra (300 nm to 550 nm, 5 nm intervals) were scanned over the range of excitation wavelengths (300 nm to 500 nm, 5 nm intervals) on the Hitachi-4500 fluorescence spectrophotometer. Slit widths for both excitation and emission monochromators were set at 10 nm.

The comparison with the unchlorinated tap water shows that in all measured samples different organic compounds of unknown origin are present. Namely, we did not have the standards for this compounds and the determination of present compounds will be task for some investigation in the future.

2.7.1.6. Conclusions

The chemical analyses of sediment in the Hubelj, Vipava and Podroteja springs have shown that pollution from the hinterlands is present and that water quality may suffer an abrupt deterioration. The results of microbiological analyses have been shown periodical pollution in the Podroteja, Hubelj and Vipava springs as well.

Investigations of water quality should be followed by appropriate actions. Actions to protect water quality wherever it is still satisfactory and rehabilitation actions where appropriate.

2.7.2. Agricultural threats to pollution of water of Trnovsko-Banjška Planota (B. MATIČIČ)

2.7.2.1. Introduction

The objective has been to determine the relationship between the soil water balance and mineral balance in the Karst region of Trnovsko-Banjška Planota in western part of Slovenia above Vipava valley and to find out if the possible excessive use of fertiliser and/or high intensity of animal husbandry in upland catchment area on Trnovsko-Banjška Planota could affect the quality of drinking water down in Vipava valley.

The altitude of Trnovsko-Banjška Planota is about 800 m. In this region mainly shallow soil types (with depth of 10-50 cm) on limestone are found with low water holding capacity (22-142 mm) and high rate of infiltration.

The amount of precipitation in Trnovsko-Banjška Planota is very high. The average annual value (1951-1980) in meteorological station Otlica was 2457

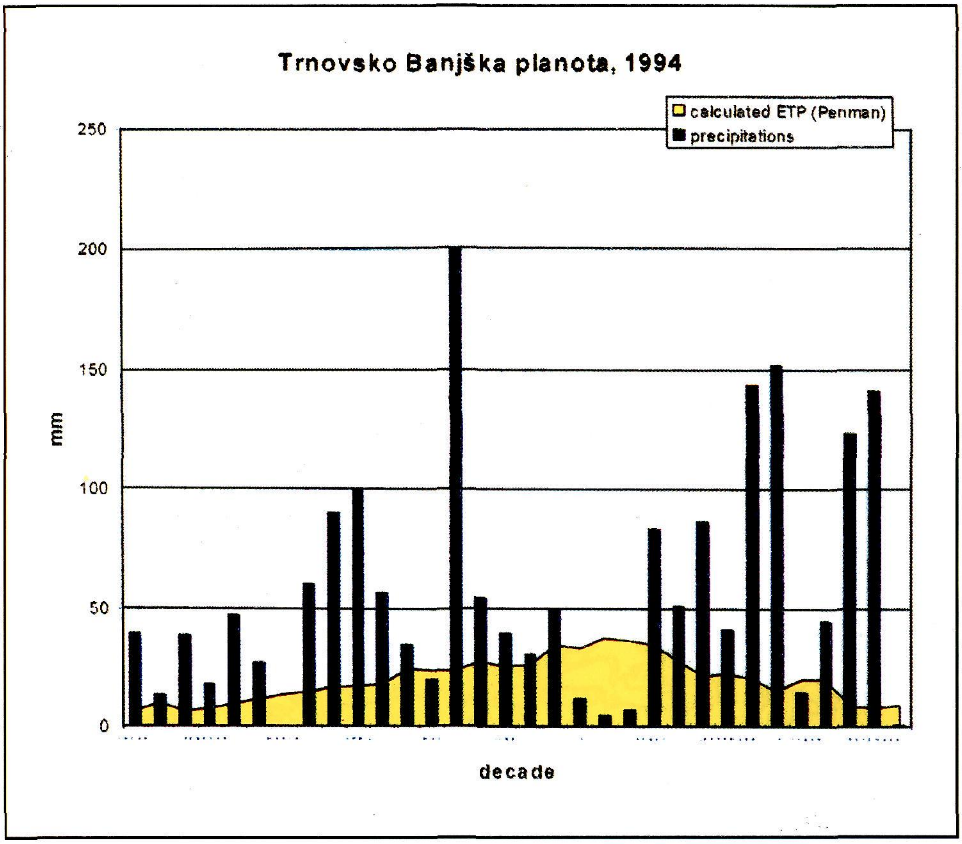


Fig. 2.29: The comparison between evapotranspiration (calculated ETP) and precipitation in the Trnovsko-Banjška Planota for the precipitation station Otlica in the observation year 1994.

mm. The extreme wet year was 1965 with 3233 mm of rain while the extreme dry year was 1973 with 1833 mm of rain (Source: Klimatografija Slovenije, Padavine, HMZ 1989).

The amount of precipitation in 1994 (the year of our evaluation of water and mineral balance) was 1822 mm (from Jan.-Nov.); the evapotranspiration in this period was 628 mm (used modified Penman's equation - by DOORENBOS). The evapotranspiration according to this evaluation represents only 40 % of the amount of precipitation (Fig. 2.29). During the period of intensive precipitation, therefore, the processes of leaching of fertilisers can occur.

It has been decided to evaluate regional and farm mineral balance for hilly karstic region of Trnovsko-Banjška Planota in order to identify vulnerability related to the nitrate problems in this less intensive agricultural region.

2.7.2.2. Groundwater and surface waters

The pollution of groundwater and surface waters by nitrates, nitrites, phosphorus and amonium was monitored for the last four years (1991-1994, data base: 'State monitoring of waters').

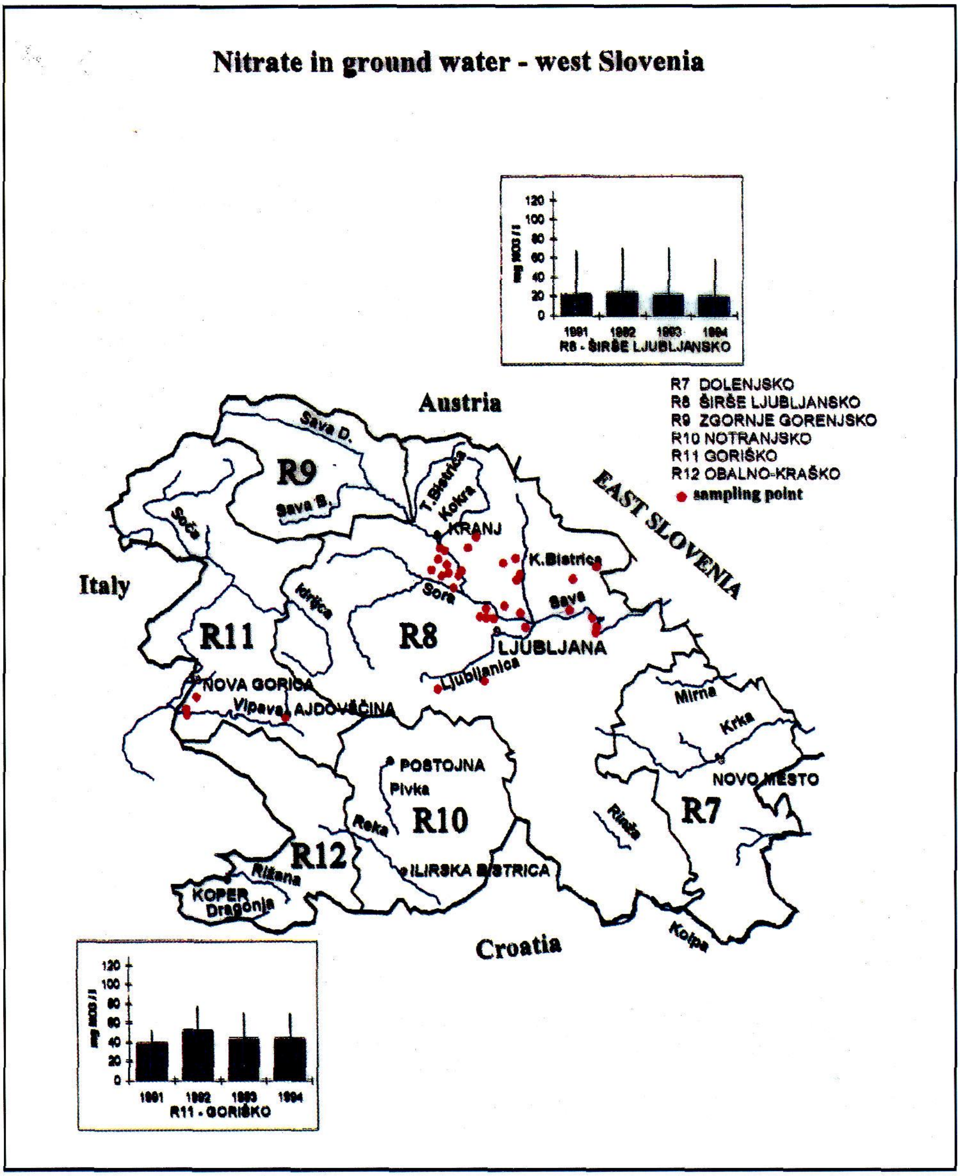


Fig. 2.31: Nitrate in groundwater of west Slovenia: average annual values and extremes.

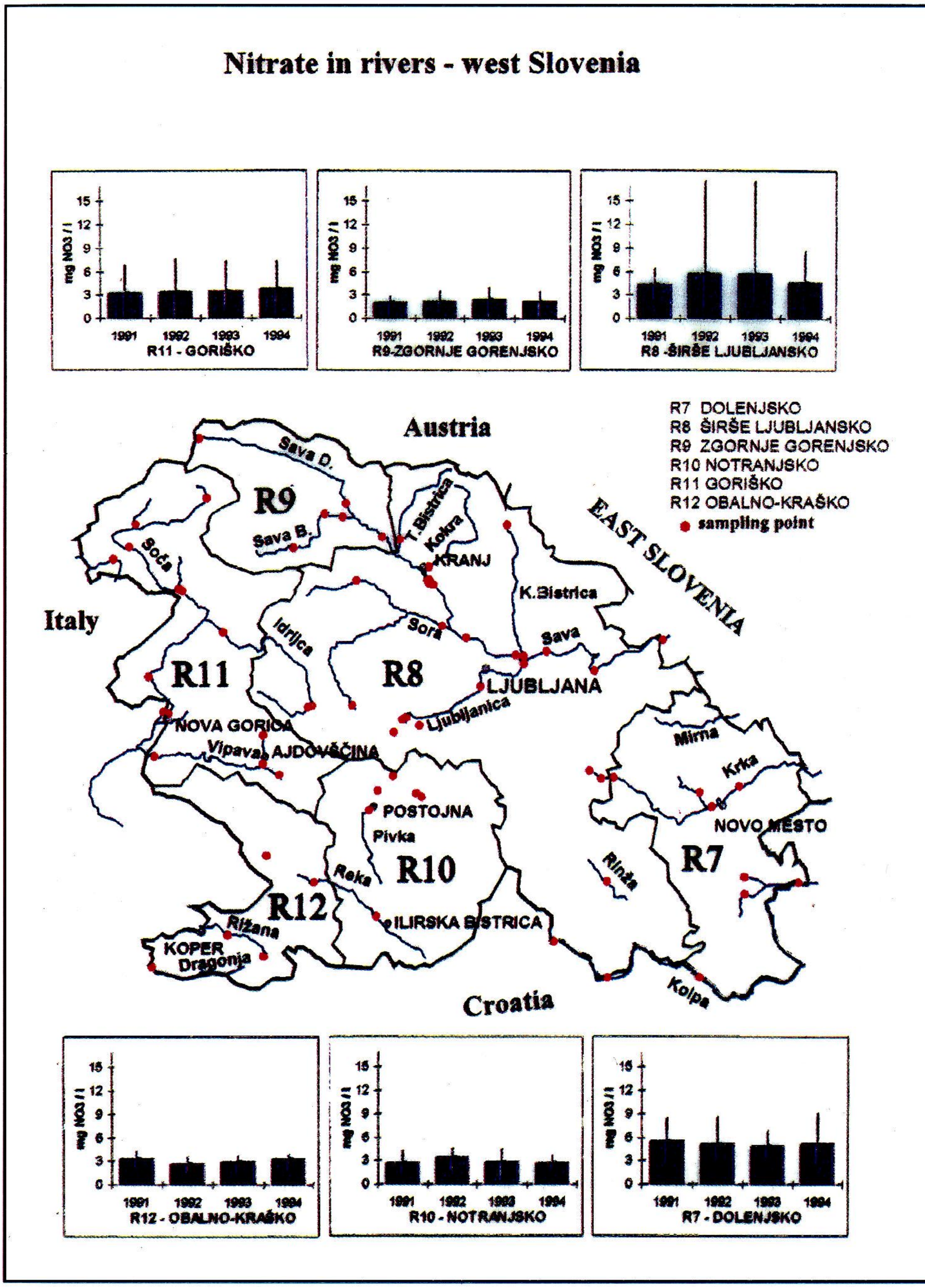


Fig. 2.30: Nitrate in the rivers grouped according to the region in west Slovenia: average annual values and extremes.

Nitrate in groundwater (1991-1994) for western part of Slovenia, where karst prevails, is presented on Figure 2.31. Average annual values for nitrate concentration (in mg/l) in the region of Gorica was 39,08 in 1991 (maximal value: 51,36 mg/l), 51,70 in 1992 (maximal value: 76,61 mg/l), 43,84 in 1993 (maximal value: 69,08 mg/l) and 44,06 in 1994 when the maximal value of NO_3 was 67,97 mg/l. (The average ammonium concentration in mg/l in this region was 0,01-1991, 0,02-1992, 0,04-1993, 0,02-1994. The average NO_2 concentration was 0,02-1991, 0,01-1992, 0,01-1993 and 0,01-1994. The average P_2O_5 concentration was 0,07-1991, 0,06-1992 no data for 1993 and 1994).

Nitrate in rivers for this region is presented on Figure 2.30. The average concentration of NO_3 in mg/l varied between 3,28 and 3,81 (maximal value was observed in 1992 being 7,53 mg/l).

2.7.2.3. Nitrogen balance at regional and farm level

For mineral balance the main agricultural crops that occupy 92 % of arable land have been taken into evaluation. Nitrogen, phosphate and potash supply was calculated by the number of livestocks in the region and at each farm and the nitrogen, phosphate and potash content of liquid manure as well as the statistical data on trade of mineral fertilisers were taken into evaluation. Two nitrogen balances have been evaluated:

GROSS-BALANCE taking into consideration nitrogen input from mineral fertiliser and animal wastes, minus nitrogen uptake by harvested crops (as being output).

NET-BALANCE taking into consideration mineral fertiliser, animal wastes and deposition from the atmosphere as input and nitrogen uptake by harvested crops and ammonia losses to the atmosphere as output.

The evaluation has been done using normative approach and methodology that has been used in EU countries.

Agriculture on Trnovsko-Banjška plateau is extensive, animal husbandry is prevailing. Landuse, yields, use of mineral fertilisers and livestock population on selected farms is presented in Tables 2.19 and 2.20.

Surface mineral balance was evaluated for 534 ha of arable land in region Dol-Otlica on Trnovsko-Banjška Planota, for 16.145 ha of arable land in Ajdovščina community (Dol-Otlica is part of Ajdovščina community).

Nitrogen balance on farm level (for 16 farms on Trnovsko-Banjška Planota) was evaluated for detecting possible point polluters in this region.

2.7.2.4. Nitrogen surpluses as possible source of water pollution

Average net-balance nitrogen surplus for Slovenia is about 56 kg N/ha. Higher values that can be considered vulnerable for the pollution of groundwater and surface waters can be found in regions with high intensity of animal husbandry in eastern part of Slovenia.

Average low nitrogen surpluses on regional level are found in Western part of Slovenia where less intensive agriculture prevails. Average net-balance nitrogen surplus for Ajdovščina and Dol-Otlica on regional level was 36 kg N/ha; this value can not be considered as possible non-point source of pollution of groundwater and surface waters. Livestock density in Dol-Otlica is 0,81 LU/ha (Livestock unit per ha). The high nitrogen surpluses can be caused by higher animal production. In Dol-Otlica the average yields and uptake by crops are low; stocking rate over 2,1 LU/ha can cause net-balance surplus over 100 kg/ha what can be considered vulnerable for groundwater and surface waters (Tab. 2.19 and 2.20).

The average nitrogen net-balance surplus on selected farms has been 36 kg N/ha and is varying between 13 and 87 kg N/ha (Fig. 2.32 and 2.33). On average nitrogen input from mineral fertiliser was observed very low - 11 kg/ha, while nitrogen input from organic manure was 72 kg/ha (Tab. 2.21). Livestock density in selected farms was between 0,4 to 2 LU/ha. The average phosphate surplus was found 27 kg/ha and the average potash surplus was 57 kg/ha (Tab. 2.22 and Fig. 2.34 and 2.35).

Tab. 2.19: Structure of livestock on farms in the karst region, Slovenia, 1994.

Region	livestock units	% of total livestock					LU/ha UAA	kg N/ha	kg P/ha	kg K/ha
		Cattle	Pigs	Poultry	Sheep	Other				
SLOVENIA 1991	**748836**	**58.4**	**16.6**	**22.7**	**0.4**	**1.9**	**1.26**	**89.82**	**50.80**	**92.05**
SLOVENIA 1994	**649916**	**62.6**	**16.0**	**19.6**	**0.3**	**1.6**	**1.10**	**77.51**	**42.34**	**76.47**
farm 7	12.3	84.8	4.9	0.5		9.8	0.94	66.18	28.96	82.88
farm 13	11.1	93.7	5.4	0.9			1.05	74.91	33.36	96.60
farm 16	10.3	81.4	5.8	1.2		11.6	1.98	139.25	61.54	169.23
farm 14	16.3	88.2	3.7	0.7		7.4	1.42	99.49	43.48	128.70
farm 3	12.4	93.7	4.8	1.5			0.77	55.58	24.66	61.22
farm 2	7.3	87.7	12.3				1.04	76.71	35.14	91.14
farm 4	10.3	94.2	5.8				0.76	54.67	24.22	72.44
farm 9	6.3	90.5	9.5				1.05	76.33	34.50	96.33
farm 6	11.0	94.5	5.5				0.91	65.12	28.76	84.30
farm 10	3.6	83.3	16.7				1.03	76.57	36.00	96.00
farm 8	4.6	87.0	13.0				1.02	75.11	34.67	96.89
farm 15	6.0	100.0					2.01	140.94	60.40	201.34
farm 1	3.0	90.0	10.0				0.40	29.20	13.20	34.67
farm 5	6.3	90.5	9.5				0.75	54.20	24.50	68.40
farm 11	8.6	93.0	7.0				1.23	88.29	39.43	119.43
farm 12	11.0	94.5	5.5				1.10	78.80	34.80	102.00
AVERAGE*	**8.8**	**90.4**	**8.0**	**0.9**		**9.6**	**1.01**	**72.33**	**32.16**	**91.63**

* average for all 16 farms

Tab. 2.20: Land use and yields on farms in the karst region, Slovenia, 1994.

Region	Arable and grassland (ha)	Arable land (%)	Grass land (%)	% of arable land: Cereals	Potatoes	Sugar beets	Fodder maize	Green fodder	Yields t/ha: Cereals	Potatoes	Sugar beets	Fodder maize	Grassland
SLOVENIA 1991	**569411**	**39.0**	**61.0**	**53.8**	**13.8**	**1.7**	**15.4**	**15.3**	**4.7**	**13.8**	**45.1**	**35.6**	**4.1**
farm 7	13.0	0.2	99.8		66.7		33.3			18.0		15.0	2.5
farm 13	10.6	2.8	97.2		100.0					18.0			2.5
farm 16	5.0	4.0	96.0		100.0					16.0			2.7
farm 14	11.5	13.0	87.0		33.3			66.7		19.0			2.8
farm 3	10.0	19.0	81.0	10.5	10.5			89.5	3.0	18.0			2.7
farm 2	7.0	28.6	71.4		25.0			75.0		17.0			2.8
farm 4	7.5	1.3	98.7		100.0					16.0			2.8
farm 9	6.0	16.7	83.3		100.0					15.0			2.7
farm 6	12.0	0.8	99.2		50.0					15.0			2.7
farm 10	3.5	2.9	97.1		100.0					15.0			2.6
farm 8	4.5	2.2	97.8		100.0					15.0			2.7
farm 15	3.0	2.7	97.3		100.0					15.0			2.5
farm 1	7.5	1.3	98.7		100.0					15.0			2.5
farm 5	8.5	0.6	99.4		100.0					15.0			2.5
farm 11	7.0	11.4	88.6		62.5		37.5			16.0		15.0	2.7
farm 12	10.0	5.0	95.0		100.0					16.0			2.7
AVERAGE*	**7.9**	**7.0**	**93.0**	**10.5**	**78.0**		**35.4**	**77.0**	**3.0**	**16.2**		**15.0**	**2.7**

* average for all 16 farms

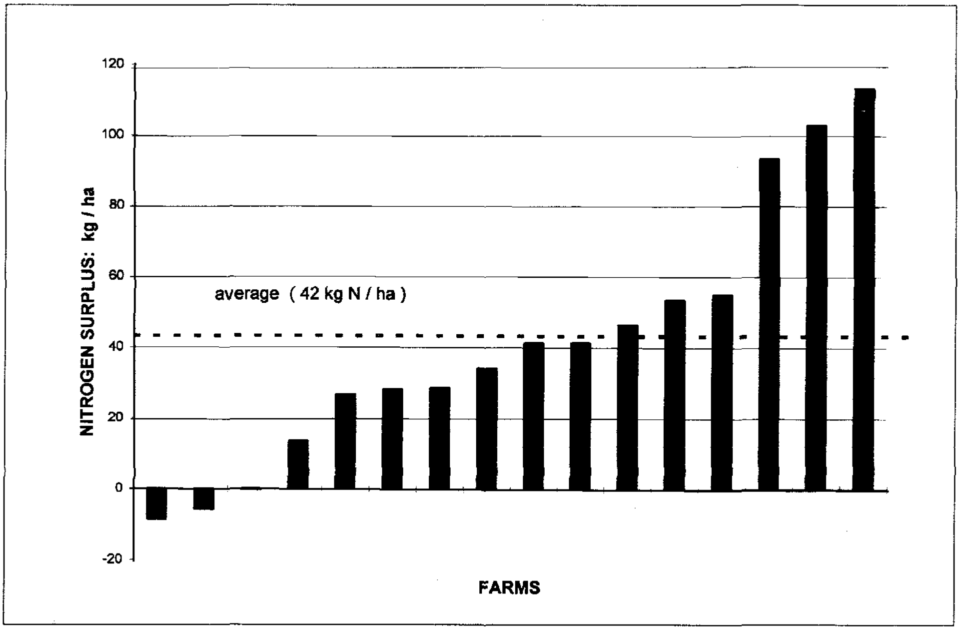


Fig. 2.32: Gross nitrogen balance, farm level, Trnovsko-Banjška Planota.

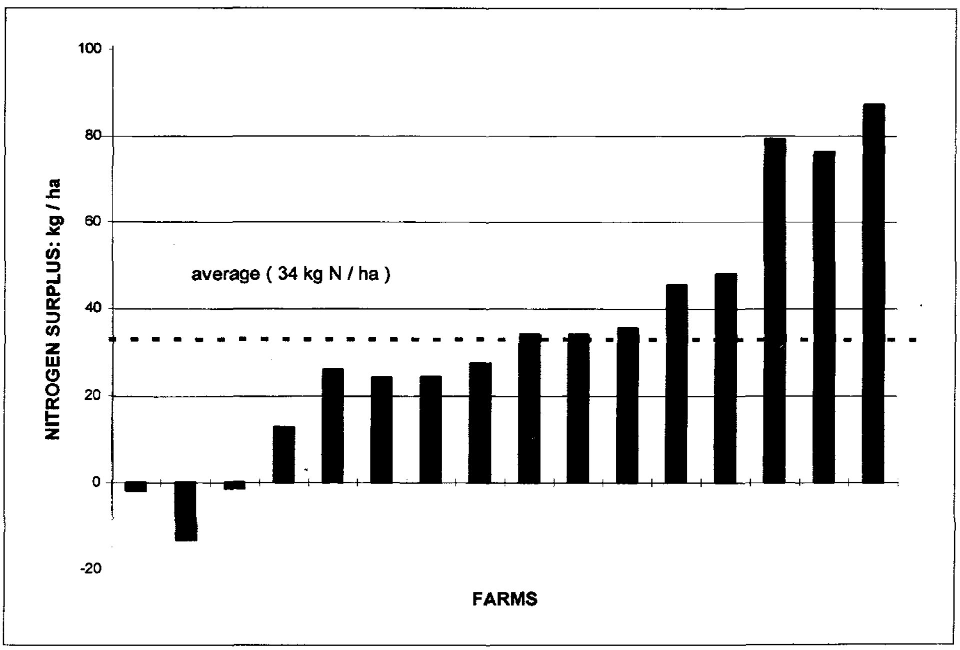


Fig. 2.33: Net nitrogen balance, farm level, Trnovsko-Banjška Planota.

Tab. 2.21: Nitrogen balance, farm level, Trnovsko Banjška planota.

	INPUT				OUTPUT	BALANCES	
	1	2,1	2,2	2,3	3	4,1	4,2
	Nitrogen	Nitrogen from agric. production			Nitrogen	Nitrogen balances	
Region	from the atmosphere kg/ha	Mineral fertilizer kg/ha	Liquid manure kg/ha	Total N supplay kg/ha	uptake kg/ha	Gross balance kg/ha	Net balance kg/ha
SLOVENIA 1991	15.5	47.2	89.8	137.0	70.8	66.3	56.3
SLOVENIA 1992	15.5	43.5	81.1	124.6	53.3	71.3	62.5
SLOVENIA 1993	15.5	57.3	81.9	139.2	52.1	87.1	78.1
SLOVENIA 1994	15.5	60.7	77.5	138.3	91.0	47.2	39.5
farm 7	15.5	0.0	66.2	66.2	37.5	28.6	24.3
farm 13	15.5	18.4	74.9	93.3	38.2	55.1	48.1
farm 16	15.5	15.4	139.3	154.6	41.1	113.5	87.2
farm 14	15.5	53.0	99.5	152.5	59.0	93.6	79.2
farm 3	15.5	13.1	55.6	68.7	69.0	-0.3	-1.4
farm 2	15.5	0.0	76.7	76.7	82.5	-5.8	-13.3
farm 4	15.5	1.1	54.7	55.8	42.2	13.6	12.7
farm 9	15.5	7.5	76.3	83.8	42.5	41.3	33.9
farm 6	15.5	3.7	65.1	68.8	40.6	28.2	24.2
farm 10	15.5	4.3	76.6	80.9	39.4	41.5	34.0
farm 8	15.5	0.0	75.1	75.1	40.8	34.3	27.3
farm 15	15.5	0.0	140.9	140.9	37.9	103.0	76.3
farm 1	15.5	0.0	29.2	29.2	37.7	-8.5	-1.8
farm 5	15.5	10.2	54.2	64.4	37.6	26.8	26.0
farm 11	15.5	0.0	88.3	88.3	41.8	46.5	35.5
farm 12	15.5	16.0	78.8	94.8	41.3	53.5	45.4
AVERAGE*	15.5	10.5	72.3	82.9	47.0	35.9	29.7

* average for all 16 farms   column 2.3 = 2.1 + 2.2   col. 4.1 = 2.1 + 2.2 - 3   col. 4.2 = 1 + 2.1 +2.2*0.7 -3

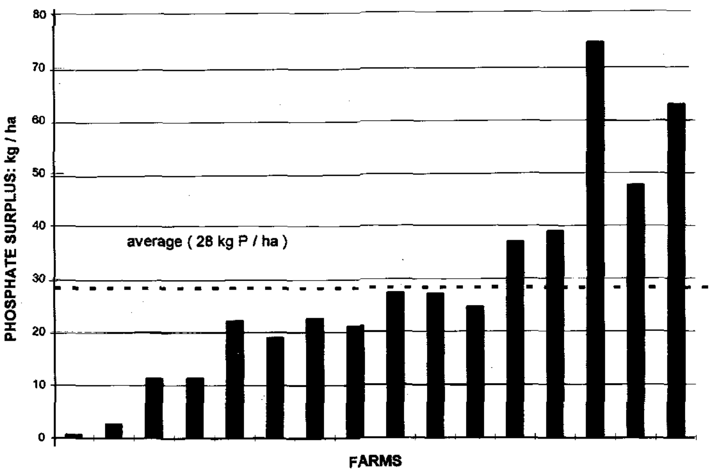


Fig. 2.34: Phosphate balance, farm level, Trnovsko-Banjška Planota.

Tab. 2.22: Phosphate and potash balance, farm level, Trnovsko Banjška planota.

	PHOSPHATE				POTASH			
	1,1	1,2	2	3	1,1	1,2	2	3
Region	Mineral fertilizer kg/ha	Liquid manure kg/ha	Uptake kg/ha	Balance kg/ha	Mineral fertilizer kg/ha	Liquid manure kg/ha	Uptake kg/ha	Balance kg/ha
SLOVENIA 1991	35.5	89.8	29.8	95.5	55.8	89.8	74.0	71.7
SLOVENIA 1992	36.4	81.1	22.5	95.0	56.6	81.1	54.8	83.0
SLOVENIA 1993	48.7	81.9	22.4	108.1	75.6	81.9	52.8	104.8
SLOVENIA 1994	42.0	77.5	37.7	81.8	66.8	77.5	97.8	46.5
farm 7	6.2	29.0	12.5	22.6	0.0	82.9	45.1	37.8
farm 13	18.4	33.4	12.9	38.9	18.4	96.6	46.8	68.2
farm 16	15.4	61.5	13.9	63.1	50.0	169.2	50.5	168.7
farm 14	53.0	43.5	21.8	74.7	60.0	128.7	72.3	116.4
farm 3	13.1	24.7	26.6	11.2	24.4	61.2	82.4	3.2
farm 2	0.0	35.1	32.6	2.6	0.0	91.1	101.1	-10.0
farm 4	1.1	24.2	14.1	11.2	1.1	72.4	51.0	22.5
farm 9	7.5	34.5	14.8	27.3	7.5	96.3	55.5	48.3
farm 6	3.7	28.8	13.6	18.9	3.7	84.3	48.9	39.1
farm 10	4.3	36.0	13.2	27.1	4.3	96.0	48.0	52.3
farm 8	0.0	34.7	13.7	21.0	0.0	96.9	49.5	47.4
farm 15	0.0	60.4	12.7	47.7	0.0	201.3	46.2	155.1
farm 1	0.0	13.2	12.6	0.6	0.0	34.7	45.6	-10.9
farm 5	10.2	24.5	12.6	22.1	3.6	68.4	45.3	26.7
farm 11	0.0	39.4	14.8	24.6	0.0	119.4	52.7	66.8
farm 12	16.0	34.8	13.9	36.9	52.0	102.0	51.0	103.0
AVERAGE*	11.1	32.2	16.6	26.6	15.9	91.6	57.2	50.3

* average for all 16 farms
column 3 = 1.1 + 1.2 - 2

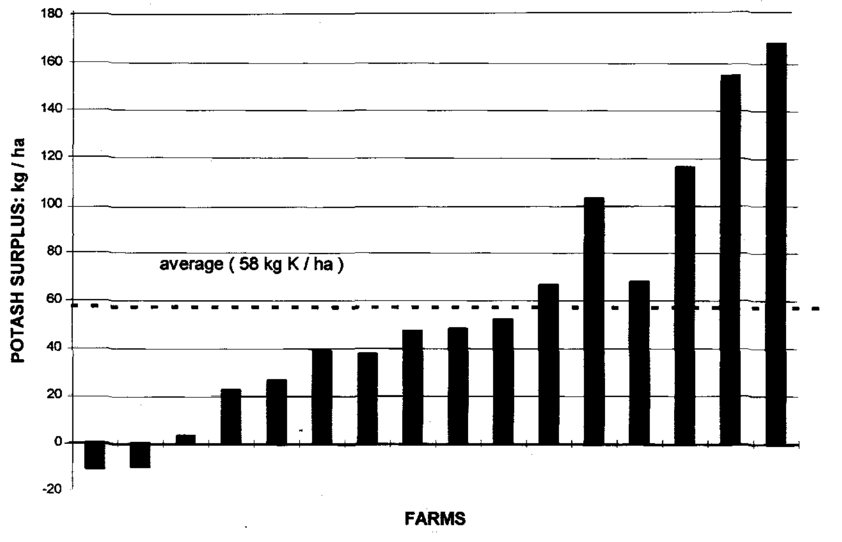


Fig. 2.35: Potash balance, farm level, Trnovsko-Banjška Planota.

Taking into consideration all the evaluated average data it could be concluded that the region Trnovsko-Banjška Planota can not be identified as vulnerable for nitrogen leaching into the groundwater. But in these regions with limited growing conditions for agricultural crops (climate, soil depth) just small increase in livestock density can cause nitrogen surpluses over 100 kg N/ha. For this reason the restrictions regarding application of chemical fertiliser and manure on hilly and karst regions have to be more rigorous than in plains. On the other hand it was found out that in many cases dung yards and cesspools on farms are not built and/or are poorly built. In this case liquid manure can cause serious problem as being point polluter of groundwater.

2.7.2.5. National nitrate policies

There are several regulations in force in Slovenia that are supposed to control water and food quality in connection to nitrates.

Slovenian legislation is quite strict as far as standards on drinking water, food quality or quality of agricultural products is concerned regarding nitrate (as well as other chemical elements or toxic substances). According to EU Nitrate Directive the maximum standard for nitrate in drinking water (according to adopted value by WHO) is 50 mg NO_3/l of water. (SOREN & BOIE 1994). Slovenian legislation on the other hand has set up standard of maximum nitrate content in drinking water being 44 mg NO_3/l of water.

Bottled water is not supposed to contain any NO_2, while regular water is allowed to contain up to 0,005 mg/l of NO_2^- N under regular conditions and not more than 0,05 mg/l of NO_2^- N in irregular conditions. And if our Slovenian legislation, which almost entirely corresponds to Nitrate Directive and Code of Good Agricultural Practice, is followed and obeyed, there should be no fear in future to expect the agriculture to be polluter of ground water and surface waters.

The most important regulation regarding expected processes of change in agriculture is supposed to be The Regulation on animal excrement's management. This regulation gives different norms. The most important are the following:

a) The highest quantity of manure allowed to be used on agricultural land as well as limitations for the use of the manure in specific soil conditions:
   - The maximal allowed intensity of raising animals is 3 LU/ha for cattle or 2 LU/h for pigs and poultry.
   - Application of organic manure is not allowed during winter time on frozen soil.
   - Application of organic fertiliser is not allowed on soil saturated with water.
   - Application of organic fertiliser is not allowed in temporarily flooded areas.

- Application of organic fertiliser is not allowed near water streams (10 m away from the stream) and in the depressions where there is no run-off of water.
- It is not allowed to apply liquid manure on bare soil in the period from Nov. 15 till Feb. 15.
- Application of organic fertilisers on water aquifer protected areas has to be done in agreement with the local regulations valid for those areas.
- In the vicinity of spring water and in underground water pumping areas waste water can not be drained to spring water or underground water in any case.

b) The highest quantity of N, P_2O_5, and K_2O allowed to be used per hectare is 210 kg N, 120 kg P_2O_5 and 300 kg K_2O.

c) Animal wastes should be stored in a suitable arranged dung yards and cesspools. Dung yards and cesspools are supposed to be arranged in the way that there is no danger of leaking through and pouring over the underground water.

d) It is set up 5 years grace period needed for the adjustment of farms to these regulations as follows:
- the adjustment of the number of animals (LU) according to the area of land available on the farm,
- possible rent of additional land according to the contract, the construction of necessary dung yards and cesspools for hard and liquid manure according to the restrictions.

The extension service is obliged to take care of the transfer of necessary knowledge to the farmers. The control over implementation of mentioned regulations is supposed to be done by agricultural inspection, belonging to Ministry of agriculture.

2.7.2.6. Conclusions

Nitrate leaching into ground water and surface waters influenced by agricultural production is supposed to be a problem in the karstic region of eastern Slovenia - Trnovsko-Banjška Planota under certain conditions; point source pollution due to the lack of dung yards and/or cesspools or higher concentration of animals per ha can cause the problem with nitrate pollution in the groundwater. Therefore a nitrate policy is being in the phase of preparation in order to reduce mineral surpluses in agriculture and to meet the standards of nitrate in drinking water.

Mineral balances at national, regional and farm level were calculated based on the 'corrected normative approach'. In Ajdovščina community and Trnovsko-Banjška Planota region the nitrogen net-balance surplus is less than 36 kg N/ha while average net-balance surplus for Slovenia is about 56 kg N/ha.

In Trnovsko-Banjška Planota the average yields and uptake by crops are low

and therefore non-point source pollution caused by mineral fertilisation in this region is not considered a serious problem. The high nitrogen surpluses can be caused by high animal density per ha. The stocking rate over 2,1 LU/ha can cause net-balance surplus over 100 kg N/ha; in this case organic fertilisation can be considered a serious pollution source

The average net nitrogen surplus in private farms in other parts of Slovenia is 46 kg/ha. It is a little bit higher than Slovenian average in 1994 (40 kg/ha). While in state farms is nearly three times higher than Slovenian average - 117 kg/ha.

In the Karst region of Trnovsko-Banjška Planota with limited growing conditions for crops (climate, soil depth, shallow soil) just small increase of livestock density can cause considerable nitrogen surplus. For that reason the restrictions for the application of chemical fertiliser and manure on hilly karstic regions had to be more rigorous than in plains.

Slovenian legislation intends to level this situation with quite strict regulations which are in agreement with EC Nitrate Directive and Code of Good Agricultural Practice.

2.8. FAUNA IN SELECTED KARST SPRINGS FROM THE TRNOVSKO-BANJŠKA PLANOTA (A. BRANCELJ)

2.8.1. Introduction

Copepoda is one of the most diverse and widespread group of so called "lower crabs - Entomostraca". Their body size usually ranges between 0.5 and 3 mm (HUYS & BOXSHALL 1991; EINSLE 1993). In inland waters they occupy very diverse of habitats, particularly taxa from groups Cyclopoida and Harpacticoida. They inhabit all types of permanent waters as well as some perennial ones (as for example puddles). They are very common members of subterranean communitus in sinking rivers, springs and percolating water. In sinking river abundance and number of epigeic species decline along the river, but number of subterranean taxa increase (BRANCELJ 1986). In percolating waters prevail stygobitic taxa, also in rare occasions some epigeic taxa are found there. This happens when thickness of ceiling is small and epigeic water bodies are in a vicinity. There is a lot of endemits among subterranean taxa, especially in that inhabiting percolating waters (SKET & BRANCELJ 1992). In some springs beside specimens of Copepoda, Ostracoda, Amphipoda, Ephemeroptera, Plecoptera and Coleoptera are present, too.

In the area of the "Karsthydrogeological Investigations in SW-Slovenia" within the framework of the ATH-project we made in 1993 a preliminary analysis of copepod fauna in four springs. No similar work has been carried

out in those springs before. The aim of analysis was to locate the sites with hypogeic taxa, i.e. cave-dwelling species, especially that of Copepoda.

Selected sampling localities were: the spring of the Vipava river, the caption in town Vipava, spring Kajža and spring Ajba. Sampling took place on March 23 1993. Material was collected by hand net with mesh size of 60 μm. Samples were stored in 4 % formaldehyde solution and transferred to a laboratory, where we use stereo microscope to pick out specimens of Copepoda, Amphipoda, Plecoptera and Ephemeroptera. Only specimens of Copepoda were determined to the species level, using determination keys of DUSSART (1967, 1969) and PETKOVSKI (1983).

2.8.2. Results

Nine species of Copepoda were determined; eight of them belong to group Cyclopoida and one to Harpacticoida. Undetermined specimens of Ostracoda, Amphipoda and Plecoptera were present in spring Kajža, too (Tab. 2.23). Specimens of Amphipoda are probably *Niphargus cf. stygius,* known from some localities nearby.

Five copepod species from Table 2.23, out of nine, are known as stygobitic, i.e. they live exclusively in subterranean habitats. Two of them, *Diacyclops slovenicus* and *Elaphoidella cvetkae*, are known from relatively small area.

Tab. 2.23: Faunistic list and localities; stygobitic taxa are indicated with asterisk.

	spring of Vipava	caption in Vipava	Kajža	Ajba
CYCLOPOIDA				
*Diacylops clandestinusKiefer, 1932				xxx
*Diacyclops languidoides (Lilljeborg 1901)			xxx	
Diacyclops languidus (Sars, 1863)			xxx	
*Diacyclops slovenicus Petkovski, 1957			xxx	
*Diacyclops zschokkei Kiefer, 1931				xxx
Eucyclops serrulatus (Fischer, 1851)	xxx			
Megacyclops viridis (Jurine, 1820)	xxx			xxx
Paracyclops fimbriatus (Fischer, 1853)	xxx			
HARPACTICOIDA				
*Elaphoidella cvetkae Petkovski, 1983			xxx	
OSTRACODA			xxx	
*AMPHIPODA			xxx	xxx
PLECOPTERA			xxx	xxx

Ostracodans are represented by shells only and detail determination was impossible. Shells were of different shapes and they probably belong to at least two species, one of them with restricted distribution.

Amphipodas are represented by few young specimens of genus *Niphargus*. Representatives of this genus are common in different types of underground waters.

Plecoptera is one group of insects. In two locations Plecoptera were represented by larvae. Whilst adults fly around, mate and lay eggs in water, larvae develop in water. They are very sensitive to organic or inorganic water pollution and are indicators of oligosaprobic water status. Adult females in some species prefer to put their eggs into springs, usually quite far from the entrance.

2.8.3. Discussion

One location, caption in town Vipava, has no animals at all, due to the fact that the water flow was too fast and therefore no animals can persist.

In spring of the Vipava we sampled just at the mouth of the spring. Fauna there was poor. We got only three taxa of Copepoda, beside some specimens of Mollusca (*Bythinia sp.*). All three taxa of Copepoda are known from epigeic habitats, including surrounding of springs. They are among the most common, and tolerant, species of Copepoda. According to previous experiences, they out competed (or preyed) subterranean species in springs.

The most interesting fauna we found in spring Kajža, actually in small puddle, c. 10 m from the entrance. Beside larvae of Plecoptera, which originated from outside, we found three interesting taxa of Copepoda: *Diacyclops languidoides*, *D. slovenicus* and *Elaphoidella cvetkae*. Whilst *Diacyclops languidoides* is common also in subterranean waters, are *D. slovenicus* and *Elaphoidella cvetkae* exclusively inhabitants of subterranean waters. We found them in SW part of Slovenia and in vicinity of Triest (Italy). Finding of both taxa indicate that water coming to the spring has no direct connection with epigeic water bodies. Origin of water in spring is solely percolating water.

Similar situation we found in spring Ajba. Specimens of *D. zschokkei* and *D. clandestinus,* beside *Niphargus* sp., indicate that water in the spring has no direct connection with epigeic water bodies. Few specimens of *Megacyclops viridis* found together with previous mentioned taxa shed slightly different light on the problem. *M. viridis* is a very common species in many oligotrophic and slow-running epigeic water bodies. At the same time it is common in sinking rivers quite far from the sink hole. Presence of specimens of *M. viridis* in spring Ajba is probably a result of human transport with water from somewhere else and not via water channel through the massif.

Springs Kajža and Ajba can be considered, according to fauna composition,

as springs with juvenile water, i.e. water filtered through soil and bed-rocks. Fauna doesn't confirm any direct connections between constant epigeic water bodies and mentioned springs. At the same time it doesn't exclude any connections through dry channels, or temporary overflowed channels, in the recharge area. Presence of relatively rich subterranean fauna, with relatively small number of specimens indicate that concentration of organic material, like communal sewage or water from waste dumps, is low.

2.9. VEGETATION CHARACTERISTICS OF THE TRNOVSKI GOZD (T. PIPAN)

Trnovski Gozd can be placed in the Dinaric phytogeographic region but forms its extreme north-western part. There is represented, therefore, a kind of transitional zone between the Dinaric and Alpine phytogeographic regions. This is most clearly reflected in the smaller number of Dinaric (Ilyric) samples of flora and the larger number of Alpine species. The southern margin of the Trnovski Gozd towards Vipava valley forms the direct border with the Submediterranean phytogeographic region. Because of the configuration of the terrain, the border is very sharp in places, the zone of transitional vegetation being mostly narrow.

Due to its characteristic geographical position, Trnovski Gozd is a kind of cross-roads of different species of flora in miniature. At the margin towards Vipava valley and on up the Čepovan valley, there are examples of quite a number of Submediterranean species. On the plateau, however, the Dinaric-Ilyrian meets with the Alpine. The most well known tract with all three types of flora mixed is Čaven where an extraordinary variety of flora flourishes. The Paleoendemit parsnips discovered by Hladnik, *Hladnika pastinacifolia* also thrive in the Trnovski Gozd, growing only on the Čaven and Poldanovec. The reason for the mixture of species, is not known; studies show that neither darkness nor temperature are causes.

The entire plateau of the Trnovski Gozd, except frost place tracts, is covered with the Dinaric plant association of beech and fir (*Omphalodo - Fagetum s. lat.*). A height zone at between 900 to 1,000 meters and 1,300 to 1,400 meters is formed in the Dinaric phytogeographic region. The combined beech and fir forest grows on other tracts of our mountainous karst (Snežnik, Javorniki, Hrušica and Kočevski Rog) besides in the Trnovski Gozd. It is distinguishable from the similar plant association of our Alpine tracts by the presence of Dinaric-Ilyrian species in the undergrowth and by the presence of a number of Central European species. However, the number of Dinaric-Ilyrian species are considerably less when compared to other tracts of the mountain karst as the Trnovski Gozd represents a kind of transitional zone between the Dinaric and Alpine regions.

Another type of vegetation in the Trnovski Gozd, is spruce. Spruce in the Dinaric region does not form a particular high zone alone but only when combined with beech. Real forest communities are only formed on the level plates with ground from chert (Mala Lazna and Velika Lazna) and in the sinkholes of Smrekova Draga. The reason for this, is the real characteristic of a frost place for these tracts. The Phytosociological forms two associations. The first is the Dinaric Subalpine spruce forest (*Lonicero caeruleae - Piceetum*), the second, spruce (*Stellario montani - Piceetum*) which is spread over Mala Lazna and Velika Lazna. In the Dinaric phytogeographic region, the last forest zone of beech grows, that is that belonging to the association, Subalpine beech, *Polysticho lonchistir - Fagetum s. lat.* Beech in this association is no longer a tree but rather more a bush which, towards the border of the forest, grows as low as two to three meters. On the margins of the Trnovski Gozd, towards the Vipava valley, beech belonging to the Submediterranean association, *Seslerio - Ostryetum* grows. In the narrow or wide zones which are still influenced by Submediterranean flora, grows a special association, *Seslerio - Fagetum* which represents the encroachment of the beech forest into the mountain forest of the karst (ZUPANČIČ et al. 1987).

Frost places

Frost places are extreme types of biotops. In the orographic, ecological and botanical respect, they are sharply distinguishable from their surroundings. Due to different causes, their temperature regime is considerably sharper than in their surroundings, determining the thriving of plant life. The majority of frost places are on the mountain karst but they also exist in the Alps and even in the Submediterranean tracts (MARTINČIČ 1977).

Mala Lazna

Mala Lazna is a frost place formed on acid chert. During the day, there is no difference between the limestone parts and the chert but at night there is great radiation of heat and on the chert, the ground cools to below 0° C. The frost place is consequently formed due to nightly temperature inversion. The thickness of inverse layers of air is two to four meters. A specific temperature regime is formed, the result of the chemical reaction of the ground. Here thrives fir which likes the cold more than beech. Most probably, the beech has disappeared due to thinning out and this has caused a biological imbalance. Trees in the association have normal growth. The sporadic examples of changed appearance (e.g. more than one top) is due to temperature inversion. The spruce in the association have considerably smaller top growths; there is no difference in thickness, which is not unusual, because of different placing of photosynthates which does not limit this direction of growth (FILIPIČ 1959).

Velika Ledena Jama V Paradani

A funnel shaped sink hole, more than 50 meters deep, can be found on the plateau of Trnovski Gozd under Golaki. The bottom opens out as a pocket into a cave where there is ice and snow all year round. The lower part of the slopes are very gravely. There is an entrance to the ice cave on the shady side 1,090 meters above sea level where there is an opening in the mighty overhanging wall. Ground temperatures from the edge of the sinkhole downwards fall rather evenly. The lowest are close to the snow and ice where they come to 1 to 2° C all year. Because this part is always in the shade, the nightly oscillation is only some tenths of a degree. The difference between the surface and lower layers of ground is equally as great. The air temperature regime is inverted in sunny weather only at a height of 0,5 meters above the ground as the ground layer of air may heat up to 30° C on the foundation of the ground. Only in cloudy weather, this effect doesn't exist so the inversion is expressed over the whole ground profile of air. The temperature inversion which causes vegetation inversion means the air temperature from the edge of the sinkhole downwards falls and, in parallel, the temperature of the ground also falls. Temperature inversion is best seen if the temperature is measured on the vertical profile. Usually a real temperature inversion develops only on the parts which are always in the shade. On the slopes, which are exposed throughout the day to sun insulation, the surface can be strongly warmed along with the air at ground level. At this time, temperature inversion is formed only at the height of one meter where the air is not warmed by the ground. BECK (1906) is verified by the ice cave in Paradana where there is a classic example of vegetation inversion as zones of vegetation are the other way around than in the Alps. The inversion is almost perfect, there being missing only the zone of dwarf mountain pine. Analysis of the flora demonstrates that the zone is developed and we call it zone of Subalpine bushes only that its structure is fragmented and dwarf mountain pine (*Pinus mugo*) is missing. As this species is quite common in the Trnovski Gozd, it is questionable whether its presence is primary or secondary (MARTINČIČ 1989).

From a floral-vegetation and ecological view point, we distinguish between the following zones in the Paradana: the zone of Dinaric beech-fir forest, the spruce zone, the zone of willow, the zone of Subalpine bushes, the zone of alpine herbs and the zone of mosses. Total inversion is exclusively present only on the exposed slopes, the east and west inclines chiefly offer a different picture (ZUPANČIČ 1980).

The zone of beech and fir forest (*Omphalodo - Fagetum s. lat.*) starts approximately 30 meters above the cave entrance and grows all around the area.

The spruce (*Lonicero caeruleae - Piceetum*) zone covers only a small area. There are present progressively worsening conditions for growth in the down-

ward direction and this is reflected in the size of the spruce. On the zone's lower edge, spruce thrives only in the form of bushes less than two meters high.

The zone of willows (*Salicetum appendiculate*) represents conditions as they are at the height of the forest border as they are very common there. This is also confirmed by other species thriving in this zone. The height of the willow is dependent on temperatures which change quickly on the downward slopes. On the upper border they reach some 3,5 meters high, on the lower only 25 centimetres.

The zone of Subalpine bushes (as a fragment of the association *Pinetum mugi*), in the phytocenological and ecological sense, is a zone of dwarf mountain pine. However, for unknown reasons, the most important species is missing. The floral inventory of the zone is very rich. Among the species preserved by the ice case are also glacial relics such as the remains of ice age flora which at this time was common in the Trnovski Gozd. The most important species are: *Rhododendron hirsutum*, *Rhodothamnus chamaecistus*, *Salix retusa* (willow), *Carex feruginea* (sedge) and *Valeriana saxatilis* (valerian).

In the zone of Alpine herbs there is a distinct mountain micro-climate. Lower temperatures, and with this worsening living conditions on the downward slope, prevents the thriving of the more demanding lignificated plants. Floral inventory is very poor. Here there thrives exclusively, cold loving species. The willow, *Salix retusa* is the only tree but Alpine meadow grass (*Poa alpina*), the two petal violet (*Viola biflora*) and the speedwell (*Veronica lutea*) can also be found.

Around the cave entrance, in the vicinity of snow and ice, is a zone of mosses. The whole area is always in the shade; temperatures are always between 1 and 3° C. Extreme micro-climatic conditions prevent the thriving of flowers. The only exception to this is the species alternate-leafed golden-saxifrages (*Chrysosplenium alternifolium*) which is, however, often sterile or even stunted. Low temperature is not the only cause of the absence of flowers, too little light also plays a part; it is insufficient for netophotosynthesis.

Frost places on conglomerated ground

Cold loving vegetation in the sink holes grows especially on part of the slope, less or not at all on the bottom. In any case the ground is skeletal, gravely or conglomerate. It is composed of relatively rough material with air spaces in between which are interconnected in an uninterrupted system. The skeletal ground is mostly due to crumbling of rock walls so frost places of this type are mainly in collapse dolines; they can also be found on open slopes. The ground at the lower part of the conglomerated slopes is the coldest. Between the skeletal material, can be found greater or smaller holes and fissures from which blows very cold air. The strongly cooling air circulating in

the ground is the most important factor for its coldness. Sometimes its effect is so great that the whole surface layer of the ground, in spite of intensive insulation, can not warm up. Air enters the upper part of the slope in a system of fissures and spaces where cooling is witnessed. Because it is heavier, it slides into the internal downwards with additional cooling; in the lower part of the slope, it comes from the fissures. However, this method of cooling only, is not sufficient. Ice is sure to form at unknown depths which has a stronger cooling effect. In the sinkholes, the ground temperature is lower in the downward direction and, as a rule, is lowest just before the bottom. The temperature can be more or less equal on the whole profile of the sinkhole. Only in the depths of the sinkhole, with steep inclines, temperature inversion in the air layer can be found at the same time which can be some metres wide. Always the night temperature is inverted (MARTINČIČ 1989).

Smrekova Draga *(Photo 13)*

The Smrekova Draga frost place is an extensive karst hollow on the northern side of Mali Golak. It is approximately 140 meters deep; its bottom is 1,100 meters above sea level. The sink hole lies in the climatic zone of the fir association, *Omphalodo - Fagetum s. lat.* which covers the higher parts of

Photo 13: Smrekova Draga karst depression with vegetation inversion (Photo by P. Habič).

the slopes and the whole surroundings. The foot and lower part of the inclines are covered with spruce and dwarf mountain pine. The only reason for the changing vegetation conditions is the very cold ground and not temperature inversion.

In the dwarf mountain pine zone, the temperature does not exceed 5° C all year. In the spruce zone it is 5 to 10° C and in the beech-fir zone the temperature is at least 10° C. In sunny weather, the ground's surface is heated strongly so there is a difference between deep and surface layers of 20° C and more. The air temperature does not show any inversion except at night. Often the highest air temperature is at the base in the zone of dwarf mountain pine. The temperature oscillates during the day and night, increasing towards the base as the nightly air temperature falls below 0° C even in summer. Extreme micro-climatic conditions affect the thriving of two cold loving communities. *Lonicero caeruleae - Piceetum* grows over most of the sinkhole and in the western part, *Pinetum mugi*. The border between spruce and dwarf pine is very sharp. The transitional zone of low spruce doesn't exist as the height of spruce at the edge is almost the same as in the association. The zone of dwarf mountain pine is limited to the coldest ground. It flourishes all over where the ground temperature at 20 to 30 cm deep does not exceed 1 to 6° C in the summer. In many places the ground temperature is only 1 to 2° C. It is not surprising that, on such ground, dwarf mountain pine grows to barely 0,5 meters although at the edge it is 3,5 meters high. From a vegetation point of view, the dwarf mountain pine is a fragment of the alpine association *Pinetum mugi*. Vegetation is sparse with most Alpine species. *Sphagnum nemoreum*, *Vaccinium uliginosum* and *Oxycoccus palustris* represent specialities forming on smaller surface areas of the high marshland.

* New names of associations:

MARINČEK, L., MUCINA, L., ZUPANČIČ, M., POLDINI, L., DAKSKOBLER, I., ACCETO, M., 1992: Nomenklatorische Revision der illyrischen Buchenwälder (Verband Anemonio - Fagion).- Studia Geobotanica, 12, 121 - 135, Trieste.

ZUPANČIČ, M., 1994: Popravki imen nekaterih rastlinskih združb v luči novega kodeksa. Hladnikia, 2, 33 - 40, Ljubljana.

3. INVESTIGATIONS OF THE WATER BALANCE (1993-1995)

3.1. HYDROLOGICAL INVESTIGATIONS IN THE AREA OF THE TRNOVSKO-BANJŠKA PLANOTA PLATEAU BETWEEN 1993 AND 1995 (N. TRIŠIČ)

The equipment at the gauging profiles that existed before 1993 in the area under investigation was not satisfactory for the forthcoming investigations. The gauging profiles were only equipped, except for the profiles on the Lijak and the Idrijca, with gauging staffs where water levels were usually read only once a day. For a more detailed registration of water waves and the establishing of water regime, we installed in summer 1993, even before the first tracing experiments were performed, water level recorders (LP) at the most important gauging profiles (Tab. 3.1). The positions of individual hydrological stations are presented in chapter 2.2, Figure 2.9.

Tab. 3.1: Gauging profiles, installed in the framework of the ATH investigations.

Gauging profile	water level recorder operating since
8630 The Hubelj-Ajdovščina	April 01, 1993
8560 The Vipava-Vipava	June 17, 1993
8350 The Idrijca-Podroteja	June 24, 1992
8345 The Idrijca-Fežnar	May 4, 1994

Since a part of investigations was focused on the catchment area of the Vipava springs, an additional observation and gauging network was established in this area, which operated from July 1993 until the end of 1995; only the operation at the Bela-Sanabor profile began later due to the troubled water level recorder (Tab. 3.2).

Tab. 3.2: Additional gauging profile with LP - water level recorder; VP - staff gauge.

Gauging profile	Station operating since
8546 The Belščica-LP Bukovje	July 27, 1993
8547 The Lokva-VP Predjama	August 25, 1993
8549 The Vipava-VP Pod Farovžem	September 14, 1993
8602 The Bela-LP Sanabor	January 1, 1994
8603 The Bela-VP Vipava	July 27, 1993

With the existing network of hydrological stations it was not possible to register discharges of the Divje Jezero and the Podroteja springs, which both join the Idrijca above the Idrijca-LP Podroteja gauging profile. Therefore, we also installed an additional station with water level recorder in 1994, on the profile 8345 the Idrijca-Fežnar. Since the distance between the profiles the Idrijca-Podroteja and the Idrijca-Fežnar is rather short (4.3 km), the difference in discharges between the both profiles can be taken as the discharge quantity from the both karstic springs. Yet, due to the torrential hydrological regime of the upper Idrijca and the Bela, and the short string of observations, we did not succeed to register so high discharges to be high enough to establish the upper part of discharge curve.

For the four representative hydrological stations (Compare Chapter 2.2.) which register the most important outflows from the karstic massif, the data were processed for the investigation period from August 1, 1993 to December 31, 1995, and comparatively, also for the period of two hydrological years, from November 1, 1993 to October 31, 1995.

The Hubelj - LP Ajdovščina

Presented are the data on daily heights of precipitation at the precipitation station Otlica (835 m above sea level), and the mean hourly discharges of the Hubelj at the gauging profile (Fig. 3.1). The maximum daily precipitation (143 mm) fell on December 27, 1995, and the second maximum of daily precipitation (134 mm) occurred on November 17, 1995. The majority of precipitation at the station Otlica fall, on the average, as to the 1961-90 period, in the autumn months (704 mm), while the shares of precipitation in the other seasons of a year are practically equal (562 mm; 587 mm; 559 mm).

The discharges of the Hubelj in both the discussed periods do not stand out from the frame of statistical values for the 1961-90 period. Both value of the mean discharges is only by approx. 10 % above the mean discharge of the

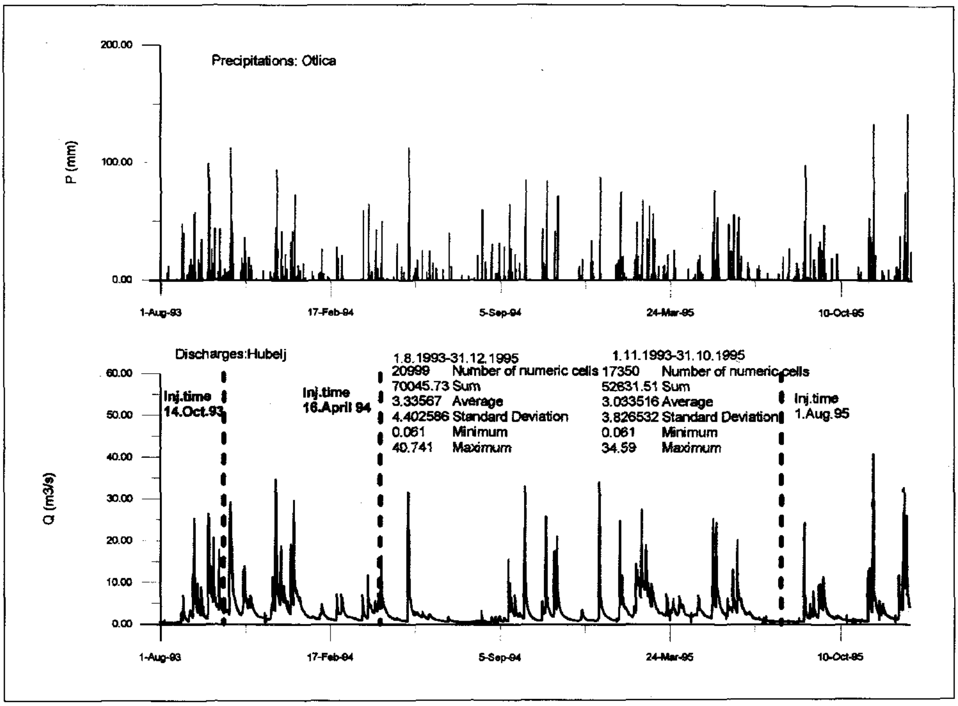


Fig. 3.1: Mean hourly discharges of the Hubelj spring at the gauging profile Hubelj-LP Ajdovščina and daily heights of the precipitations at the precipitation station Otlica.

period. The maximum discharge in the shorter period of two hydrological years also coincides with the mean maximum discharge of the 1961-90 period (34.59 m^3/sec; 33.4 m^3/sec). When dealing with minimum discharges it should be emphasised that these data refer to discharges at the gauging station, and not to discharges at the Hubelj spring. There, a certain quantity of its water is tapped for the water supply of Ajdovščina and its surroundings, and also for the operation of the Hubelj hydropower plant. Evident in the hydrograph at lower discharges are the abnormal extremes in time distribution of discharges which are due to the hydropower plant operation. This influence on the discharges of the Hubelj had not been registered in the profile of the gauging station before the installation of a water level recorder. The lowest discharge of 0.061 m^3/sec was registered on August 5, 1994, when the regular maintenance works were performed on the sluice gate at the dam below the Hubelj spring. The exact data on the water quantity taken for water supply do not exist; but by approximate assessment, between 50 and 100 l/sec are taken on average, during the summer droughts, even up to 150 l/sec.

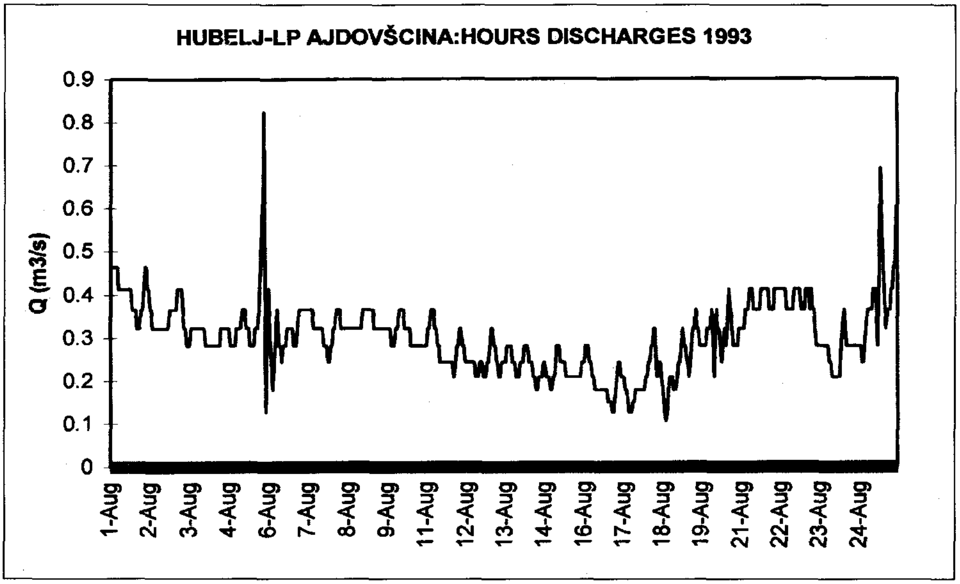


Fig. 3.2: Hydrograph of the Hubelj discharges during low water conditions in August 1993 exhibiting an explicit daily variation caused by water abstractions for both the hydropower plant and for water supply.

On the hydrograph of the Hubelj discharges, an explicit daily oscillation of discharges is evident at low water situation in August 1993, which is due to the tapping for water supply, while the oscillation on August 5 and 6 is due to the Hubelj hydropower plant operation (Fig. 3.2). Such oscillations are frequent because they occur at each disengagement or omission of turbine operation. On the basis of the registered minimum discharges and the known influences, the minimum discharge of the Hubelj spring can be assessed to amount to 0.250 m^3/sec.

The Vipava - LP Vipava

For the presentation of discharges at the Vipava springs and precipitation in the catchment area, the data were processed, from the station with a water level recorder at Vipava, and the precipitation station Nanos-Ravnik at the altitude of 915 m (Fig. 3.3). The height of precipitation here is lower (the average of 1834 mm) than at the station Otlica. The largest daily quantity of precipitation fell on October 29, 1994 (99.8 mm), and the second maximum of the discussed period occurred on August 29, 1995, with 91.6 mm of daily precipitation. In this area, too, the majority of precipitation fall in the autumn months, 524 mm on average, and in the remaining seasons, the heights are essentially lower (399 mm; 447 mm; 468 mm).

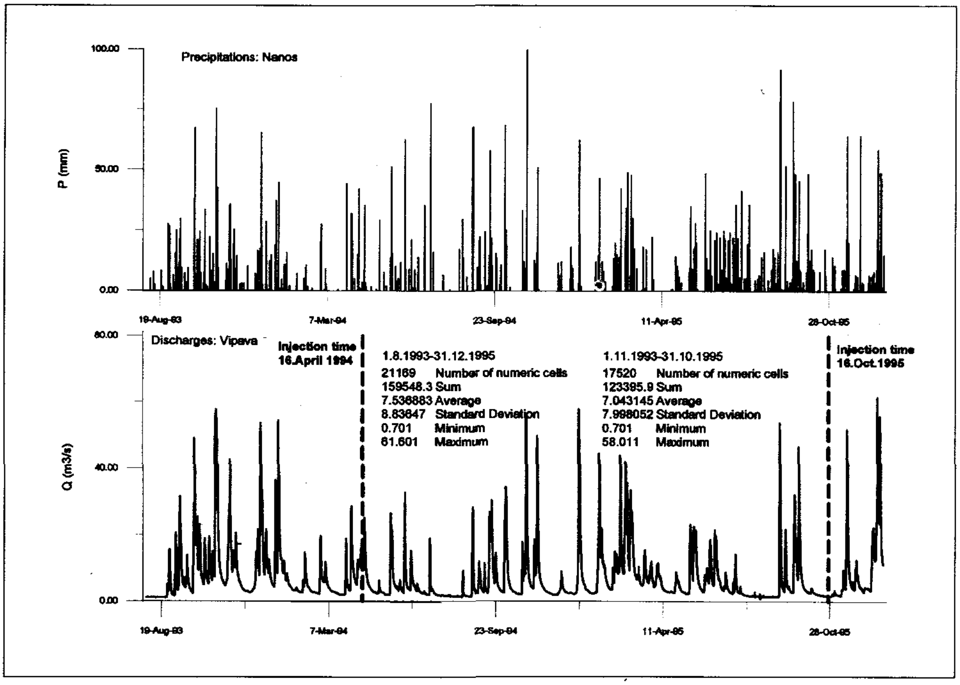


Fig. 3.3: Mean hourly discharges of the Vipava spring at the gauging profile Vipava-LP Vipava and daily heights of the precipitations at the precipitation station Nanos-Ravnik.

The mean discharge of the Vipava in the discussed 1993-95 period is by gross 20-30 % higher than the mean discharge of the 1961-90 period (6.78). The maximum discharge in the two-year period (61.6 m^3/sec) did not reach the highest registered discharge in the entire observation series. Yet, the extremes of high-water waves exceeded nine times the discharge of 50 m^3/sec. However, in the 1993-95 period, the lowest discharge was registered in the entire observation period (0.701 m^3/sec), but not even in this case it was the natural lowest discharge of the Vipava springs but an artificial result due to the opening and closing of sluice gates that dam up both groups of the Vipava springs. These effects were also registered several times by the data logger at the spring Pod Farovžem (VIP-7), as well as by the water level recorder at the gauging station Vipava. The natural lowest discharge at the profile of the gauging station amounted to 1.032 m^3/sec in July 1993. Also one of the Vipava springs, the spring Pod Lipo (VIP-2) serves for water supply of the surroundings, yet the tapped quantities here are smaller than those at the Hubelj spring, and due to higher discharges of the Vipava, the share of the pumped water is negligible. For a clear determination of the Vipava discharges

an additional network of hydrological stations in the catchment area of the Vipava was used. On the streams Belščica, Lokva and Bela, their quantitative shares in the discharges of the Vipava were determined for the 1994-1995 period.

Tab. 3.3: Characteristic discharges (m^3/sec) measured in the gauging profiles in the catchment area of the Vipava for 1994-1995.

	Q_{max}	Q_{mean}	Q_{min}
The Belščica-Bukovje	2.77	0.132	0.021
The Lokva-Predjama	10.8	0.215	0.019
The Bela-Sanabor	4.51	0.313	0.003
The Vipava-Vipava	61.6	7.04	1.032

The share of mean discharges at the gauged profiles in the catchment area does not reach 10 % of the mean discharges of the Vipava, and the shares of low and high discharges are even lower (Tab. 3.4). There are also some ponor streams in the catchment area of the Vipava springs, yet the share of their discharges is small and cannot change the ratio.

Tab. 3.4: Comparison of the discharges of the gauged profiles in the catchment area (Belščica, Lokva, Bela) to discharges of the Vipava (m^3/sec).

	Q_{max}	Q_{mean}	Q_{min}
The catchment area	18.08	0.66	0.043
The Vipava	61.60	7.04	1.032

The springs Pod Farovžem - Vipava (VIP-7)

The water levels in the area of the western group of the Vipava springs, called the Izviri pod Farovžem, were registered by a data logger. Due to the operation interruption of the data logger, the string of data is not continuous; therefore, the characteristic values for the two-year period under observation cannot be presented. For the time of the second tracing experiment, i.e. October 1995, a hydrograph of discharges was made on the basis of which were determined the discharges of the eastern group of the Vipava springs (from VIP 1 to VIP 5) using the difference between the discharges at the LP Vipava station and the discharges of the springs Pod Farovžem. At low water levels, the ratio of discharges between both groups of the springs is almost

even (Pod Farovžem : Pod Skalco = 1:1.2), but at high water levels, the discharges of the eastern group of the springs are even more than by 5-times higher than those of the springs Pod Farovžem. The maximised quantity of the springs Pod Farovžem (about 10 m^3/sec) is compensated by the springs between Vrhpolje and Vipava which are activated at higher water levels and contribute their discharges to the Bela. Therefore, for the study of discharge conditions in the catchment area of the Vipava springs, and in the Nanos massif, it would be necessary that a water level recorder register the Bela discharges at Vipava (town), since a part of the Bela waters sink below the village Sanabor and are linked with the Vipava springs, while at high waters, also the springs below the settlement Vrhpolje are active, and contribute their waters to the lower section of the Bela (Tab. 3.5).

Tab. 3.5: Comparison of the discharges of the Vipava and the Bela in September 27, 1993.

Bela-Sanabor gauging at 12:00	**Bela-Vipava** gauging at 11:00	**Pod Farovžem** gauging at 09:45	**Pod Skalco** difference (48.7-9.74)	**Vipava - LP Vipava** reading at 10:00
1.81 m^3/sec	3.89 m^3/sec	9.74 m^3/sec	38.96 m^3/sec	48.7 m^3/sec

The Lijak - LP Šmihel

In the central part of the Trnovski Gozd, in the area of Lokve (965 m above sea level), 2381 mm of precipitation fall on average. They are most abundant in the autumn months (703 mm), and evenly distributed in the remaining seasons (from 541 to 586 mm) (Fig. 3.4). The distribution and the quantity of precipitation at the station Lokve is entirely comparable to the area of Otlica (Fig. 3.1).

The station with a water level recorder which registers the discharges of the Lijak spring is located approx. 500 m downstream of the spring. Although the surface part of the catchment area between the spring and the hydrological station contributes a part of discharges to the gauging profile, it is negligible. The discharges of approx. 60 l/sec are a share of this surface part of the catchment area. The spring Lijak is only active at waves the course of which is clearly visible on the hydrograph (Fig. 3.4). The maximum discharge in the discussed period was 17.2 m^3/sec. It occurred after the heavy precipitation of November 17, 1995, when as much as 216 mm of rain was registered at the precipitation station Lokve. The spring Lijak was not under the continuous observation between 1961 and 1990, so that the exact comparison of the characteristic data, above all of the data on mean discharges, is not possible. In the years of observations, 1964-73 and 1989-90, the calculated mean

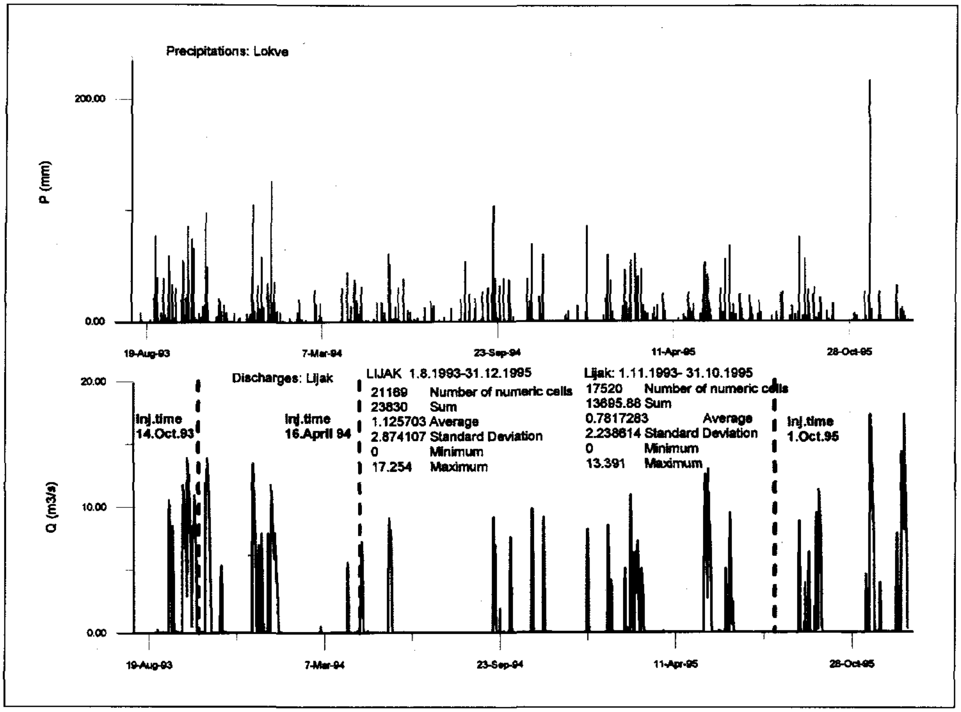


Fig. 3.4: Discharges of the periodical Lijak spring at the gauging profile Lijak-LP Šmihel and daily heights of the precipitations at the precipitation station Lokve.

discharge of 0.6 m³/sec is lower than the mean discharge in the time of investigations, 1993-95 (1.12 m³/sec and 1.00 m³/sec).

The Idrijca - LP Podroteja

Due to the longer interruption of observations at the precipitation station Črni Vrh Nad Idrijo (683 m above sea level), the data on precipitation at the precipitation station Vojsko (1070 m above sea level) are comparatively presented for the station with a water level recorder the Idrijca-LP Podroteja (Fig. 3.5). On the average, the precipitation in the 1961-90 period were slightly higher at the station Črni Vrh (Črni Vrh - 2589 mm; Vojsko - 2450 mm), while in the individual precipitation situations, great differences can occur in the daily heights of precipitation. The maximum daily height of precipitation in the 1993-95 period amounted to 223 mm at the station Črni Vrh (on November 17, 1995), but only 102 mm at Vojsko. After the most abundant precipitation on November 17, 1995, only the height of 70 mm was registered

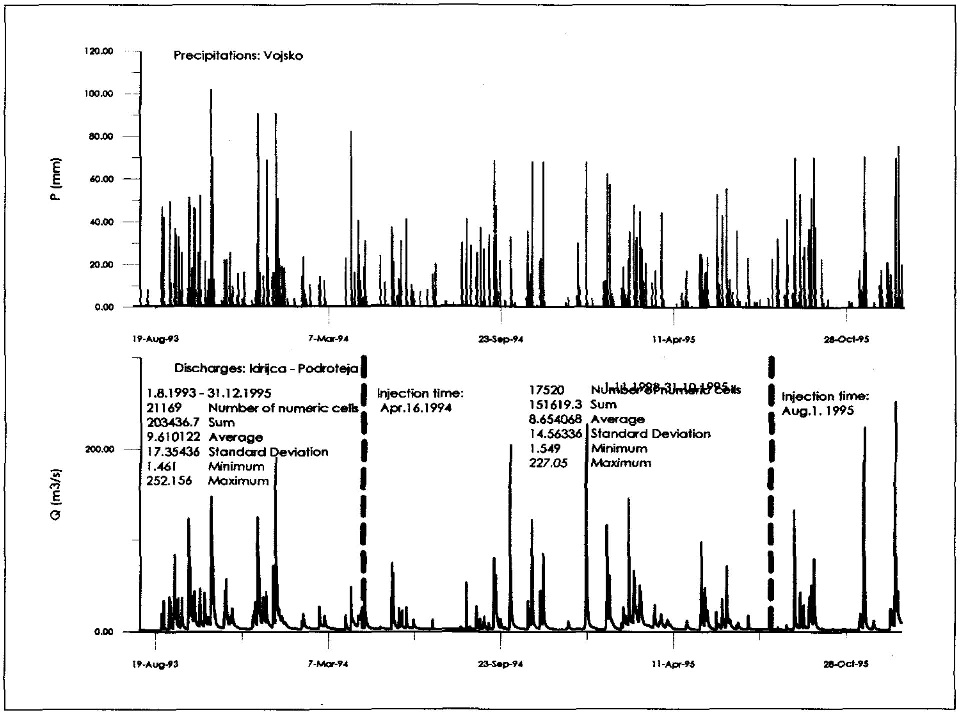


Fig. 3.5: Mean hourly discharges at the gauging profile Idrijca-LP Podroteja, which comprises the surface waters of the Belca and Idrijca as well as the discharges of the karst springs Podroteja and Divje Jezero and the daily heights of the precipitations at the precipitation station Vojsko.

at the station Vojsko, and the next day, further 30 mm, which is less than a half of the daily precipitation at the stations Lokve and Črni Vrh.

In the Idrijca-LP Podroteja gauging profile, the discharges are comprised, so from the surface part (the Belca, the Idrijca), as from the karstic part (the Divje Jezero-Jezernica, the Podroteja springs) of the catchment area. From the difference between the obtained discharges at the profiles the Idrijca-LP Feznar and the Idrijca-LP Podroteja, the influx from the karstic part of the catchment area can be calculated; yet, these data are only representative of the situations when the gauging of discharges was performed (Tab. 3.6). Due to the time lag in reaction on precipitation of the karstic part of the catchment area, only the stable situations can be comparable, above all, at low water situations.

Tab. 3.6: The gauged discharges at the stations Idrijca-LP Fežnar and Idrijca-LP Podroteja (m^3/sec). The difference between both profiles represents the approximately influx of the karst springs

Date	LP Fežnar	LP Podroteja	Difference
Jun/07/94	1.250	4.762	3.512
Jul/26/94	0.357	1.870	1.513
Aug/30/94	0.991	5.658	4.667
Sep/27/94	2.802	4.679	1.877
Nov/23/94	0.814	2.635	1.821
Jan/31/95	1.82	11.12	9.3
Feb/23/95	2.22	11.41	9.19
Apr/26/95	2.60	6.96	4.36
Jun/14/95	2.51	11.78	9.27
Aug/17/95	0.51	1.991	1.481
Oct/05/95	0.806	3.327	2.521
Nov/23/95	1.583	6.13	4.547
Mar/19/96	1.225	5.289	4.064
May/09/96	6.315	15.235	8.99
Jul/03/96	8.373	63.183	54.81

The contribution of the surface part of the catchment area between the profiles Fežnar and Podroteja is negligible at low water situations (approx. 50 l/sec), but within the low mean discharges it already amounts to 0.3 - 0.5 m^3/sec.

Nonparametric Spermann's correlation (Fig. 3.6) of the gauged discharges between both gauging profiles indicates the possibility of the occurrence of two populations and therefore, lower correlational dependence. The nonparametric Spermann's coefficient of correlation results in $R = 0.83$.

From the presented data, it is not possible to determine the lowest discharge from the karstic catchment area. The lowest discharges in the 1993-95 period were still within the range of the characteristic mean low discharges (1.461 - 1.66 m^3/sec). Also the calculated lowest discharge from the karstic catchment area of 1.481 m^3/sec ranks, together with the discharge of 1.991 m^3/sec of the Idrijca on the LP Podroteja profile, into the range of mean low

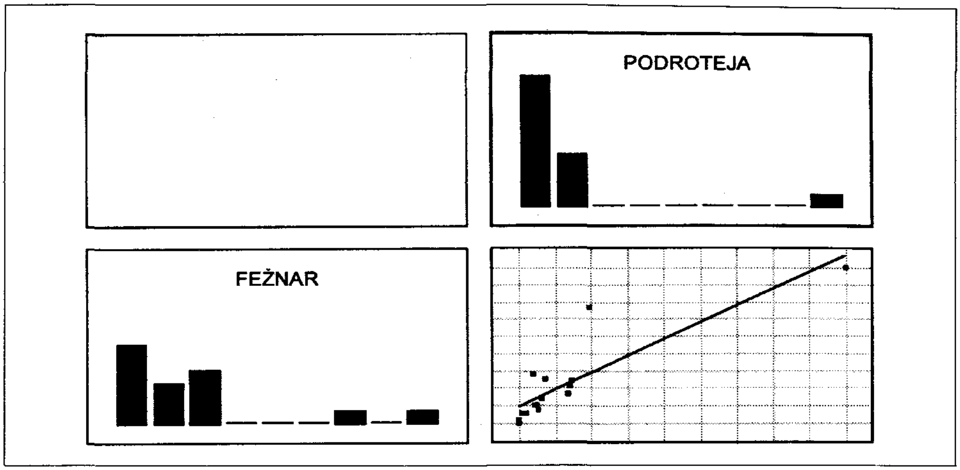


Fig. 3.6: Results of the nonparametric Spermann's correlation between the gauging profiles Idrijca-LP Fežnar and Idrijca-LP Podroteja showing the frequency distribution and the correlational dependence between both groups of data (N = 15).

discharges of the period. However, it was not possible to determine the share of discharges from the karstic catchment area, neither at the lowest (0.840 m^3/sec) nor at the highest (306 m^3/sec) discharges of the Idrijca on the LP Podroteja profile, in so short a period of observations (from May 1994).

For the assessment of contributing share of the remaining water springs in the investigated area, two series of gauging were completed, on the springs Hotešk, Avšček (below Bolterjev Zdenc) and Kajža, and on the ponor streams Slatna at Grgar and Čepovanski Potok (Tab. 3.7).

Tab. 3.7: The gauged discharges of the karst springs Hotešk, Avšček and Kajža, of two ponor streams and of the Idrijca-LP Podroteja (m^3/sec).

Springs	**Apr/13/95**	**May/23/95**
Hotešk	0.093	0.264
Avšček	0.018	0.043
Kajža	0.023	0.112
Altogether	0.134	0.419

Ponor Streams	Apr/13/95	May/05/95
Slatna	0.013	0.048
Čepovanski Potok	0.012	0.020
Altogether	0.025	0.068

The Idrijca-LP Podroteja	2.91	5.01

It is assessed that the mean discharge of the gauged springs amounts to 0.8-1.0 m^3/sec. The most abundant is the Hotešk spring which is also the least investigated.

Calculations Of The Quantities Of Recovered Tracers

For the calculation of the quantities of recovered tracers the data were used, on the discharges at the hydrological gauging stations the Vipava-Pod Farovžem, the Hubelj-Ajdovščina, and the Lijak-Šmihel. The quantities of recovered tracers on the other springs of the Vipava, Pod Skalco and Pod Lipo, were calculated with the difference in discharges between the profiles the Vipava-LP Vipava and the Vipava-Pod Farovžem. In the analysis of tracers, the discharges at the sampling time were taken into account. The quantities were calculated by means of the following equations (1) and (2):

$$K_{ti} = \frac{t_{i+1} + t_{i-1}}{2} \times Q_{ti} \times C_{ti} \qquad (1)$$

K_{ti} - the quantity of tracer in the time between $t_i+1 \Leftrightarrow t_i-1$
Q_{ti} - the discharge in the time t_i
C_{ti} - the concentration in the time t_i
or:

$$K = \sum_{i=1}^{n} \left(\frac{t_{i+1} + t_{i-1}}{2} \times Q_{ti} \times C_{ti} \right) \qquad (2)$$

K - the total recovered quantity

For the calculation of recovered tracers at the Mrzlek spring, the mean discharge was assessed on the basis of the mean ratio between the discharges at the profiles under observation (the Idrijca-Podroteja and the Hubelj-Ajdovščina) in the time of tracer occurrence in the Mrzlek, and the statistical value of discharge at both profiles in the 1961-90 period.

With the obtained coefficient the datum was calculated, from the balance of the mean discharge of the Mrzlek in the period (10.12 m^3/sec), of the mean discharge of the Mrzlek in the time of an individual tracing experiment (Tab. 3.8). More details are given in Chapter 6.

Tab. 3.8: The data base of the Mrzlek spring used for the estimation of the quantity of recovered tracer. Due to technical reason only in 1995 sampling from both the Mrzlek-spring in the Soča (i) and from the pumping station (v) was possible. In 1993 and 1994 only samples from the pumping station are available.

	1993	1994	1995
tracer presence: from - to	10/23 - 12/23	04/24 - 06/01	09/03 - 12/31
average concentration [mg/m^3]	0.022	0.125	0.041(i) 0.038 (v)
coefficients (k) used for the discharge estimation	1.7	0.9	1.2
average discharge $Q = 10.12 \cdot k$	17.20	9.11	12.14
average discharge $Q = 7.29 \cdot k$	12.39	6.56	8.75

3.2. THE WATER BALANCE OF THE TRNOVSKO-BANJŠKA PLANOTA

(J. POLAJNAR, J. PRISTOV, M. BAT, M. KOLBEZEN)

3.2.1. Introduction

By making water balance, the ratio was established between the average quantity of precipitation, evapotranspiration and water runoff into the border rivers in the area of the Trnovsko-Banjška Planota (TBP); the aim was to determine the shares of the underground drainage from the entire TBP, and of the still unknown drainage from the karstic massif into the area of the underwater spring Mrzlek.

The water balance of the TBP plateau was determined for three periods.

The thirty-year water balance (1961-1990)

Following the WMO recommendations, the 30-year period, from 1961 to 1990, was to be taken into account for the study of hydrological and meteorological data over several years.

The two-year water balance (1993 - 1995)

For the period of two years the time when the tracing experiments were performed in the area of the TBP (Chapter 6) was used (November 1, 1993 to October 31, 1995).

The five-year water balance (1991 - 1995)

For the period of five years 1991 to 1995 was chosen as a comparison to the thirty-year and two-year hydrological balances.

Two methods were applied for the calculation of water balance. With the first one, the runoff was determined, from the area of the TBP to the border rivers, the Idrijca, Soča and Vipava. No separation between the surface and the underground runoffs is included. With the second method, the runoff from the karstic area of the TBP was determined. For the discussed periods both the runoff conditions in the areas with the surface runoff, and the runoff conditions in the areas with underground runoff to the surface streams were separately calculated.

3.2.2. The method of establishing water balance for the area of the TBP without separation

Following the described methods, the water balance was established for the 30-year period, from 1961 to 1990.

The starting point for establishing the water balance was the calculation of the common, surface and underground runoffs from the area of the TBP, on the basis of the data on precipitation, evapotranspiration, and the data on discharges at the gauging stations on the border rivers and their tributaries. The catchment area which was taken into account, stretches over the entire upper Soča river basin, to the confluence with the Idrijca, the contributing basin of the Soča on its right bank between Most na Soči and Solkan, the Tolminka contributing basin, the contributing basin on the right bank of the Idrijca between Podroteja and the confluence with the Soča, the contributing basins of the Bača and the Cerknica, the contributing basins of the Vipava springs in the area of the Nanos, and the contributing basin on the left bank of the Vipava, between Vipava and Miren, and the contributing basins of the Močilnik and the Branica; the entire area measures 1337.5 sq km. The foregoing area was divided into 12 contributing sub-basins of which only the sub-basin no. 2 includes the contributing area of the TBP (Fig. 3.7).

This is a part of the Soča contributing basin on the left bank, between Most na Soči and Solkan, the Idrijca contributing basin on the left bank, and the Vipava contributing basin on the right bank, between Ajdovščina and

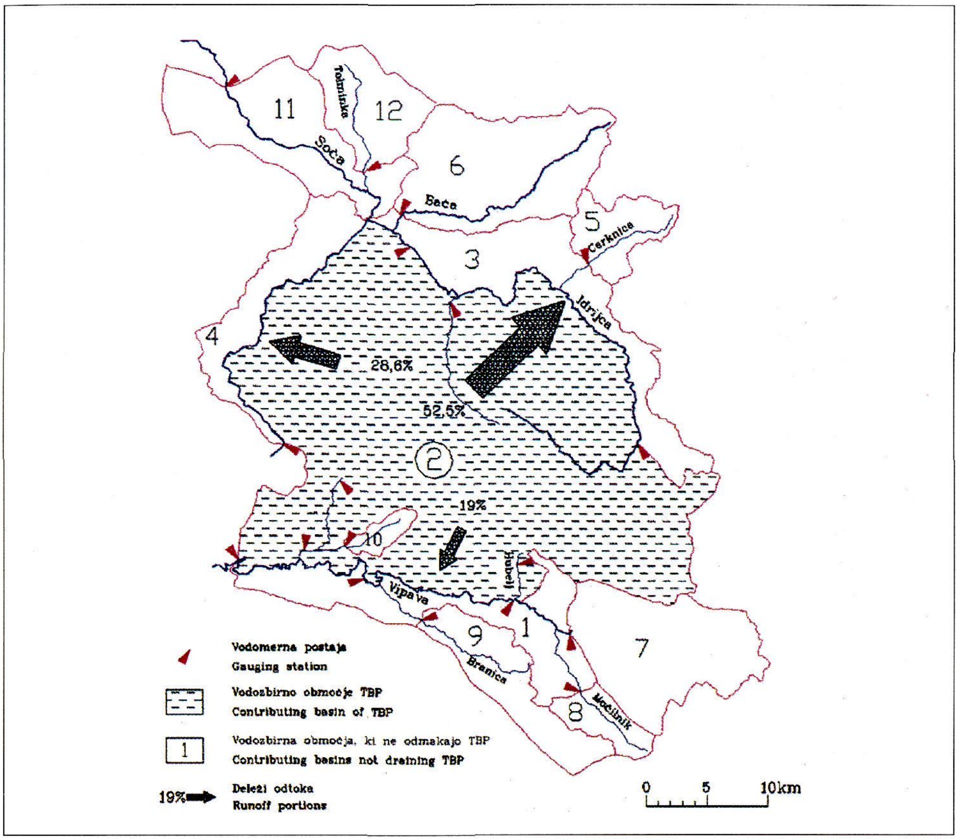


Fig. 3.7: Runoff from the TBP for the 30 years period (1961 to 1990) without distinguishing surface and underground discharge.

Miren, with 832.8 km^2. The remaining sub-basins with their contributing areas and rivers extend outside the area of the TBP; yet, their water quantities were taken into account in the establishing of water balance.

For each sub-basin the database used consisted of the mean precipitation and evapotranspiration quantities in the period, as well as the discharges at the following gauging stations (VP) on the border rivers:

Idrijca:
VP Podroteja and VP Hotešk
the Idrijca and the Soča confluence (calculated data)
tributaries: the Cerknica-VP Cerkno
the Bača-VP Bača Pri Modreju
the Trebuša-VP Dolenja Trebuša

Soča:
VP Solkan
VP Kobarid
the Idrijca and the Soča confluence (calculated data)
tributary: the Tolminka-VP Tolmin

Vipava:
VP Vipava
VP Dolenje
VP Dornberk
VP Miren
tributaries: the Močilnik-VP Podnanos
the Branica-VP Branik
the Hubelj-VP Ajdovščina
the Lijak-VP Šmihel
the Lijak-VP Volčja Draga
the Vogršček-VP Bezovljak

For the sub-basins without gauging stations, the mean discharges (sQs) of the period were calculated by discharge coefficients. With this method, the underground runoff is not separate from the surface runoff. Only the ratio was established between the precipitation and the run off water from the wider area of the TBP. By eliminating the discharges from the contributing sub-basins outside the TBP, also the runoff from this plateau was determined.

Following the foregoing method, the result was obtained for the wider area of the TBP; i.e., 34.92 m^3 of water was discharged per second, on average, from the wider area of the TBP during the period of thirty years:

$$sQs_{(TBP)} = sQs_{(\text{discharge to the Idrijca})} + sQs_{(\text{discharge to the Soča})} + sQs_{(\text{discharge to the Vipava})}$$

$$sQs_{(TBP)} = 17.72 \text{ m}^3/\text{sec} + 10.57 \text{ m}^3/\text{sec} + 6.63 \text{ m}^3/\text{sec}$$

$$sQs_{(TBP)} = 34.92 \text{ m}^3/\text{sec}$$

The major share, i.e. 52.5 % into the Idrijca, 28.5 % into the Soča, and 19 % into the Vipava. The runoff coefficient for the hydrologically diverse area amounts to K = 0.57. The specific runoff of the thirty-year period amounts to 41.8 l/sec/km^2.

3.2.3. The method of establishing water balance for the area of the TBP with the underground drainage

The purpose of the second part of the water balance of the TBP was to obtain the underground runoff. By applying the method of gradual elimination of contributing sub-basins with the surface runoff, the runoff from the karstic

contributing sub-basin, characterised by almost exclusively underground drainage, was calculated. Besides, the assessment was also made, of the discharge in the area of the underwater spring Mrzlek. This is the lowest lying karstic spring in the area of the springs at the western rims of the TBP where, hypothetically, the basic runoff from the karstic massif comes to the surface. The water balance and the assessment of discharge in the spring area of the Mrzlek were calculated by applying the described method, for the thirty-year, five-year and two-year periods.

The area of the TBP was divided in detail to the sub-basins with the surface runoff and with the underground runoff. The karstic sub-basin with the underground runoff comprises the central part of the TBP with the major karstic springs: the Hubelj, Lijak, Mrzlek, the Podroteja karstic springs, and the Divje Jezero, and measures 348.5 km^2 (sub-basin 108, Fig. 3.8).

The mean discharge of the period from this sub-basin was calculated by applying the data on the mean precipitation quantities for the discussed periods (30 years, 5 years, 2 years) and the mean quantity of evapotranspiration for the thirty-year period. (Tab. 3.9).

Tab. 3.9: The calculated mean discharges for the karstic area of the TBP plateau (Fig. 3.8: sub-basin 108) for the 30, the 5 and the 2 years periods.

Sub-basin 108 with the prevailing underground runoff	**30 years**	**5 years**	**2 years**
Mean discharge of the period (sQs in m^3/sec)	20.02	19.43	18.32
Specific runoff (q in $l/sec/km^2$) Runoff coefficient (k)	57.45 0.74	55.75 0.73	52.56 0.72

The water from the karstic massif comes to the surface in the karstic springs of which only the following were longer under the observations: the Hubelj, the Lijak, the Podroteja springs, and the Divje Jezero. For the calculation of discharges of the Podroteja springs and the Divje Jezero, the discharge of the Idrijca from the part of its contributing basin with the surface runoff above the gauging station and the karstic springs (sub-basin 41), was deduced from the discharge of the Idrijca at the gauging station Podroteja where the underground and surface runoff are joined (see also Chapter 3.1).

From the assessment of discharges of the remaining karstic springs, the strongest of which is the underwater spring Mrzlek, the gauged mean discharges of the foregoing springs were deduced from the mean discharges from the karstic massif (sub-basin 108).

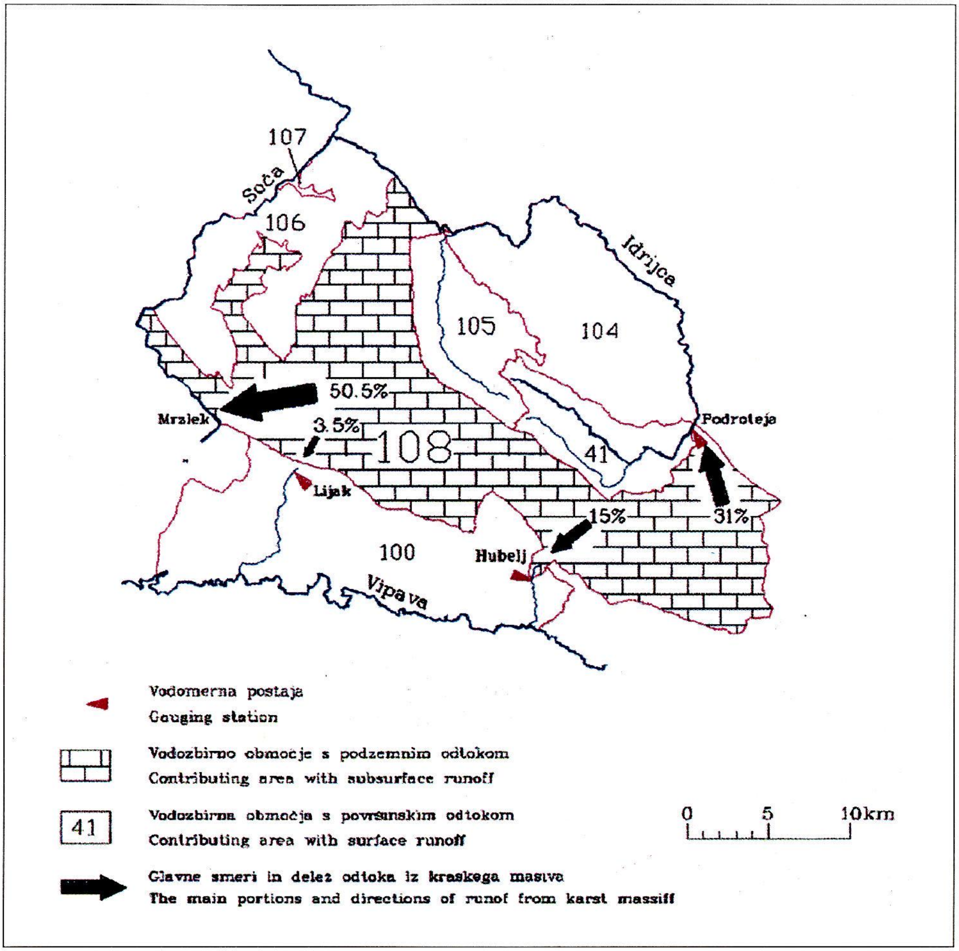


Fig. 3.8: Runoff from the karst region of the TBP for the 30 years period (1961 to 1990).

The difference is supposed to flow mainly into the Soča in the area of the underwater spring Mrzlek, and partly also with the other springs on the left bank of the Soča, between Most na Soči and Solkan:

$$sQs_{\text{Mrzlek}} = sQs_{\text{contributing sub-basin 108}} - sQs_{\text{Hubelj}} - sQs_{\text{Podroteja}} - sQs_{\text{Lijak}}$$

The calculated discharges in the area of the Mrzlek spring are only an assessment of the actual discharges in the underwater spring (Tab. 3.10).

Tab. 3.10: The calculated mean discharges for the catchment area of the Mrzlek spring for the 30, the 5 and the 2 years periods.

	30 years	**5 years**	**2 years**
Contributing sub-basin 108 with the prevailing underground runoff (sQs in m³/sec)	20.02	19.43	18.32
Mrzlek spring area (sQs in m³/sec)	10.12	9.80	7.29

In the 30-year and 5-year periods, the water from the karstic underground of the TBP was discharged as follows: a half of it to the Soča, one third to the Idrijca, and one fifth to the Vipava. While in the last two years, i.e. in the time of performing tracing experiments, 40 % was discharged to the Soča, 36 % to the Idrijca, and 24 % to the Vipava.

The water balance for the 30-year period was established by applying both the described methods. Following the first one (without separation), the data on the gauged discharges were made use of for the contributing sub-basins with the gauging stations, and following the second method, the data were applied, on the discharges that had been calculated by making use of the precipitation and evapotranspiration data.

Established was the average difference of 15 % between the gauged and calculated mean discharges of the period in individual contributing sub-basins. The theoretical discharge is by 15 % higher, on the average, than the gauged discharge.

In case that the values of the calculated mean discharges of the period in the sub-basin with the underground runoff (sub-basin 108) are reduced by the foregoing 15 %, the mean discharges of the period in the Mrzlek spring area amount: 7.10 m^3/sec for the thirty-year period, 6.9 m^3/sec for the five-year period, and 4.54 m^3/sec for the two-year period.

3.2.4. Conclusions

The results of water balance on the TBP show the main directions and the shares of the underground runoff. In the periods longer than two years, the greatest share of water from the karstic underground is discharged to the Soča, less to the Idrijca, and the least to the Vipava. The majority of the underground runoff gravitates westwards to the spring Mrzlek, which indicates the location and inclination of the impermeable basis (see Chapter 2.6) where the greatest part of basic runoff flows along the flysch depression into the Soča.

3.3. PRECIPITATION PROBLEMS IN RELATION TO WATER RUNOFF ON THE TRNOVSKI GOZD

(J. PRISTOV)

As the basis for the study of precipitation problems served the daily precipitation gauged at 07 hrs. From among 15 stations in the area of the Trnovski Gozd and the Nanos, only the station Podkraj is equipped with a gauge of Hellmann type which continuously registers the precipitation. Indeed, it is not enough for the analysis of precipitation situation because the distribution of precipitation in individual areas of the Nanos and the Trnovski Gozd considerably differs, from one precipitation situation to another.

For the comparison of precipitation with discharges, the data from the following four hydrological gauging profiles in the area of the Trnovski Gozd and the Nanos and their rims were selected:

the Idrijca-LP Podroteja
the Vipava-LP Vipava
the Hubelj-LP Ajdovščina
the Lijak-LP Šmihel

Analysis of the precipitation was performed on data from precipitation situations after the end of the long-lasting dry period in 1993. Heavy precipitation occurred on September 25, and were recurring until the end of October 1993. The precipitation situation between October 21 and 25, 1993 was studied in detail.

The precipitation situation between October 21 and 25, 1993

The time and spatial distributions of precipitation were even over the entire area in this situation. The precipitation maximum occurred between Črni Vrh Nad Idrijo and Mrzla Rupa. This is the only case that the ratio of precipitation quantities was only 1:2 (Ozeljan 134 mm; Črni Vrh 265 mm). Podkraj received 206 mm of precipitation. This even distribution was possible due to more permanent precipitation without any longer interruptions. The precipitation in this case did not fall in the form of rainstorms.

More abundant precipitation began in Podkraj on October 21, at 06 hrs, and by 09 hrs, 25 mm of precipitation fell; followed an interruption by 14 hrs, then followed more or less continuous precipitation by 01 hrs on October 23. Then, interruptions began to occur and precipitation completely ceased on October 24, at 15 hrs.

The discharges at the gauging station Vipava reacted on the beginning of rather heavy precipitation with a 6-hour lag. A five-hour interruption of precipitation is almost unnoticeable on the diagram of discharges. The latter only began to lower some six hours after the end of precipitation. The

precipitation, or, storms under 10 mm in short time are much blurred on the diagram of discharges, and there are no sharp extremes.

Quite different are the discharges of the Hubelj. They react much faster on the precipitation than those of the Vipava, and also, any several-hour interruption is already manifested in the decrease of discharges. The lag of discharges behind the precipitation is 3 to 5 hours. The discharges of the Hubelj are lower by approx. one half than the discharges of the Vipava.

There are two possible explanations:

- that the precipitation catchment area of the Hubelj is much smaller, or,
- that, at certain high water levels, the waters from this area reorient elsewhere.

In this case, too, the spring Lijak behaves quite differently than the spring Hubelj or the Vipava springs. The increase, or the beginning of the increase of discharges lags behind the increase of the Vipava as much as 10 hours, and from the beginning of precipitation to the beginning of the Lijak discharge, as much as 16 hours. Also its hydrogram differs a lot. After the very fast increase of discharges, they amount to 10 - 14 m^3/sec as long as four days. However, the Lijak did not exceed this upper limit in the discussed case, and it only reached this value when the discharges of the Vipava, Hubelj and Idrijca already decreased a lot. This could somehow confirm the hypothesis that the Lijak lacks its own contributing area in the close proximity of the spring, but the water flows in from a more distant contributing area, and therefore, it is impossible to determine or delineate the area from which the Lijak is supplied.

A quite different scene is offered by the discharges of the Idrijca at Podroteja which react much faster on the time distribution of precipitation. The beginning of the increase of discharges lags behind the beginning of precipitation by 9 hours, and at the following interruptions, i.e. during the already established high wave, these lags are only from 2 to 6 hours long.

The ratio of discharges at the high wave approximates the following:

Lijak - Hubelj - Vipava - Podroteja = 1:2:4:8, or it is slightly higher.

Determined in the described case of October 1993, were only the occurrence and duration of precipitation in the entire area, and the reaction of discharges on the precipitation at the following gauging profiles: Podroteja on the Idrijca, Vipava on the Vipava, Ajdovščina on the Hubelj, and Šmihel on the Lijak.

We tried to discover the time reaction of discharges on the precipitation; naturally, we had troubles in doing it since the entire area is rather well covered with a network of stations for daily gauging of precipitation heights, but very poor (only one gauging point, and even this one located at the eastern rims of the discussed area) in the continuous registration of precipitation.

The crucial problem still remains; this is the co-ordination of the total quantity of precipitation with the discharges by individual precipitation situa-

tions in the month of October 1993, and for the 1961-90 period. For these cases, the complex water balance analysis will be made. This problem is difficult because the gauged waters at the rims of the Trnovski Gozd and the Nanos do not represent the total quantity, because a part of the waters from this area drain underground towards the Soča (the Mrzlek spring). These quantities have not been determined so far, and it is very difficult to do it due to the reservoir of the Solkan hydropower plant.

3.4. CORRELATION AND SPECTRAL ANALYSIS

(PH. MARTIN, J. KOGOVŠEK, M. PETRIČ, S. ŠEBELA, C. MARTIN)

3.4.1. Methodology

The hydrodynamic functioning of the Hubelj and Vipava springs was studied also with the time series analysis - with correlation and spectral analysis (BOX & JENKINS 1976; JENKINS & WATTS 1968). For this purpose the STOCHASTOS programme, which was designed by MANGIN (1981a, 1981b, 1984) and written by D'HULST of the "Laboratoire Souterrain du CNRS" at Moulis (Ariège, France) was used. Presented results were obtained in a co-operative research of CNRS URA 903 (Aix-en-Provence, France) and Karst Research Institute ZRC SAZU (Postojna, Slovenia).

This approach is based on the concept of the karst system (MANGIN 1975). We can define a karst system as an underground carbonate basin, which can however integrate unkarstified superficial sub-basins in the background. In this karst flows form the drainage network, which has in general a branching structure. Such karstic system is a place of dynamic processes, determined by inflows (precipitation and/or loss of water from rivers, CO_2, etc.) and outflows (discharges, aqueous solutions and so on). The karstification efficiency must be defined as work capacity within the system, it means that in case of gravitational karst as a runoff product in regard to the altitude of gradient (the altitude difference between the inflow and outflow (spring) points). The heterogeneity of the area, the non-linearity of the flows and the contrast in hydraulic conductivity between the different parts of the aquifer (IURKIEWICZ & MANGIN 1994) are conductive to the adoption of the systemic and functional approach which is based on the study of the relations input - output.

The use of correlation and spectral analysis necessitates time series of precipitation and discharges which are uninterrupted and of an identical duration. This approach first of all aims to describe the structure of time series (with random and periodical components, tendencies etc.), and then to establish the form of unit hydrogram and finally to draw attention to the multiple relationships between input and output.

Graphs resulting from calculations made on each of the time series allow us to understand these structures. They are obtained using two initial choices: one is the maximum value of lag (m) which corresponds to the window of observation, the second, the step (k) corresponds to the amplitude of each change. The information of a duration less than 2k does not show up in the results.

The correlogram shows how events are linked together for increasing intervals of time. High values indicate the presence of a tendency, low values suggest that events are not linked. A rapid decrease in the values of correlative coefficients indicate an absence of liaison at the end of a relatively short period of time. The size of interval corresponding to a value of the correlative coefficient of 0.2 is known as the "memory effect" (MANGIN 1984).

The spectrum of density of variance which corresponds to a change in the variable (Fourier transform), expresses the components of the time series in the frequency domain. In order to avoid the possibility that the results are biased, it is necessary to balance the calculations with an function such as that of Tukey or Parzen which are both very appropriate for use in hydrology (MANGIN 1984). The function of Tukey filters out less than that of Parzen. It is therefore preferable in the first approach since less information is lost. Nevertheless, it can allow artefactual peaks to appear. In order to alleviate any doubt a second calculation using Parzen filter can be used. High values for frequencies around zero indicate the existence of a tendency. By dividing the maximum value by two, we can obtain the "regulation time" which represents the duration of the impulse response. Each peak indicates the presence of periodical phenomena. The frequency from which the values become negligible is known as the truncation frequency (f_c). Beyond this, towards the higher frequencies, the spectrum only indicates the presence of white noise. The smaller the value of truncation frequency, the more the system is inert, which is to say less karstified.

The cross-correlogram is calculated for the time series of precipitation and discharges. If the input signal is random, the cross-correlogram is a good image of the impulse response of the system, which is a good representation of the unit hydrogram. In the domain of frequencies, we reach on the one hand the amplitude function which establishes the relations between the input and output of the system, and on the other the phase function which for each frequency defines the phase lag between input and output. The phase lag (τ) is defined with the equation $\tau = \theta/2\pi f$.

This information can be completed by calculating the functions of coherence and gain in frequency domain. The first expresses the linearity of the system. One non-linearity often indicates that the output function is not uniformly determined by the input function which was used. The other, the function of gain, indicates phenomena of attenuation (value < 1) or amplification (value > 1) in the signal for each frequency. An attenuation in the higher

frequencies is generally accompanied with an amplification of the lower frequencies.

3.4.2. Characteristics of the Used Data

Basic hydrological characteristics of the studied karst area in the background of Vipava and Hubelj springs are presented in the previous chapters. Here we would just like to give some comments on the choice of the input function. For the purposes of this study, we selected the meteorological station at Otlica (820 m) which lies in the background of the Hubelj spring. An experience showed (MARTIN 1991 a, b) that it is useless to set up one rain-gauge station in a catchment area as rain is purely regional data that occurs at various places of the climatic micro-region as is Trnovski Gozd and Banjšice.

For the Otlica meteorological station the average daily precipitation for the period 1985 - 1995 are 6.28 mm. The maximum daily value is 170.6 mm and for the interval of three days 230.6 mm. In four three-days periods the amount of precipitation exceeded 220 mm. The wettest month was October 1992 with 580.5 mm. We can conclude (Fig. 3.10) that the period with highest amount of precipitation is between October and December, and the second maximum is from April to May. Regarding the dry seasons the interval January - February is more significant than the period between July and August.

The used data take account of the snow on the day of its fall, in a volume equivalent to that of meltwaters. In its natural environment, on the higher parts of the basin, the snow may last for several weeks. Based on the data gathered by the Hidrometeorološki Zavod RS, we counted for stations Otlica and Vojsko (1070 m) the number of days each year when the ground was covered by snow. From 1985 to 1995 the average number of days per year when the ground was covered with snow at Vojsko was 107. In 1985 the ground was covered for 166 days and in 1989 for only 49 days. At Otlica during the period of 1989 to 1995, the mean number of days when the ground was covered was 29 days with the maximum of 60 in 1995 (135 at Vojsko) and a minimum of 8 days. At the Postojna station (500 m), which lies further to the east, the ground was covered with snow for a period of 30 days in 1985; the snow represents 7 % of total precipitation. In 1991, the snow only accounted for 28 mm out of a total of 1681 mm.

The volume of persistence of snow must be seen in terms of the mean altitude of the basins. This can be determined by conducting a study of ^{18}O concentrations (URBANC & PEZDIČ 1995). These would be 900 m for the Hubelj basin with a confidence interval of 750 m to 1000 m. And for Vipava basin the figure would be 850 m (with the confidence interval between 700 m and 950 m).

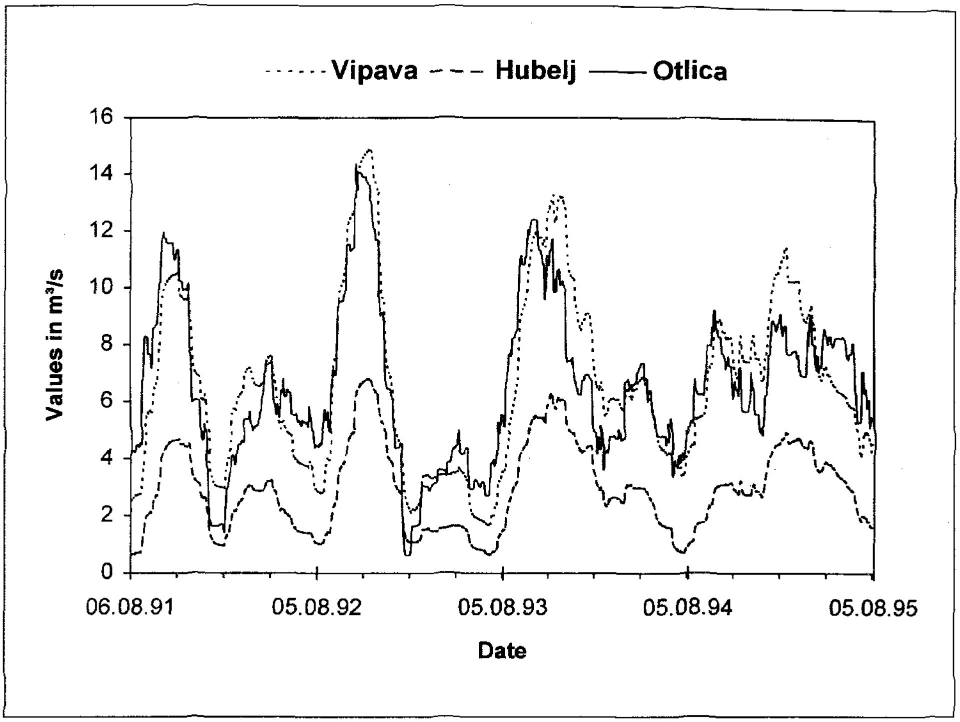


Fig. 3.10: The data of precipitation (Otlica) and discharges (Vipava and Hubelj springs) in the period 1991-1995 smoothed with the moving average (window of 93 days).

It appears that for medium and low altitudes like that of Postojna, the percentage of snow precipitation is negligible.

For the Hubelj and Vipava backgrounds the persistence of a covering of snow over several weeks each winter causes delay between the moment when the precipitation are measured (meltwater for the measuring apparatus) and the moment when the snow covering melts. Because the duration cover varies according to the different altitudes, we might conclude that the recharge of the aquifers is retained and that constitutes a sort of support of the hydrological phases in spring.

In this case it seems that the influence of snow is felt at the margin only and it almost does not affect the global statistical approach presented below. Yet it does not exclude the possibility that increase of snow cover is determining in some cycles. It would be convenient to divide the observed periods into those with particularly lot of snow or without it and make the comparisons.

On the other hand, the evapotranspiration (on the base of Penman method the following values were calculated: 678 mm for the period 1959 -1979 (STAHL 1994), 637 mm for the year 1993 and 628 mm for 1994 (AVBELJ 1995)), which reaches about a third of the volume of precipitation during the year, reduces the available discharge with a maximum effect towards the end of spring and during the summer.

3.4.3. Analysis of Results and Comparative Study of Both Springs

The daily data of precipitation on the meteorological station Otlica and discharges of Hubelj and Vipava springs, which were gathered by the Hidrometeorološki Zavod RS, were used in the analysis. The observation period was 11 years or 4017 days from 1 January 1985 to 31 December 1995. The correlation coefficient and the spectrum values were calculated with the use of step k = 1 and the maximum value of lag m = 125.

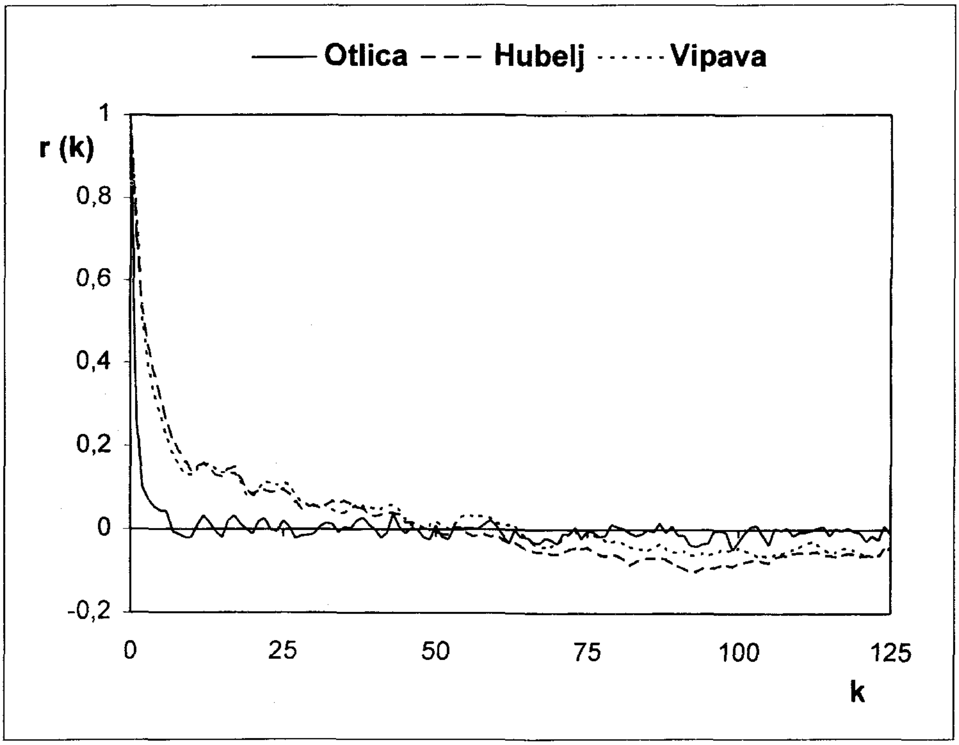


Fig. 3.11: Correlogram of precipitation (Otlica station) and discharges (Hubelj and Vipava springs) for the period 1985-1995 (n=4017 days, k=1, m=125).

The correlogram calculated according to the data of daily precipitation at Otlica (4017 days, average 6.2 mm, maximum 170.9 mm, minimum 0 mm, variance 244) shows an extremely rapid decrease in the values of correlative coefficients (Fig. 3.11). The value 0 was reached after 7 days. For the values of k > 3, only random fluctuations around 0 are persistently obtained. The interdependence of events is therefore very weak. It is nothing over 2-3 days which is the period corresponding to a climatic episode or to the passage of one perturbance.

The two other correlograms were calculated using data of average daily discharges of Vipava (average 6.5 m^3/s, maximum 66 m^3/s, minimum 0.73 m^3/s; variance 69.9) and Hubelj springs (average 2.8 m^3/s, maximum 36 m^3/s, minimum 0.18 m^3/s; variance 15.2). These show an extremely rapid decrease in the values of the correlative coefficients with r = 0.2 for a very low value of k (Tab. 3.11). In these two cases the decrease is regular until r = 0.15 and k = 11. For higher k values, the correlative coefficients are always less than r = 0.15 and at k = 50 they reaches 0. Therefore there exists a statistical

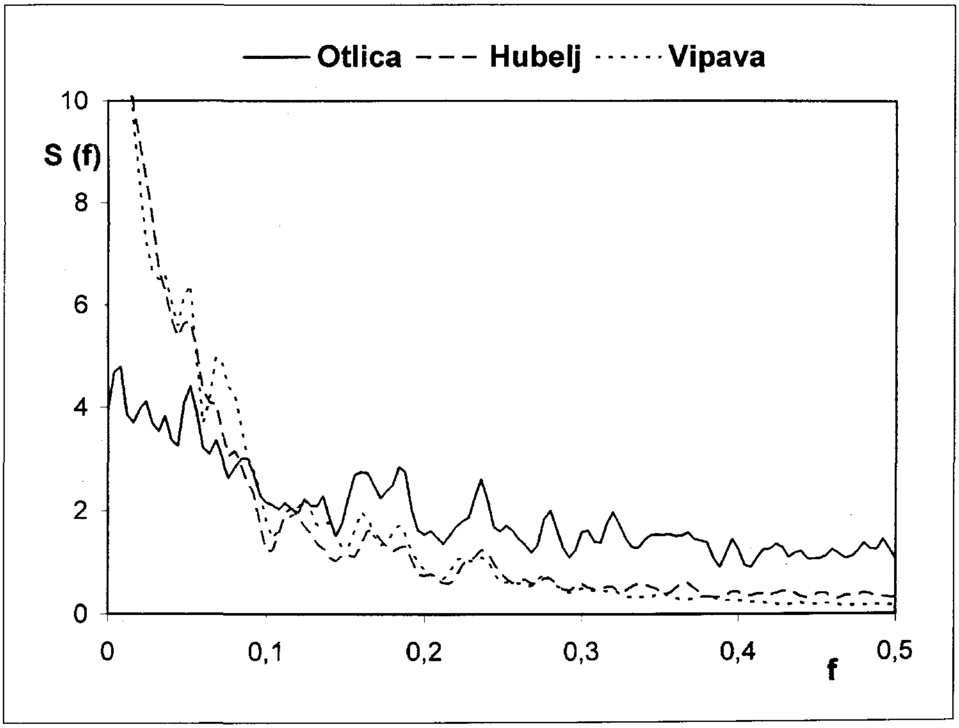


Fig. 3.12: Spectrum of precipitation (Otlica station) and discharges (Hubelj and Vipava springs) for the period 1985-1995 (n=4017 days, k=1, m=125) - calculated with the use of Tukey filter.

independence between the discharges which occur at about 12 days apart. We can conclude that the memory effect is considerably low, which would represent a small storage capacity and well developed karst drainage. Finally, let us note that the correlograms of the precipitation and discharges are very similar.

The spectrum of precipitation shows low values for all frequencies and very low values for frequencies of more than 0.1 (Fig. 3.12). Such spectrum corresponds to a random character of the function of precipitation, even if two small peaks appear at the points when f = 0.008 and f = 0.052. The first of these corresponds to a periodicity of 125 days, the second to a periodicity of 20 days. Both peaks can be seen also on the spectrum calculated using Parzen filter (Fig. 3.13). Therefore we can reject the possibility of artefacts and a certain periodicity which shows characteristics of the Mediterranean climate can be defined. The value of the periodicity (125 days) corresponds to four months, which is more or less the duration of the two rainy periods (autumn and spring) which are separated by two dry periods (winter and summer) of about two months (Fig. 3.10).

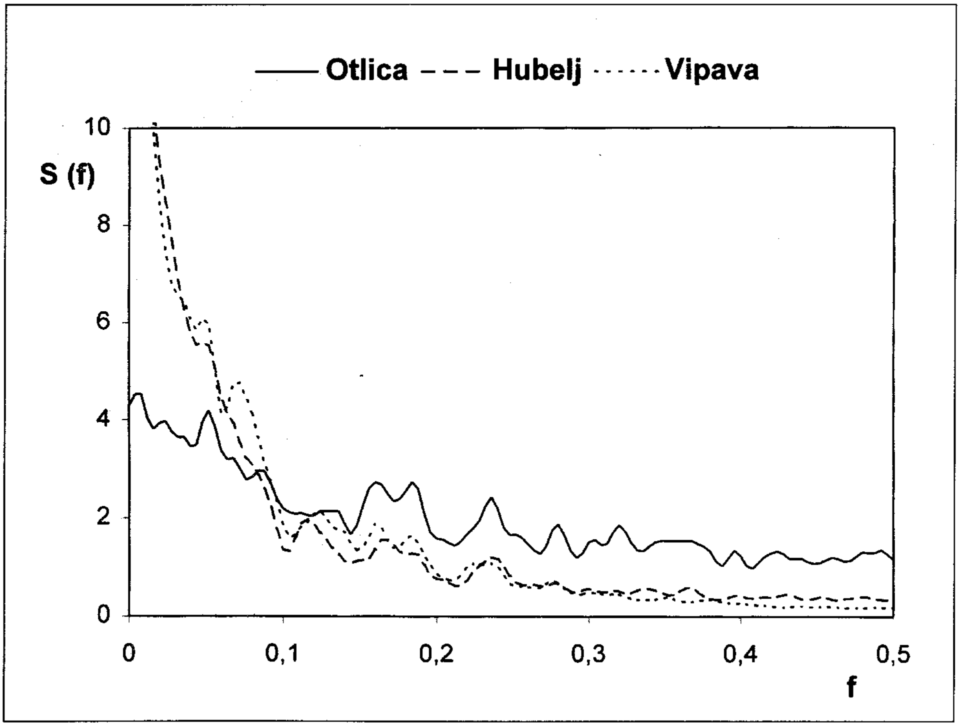


Fig. 3.13: Spectrum of precipitation (Otlica station) and discharges (Hubelj and Vipava springs) for the period 1985-1995 (n=4017 days, k=1, m=125) - calculated with the use of Parzen filter.

With the use of Tukey filter (Fig. 3.12) also the spectrums of discharges for both springs were calculated. They show a very strong levelling out of frequencies of more than 0.1 and a disappearance of all information for frequencies of more than 0.25. The values obtained for f = 0 (23.8 for Vipava and 22.1 for Hubelj, and the regulation time of 12 and 11 days respectively) points to a levelling out of the higher frequencies and a consequent pronouncing of the lower frequencies. Besides this, the Hubelj spectrum shows a peak at the frequency 0.004 which corresponds to a periodicity of about 250 days. This feature is not found in the Vipava spectrum. The utilisation of the Parzen filter (Fig. 3.13) causes this peak to disappear. In this case we are witnessing an artefact which is probably linked to the periodicity of four months which become evident through the precipitation data. The resulting graphs show that the drainage of these two karst systems is well organised.

A strong similarity (Fig. 3.14) is present in the cross-correlograms calculated using the precipitation occurring at Otlica and the discharges at Vipava and Hubelj springs (analyses of 4017 days). Both are tapered (the maximum

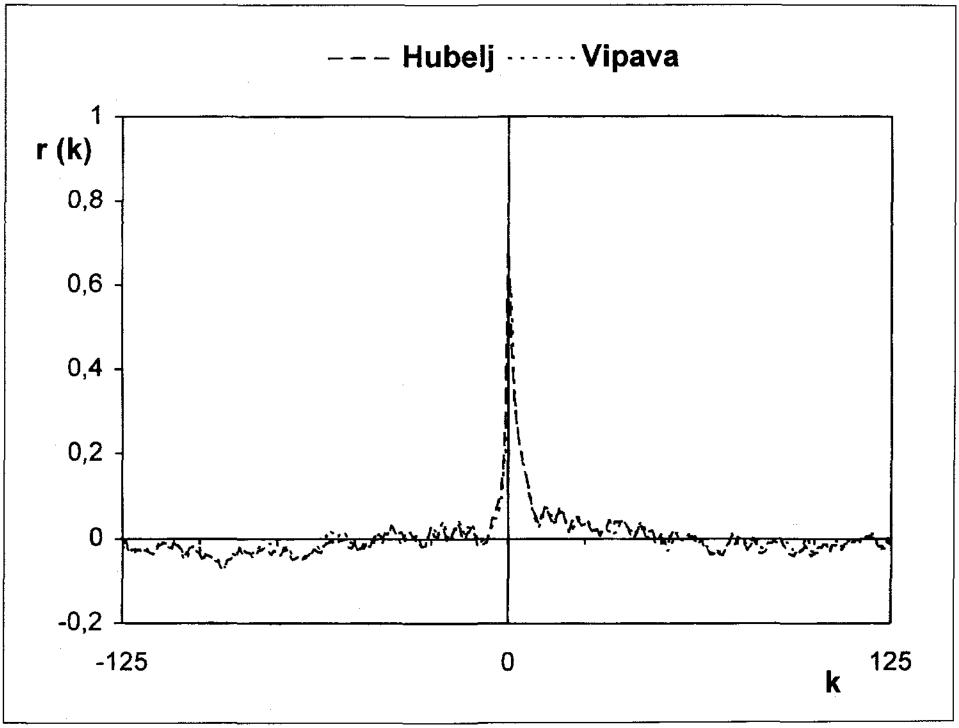


Fig. 3.14: Cross-correlogram between precipitation (Otlica station) and discharges (Hubelj and Vipava springs) for the period 1985-1995 (n=4017 days, k=1, m=125).

correlation coefficient for Vipava springs is 0.62 and for Hubelj springs 0.70) and descend after only 10 days to a very low r value (0.02 and 0.03). For greater intervals, the fluctuations are slight and random.

The part corresponding to negative values of k also shows random fluctuations around 0. However, at similar analyses conducted on binary karst higher values of r for the negative values of k were observed. This characteristic doesn't indicate that the discharges precede precipitation (which has no sense), but that the input signal is not random. We know that the Vipava springs are partly recharged by the surface rivers, yet in the cross-correlogram the values of r are very low for the negative values of k. This indicates that the portion of the river recharge is very low and/or that the time series of river discharges have a structure similar to the one of the precipitation.

The function of precipitation is therefore random and each cross-correlogram constitutes a good image of the impulse response of the studied karst system and thus a good representation of its unit hydrogram. These cross-correlograms thus point to the existence of functional drainage structures which are capable of the rapid transferral of rainwater or meltwaters to the springs. In this case, these structures can only be karstic networks with shafts, galleries, etc.

Two obtained amplitude functions are very similar (Fig. 3.15) with positive values for all frequencies and larger values for $f < 0.1$. The curve for the Vipava springs is more smooth than the curve for the Hubelj spring. The existing functions within the frequencies of relations between inflow and outflow of the system must not be zero because otherwise other functions (phase, coherence, gain) cannot be interpreted as, when the relations are missed it is obviously impossible to study their properties. The zone of relation input-output or the zone of exchange is between $f = 0$ and $f = 0.168$. The small peaks correspond with periodicity. On both curves we can identify the peak at $f = 0.056$, which represents the period of 18 days. This periodicity is similar to periodicity, which was defined in the spectrum of precipitation for $f = 0.052$. For basic frequencies the peak for Vipava-curve is at $f = 0.008$ (125 days), and for Hubelj-curve at $f = 0.012$ (83 days). These two curves indicates the importance of phenomena of basic and middle frequencies on the relation precipitation - discharge.

The phase lag is 7 days for the Hubelj spring and 8 days for the Vipava springs (Tab. 3.11). Calculated for the boundary frequency of the zone of exchange ($f = 0.168$) the phase lag for the first spring is ½ day and for the second 1 day.

In the zone of exchange the coherence functions ranges between 0.75 and 0.95. These values indicate good linearity of the system for basic frequencies, which essentially reflect the general functioning of the system.

The gain functions show amplificated values for periods greater than 16 or 17 days. For other frequencies the values are attenuated. The maximal amplification for the lowest frequencies is limited.

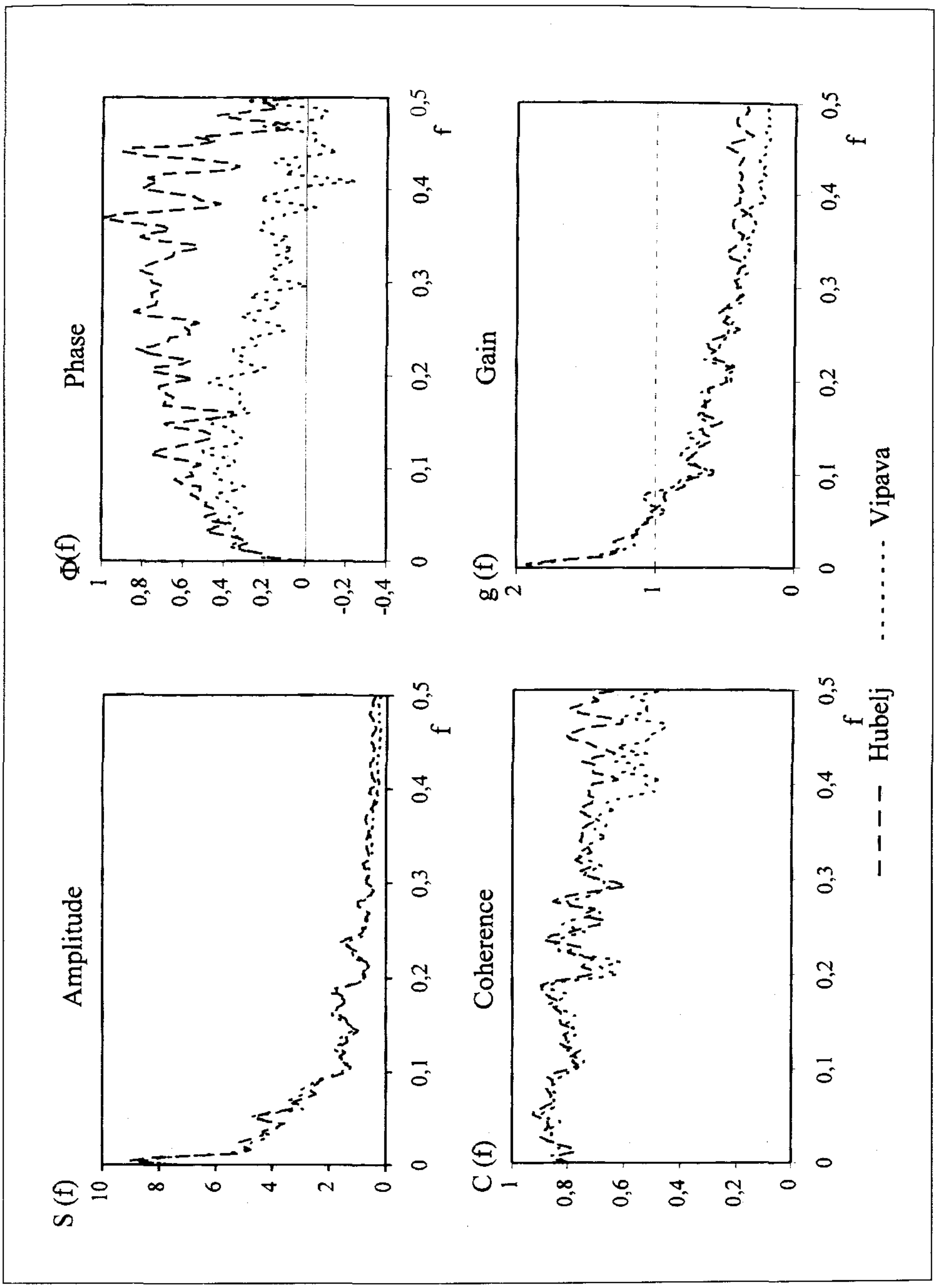


Fig. 3.15: Functions of amplitude, phase, coherence and gain for the period 1985-1995 (n=4017 days, k=1, m=125).

Tab. 3.11: Classification of karstic aquifers from the results of correlation and spectral analysis

	memory effect (r=0.2)	truncation frequency	regulation time	phase lag (f=0.004)	system type	unit hydrogram
Hubelj (4017 days)	8	0.25	11	8	ALIOU	
Vipava (4017 days)	7	0.25	12	7	ALIOU	
Hubelj (2 cycles)	11	0.35	12	13	Aliou	
Vipava (2 cycles)	5	0.35	11	12	Aliou	

3.4.4. Separate Analysis of the Cycles 1993-1994 and 1994-1995

The study was carried out with the aim to providing, for a period corresponding to the tracing tests, elements for comparison (for example, a cross-correlogram which is to be compared with the residence time). The calculations were based on data of precipitation (at Otlica) and the discharge (at Vipava and Hubelj springs) which were gathered during the hydrological cycles of 1993-94 and 1994-95, beginning and ending with the period at which the water was at its lowest level on the day of minimum discharge. For the Vipava springs two hydrologic cycles were defined in the interval from 24th August 1993 to 23th August 1995 (average discharge 7.5 m^3/s, variance 65.8), and for the Hubelj springs between 18th August 1993 and 19rd August 1995 (average discharge 3.3 m^3/s, variance 15.5). So for the first spring 730 daily values and for the second 732 daily values of discharge were compared with the same interval of precipitation at the Otlica station.

The correlograms obtained are very similar to those calculated on the basis of the report of the 4017 days (the memory effect in Tab. 3.11, Fig. 3.16).

The spectra have maximum values which are little different (the regulation time in Tab. 3.11) but which in contrast present a very significant peak at the point f = 0.04 (25 days) whichever filter is used, and a secondary peak for f = 0.052 (20 days). This last figure corresponds to a well defined periodicity

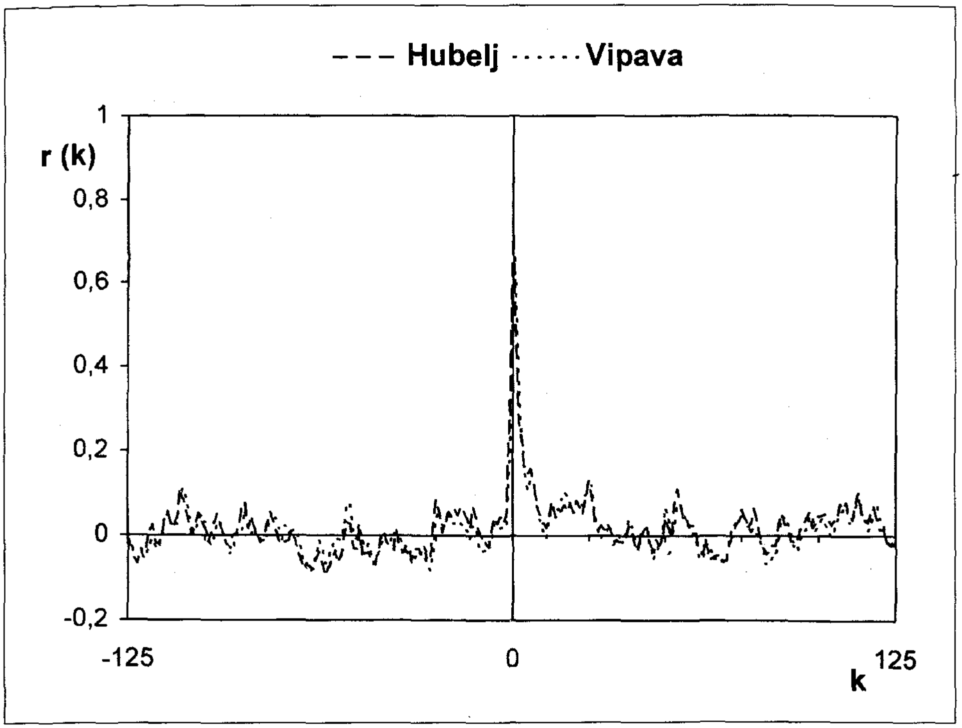


Fig. 3.16: Cross-correlogram between precipitation (Otlica station) and discharges (Hubelj and Vipava springs) for two hydrological cycles 1993-1995.

in the two short time series. In contrast to this, the latter clearly show the periodicity of 125 days. This should perhaps be linked to the major periodicity in the discharge time series.

3.4.5. Conclusions

The study of the discharge time series of the Vipava and Hubelj springs demonstrate that these hydro-systems are karstic systems of the Aliou type. They are well drained by efficient drainage structures which can be geomorphologically assimilated to a drainage network made up of a succession of sectors whose geometry facilitates the running off of rain and meltwaters.

The hydrodynamic functioning which is identified by the correlation and spectral analysis appears to be - in contrast with the results obtained in Provence (France) at the Sainte Baume (MARTIN 1991 a, b, c) - very similar, even though other hydrological indicators show significant differences.

A quick comparison of 1994 hydrograms of these two springs clearly shows (Fig. 3.17):

- a synchronisation of hydrological phases is also temporally very reduced (some days);
- steeper recession curve for Hubelj low waters than for Vipava low waters;
- during low water level the discharge in the Vipava is always higher than this in the Hubelj;
- a remarkable difference of high waters quantity in the moment of aquifer recharge; high waters at Vipava are much higher and similar during the year which is not a case at Hubelj.

The presented characteristics are not quantitatively defined, but with their description we tried to emphasise that on one hand it is not good to be limited only on one researching method and on the other that some important differences in the hydrodynamic functioning can not be detected with the methods of correlation and spectral analysis.

Although we consider the above remarks and although the altitude location of each spring is different, the uniformity functioning as it is described (Tab. 3.11) opens a problem in respect of certain karsts where the variations of functioning may be considerable (MARTIN 1991 a, b).

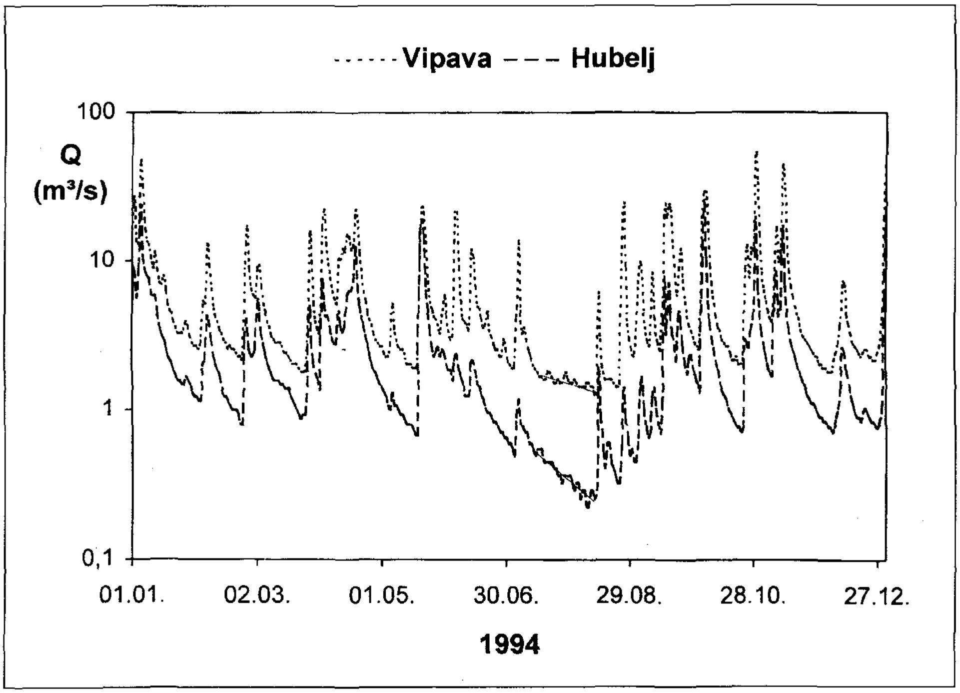


Fig. 3.17: Comparison of the hydrograms of Vipava and Hubelj springs for the year 1994.

These similarities in functioning should be interpreted as an antagonistic effect between geological and geomorphological characteristics which may not facilitate the establishment of efficient networks, and as a potential for karstification which in this example remains very significant.

In fact the quantity of rainfall associated with dense vegetation that produces CO_2 permits that water achieves efficient drainage conduits and reorganises displacement into underground very quickly. Seemingly it happens faster than the incision of the valleys which would disorganise the endo karstic drainage (MARTIN 1991 a, b).

3.5. HYDROLOGICAL DESCRIPTION OF THE VIPAVA AND HUBELJ SPRING SYSTEMS

(S. SCHUMANN, C. LEIBUNDGUT)

3.5.1. Discharge Frequency Density

In order to classify the Vipava and the Hubelj spring systems hydrologically an evaluation for the discharge data of the years 1961 to 1990 of the hydrological flow parameters was carried out.

A discharge frequency density diagram was developed for both springs on the basis of daily discharge values. The diagram includes an abscissa-averaged duration curve, the calculated mean discharges, MQ, and the Q_{95} of the springs.

In order to arrive at an abscissa-averaged duration curve the number of days per class interval is averaged over the required period (MANIAK 1993). The Q_{95} represents a reference value for regional water use and summarises the discharge which is reached or exceeded in 95 % of the time, i.e. in 347 days of the year. As the daily discharge data of a 30 years period were used the data was not revised as "records of this length need no adjustment or standardisation as the period of data will probably provide a sufficient accurate flow duration curve" (INSTITUTE OF HYDROLOGY WALLINGFORD 1980).

The discharge frequency diagrams of the Vipava and the Hubelj springs for the period 1961 to 1990 are presented in Fig. 3.18 and Fig. 3.19. Both springs show similar pattern:

- About 260 days of the year the discharge stays below the mean discharge, MQ.
- The curve representing the probability that the discharge stays below a certain value shows only gentle sloping. I.e. the frequency of the occurrence of extremely high discharge values is low.

The diagrams also point out the differences of the spring behaviours:

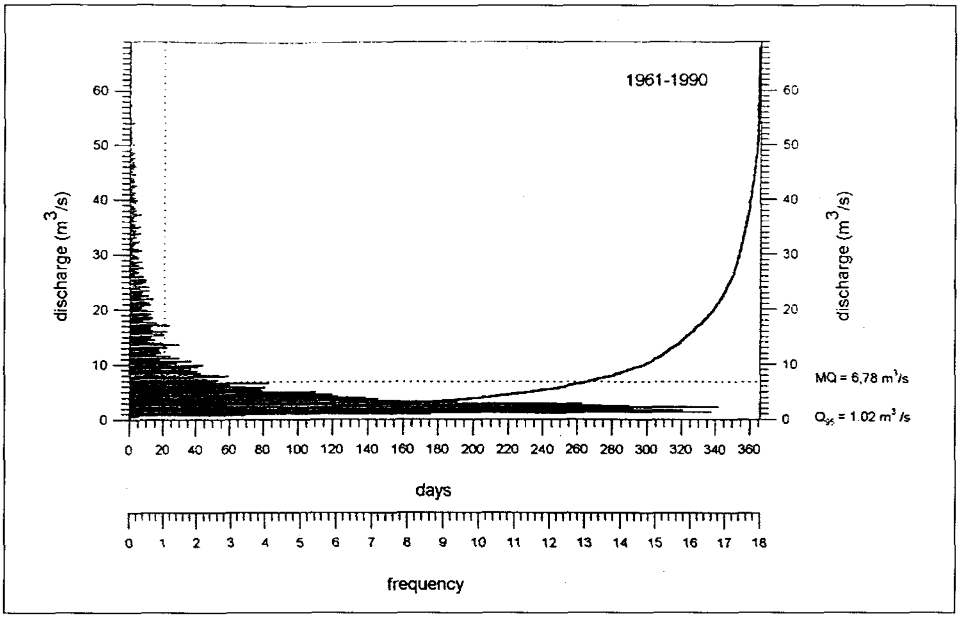


Fig. 3.18: Abscissa averaged discharge frequency diagram of Vipava springs for the years 1961 to 1990.

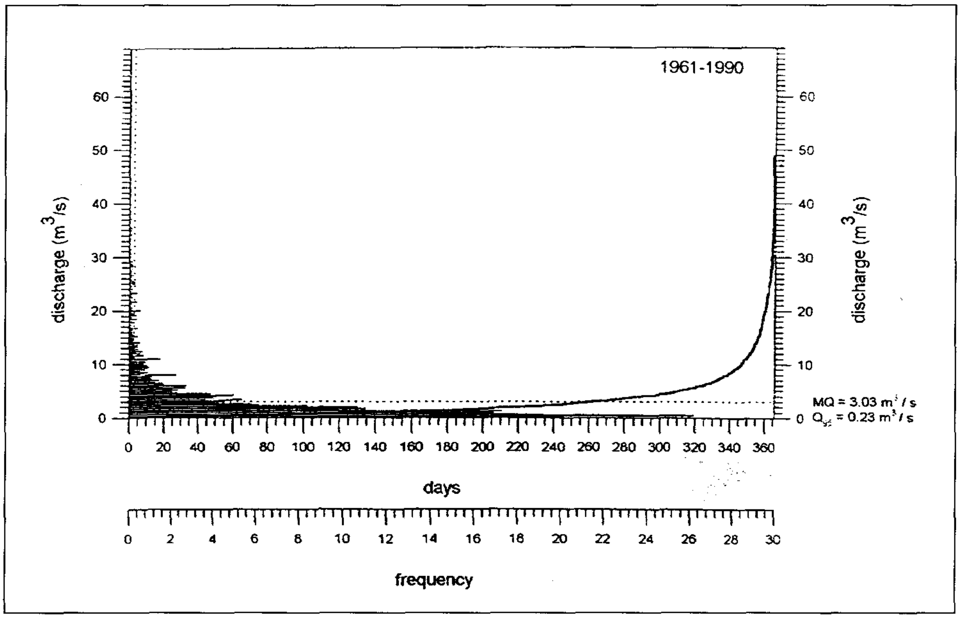


Fig. 3.19: Abscissa averaged discharge frequency diagram of Hubelj springs for the years 1961 to 1990.

- The factor of minimum to maximum discharge at the Vipava springs equals to 1:100 while this factor equals to 1:267 at the Hubelj springs.
- At the Vipava springs the Q_{95} accounts to approximately 1/7 of the MQ while at the Hubelj springs the Q_{95} accounts to approximately 1/13 of the MQ.
- The MQ at Vipava spring accounts to 1/10 of its highest discharge. At the Hubelj springs this accounts to 1/16.
- Very high discharges occur more frequently at the Vipava springs than at the Hubelj springs.
- Low discharges occur with similar frequencies at both springs. However, the range of low discharges at the Vipava springs is broader. At the Hubelj springs the low discharges occur with more changing frequencies.

The thirty year's time series were also interpreted using an autocorrelation analysis. An "investigation of sequential properties of a series by autocorrelation is already classical statistical technique. It is used to determine the linear dependence among successive values of a series that are a given lag k apart" (YEVJEVICH 1972). As the measure for the linear dependence between the two values the autocorrelation coefficient, rk is used.

The equation used for the analysis corresponds to the form proposed by Jenkins and Watts and used by (MANGIN 1984) during his analysis of three karstic flow regimes in the Pyrenees. The open-series approach was used for

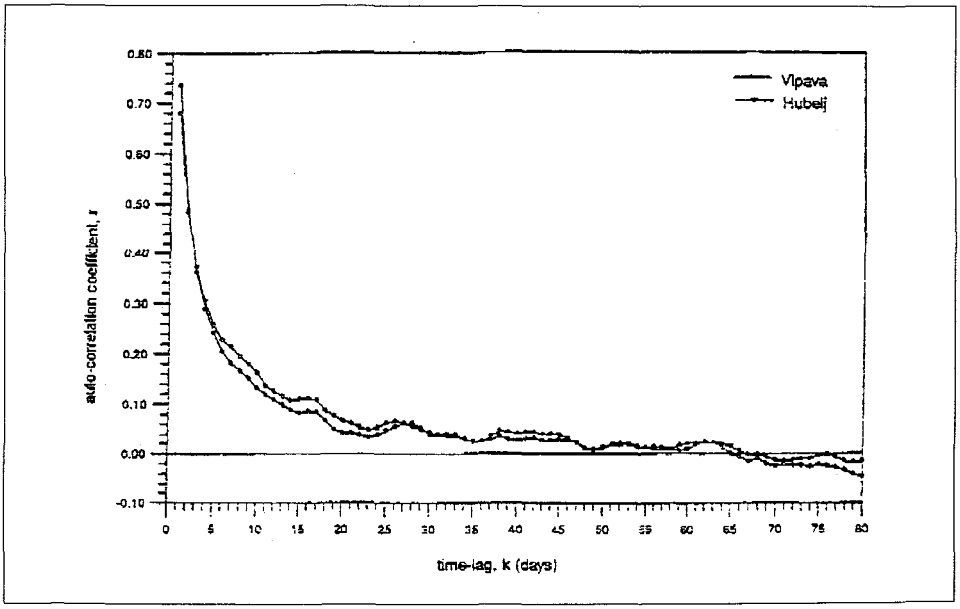


Fig. 3.20: Autocorrelation functions with time-lags 1 to 809 of Vipava und Hubelj discharges. As basis for the 30 year's time series was used.

the analysis since according to (YEVJEVICH 1972) it is not advisable to use a circular-series approach because the first and the last part of the series might be independent.

In Fig. 3.20 the results for the autocorrelation using a time lag from 1 to 80 is shown. Fig. 3.21 represents the autocorrelation functions with time-lags from 1 to 3650. The autocorrelation curves of the Vipava and Hubelj springs, considering a time lag k = 1 to 80 days, are very similar. They both show that the "memories" of the springs are bad, i.e. that the discharge depends only little on the discharge of the previous two to five days and that it is practically independent from the discharge of six or more days ago. However, Vipava shows a slightly higher k=1 autocorrelation coefficient than Hubelj. For the successive time lags the autocorrelation coefficient of Vipava drops faster. This means that the discharge of the Vipava springs is slightly higher influenced by the discharge of the previous day than in the case of Hubelj springs, while the memory of the Hubelj springs improves in comparison to the Vipava springs from the third day onwards.

The autocorrelation diagram for the Vipava and Hubelj springs with a time-lag, k=1 to 3650 shows once more that the correlation coefficients drop very fast during the first few k's. Thereafter they fluctuate sinusoidally around the zero-line.

Though their amplitudes reach only a rk of 0.08, the form of the correlation curve is interesting. It can be observed that the correlation coefficient

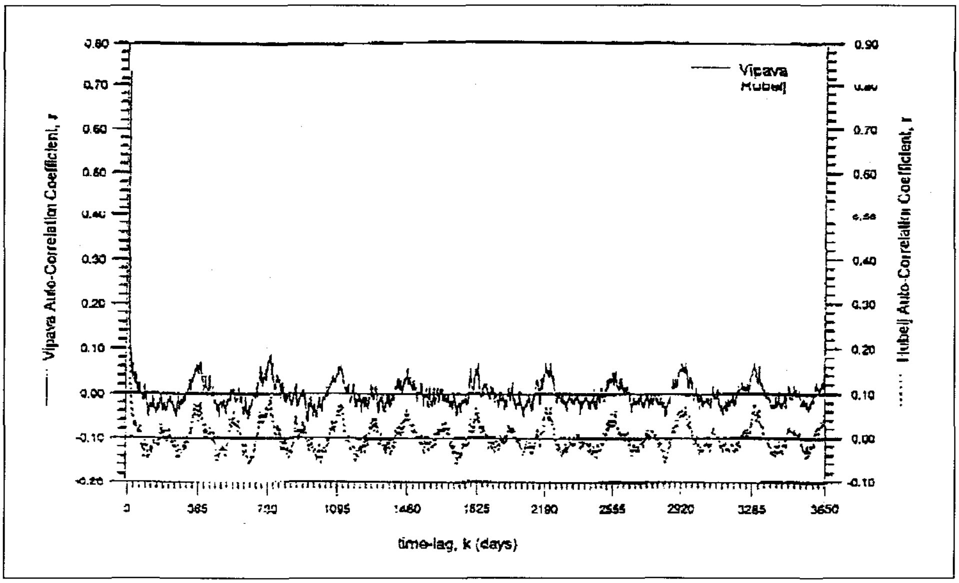


Fig. 3.21: Autocorrelation functions with time-lags 1 to 3650 of Vipava and Hubelj discharges. As basis for the 30 year's time series was used.

fluctuates with a period of exactly one year (both curves). This means that the yearly discharge values are correlated. Hence it can be supposed that the daily discharges do have a deterministic component and are not exclusively aleatory.

It is conspicuous that the Vipava springs autocorrelation curve fluctuates very little and that the Hubelj autocorrelation curve fluctuates, obviously, not only with a yearly period but also with a half-yearly period. The half-yearly amplitude though is less than for the yearly fluctuation. It actually means that the discharges of at least Hubelj springs are also correlated on a half-yearly basis, i.e.there is some sort of a relationship between the discharge today and half a year later.

Furthermore the mean discharge curves for the Vipava and the Hubelj springs were evaluated. Bases for the curves were once more the 30 years daily discharge data of the period 1961 to 1990. To emphasise on the course throughout the year a regression of the 10th grade was fitted. Additionally the 30 days running mean was calculated and plotted. The daily mean discharge curves are presented in Fig. 3.22 and Fig. 3.23. It is striking that the courses of the mean discharge curves of the two springs are identical. They both show minima in July/August and maxima in spring and autumn.

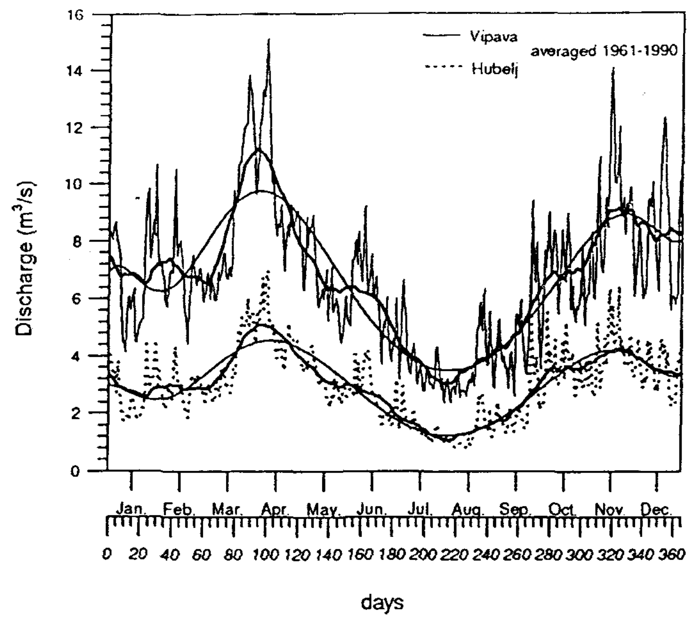


Fig. 3.22: Daily mean discharge curves of Vipava and Hubelj springs for the period 1961 to 1990. To emphasize the course a regression of the 10th grade was fitted (thin line) and the 30 days running mean plotted (bold line).

These mean discharge curves should furthermore be compared with the mean precipitation curve shown in Fig. 3.23. The following is conspicuous:

- When the main precipitation occurs, i.e. in June, the mean discharge curve drops. This might be due to the high evapotranspiration in summer.
- The increase of precipitation after the precipitation minimum in July causes an increase in the mean discharge with a delay of approximately one month.
- Though the precipitation amount drops during the winter months, the mean discharge rises to a second peak in spring. This could be due to the snow melt, i.e. water which was stored as snow comes to a discharge.

It appears though, that the amount of precipitation fallen during the autumn and winter times is too little to produce:

1. the rising mean discharge during winter time caused by rain and
2. the rising mean discharge in spring caused by the snow melt.

This can only be explained by too little precipitation measured in this period of the year. As reported by IVANCIC (1995) the Hydrometeorological Institute Ljubljana estimates the error due to wind influences during the measurements of snowfall to 50 %. This could explain where the lacking precipitation volume comes from.

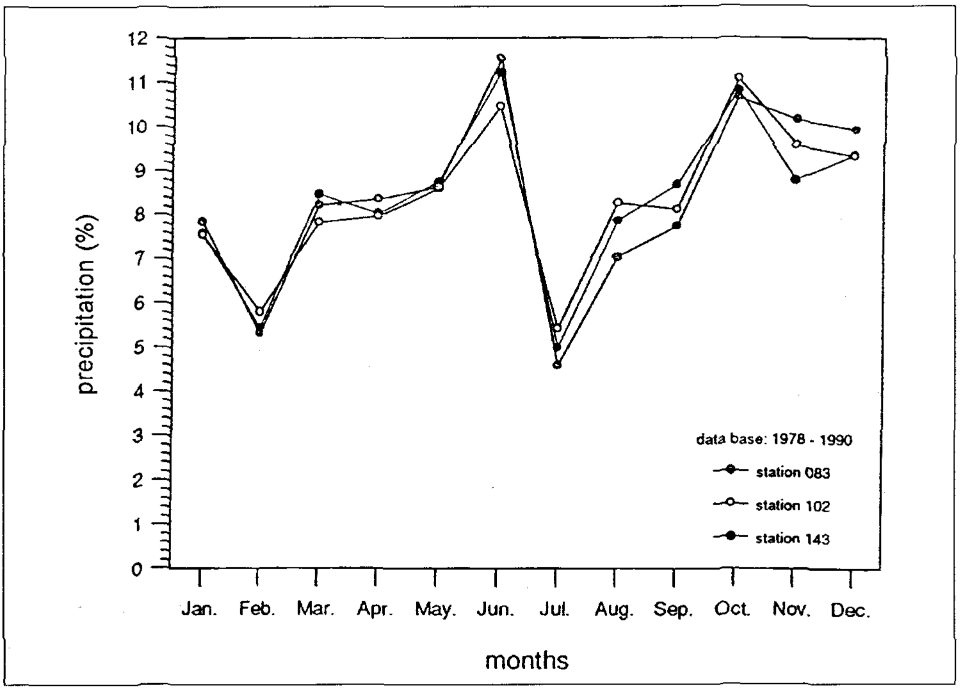


Fig. 3.23: Monthly mean precipitations as percentages of the annual mean presented for the stations 83, 102, 143. Data base is the period 1978 to 1990.

3.5.2. The Recession Curve Analysis

For both springs, the Hubelj and the Vipava springs a recession curve analysis was carried out based on the discharge data of the month July to October of the years 1961 to 1990. Aim of the analysis was to develop a master recession curve for each of the two springs.

The recession curve analysis dates back as far as 1905 when Maillet defined an analytical expression for recession curves of long-lasting dry periods (equation (3)):

$$Q_t = Q_0 \exp(-\alpha t) \qquad (3)$$

where Q_t is the discharge at time t; Q_0 is the previous discharge; t is the time elapsed between Q_0 and Q_t and a is the recession coefficient of dimension T^{-1} (FORD & WILLIAMS 1989).

Though this expression was actually designed for recession curves of porous aquifers it is widely used in karst hydrology, i.e under non-homogeneous and non-isotrope conditions. BONACCI (1987) as well as FORD & WILLIAMS (1989) have provided detailed reviews on the use of recession curves in karst aquifer analysis.

If the curve of the equation (3) is plotted semi-logarithmic (Q on the logarithmic ordinate) it is represented by a straight line with the slope $-\alpha$.

According to MARTIN (1973) a better concept to be used in hydrology is the use of the half-life of the discharge. The half-life $t_{(0.5)}$ corresponds to the time needed that the discharge is reduced by 50 %. The half-life corresponds to:

$$t_{0.5} = \ln(1/2)/\ln(\exp-\alpha) \qquad (4)$$

According to MILANOVIĆ (1976) the emptying of a karst aquifer is frequently characterised by recession curves that may be fitted by several short, straight lines, each being characterised by a different slope, hence having different recession coefficients (α_{01}, α_{02}, ..., α_{0n}). This type of recession curves reflect the complex hydrogeological characteristics of karstified rocks. Assuming the theory of the linear reservoir this complex recession curve can be mathematically expressed as:

$$Q_t = Q_{01} \exp(-\alpha_{01t}) + Q_{02} \exp(-\alpha_{02t}) + \ldots\ldots + Q_n \exp(-\alpha_{nt}) \qquad (5)$$

MILANOVIĆ (1976) also states that under the conditions of a well-developed karst system, three recession coefficients may usually be expected a good fit. The greatest reflects the rapid outflow of caves and channels, the medium the outflow of well integrated karstified fissures and the smallest the drainage from pores and narrow fissures. BONACCI (1993) states that different segments of the recession curve might not only reflect a decrease in effective porosity but may also be a result of a decrease in the catchment area.

He showed a such caused decrease due to the decrease of the underground hydrogeological catchment area at three springs down the Neretva river in the Dinaric karst (BONACCI 1993).

The aim of recession curve analysis is to derive a characteristic recession of a particular discharge region. One of the problems most often encountered during such an analysis is the high variability encountered in the recession behaviour of individual segments. A physically based short-term or seasonal variation in the recession behaviour adds to the problem of deriving a characteristic recession (TALLAKSEN 1995). According to TALLAKSEN (1995) the master recession methods try to overcome the problem by constructing a mean recession curve. This is then known as the master depletion curve. All the information on variability is lost in this type of curve. There exist several methods of deriving a master recession curve. (McCUEN 1989) describes simple procedures to derive the master depletion curve. One, the analysis of covariance method, is described by BAKO & OWOADE (1988) for a field application. BONACCI (1993) states that in karst areas the last section of the recession curve (on semi-logarithmic presentation) actually represents the master depletion curve. He furthermore concludes that this latter section of the recession curve is significant and that its function is to define and predict the behaviour of the remaining groundwater reserves during drought periods.

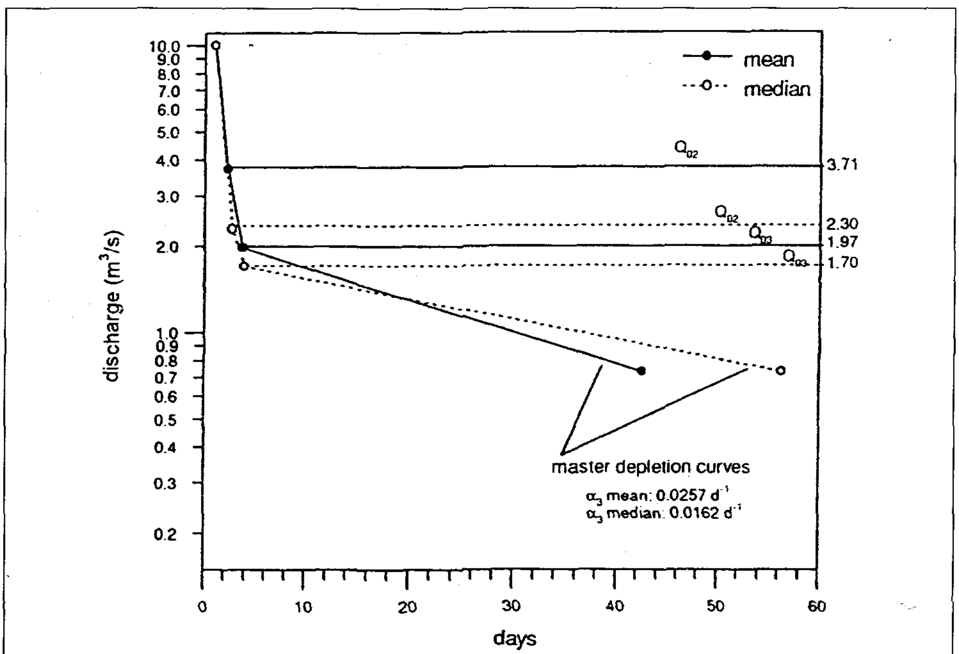


Fig. 3.24: Mean and median recession curves for Vipava, obtained by the results generated by the program FIEBEL assuming a starting discharge for reservoir 1 of 10 m^3/s.

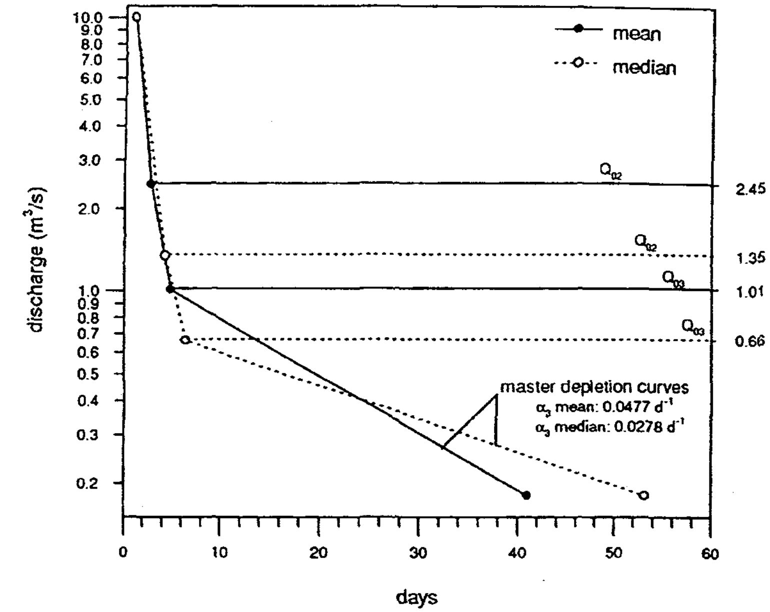


Fig. 3.25: Mean and median recession curves for Hubelj, obtained by the results generated by the program FIEBEL assuming a starting discharge of 10 m^3/s for the first reservoir.

The master depletion curve was determined on the basis of long term valuations of recession parameters. For this purpose an objective programme, called FEIBEL was used (SCHUMANN 1995). It automatically selects the recession branches to be used for the analysis according to the following criteria:

1. They have to begin underneath the mean discharge and have a length of at least 8 days.
2. The discharge values need to reduce continuously (error limit being 5%)
3. The second discharge value of a beginning recession branch needs to be really smaller than the first one (i.e. the error limit is only valid from the third discharge value onwards).

Since using this method one gets for each recession branch considered one a-value, out of these one representative a-value needs to be calculated. This has been done by using the mean and the median values. The results of the recession curve analysis are shown in Tab. 3.12 (Vipava) and Tab. 3.13 (Hubelj) as well as in Fig. 3.24 (Vipava) and Fig. 3.25 (Hubelj).

Tab. 3.12: Results obtained for the spring Vipava, using the program FEIBEL.

		no. of branches	α	range of α	mean starting Q	half life [days]	volume [m³]
mean	α_1	3	0.7951	0.6288	?	0.9	-
	α_2	113	0.4164	1.1895	3.71	1.7	-
	α_3	164	0.0257	0.1835	1.97	27.0	$6.62 * 10^6$
median	α_1	36	0.8605	1.4291	?	0.8	-
	α_2	146	0.2595	0.8607	2.30	2.7	-
	α_3	164	0.0162	0.1835	1.70	42.8	$9.07 * 10^6$

Tab. 3.13: Results obtained for the spring Hubelj, using the program FEIBEL.

		no. of branches	α	range of α	mean starting Q	half life [days]	volume [m³]
mean	α_1	10	0.7944	1.1609	?	0.9	-
	α_2	93	0.4360	1.1895	2.45	1.6	-
	α_3	167	0.0477	0.2834	1.01	14.5	$1.80 * 10^6$
median	α_1	28	0.6253	1.0785	?	1.1	
	α_2	134	0.3287	0.7463	1.35	2.1	
	α_3	167	0.0278	0.2834	0.66	24.9	$2.05 * 10^6$

Both tables Tab. 3.12 and Tab. 3.13 show for each reservoir the number of branches used for the calculations, the calculated a-values, the range of the occurring a-values, the mean starting discharge of the recession branches, the half-life according to the a-value and the volume of groundwater left above the spring water level when the reservoir begins to empty. The volume was only calculated for the third recession branch as the calculation of the volume presumes diffuse flow. This is only valid during the low flow period i.e. when the last reservoir is exclusively discharging. The tables do not allow a conclusion which calculation procedure (mean or median) is the better one. However, it can be stated that range of a decreases for the second and first reservoir when the median is used to determine the representative a. Furthermore a higher number of branches are left to calculate the recession coefficients of the second and first reservoir as the values for the representative a and mean starting discharge are lower when using the median as the representative recession values. From the statistical point of view the median value is to be preferred, hydrologically though it can not be decided which value is the more appropriate.

It is striking that the volume of water left above the spring water level in the aquifer of Vipava is about four times larger than the volume of the water left in the aquifer of the Hubelj springs. This could be due to:

- A higher effective porosity in the Nanos karst aquifer than in the Trnovski Gozd karst aquifer.
- A greater thickness of the high water stand zone above the spring water table in the Vipava springs aquifer than in the Hubelj springs aquifer.
- A greater 'surface area' of the high water stand zone of the Vipava springs aquifer than the Hubelj springs aquifer.

Fig. 3.24 and Fig 3.25 show the results obtained in a graphical form. The starting discharge of 10 m^3/s for the first reservoir is assumed to visualise the situation. The lowest discharges correspond to the springs' minimum discharges of the period 1961 to 1990.

They primarily show that for the first and second reservoirs of the spring groups do not exist remarkable differences when considering the ranges of the occurring α-values. The recession coefficients of the two reservoirs are alike, hence their half-lives. A statement to the first reservoir should anyway be made very carefully as the number of recession branches left over for the analysis, (using the mean values) was with 3 and 10 very low. But still it might be stated that the median recession coefficients are alike. A difference in the mean starting discharges can be noted. For the Vipava springs the mean starting discharge (of the mean and median calculation procedure) of the second reservoir (i.e. when the first reservoir stops emptying and the second reservoir becomes the dominating one) is about 1 m^3/s higher than for the Hubelj springs.

A different situation can be observed for the outflow of the third reservoir. The mean starting discharge for the exclusive outflow of this reservoir, which corresponds to the base flow generating reservoir is about 1 m^3/s lower at the Hubelj springs than at the Vipava springs. This is about the same situation as for the second reservoir. In both cases this correspond to approximately 2/7 of their MQ's. The recession coefficients, however, for these third reservoirs are remarkably different for the two spring groups Vipava and Hubelj. The Vipava recession coefficients (mean and median values) are close to half of the Hubelj springs recession coefficients. Hence the half-life for the Vipava springs is about double the half-life of the Hubelj-springs. Assuming that these master depletion curves are exclusively a result of diffuse flow this situation allows two possible interpretations:

- The hydraulic gradient at the Vipava springs is smaller than at the Hubelj springs.
- The permeability of the aquifer discharged by the Vipava springs is smaller than the permeability of the aquifer discharging the Hubelj springs. A very high hydraulic gradient of the underground water behind the Hubelj springs is confirmed by (HABIČ 1985 as quoted in JANEŽ 1994) but no explicit statement has been made on the hydraulic gradient of the underground water behind the Vipava springs.

3.6. THE ELECTRICAL CONDUCTIVITY AS INDICATOR FOR HYDRODYNAMIC PROCESSES IN THE VIPAVA SYSTEM (T. HARUM, H. STADLER, N. TRIŠIČ)

3.6.1. Measuring Equipment

In Vipava dataloggers were installed at the spring 4/7 (water level, electrical conductivity and temperature), 4/3 (conductivity and temperature) and at the gauging station for total runoff (4/8, conductivity and temperature). The discharge of the Vipava springs is being measured at two gauging stations: springs 6-4/7 and total runoff 4/8. Therefore it is only possible to separate two groups concerning the discharge of the 4/7 main outlets. The group of the springs 4/1 to 4/5 can be calculated as the difference between the total discharge of no. 4/8 and the measured discharge of the springs no 4/6 and 4/7 (compare Chapter 4, Fig. 4.12). The conductivities are compensated to 25° C, temperature effects can be neglected.

The dataloggers measured every 5 minutes and stored an average value every 15 minutes. The gauging station no. 4/8 is being equipped with a water level recorder by HMZ Ljubljana, long-time series from 1960 - 1995 are available.

3.6.2. Suppositions and Methodological Aspects

The discharge of karstic spring consists of different components with different residence times in the aquifer. Usually it can be separated into two components, which are termed **base flow** and **direct flow** corresponding to their different residence time and flow behaviour. The direct flow component represents the portion of water infiltrated from precipitation, which flows directly with short retardation through the main channels in the karst system to the spring. The base flow component consists of water stored in microfissured zones of the the aquifer over a longer time.

The conventional hydrograph separation procedures using the exponential function after MAILLET (1905) and extrapolating this depletion function back under the peak of the total hydrograph allow an approximate separation of the two components base flow and direct flow (s. Chapter 3.5). This method gives only information about the hydraulic behaviour of the aquifer (MÜLLER & ZÖTL 1980; BEHRENS et al. 1992). The volumes of reservoir water calculated are corresponding to the volume of mobile water, not including temporarily stagnant water, i.e. water, which can only be discharged by hydraulic stimulation under increasing hydraulic head.

Contrary the measurement of natural tracers as stable isotopes and chemical parameters of input and output gives the possibility of estimating the portions of **older reservoir water** and **event water** discharged at the spring and provides information about the mixing and solute transport processes in the aquifer. The water volumes calculated by means of natural tracers include the volume of temporarily stagnant water in the system and are not directly comparable with the volumes of direct and base flow components computed by the classical hydraulic separation method. For hydrogeological investigations it has to be emphasised to include both methods due to their complementary information about the aquifer characteristics.

Therefore and contrary to the assumptions in Chapter 3.5. and according to previous investigations of the ATH-group in Karst aquifers of the Swiss Jura (MÜLLER et al. 1980) and of the Lurbach system (BEHRENS et al. 1992) it is important to emphasise the difference between

"older" reservoir water ≠ base flow and event water ≠ direct flow.

Assuming the existence of only two discharge components, they can be separated combining the simple mixing equations

$$Q_T = Q_E + Q_R \quad (6)$$

and

$$Q_T * C_T = Q_E * C_E + Q_R * C_R \quad (7)$$

to

$$Q_R = Q_T * (C_T - C_E)/(C_R - C_E) \quad (8)$$

where Q_T = Total discharge at the spring in l/s
Q_R = "Older" reservoir water in l/s
Q_E = Event water component in l/s
C_T, C_R, C_E = Corresponding tracer concentrations

The following suppositions have to be taken into account (HARUM & FANK 1992):

1. Sudden input of event water into the aquifer.
2. Significant differences in the contents in input and output.
3. No physical, chemical or biological reactions of the tracer during the transport in the aquifer.
4. Negligible or well known fluctuations in the background concentrations.
5. Exact measuring of discharge and tracer concentration.
6. Especially in karst systems as the Vipava aquifer sufficiently short interval of the measurements.

For most of the "ideal" tracers as the stable isotopes ^{18}O, ^{3}H and some chemical parameters as i.e. Mg^{++}, NO_3^- and SO_4^- the exact determination of the time-concentration curves is hindered due to economic problems (especially in karstic regions with a quick response of discharge to precipitation events short sampling interval are necessary causing a high amount of expansive analyses). The electrical conductivity represents only a measure for the total mineralization, but it is has the big advantage that it can be measured on-line with relatively high accuracy. The disadvantage is that the dilution of certain chemical parameters due to the lower mineralised precipitation water is overlaid by increasing concentrations of other ions due to processes of out-washing of dunging substances and solution during the passage of the infiltrated precipitation water through the unsaturated zone (BEHRENS ET AL. 1992; HARUM et al. 1990; HARUM & FANK 1992; KENNEDY et al. 1986). Therefore the electrical conductivity cannot be considered as an ideal tracer, but the the analysis of the exactly recorded time series of discharge and conductivity can give approximate ideas of the processes of solute transport and mixing in the aquifer during the underground passage. Assuming that a part of infiltrated water is flowing directly without greater retardation and without processes of solution through karst channels to the outlets, the conductivity can be used for an estimation of the portion of this quick flow component (called event water) on the discharge of the springs and allows a relative comparison of the hydrodynamic behaviour of springs.

3.6.3. Separation of the discharge components

3.6.3.1. Analysis of long-term fluctuations of the runoff year 1995

For the year 1995 discharge and conductivity data exist for the springs Vipava 4/6 - 4/7, 4/8 (total discharge) and partly 4/3. The discharge of the spring group 4/1-4/5 can be calculated by the difference between Vipava 4/8 and 4/6-4/7. For the analysis of the data mean daily values of discharge and conductivity were used.

The first step is a comparative analysis of the different springs. In Fig. 3.26 the weighted means over 30 days are plotted compared to the weighted discharges. It is clearly visible that the total discharge Vipava 4/8 and spring 4/3 have nearly the same fluctuations of conductivity, whereas the graph of Vipava 4/7 shows significant differences which are probably due to the partly different recharge area (mixing with karst water coming from the Bela creek (sinkhole downstream of the village of Sanabor) as indicated also by the results of the tracer experiment). The similarity of the EC-fluctuations of total discharge (4/8) and spring 4/3 indicate that the springs group 4/1-4/5, which represents the greatest part of the total discharge at the gauging station have nearly the same regime. This conclusion is also confirmed by the results of the tracing experiment and short-term conductivity measurements by data loggers at the other springs. Therefore the EC-values of spring 4/3 (no measurable discharge) are assumed to be representative for the group 4/1-4/5.

It is visible in Fig. 3.26 that the EC-curve measured at the total discharge shows sometimes stronger dilution effects. This effect can be explained by a

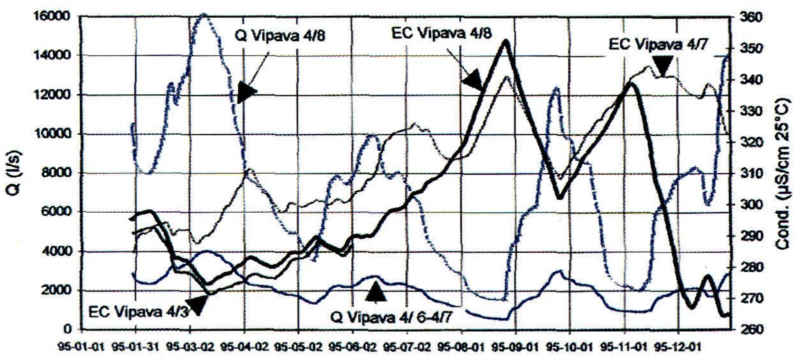


Fig. 3.26: Weighted means over 30 days of discharge and electrical conductivity of the Vipava springs 4/3 (representative for the group 4/1-4/5), 4/7 and the total runoff at the gauging station (4/8).

certain portion of surface water originating from local precipitation events in the village of Vipava (water from roofs and streets) which is situated upstream of the gauging station.

For the long-term analysis of the different discharge components it has to be taken into account that the background conductivity CB of the longer stored reservoir water in a karst aquifer has seasonal variations which have to be included in the mixing equation mentioned above. Therefore it was assumed, that the highest monthly conductivity values are representative for the "older" reservoir component.

The input concentration CE was assumed to be constant with a mean conductivity of CE = 30 μS/cm 25 °C. Variations of it of ± 10 μS/cm give no significant differences in the results.

From spring 4/3 only conductivity data from the first 6 months of the year 1995 exist. But a correlation analysis of the measured total discharges QT and computed reservoir discharges QR indicated a strong linear relation between both parameters. Therefore and for the reason of a comparison of the results of one annual runoff period the missing values could be estimated with sufficient accuracy using the linear regression equation in Fig. 3.27.

The results of calculations are plotted in Fig. 3.28 (total discharge Vipava 4/8), Fig. 3.29 (Vipava 4/6-4/7) and Fig. 3.30 (Vipava 4/1-4/5). All values are daily means except the background conductivity of the "older" reservoir water (highest monthly values). The discharge hydrographs are plotted in comparison to the event water component computed by the mixing equation.

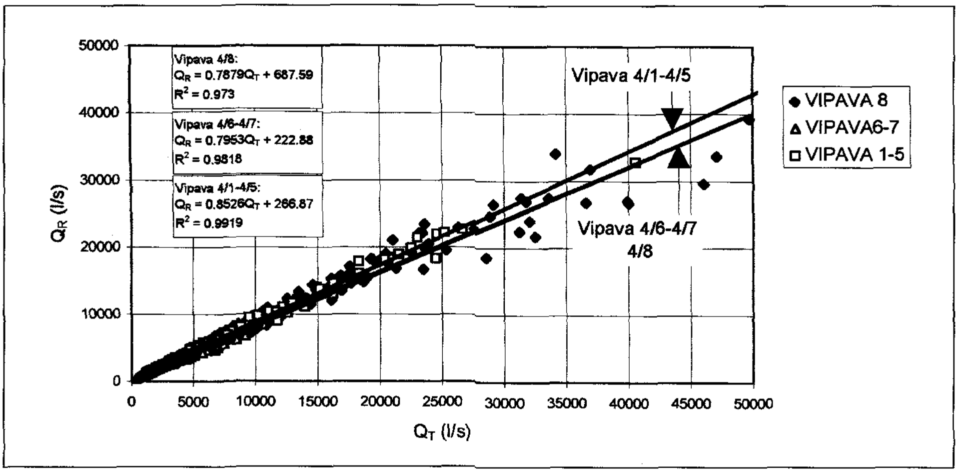


Fig. 3.27: Relation total discharge Q_T to reservoir component Q_R for the Vipava springs.

The results indicate for all springs that during flood events the greatest portion of discharge consists of "older" reservoir water. The portions of "young" event water, which are plotted in Fig. 3.31, reach maximum 27 % at the springs and 36 % at the gauging station Vipava 4/8, where surface water from roofs and streets in the village of Vipava is drained to the Vipava river. The mean annual portion of event water of the total discharge is only in the range of 10 % for the springs and 12 % at the gauging station including

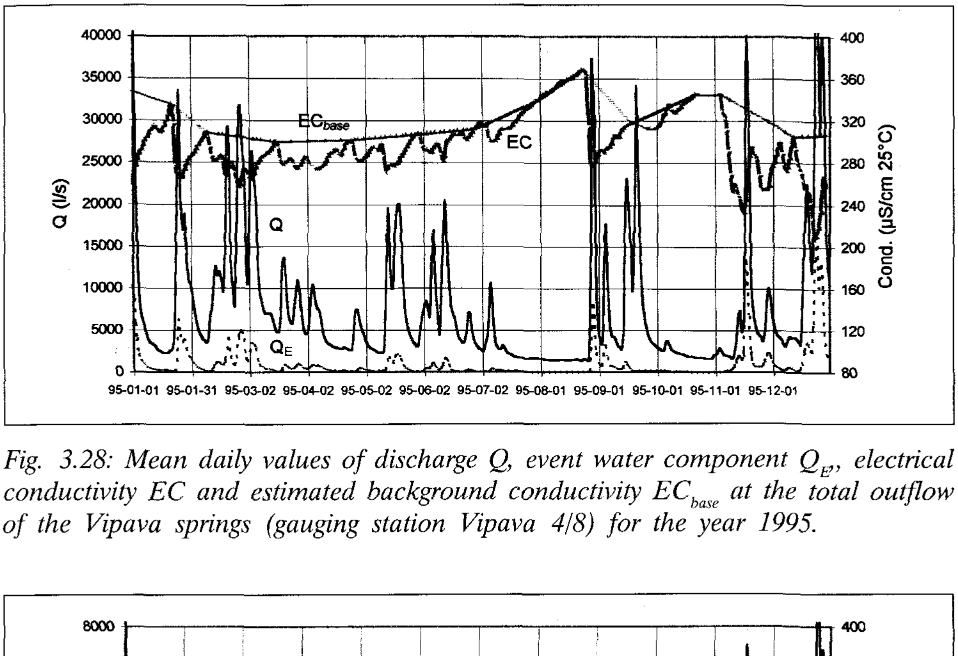


Fig. 3.28: Mean daily values of discharge Q, event water component Q_E, electrical conductivity EC and estimated background conductivity EC_{base} at the total outflow of the Vipava springs (gauging station Vipava 4/8) for the year 1995.

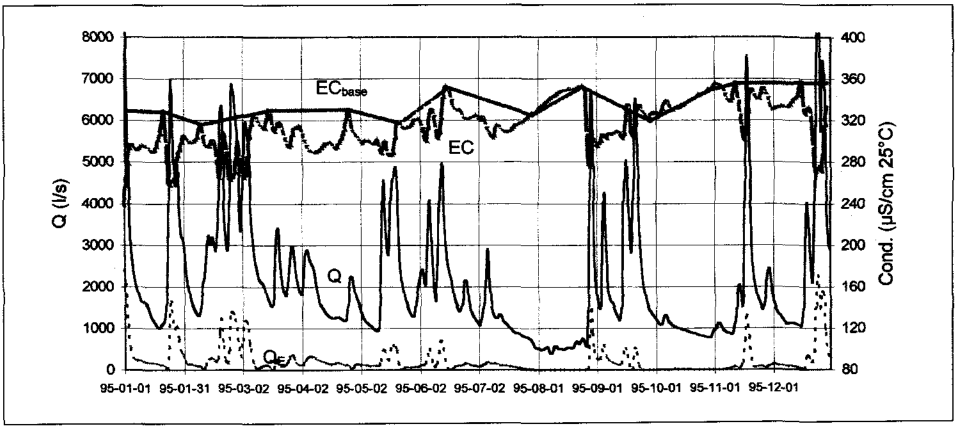


Fig. 3.29: Mean daily values of discharge Q, event water component Q_E, electrical conductivity EC and estimated background conductivity EC_{base} at the spring Vipava 4/7 (discharge = Vipava 4/6 - 4/7)) for the year 1995.

surface water. At higher discharges the spring group 4/1-4/5 seems to have a higher portion of "older" reservoir water, a fact, which is probably due to the greater distance of permanently active sinkholes. These results agree well with those of the isotope investigations (Chapter 5.), where the portion of event water on the discharge of the Vipava springs was calculated as 21 % for selected single events.

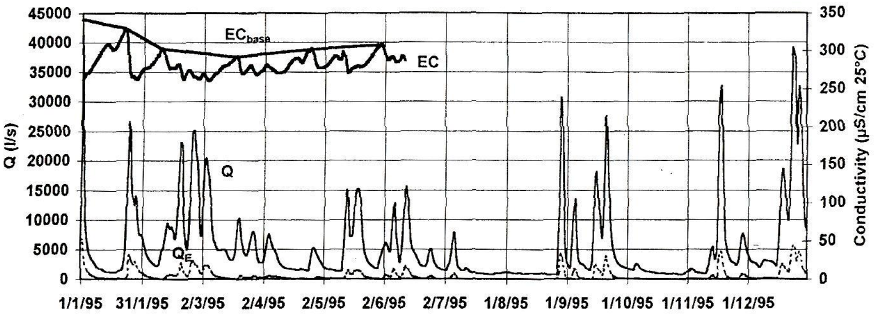


Fig. 3.30: Mean daily values of discharge Q, event water component Q_E, electrical conductivity EC and estimated background conductivity EC_{base} at the springs Vipava 4/1-4/5 (EC measured at Vipava 4/3) for the year 1995. The event water components Q_E from June to December 1995 where calculated using the linear regression equation in fig. 3.27.

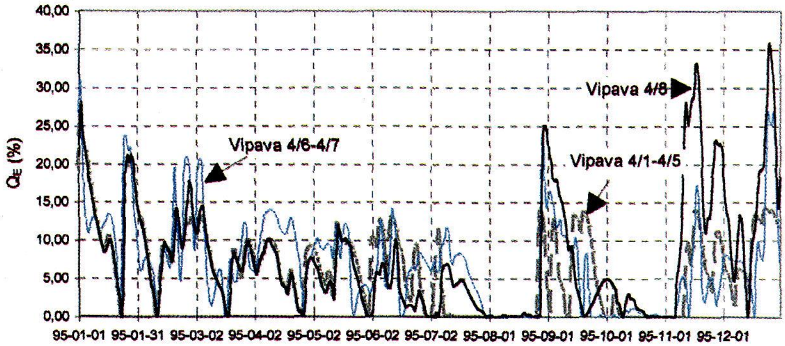


Fig. 3.31: Mean daily values of the event water component Q_E for the springs Vipava 4/6-4/7, 4/1-4/5 and the total runoff at the gauging station Vipava 4/8 for the year 1995.

The water volumes, mean annual discharges and portions of the reservoir components are summarised in Tab. 3.14. They underline the great importance of the "older" reservoir water component, which is stored over a longer time.

Tab. 3.14: Water volumes of the discharge components at the Vipava springs for the year 1995.
V_T = total volume, V_R = older reservoir water, V_E = event water.

		V_T	V_R	V_E
VIPAVA 4/8	m^3/y	$2.46\ 10^8$	$2.16\ 10^8$	$3.06\ 10^7$
	l/s	7813	6843	970
	%	100.0	87.6	12.4
VIPAVA 6-4/7	m^3/y	$6.80\ 10^8$	$6.11\ 10^7$	$6.89\ 10^6$
	l/s	2157	1938	219
	%	100.0	89.9	10.1
VIPAVA 4/1-4/5	m^3/y	$1.78\ 10^8$	$1.60\ 10^8$	$1.87\ 10^7$
	l/s	5656	5062	597
	%	100.0	89.5	10.5

3.6.3.2. Analysis of single events

In Fig. 3.32 the measured discharges and conductivities of the springs 4/3 and 4/7 and the gauging station (4/8) are plotted for three selected events (period October 25th to December 26th, 1994). The values of the discharge of the spring group 4/1 - 4/5 were calculated as difference between total runoff and runoff of the springs 6 and 4/7. It shows, that the graph of conductivity of spring 4/7 differs fundamentally to the two other, especially during flood events. The reason is probably, that the discharge of this spring consists of two

components, one draining the same catchment as the springs 4/1-4/5, the other containing a portion of water from the region of the Bela sinkhole near Sanabor. The conductivity of spring 4/3 is very similar to the conductivity at the gauging station of total runoff (4/8), which proves the assumptions of Chapter 3.6.3.1. that springs 4/1-4/5 drain the same well mixed drainage system and the conductivity of spring 4/3 is representative for this group. Their discharge is the main component of the total runoff measured at the gauging station (4/8).

The three flood events plotted in Fig. 3.32 show different responses of the total mineralisation represented by the electrical conductivity. The first two events with higher discharge peaks are characterised by different reactions of springs 4/1-4/5 and 4/7. At the group mentioned first the conductivity at the first event on October 1st, 1994 increases in a significant way with increasing discharge which proves that at first "older" reservoir water with higher mineralization is discharged hydraulically stimulated by the flood. The dilution starts about 5 h after the beginning of increasing discharge and reaches its maximum approximately one day after the discharge peak.

Contrary to group 4/1-4/5 the dilution starts at Vipava 4/7 with short retardation indicating the quicker outflow of low mineralised event water at the spring. Probably this is the portion of water from the Bela creek with an active sinkhole downstream of the village Sanabor, which is the nearest punctual input to the Vipava springs.

The same phenomena can be observed for the second flood event with comparable discharge peaks.

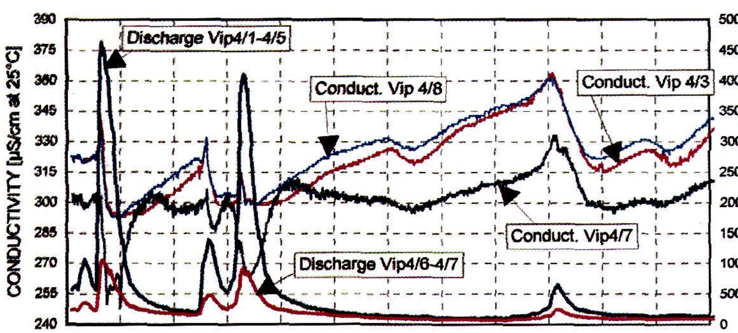


Fig. 3.32: Discharge and electrical conductivity of the Vipava springs 4/1-4/5, 4/6-4/7 and the total runoff at the gauging station (4/8) during three flood events in autumn 1994.

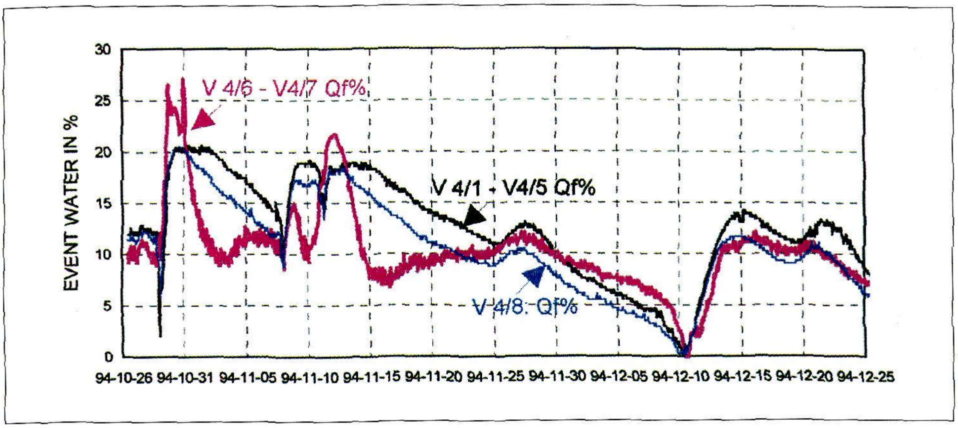


Fig. 3.33: Event water component Q_E, for the springs Vipava 4/6-4/7, 4/1-4/5 and the total runoff at the gauging station Vipava 4/8 during three flood events in autumn 1994.

The third event with lower discharges at all springs shows a completely different hydrodynamic behaviour. Due to the slower increasing discharge dilution starts with higher retardation, Piston effects are not so clearly visible.

In Tab. 3.15 the results of the calculations, based on the mixing equation (Chapter 3.6.2.) are summarised. An input concentration of 20 μS/cm (25 C) and a stable background conductivity were assumed. The values are calculated for the time from 26.10.1994 to 25.12.1994.

In Fig. 3.33 the calculated event water in % of the total discharge is plotted for the groups Vipava 4/1-4/5, Vipava 4/6-4/7 and Vipava 8. It shows, that the hydrograph of Vipava 4/6-4/7 differs from the two other groups especially during and after the events at the end of October and in November. The part of event water decreases below 10 % in two days. At Vipava 4/8 and Vipava 4/1-4/5 the decrease of event water under 10 % lasts 12 days.

These two events in October and November 1994 show different hydrographs between the groups of Vipava springs. The event at Dec. 11th shows a similar shape of the time series for all groups. This small flood event increases the discharge of "older" reservoir water, the increase of event water starts after the discharge peak. This means, that the infiltrated precipitation water does not directly contribute to the discharge, but increases the discharge by hydraulic stimulation due to the increasing water head in the karst aquifer. Greater events increase the discharge partly directly.

Tab. 3.15: Water volumes of the discharge components at the Vipava springs for three single flood events in autumn 1994. V_T = total volume, V_R = older reservoir water, V_E = event water.

MAXIMUM VALUES of Background 26.10.94 12:00 bis 27.10.94 23:00			
Input Conductivity:		20	µS/cm at 25°C
Backgr V4/3	MAXIMUM	364	µS/cm at 25°C
Backgr V4/7	MAXIMUM	333	µS/cm at 25°C
Backgr V4/8	MAXIMUM	362	µS/cm at 25°C
VOLUMES in ml			
	VT	VR	VE
Vip4/3	26 546 408	22 594 783	3 951 626
Vip4/7	10 790 000	9 412 808	1 377 192
Vip4/8	37 336 398	32 177 979	5 158 419
VOLUMes in %			
	VT	VR	VE
Vip4/3	100.0	85.1	14.9
Vip4/7	100.0	87.2	12.8
Vip4/8	100.0	86.2	13.8

The results for single events are well comparable with those of the isotope (Chapter 5.) and of hydrodynamic investigations (Chapter 3.6.3.1.). They indicate the important role of "older" reservoir water which is stored for longer time in the great catchment area of Vipava. Even during high flood events the greater portion of discharge consists of "older" reservoir water.

3.6.4. Reservoir water volumes and aquifer characteristics

The isotope investigations (Chapter 5.) indicate a mean transit time for the Vipava springs of T_m = 4.4 months. The total volume of reservoir water can be calculated using the equation (9):

$$V_R = T * MQ = 8.91 \cdot 10^7 \ m^3 \qquad (9)$$

The total aquifer volume of the Vipava catchment including the unsaturated zone can be estimated by the following equation (10):

$$V_A = A * (H_m) = 1.12 \cdot 10^{11} \ m^3 \qquad (10)$$

where Hm = 800 m = roughly estimated mean thickness of the karstified rocks,
A = 139.4 km^2 = estimated surface of the recharge area.

On this basis the effective porosity Ne referring to the total volume of mobile water (including portions of periodically stagnant water mainly in the unsaturated zone can be estimated (11) as:

$$Ne = V_R \ / \ V_A = 0.08 \ \% \qquad (11)$$

On the basis of the α-values (from the analysis of discharge recessions after MAILLET (1905, s. Chapter 3.5.) the freely dischargeable volume can be estimated (12) as

$$V_{fd} = MQ * 86.4 \ / \ \alpha = 9.83 - 3.35 \cdot 10^7 \ m^3 \qquad (12)$$

giving with α-values between 0.00687 and 0.0201 d^{-1} (Chapter 3.5.) an effective porosity (N_{efd})of

$$N_{efd} = V_R \ / \ V_{fd} = 0.03 - 0.09 \ \%. \qquad (13)$$

In contrast to the analysis of discharge recessions including only the water volume which can flow out without hydraulic stimulation the volume computed by modelling of the isotope data includes also temporarily stagnant water which can only be discharged under increasing hydraulic head. Therefore the water volumes computed from isotope data usually give significantly higher results than those of the discharge recessions. Taking into account the high thickness of the unsaturated zone of the karst massif (up to 1000 m) and the fact that the volume of greater flow channels in karst massifs is usually significantly smaller than the volume of the microfissured less permeable zones

much higher values of VR corresponding to a higher effective porosity are expectable.

Furthermore the water volume calculated from the discharge recessions gives always a too low volume and effective porosity. The reason is, that the discharge recession periods without input due to precipitation or snow melt are usually too short in humid climates such as in the area under investigation. As it was also the case in previous investigations of the ATH-group in the karst of Lurbach system even the longest discharge recessions include still parts of the karst reservoir with a steeper recession limb which do not reflect the depletion function of the reservoir parts with the highest storage capacity (BEHRENS et al. 1992). The comparison of the similar depletion coefficients of the karst systems of Lurbach aquifer (BEHRENS et al. 1992) and Vipava with those computed from long discharge recession limbs of karst springs in the semiarid climate of Central and Eastern Peloponnesus (MORFIS & ZOJER 1986) shows that the depletion coefficients of these springs mentioned at last are partly about 10 times lower during the long dry season reflecting the depletion characteristics of the reservoir parts with higher storage capacity more significantly.

The drainage systems of the karst springs of Vipava are partly well comparable with those of the springs in the Lurbach area (BEHRENS et al. 1992), both draining mainly forested plateaux with a soil cover and a high thickness of the unsaturated zone (Lurbach: 300 - 350 m, Vipava: 1000 m) and both having a portion of water from permanently active sinkholes which is drained with short residence time through larger karst channels to the springs (compare Chapter 6).

The investigations in the Lurbach system showed, that only a small amount of precipitation water infiltrating on the forested karst plateau reaches with shorter residence time the flow channels of the saturated zone. Tracing experiments with injections in dolines on the plateau gave in spite of the long observation period only recovery rates in the range of 2 - 3 % (BEHRENS et al. 1992). The mean residence times of the water from the unsaturated zone computed by modelling of the Tritium data (40 years for water from the unsaturated zone, 20 years for the total flow of the main spring including an important component of quick channel flow) confirm that a high portion of precipitation water infiltrated on the karst plateau is being stored over a longer time in microfissured zones, fine-clastic cave sediments and in periodically inactive cave parts. The isotope investigations in Vipava indicate only a mean transit time of 4.4 months in spite of the 10 times greater recharge area and the higher thickness of the unsaturated zone.

The total volume of water stored in the Lurbach karst massif computed by the isotopic investigations corresponds to a total porosity of 4.9 % (BEHRENS et al. 1992), in the Vipava system only 0.08 %. The analysis of discharge recessions from the Lurbach springs gives with α-values similar to

Vipava a 93 times smaller volume comparing to the total water volume (at Vipava nearly the same or maximum 1.5 times smaller) corresponding to a an effective porosity comparable to Vipava (< 0.1 %).

The contradiction of these results can be explained as follows:

1. The mean transit times of the Vipava system are underestimated due to the relatively wet years of the investigation period. Therefore the component of reservoir water stored over long time mainly in the thick unsaturated zone is "hidden" by young water coming from the frequent precipitation events. In this case the mean transit time of 4.4 months calculated from the stable isotope ^{18}O (Chapter 5) is mainly representative for the younger component (precipitation water which reaches the karst channels in short time). An important portion of water is stored over very long time (some decades) mainly in the thick unsaturated zone. Its tritium concentration (Chapter 6) does not correspond to the actual one in the precipitation but to a mixing to very old infiltrated water with low tritium contents.
2. The volume of water stored in the unsaturated zone in microfissures and in the vegetation covered soil is of less importance. It means that in the great catchment area of the Vipava springs quick channel flow is predominant. This explication seems to be plausible comparing to other investigations

4. HYDROCHEMICAL INVESTIGATIONS

4.1. LONG-TERM OBSERVATIONS (M. ZUPAN)

The main purpose of the long-term observations was to collect the data about physical and chemical properties of the springs. On the basis of the collected physical, chemical and geological data we intended to estimate the background characteristics of the springs.

In twelve springs at the food of Trnovsko Banjška plateau monthly sampling and analyzing was carried out for two years.

In the two main springs, Hubelj and Vipava (4/2), weekly samples had been taken. In the Hubelj the sampling lasts from March 1993 to May 1996 while in the Vipava from July 1993 to May 1996.

From September 1995 to February 1996 daily samples have been taken in the springs Hubelj, Vipava and Mrzlek. The aim of this investigation was to define the changes of physical and chemical parameters depending on the water quantity more detail.

In November 1995 the water pulse of the Vipava spring 4/2 was observed to estimate the changes during discharge increasing.

In the spring Hubelj continuous measuring of temperature, pH value and conductivity was performed during entire investigation period. In the springs Vipava more extensive measurements of mentioned parameters last from September 1995 till February 1996. The precipitation was observed on 5 sampling sites from January 1993 to December 1995.

4.1.1. Monthly observations of water of the karst springs and selected rivers (J. KOGOVŠEK)

For two years observations, measurements and analyses were undertaken by sampling approximately once per month, the springs at the border of Trnovsko-Banjška Planota: Vipava, Hubelj, Lijak at overflow, Mrzlek, Kajža, Hotešk, and Podroteja, and also Prelesje and the rivers Soča, Bela and Belščica. Altogether 24 series of samples were taken from January 1993 to June 1995. The Vipava

was sampled at first at the spring 4/5 Pod Skalco, and later at 4/3 Perhavčeva Klet. Prelesje was sampled at test-well No. 3, the Soča in front of Mrzlek, the Bela at Sanabor and the Belščica at its swallow-hole near Belsko.

In the field we measured temperature and specific electric conductivity (SEC) with the instrument WTW-LF 91 and pH with the WTW-pH 90. Other analyses were done in the laboratory of the Karst Research Institute. Carbonate, calcium and total hardnesses and also chloride levels were defined titrimetrically, nitrate levels spectrophotometrically and sulfate levels turbidimetrically according to standard methods (STANDARDS METHODS 1992). Analyses of sodium and potassium were done by HMZ.

4.1.1.1. Temperature

During the whole observation period the temperature of spring waters (Hotešk, Hubelj, Kajža, Podroteja and Vipava) varied in a narrow temperature band (Fig. 4.1). At Podroteja and Vipava seasonal variations of temperature were felt, having maximum in summer and minimum in winter; these variations were less distinct at Hotešk and but more so at Kajža, however with more intermediate variations. The temperature at Hubelj varies between 8.0 and 8.5° C (unfortunately we have only 9 measurements from February to September), at Hotešk between 8.6 and 10.3° C, at Vipava between 8.9 and 10.9° C and at Kajža from 8.7 to 11.0° C. Slightly higher variations appeared at Korentan (8.5 - 11.9° C), while at Prelesje the measured temperature was substantially higher due to seasonal fluctuations (10.3 - 16.8° C). In summer months its temperature increased proportionally to the Soča temperature, yet

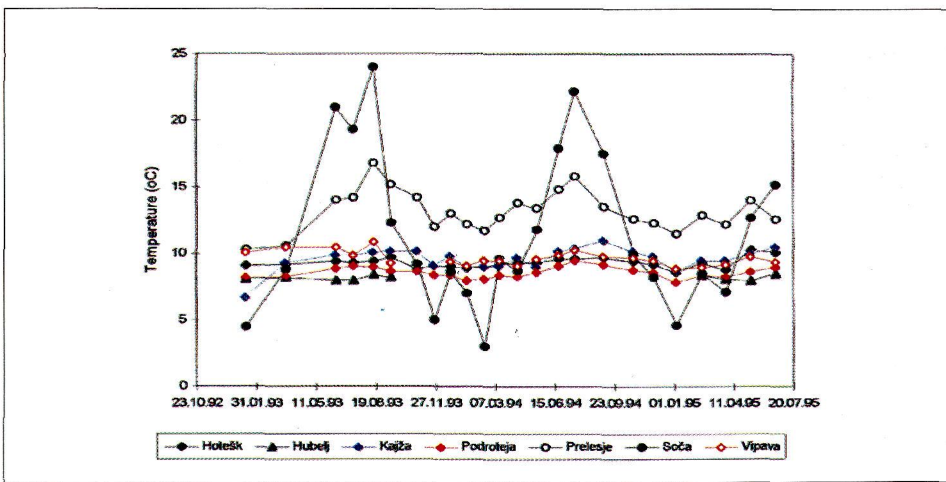


Fig. 4.1: Temperature variations of the observed karst spring waters and of the Soča river water during the observation period (monthly samples).

the amplitude is lower, probably reflecting the Soča influence. The temperature of Mrzlek, measured at the resurgence within the Soča riverbed, in face of a water-works, showed that the inflow water of Mrzlek replaces the Soča water at high water level only, while in dry periods the mixing of both waters moves deeper into the spring. The calculated Ca/Mg ratio as also the isotopic analyses of $\delta^{18}O$ (Chapter 5.2) indicate the same.

HABIČ (1981) reports on the relatively permanent temperature of Mrzlek, between 8 and 10° C. He concluded that water drainage is relatively slow and that it is retained for a long time underground. The temperature measurements in 1993 to 1995 showed rather constant values from 8.3 to 8.9° C at the spring from September to March; this probably reflects the real temperatures of Mrzlek at this time of the year. From March onwards, in the same period of year, we measured the values from 8.4 to 12.0° C in the water-works, even at the end of July 13.5° C but this probably reflects the influence of the Mrzlek and Soča mixing during pumping. The Soča rate depends each time on how much the catchment area of the Mrzlek is filled and also on the quantity of pumping.

The superficial flows such as the Soča, Bela and Belščica reflect the outer temperature and their seasonal variations are considerable. The temperature oscillations of all the sampled waters are shown in Fig. 4.1.

4.1.1.2. Calcium, magnesium and total hardness

Different levels of magnesium and calcium, or calculated ratio Ca/Mg, indicate different recharge areas (Fig. 4.2). The values of single springs vary

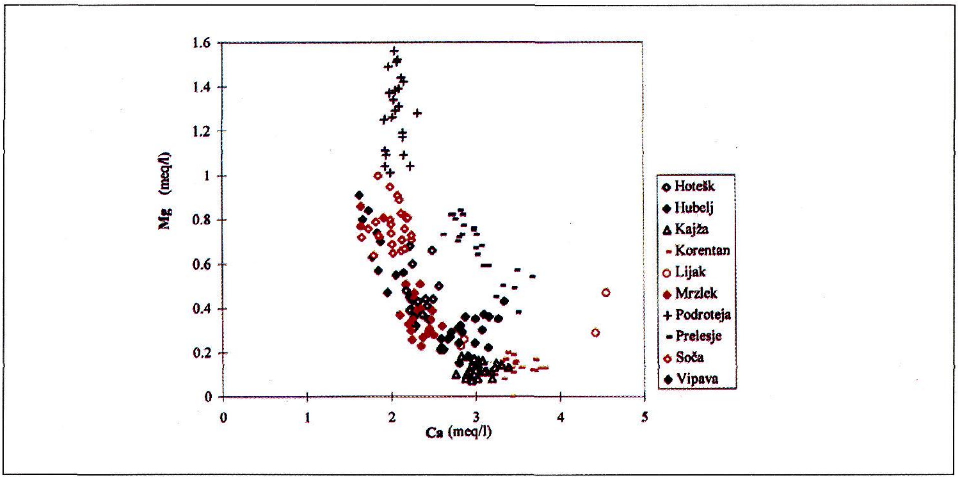


Fig. 4.2: Calcium and magnesium levels in the analysed waters (analyses of the monthly samples).

during the year by different amounts (Fig. 4.3). The lowest Ca/Mg ratio and the smallest variations during the year were recorded at Podroteja where the variations in temperature are minimal showing long water retention in its background and a strong suppression of its influence. In the Hotešk, Mrzlek, Prelesje, Bela and Vipava the Ca/Mg ratio varies more, but not over the value 10; at Vipava only we periodically recorded higher values. The Ca/Mg varia-

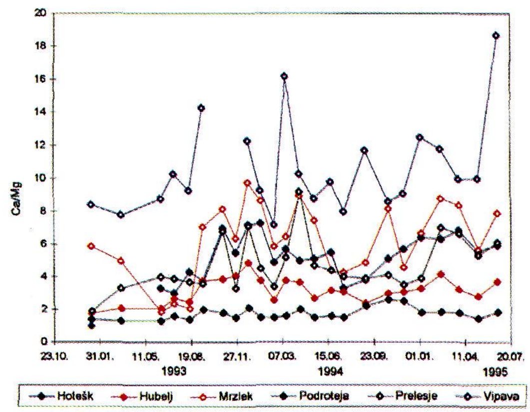


Fig. 4.3: Variations of the Ca/Mg ratios of the various karst springs during the observation period (monthly samples).

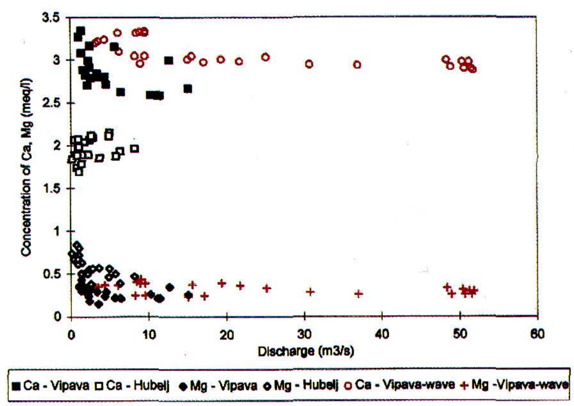


Fig. 4.4: Relationship between the spring discharge and the calcium and magnesium levels of the springs Hubelj and Vipava for the monthly measurements and for various water pulses.

tions in the Hotešk and Mrzlek (excluding the measurements when this water is mixed with the Soča water) may be compared to that of the Podroteja; the variations in the Vipava are higher, and still higher again in the Prelesje. Considerably higher values of the Vipava ratio compared to the Belščica indicate the latter's insignificant share to the Vipava springs.

The highest Ca/Mg ratio (average value 26) with greatest variations during the year was recorded in Kajža. The faults between Banjški and Avški fault are hydrogeologically very important for this spring. The spring reacts to rainfall very quickly (JANEŽ & ČAR 1990), and it explains considerable variations in Ca/Mg ratio.

At monthly sampling the comparison of Ca and Mg level related to discharge indicated that Ca level in the Vipava decreases by the increase of discharge (up to 10 m^3/s); also the analyses of water pulse, however in smaller extent, indicated the same (Fig. 4.4). But the seasonal variations in hardness are felt; the lowest hardness appears in late winter and in spring. The Ca level in Hubelj varies slightly more without an obvious trend, while the Mg level decreases slightly when discharge is increasing. In the Vipava this was not perceived, neither at monthly sampling nor in the water pulse when we have taken the samples during higher water level during monthly sampling.

The total hardness of all the springs varies from 2.4 to 4.2 meq/l. Total hardness of Hotešk, Kajža and Korentan varies seasonally while these oscillations are less prominent at other springs. A similar picture is displayed by specific electric conductivity and carbonates content. The highest value of total hardness was recorded in Prelesje, followed by Korentan, Podroteja, Kajža, Vipava and Hotešk, while Mrzlek and Hubelj had the lowest values. Total

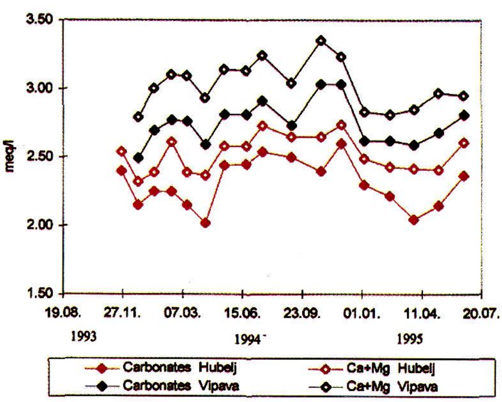


Fig. 4.5: Variations of the total hardness and the carbonate contents in the springs Hubelj and Vipava during the observation period (monthly samples).

hardness of Prelesje, Korentan and the Vipava oscillate the most, within an interval of 1 meq/l. They are followed by Podroteja, Kajža, Hotešk, Mrzlek and Hubelj, the latter oscillating the least, within an interval of 0.5 meq/l. Fig. 4.5 shows rather constant level of carbonates and total hardness in the Vipava and Hubelj.

4.1.1.3. Chloride, nitrate, sulfate, sodium and potassium

In the monthly samples the levels of chloride, nitrate, sulfate, sodium and potassium were also recorded. Over a two years period in all the springs and in the Bela and Soča the level of chloride was up to 4 mg Cl^-/l. The only deviation was recorded in the Belščica; it increased up to 8 mg Cl^-/l, and once even to 12 mg Cl^-/l, indicating the human impact on its superficial flow to the swallow-hole.

The levels of nitrate in the Hotešk, Kajža and Soča never rose beyond 5 mg NO_3^-/l. Their average value is between 3.1 in 3.6 mg NO_3^-/l. Slightly higher values were recorded in Mrzlek, Korentan, Bela and Prelesje with average values between 3.9 do 4.3 mg NO_3^-/l . The highest values were recorded in the Hubelj, Podroteja, Belščica and Vipava with average values from 5.7 to 6.5 mg NO_3^-/l. In Vipava the values varied between 4.3 and 10 mg NO_3^-/l, in Belščica between 4.4 and 7.5 mg NO_3^-/l. Actually, in the Vipava slightly higher values of nitrate levels were recorded than in the Belščica. The variations of the nitrate levels during these two years were observed, yet there is no evident mutual connection. Probably the more distinctive pollution is due to nitrates, but also chlorides and sulfates appear during the initial time of a water pulse.

The lowest sulfate level was recorded in Kajža (average value 6.8 mg SO_4^{2-}/l), followed by Podroteja, Mrzlek and Hotešk being up to 9 mg SO_4^{2-}/l; the Vipava, Korentan and Soča had up to 11 mg SO_4^{2-}/l. Higher values were recorded in the Belščica, and in particular in Prelesje and the Bela where up to 18 mg SO_4^{2-}/l were measured.

The lowest levels of Na were recorded at Hubelj, Mrzlek, Podroteja, Soča and Kajža (up to 1,7 mg/l). They are followed by Hotešk, Prelesje and Korentan with maximal values up to 2.9 mg/l and Vipava with values in an interval from 0.9 to 3.1 mg/l. The highest values were measured in the Bela and Belščica. In the Bela up to 4.8 mg/l and in the Belščica up to 7.2 mg/l.

Hubelj, Podroteja, Mrzlek, Hotešk and Kajža contain less than 0.5 mg/l of potassium. The Vipava and Soča contained up to 0.7 mg K^+/l, Korentan and Prelesje up to 1.3 or 1.6 mg/l; the highest values were measured in the Belščica (1.9 mg/l) and Bela (2.4 mg/l).

4.1.2. Monthly observations of the precipitation
(M. ZUPAN)

The monthly precipitation sampling started in December 1992 at the four meteorological stations Vojsko, Trnovo, Podkraj and Bilje (changed in January 1995 by Slap). In April 1993 Lokve and Postojna were added. The sampling on Trnovo was stopped in July 1994 from technical reasons. The main purpose of the precipitation sampling was to provide the samples for isotope analyses. However we wanted to get some information about the physical and chemical composition of precipitation as well.

The sampling was carried out by Bergerhoff (VDI 1972) samplers. In the precipitation samples we analyzed the same parameters than in the spring water samples. The same methods were used (chapter 2.5) and the same control criteria (chapter 4.1.2) than for spring water analysis. The data analysis showed some seasonal trends in some of the sampling points. However, we decided the meteorological data should be taken in to the consideration. Unfortunately it could not be done in the short period of time we had.

4.1.3. Weekly sampling in the springs Hubelj and Vipava
(M. ZUPAN)

In weekly samples we measured pH value, conductivity, calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), bicarbonate, nitrate, chloride and sulfate. The methods used are described in chapter 2.5 (Water Quality).

All measured data were controlled by conductivity (measured and calculated) and ion difference. The permissible value of the coefficient between calculated and measured conductivity 0.9 - 1.1 was taken in to account (GREENBERG et al. 1992). In the Hubelj spring 90 % of analyzed samples were in this range while in the Vipava spring 87 %. The highest value of coefficient for the rest of samples was in the Vipava 1.24 and the lowest 0.85. In the Hubelj the highest coefficient was 1.19 and the lowest 0.85. The calculated ion difference (GREENBERG et al. 1992) was for the Hubelj between -3,5 % and +1.6 % and for the Vipava between -3.4 and +1.6 %.

The summary of the measured concentrations of single parameters is presented in Tab. 4.1. In both springs the most changeable parameters have been conductivity and bicarbonate. The differences between minimum and maximum values have been higher in Vipava than in Hubelj. The changes of calcium concentration have been higher in the Vipava while the changes of magnesium concentration higher in the Hubelj (Fig. 4.6).

For the establishment of seasonal changes in the investigation period of time we used AARDVARK (WRc 1995) seasonal model. In the Hubelj spring

Tab. 4.1: The summary of the weekly samples in the springs Vipava and Hubelj in the entire investigation period

THE SPRING HUBELJ

Parameter	Number of samples	Minimum value	Maximum value	Mean value	Median value	Standard deviation
Conductivity - µS/cm - 25° C	145	155	273	217	219	14.4
pH	140	7.2	8.5	8.0	8.1	0.23
Calcium	145	26.1	45.8	38.2	38.3	3.4
Magnesium	144	3.7	11.1	6.9	6.7	1.5
Sodium	145	0.4	1.3	1.0	1.0	0.16
Potassium	145	0.1	0.5	0.2	0.2	0.04
Bicarbonate	114	106.8	158.6	141.7	143.4	6.1
Nitrate	143	3.8	10.4	5.9	5.6	1.1
Sulphate	144	5.3	17.4	9.0	8.7	1.9
Chloride	144	1.2	7.7	2.0	1.8	0.75

THE SPRING VIPAVA 4/2

Parameter	Number of samples	Minimum value	Maximum value	Mean value	Median value	Standard deviation
Conductivity - µS/cm - 25° C	142	207	333	270	269	22.9
pH	140	7.3	8.4	8.0	8.1	0.19
Calcium	142	28.4	67.2	54.9	55.2	6.4
Magnesium	140	1.1	5.8	3.2	3.1	0.82
Sodium	141	0.5	3.3	1.5	1.5	0.46
Potassium	141	0.1	2.3	0.39	0.3	0.25
Bicarbonate	103	128.1	213.5	171.1	164.7	16.0
Nitrate	142	3.4	9.4	6.6	6.0	0.98
Sulphate	142	7.8	20.1	11.2	10.8	1.7
Chloride	142	1.5	3.9	2.3	2.2	0.44

we found seasonal changes for conductivity, Ca, Mg, Ca/Mg, bicarbonate and nitrate (Fig. 4.7). For other measured parameters the seasonal changes had not appeared. In the Hubelj spring the parameters characterizing the geological origin showed the seasonal changes. The conclusion from the seasonal model could be the hinterland of the Hubelj is not changing a lot in different hydrological conditions.

In the Vipava spring only conductivity, the sum Ca+Mg and bicarbonate disclosed the seasonal changes. We could presume the hinterland of the Vipava

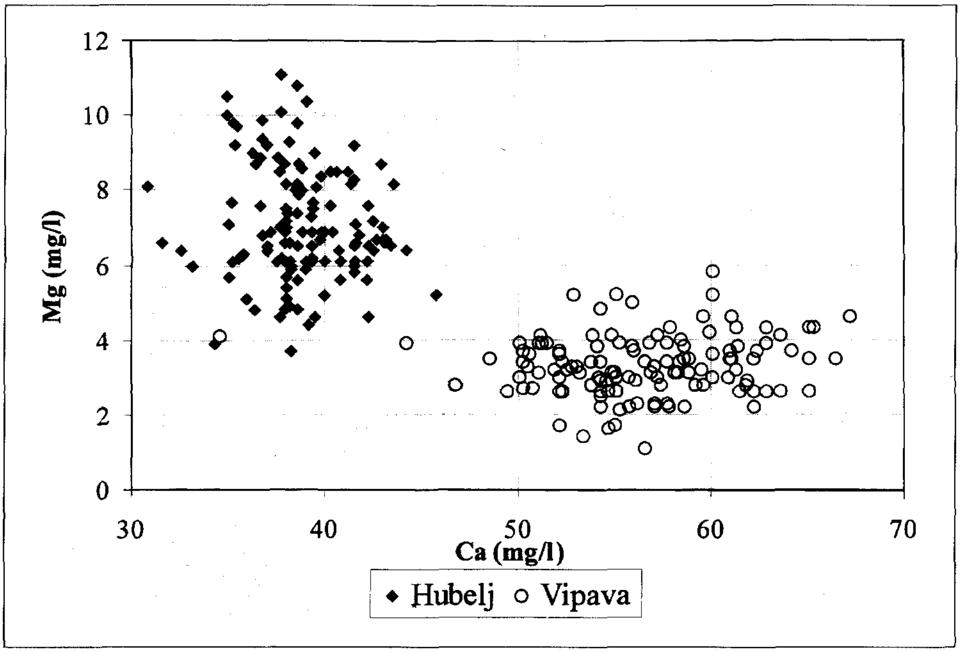


Fig. 4.6: Calcium and magnesium concentrations in the springs Hubelj and Vipava (4/2) from the analyses of all weekly samples taken during the observation period.

is changing at different hydrological conditions. Namely the concentrations of Ca and Mg are changing very unregularly (Fig. 4.8).

Very similar behavior we establish by the comparison of the ratio Ca/Mg with the flow (Fig. 4.9). In the Hubelj the ratio is very constant while in the Vipava much more variable. However, we observed the diminution of the magnesium concentration in the Hubelj up to the discharge about 5 m^3/s (Fig. 4.10) while in the Vipava spring this interdependence did not occur.

Other analysed parameters (pH, sodium, potassium, sulphate, and chloride) have not shown any seasonal variation. Probably they are influenced besides geological structure from pollution sources (wastewater, fertilizers) as well.

Finally we tried to find out which time period and frequency of sampling would be enough to get satisfied statistical confidence level. The calculation of the statistical characteristics showed that the results for one year weekly sampling gave us almost the same result than three years long weekly sampling (Tab. 4.2 and Fig. 4.11). For the comparison we choose the year 1994 which was after hydrological characteristics a dry year and the year 1995 which was after hydrological characteristics an average year.

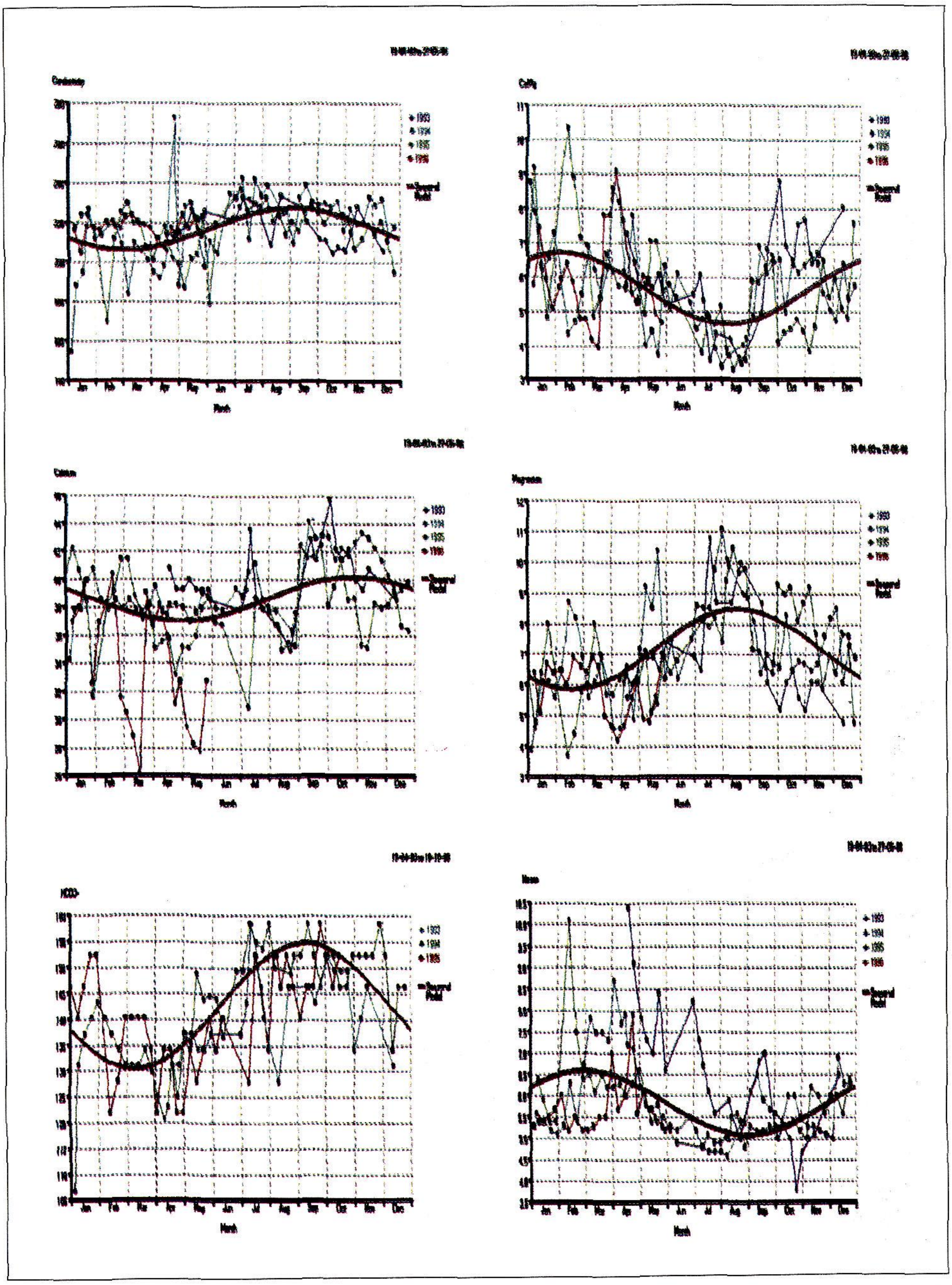


Fig. 4.7: Seasonal variation of conductivity, Ca/Mg ratio, calcium, magnesium, bicarbonate and nitrate in the Hubelj spring during the whole investigation period (weekly samples).

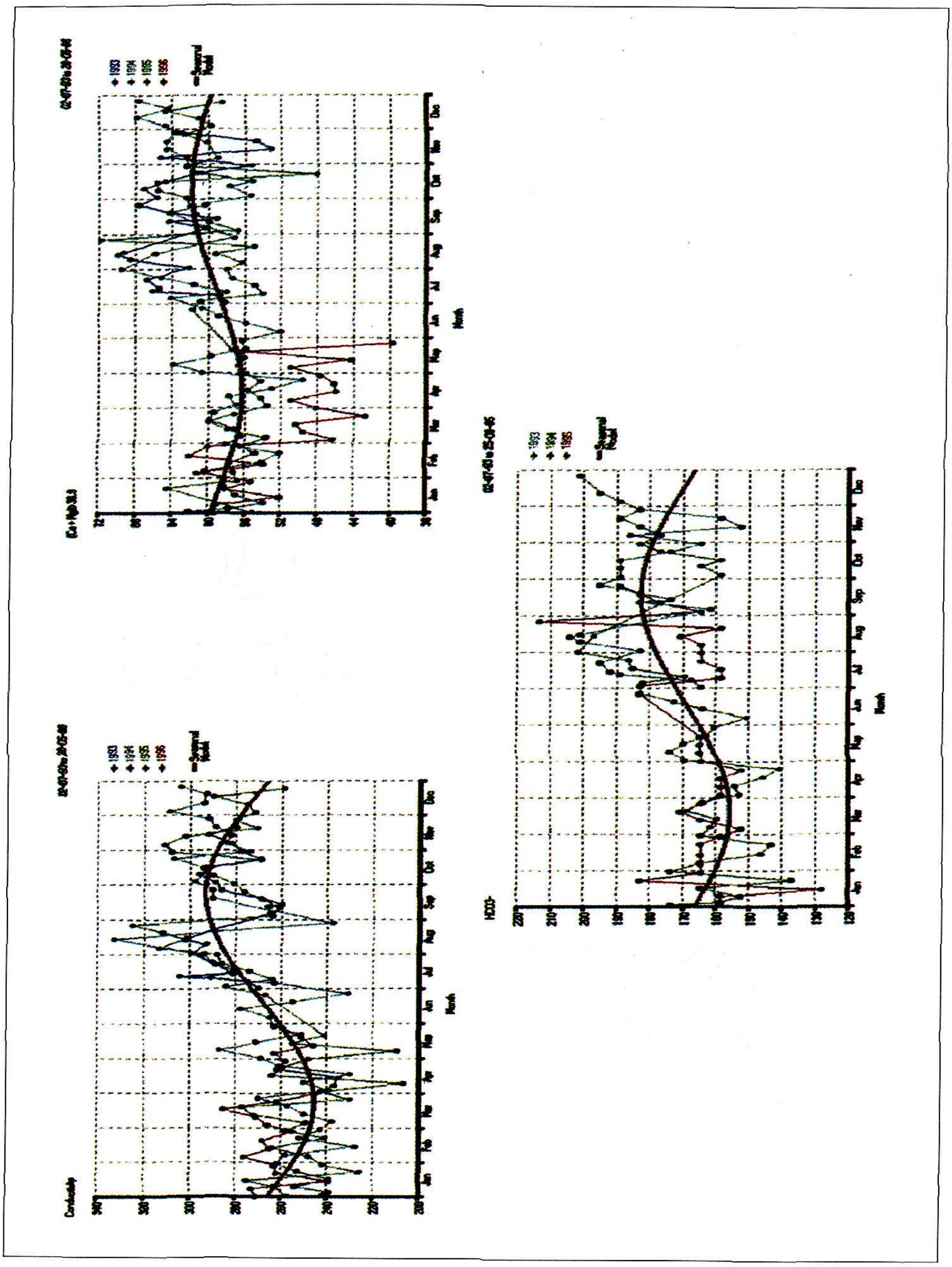


Fig. 4.8: Seasonal variation of conductivity, the sum of calcium, magnesium and bicarbonate in the Vipava spring 4/2 during the whole investigation period (weekly samples).

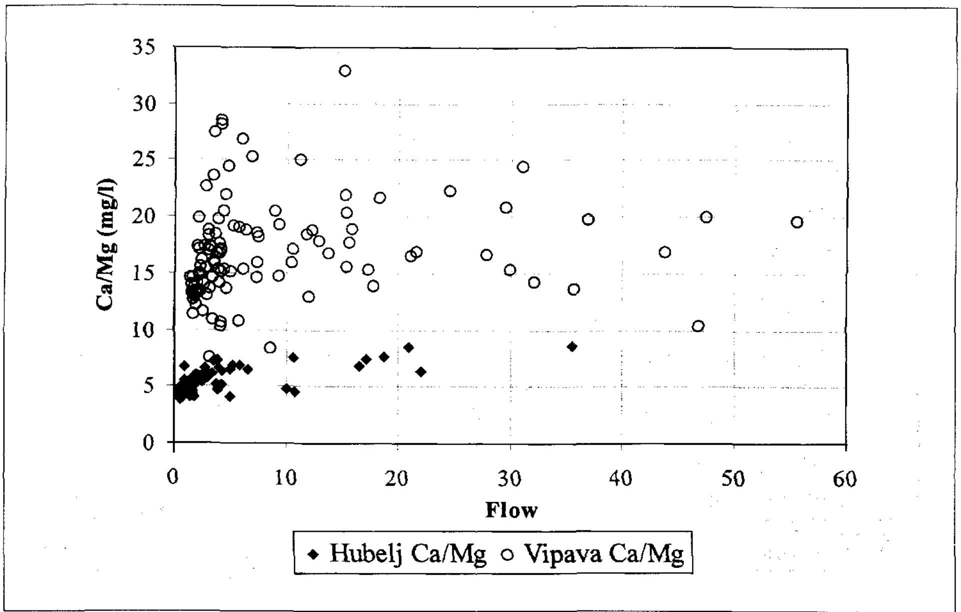


Fig. 4.9: Measured Ca/Mg-ratios versus discharge of the Hubelj and Vipava (4/2) springs for all weekly samples.

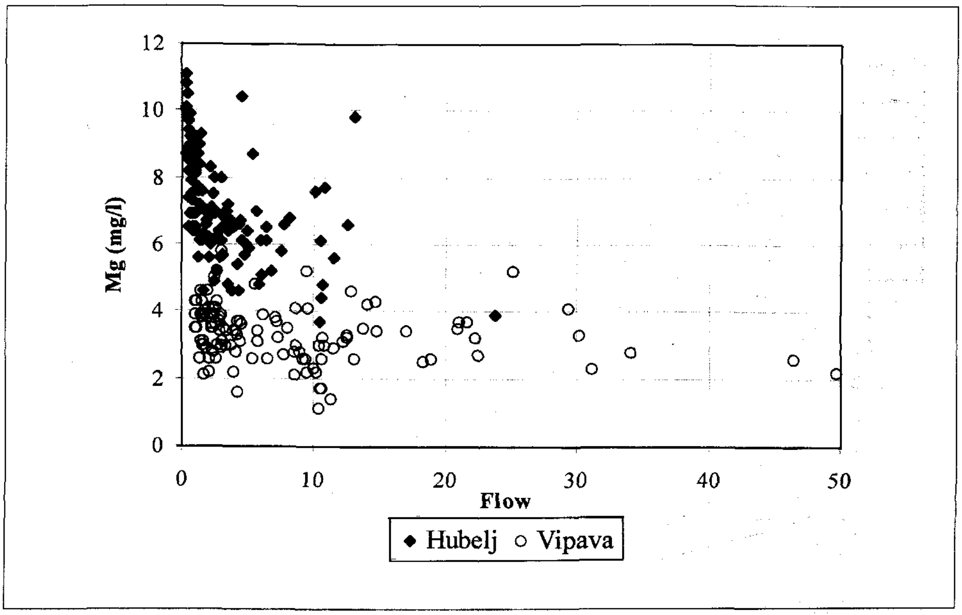


Fig. 4.10: Analysed Mg concentration versus discharge in the Hubelj and Vipava (4/2) spring for all weekly samples.

Tab. 4.2: The summary of the weekly samples in the spring Vipava and Hubelj in year 1994 and 1995.

THE SPRING HUBELJ

Parameter	Number of samples		Minimum value		Maximum value		Mean value		Standard deviation	
Year	1994	1995	1994	1995	1994	1995	1994	1995	1994	1995
Conductivity - µS/cm - 25 °C	51	49	155	170	273	237	218	216	19.2	13.4
pH	46	49	7.2	7.2	8.3	8.5	8.0	8.0	0.27	0.21
Calcium	51	49	34.3	30.9	44.2	42.5	39.5	37.8	2.2	2.7
Magnesium	51	48	3.9	3.7	11.1	10.5	7.2	7.1	1.6	1.6
Sodium	51	49	0.9	0.8	1.2	1.2	1.0	1.0	0.08	0.14
Potassium	51	49	0.2	0.1	0.5	0.3	0.2	0.2	0.04	0.04
Bicarbonate	51	39	106.8	122.0	158.6	158.6	142.7	140.6	11.4	10.1
Nitrate	51	47	4.6	4.8	8.7	10.1	5.9	5.8	0.97	0.88
Sulphate	51	49	5.3	5.8	15.5	17.4	9.1	9.1	2.1	2.1
Chloride	51	49	1.3	1.5	3.3	2.5	2.0	1.8	0.38	0.31

THE SPRING VIPAVA 4/2

Parameter	Number of samples		Minimum value		Maximum value		Mean value		Standard deviation	
Year	1994	1995	1994	1995	1994	1995	1994	1995	1994	1995
Conductivity - µS/cm - 25° C	49	48	228	207	333	325	270	269	24.6	25.7
pH	47	48	7.5	7.4	8.3	8.4	8.0	8.0	0.18	0.17
Calcium	49	48	46.8	28.4	65.3	67.2	56.3	53.8	4.2	6.8
Magnesium	49	46	1.1	1.4	5.8	5.0	3.3	3.3	0.93	0.73
Sodium	49	47	1.1	0.8	2.3	3.3	1.6	1.5	0.25	0.40
Potassium	49	47	0.2	0.2	0.7	2.3	0.4	0.4	0.11	2.3
Bicarbonate	45	35	137.3	128.1	201.9	213.5	169.3	166.3	16.1	13.7
Nitrate	49	48	5.2	3.4	8.0	8.4	6.3	6.7	0.62	0.92
Sulphate	49	48	7.8	8.2	17.5	14.5	10.9	11.3	1.7	1.4
Chloride	49	48	1.5	1.6	3.9	2.9	2.3	2.2	0.46	0.34

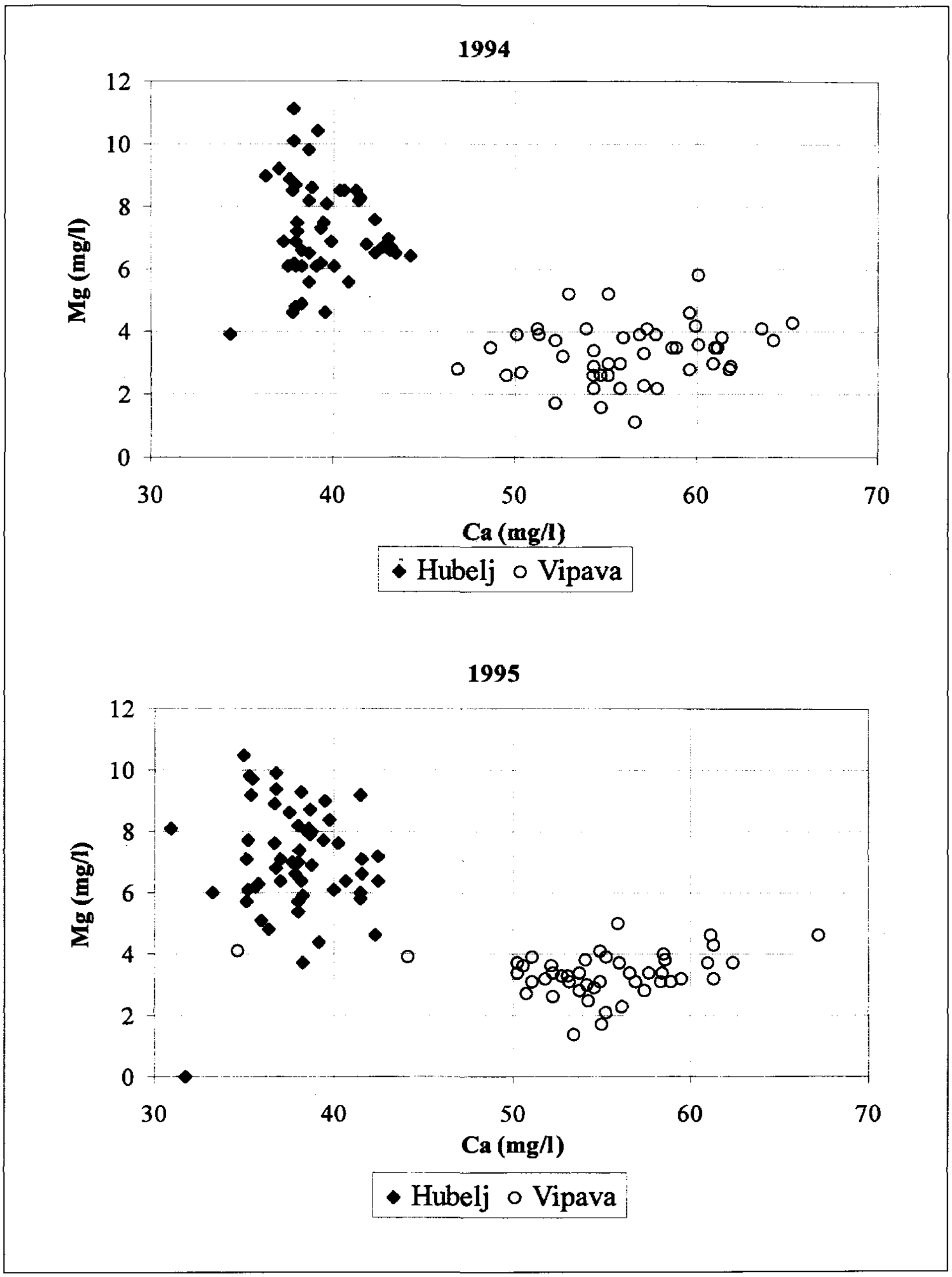


Fig. 4.11: Calcium versus magnesium concentration in the Hubelj and Vipava (4/2) spring, separately for the weekly samples in the hydrological dry year 1994 (above) and the hydrological average year 1995 (below).

4.1.4. Comparative measurements of the Vipava springs

(J. KOGOVŠEK)

In the years 1964, 1965 and 1979 HABIČ (1983) already made the comparative measurements in the several Vipava springs (Fig. 4.12) when he compared the temperature and carbonate levels. Based on five series of measurements in March, May, June, November and December he stated that the southernmost springs Pod Lipo and Pri Kapelici are the most warm, 0.1 to 1.3° C warmer than other Vipava springs, and that the variations in temperature of all the Vipava springs do not exceed 1,5° C during a year.

Repeated measurements and analyses in the Vipava springs were done within the 7. SWT project. At the time of low and lowest waters we measured at all the seven springs of the Vipava their temperature, specific electric conductivity, pH and we analyzed total hardness and carbonate, calcium,

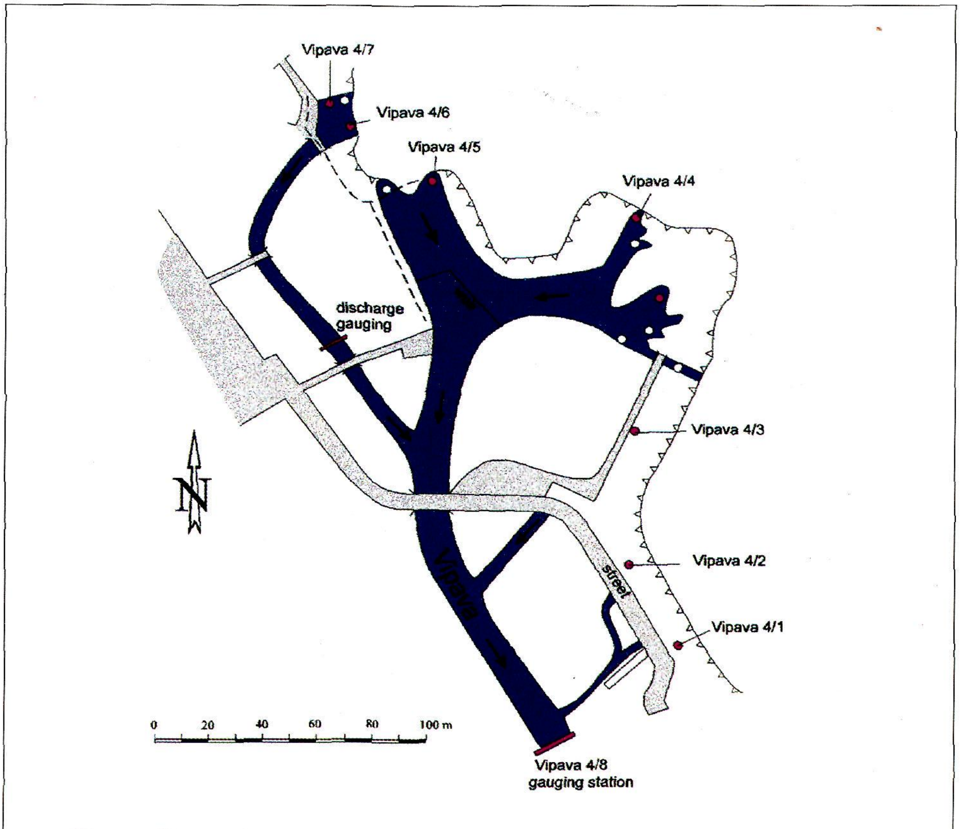


Fig. 4.12: Sampling points at the Vipava spring group (map after IHG).

chloride, nitrate and sulfate levels to find out the differences or similarities. The measurements and samplings took place on July 28 and December 2, 1994, May 25, 1995 and June 3 and September 16, 1996.

The measured parameters of the spring Pod Farovžem Levo 4/7 differ considerably from the others where the differences are smaller. It reached the highest values of the specific electric conductivity (the average value was 361 μS/cm), the highest total hardness (the average value was 3.82 meq/l), and

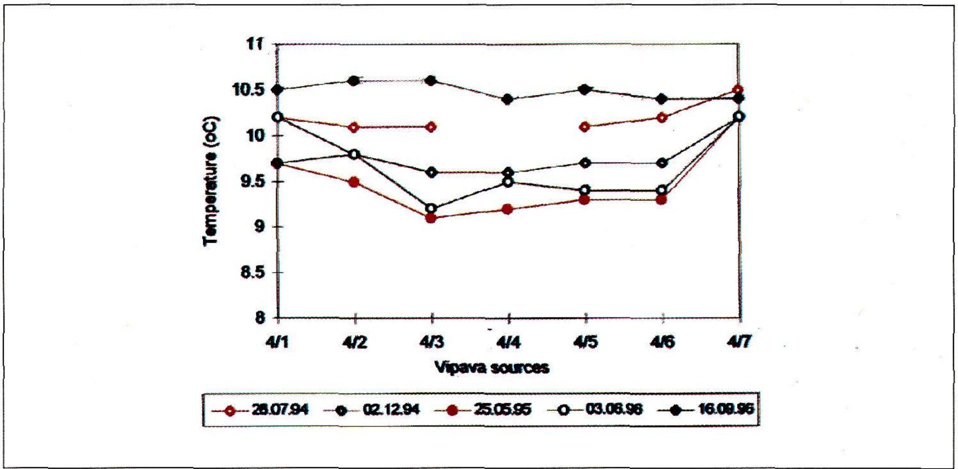


Fig. 4.13: Temperature variations in the Vipava springs at low and lowest water level.

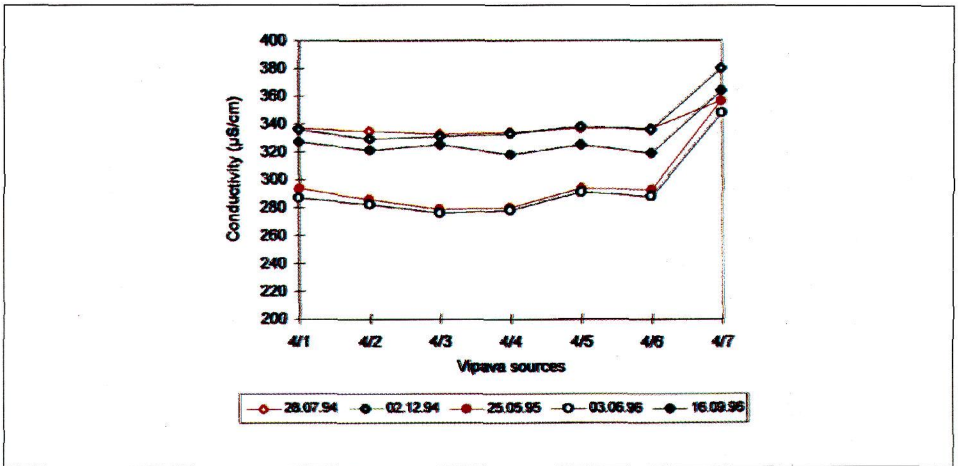


Fig. 4.14: Variations in the specific electric conductivity in the Vipava springs at low and lowest water level.

also the highest levels of carbonate and calcium as well nitrate and sulfate. At other springs only smaller differences were perceived. Compared with the spring 4/7 they have an average a 55 μS/cm lower SEC, and 0.6 meq/l lower carbonate and calcium levels and total hardness.

Regarding the temperature (Fig. 4.13) the spring 4/7 is very constant during a year. During mentioned measurements we recorded the temperature as always between 10.2 to 10.5° C. The temperature of other springs varies over the year by up to 1.5° C. In the observation time the temperatures of all the springs, with exception of 4/7, varied by from 0.2 to 0.3° C. Only in spring time when snow melts in the catchment area of high Nanos Mt. (measurements in May and June) the springs Pri Kapelici 4/1 and Pod Lipo 4/2 had higher temperatures (0.5 to 1,0° C) than the average temperature of other springs. This confirms the Habič's supposition that these springs are locally more influenced by sunny slopes of Nanos.

Also other measured parameters indicate smaller variations at the spring 4/7 than at the others. SEC varied by 32 μS/cm, while at the others by 51 μS/cm (Fig. 4.14). Yet the differences between the springs, with exception of the spring 4/7, in the observed time are very small, up to 9 μS/cm; the exceptional ones are the measurements of May and June when the range of difference is 15 μS/cm.

The carbonate and calcium level varied at the spring 4/7 by 0.2 meq/l while at the other springs it was more than 0.4 meq/l. The total hardness oscillated at the spring 4/7 in an interval of 0.4 meq/l while at others springs it was 0.6 meq/l (Fig 4.15). There are considerably lower values of SEC, and also of carbonate and calcium levels in spring time, and higher values at the end of summer and in autumn indicating seasonal variations.

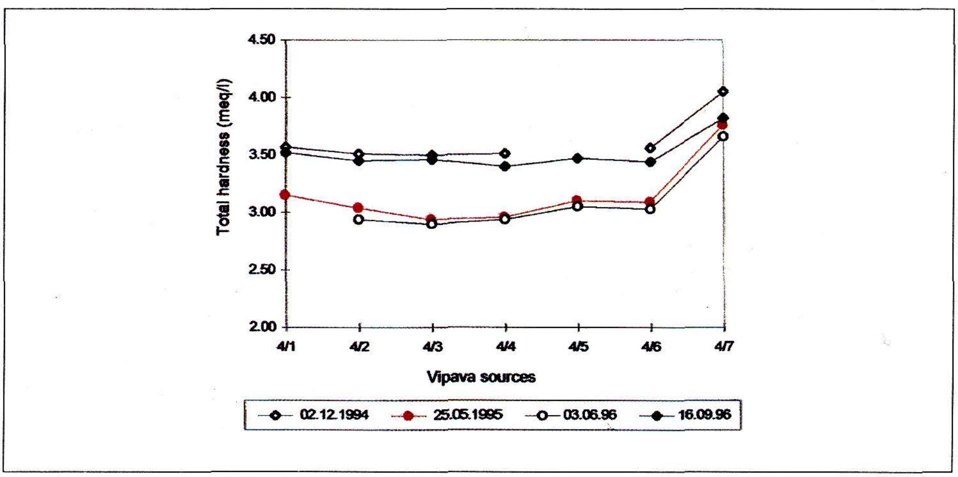


Fig. 4.15: Variations in the total hardness in the Vipava springs during low and lowest water level.

4.2. OBSERVATION OF SINGLE EVENTS

4.2.1. Daily sampling in the springs Hubelj, Vipava and Mrzlek (M. ZUPAN)

Tab. 4.3: The summary of the daily sampling in the springs Vipava and Hubelj in the investigation period from 18-09-95 to 29-02-96.

THE SPRING HUBELJ

Parameter	Number of samples	Minimum value	Maximum value	Mean value	Standard deviation
Conductivity - µS/cm - 25° C	134	118	237	216	12.3
pH	134	7.8	8.5	8.2	0.16
Calcium	134	29.8	43.3	37.9	2.5
Magnesium	134	4.0	9.3	6.9	1.2
Sodium	134	0.2	2.1	0.9	0.25
Potassium	134	0.1	0.3	0.2	0.04
Nitrate	134	4.5	8.6	5.6	0.51
Sulphate	134	5.8	16.4	9.3	1.8
Chloride	134	1.2	2.5	1.9	0.23

THE SPRING VIPAVA 4/2

Parameter	Number of samples	Minimum value	Maximum value	Mean value	Standard deviation
Conductivity - µS/cm - 25° C	169	233	386	274	195
pH	169	7.7	8.5	8.1	0.16
Calcium	169	30.3	67.2	55.8	4.8
Magnesium	169	1.7	6.6	3.5	0.92
Sodium	169	0.9	2.4	1.4	0.28
Potassium	169	0.2	3.3	0.5	0.62
Nitrate	169	2.8	9.1	6.5	1.1
Sulphate	156	7.2	16.9	11.0	1.9
Chloride	169	1.5	3.1	2.1	0.30

In the time period from September 1995 to February 1996 daily samples in the springs Hubelj, Vipava and Mrzlek have been taken. From September 1996 to February 1997 we had taken the daily samples in the spring Vipava 4/2 (Fig. 4.12). The purpose of this sampling was to follow the changes in shorter time period and to define the changes of physical and chemical parameters depending on the water quantity more detailed. At the same time we wanted to compare the results of long-term weekly observations during three years with the results of daily sampling in much shorter period of time. The results of these observations are shown in the Tab. 4.3 and Fig. 4.16, 4.17 and 4.18. The distribution of the results of daily sampling in six-month period is very similar to those of weekly sampling. It means that we could get the information in much shorter time if we would sample with higher sampling frequency. The calculation of one-month daily samples did not give enough reliable information.

In the first period of sampling for the 3rd tracing experiment (Chapter 6) we took the daily samples for physical chemical analyses in the spring Mrzlek both on the right bank of the Soča and in the pump station for water supply. The daily samples we took from August 9, 1995 to August 17, 1995 and from August 30, 1995 to September 23,1995. Afterwards we continued with weekly sampling till December 12, 1995. The data should give us some information

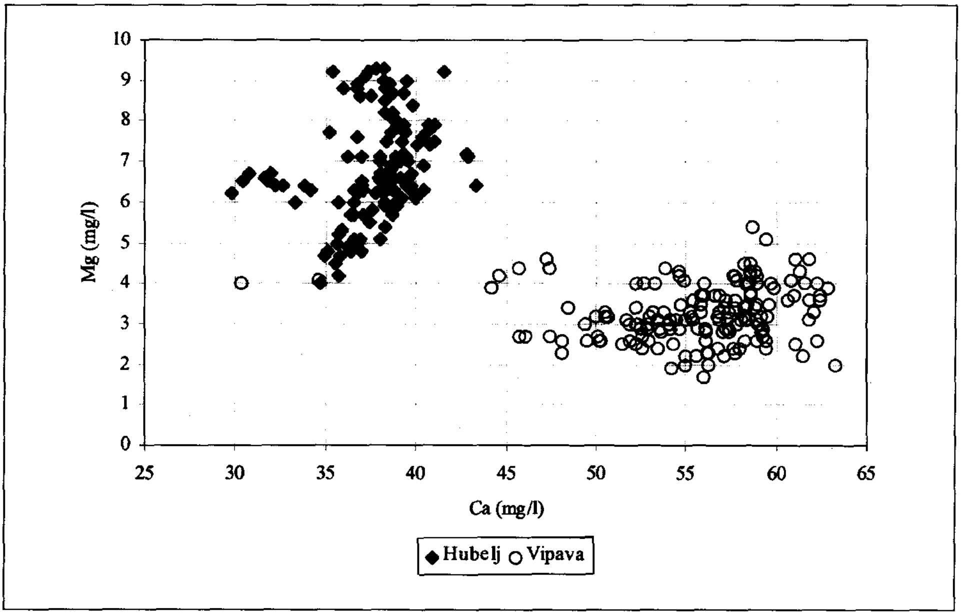


Fig. 4.16: Calcium and magnesium concentrations in the Hubelj and Vipava (4/2) spring; analyses from all daily samples during the investigation period.

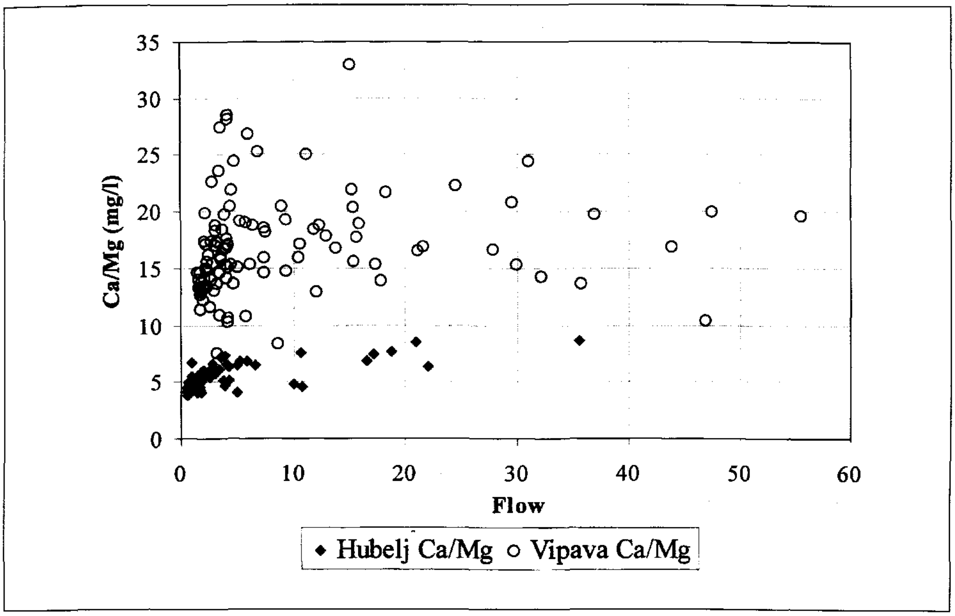


Fig. 4.17: Measured Ca/Mg ratios versus discharge in the Hubelj and Vipava (4/2) spring; analyses from all daily samples during the investigation period.

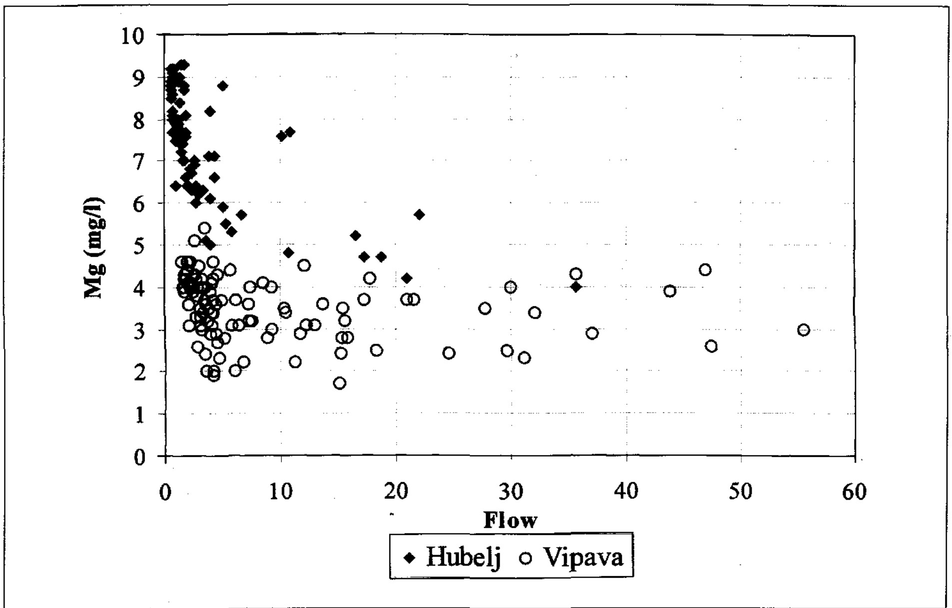


Fig. 4.18: Analysed Mg concentrations versus discharge in the Hubelj and Vipava (4/2) spring; analyses from all daily samples during the investigation period.

about the influence of the Soča to the Mrzlek spring on both sampling sites. During the dry period in the beginning of August the magnesium concentration in the pump station was higher than in the spring while the calcium concentration was lower in the pump station. This fact would allow us to presume that some influence of the Soča river to the spring exist (Fig. 4.19). Namely the magnesium concentration is significant higher in the Soča while the calcium concentration is lower. Mean concentration of magnesium in the

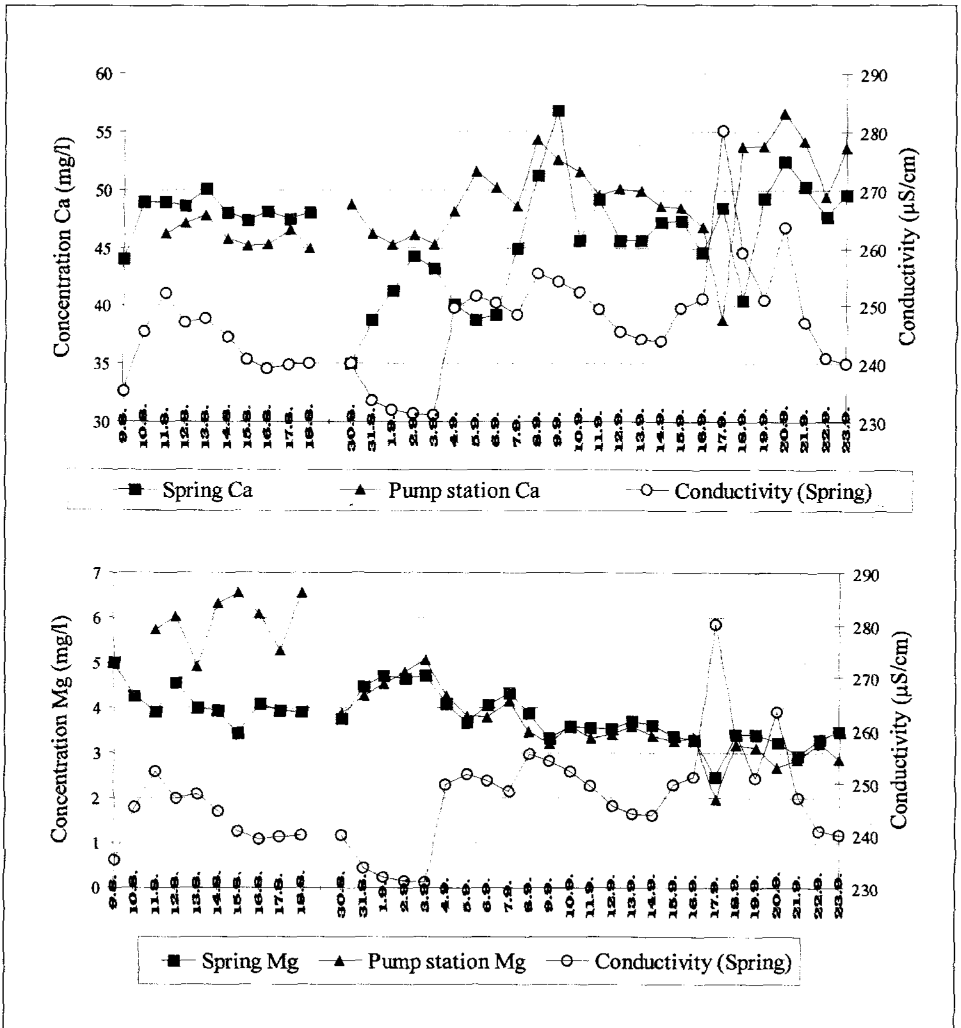


Fig. 4.19: Conductivity and calcium concentration (above) and conductivity and magnesium concentrations (below) in the Mrzlek spring and in the pump station, analyses from all daily samples during the investigation period.

Soča during the daily sampling period was 10.6 mg/l while in the Mrzlek it was 3.9 mg/l. Mean calcium concentration in the same period of time was in the Soča 43.3 mg/l and in the Mrzlek 48.4 mg/l. In September during rainy period the magnesium concentration was very similar in both sampling points while the calcium concentration was much different.

The seasonal model showed the catchment area of the Hubelj is not changing much at different hydrological conditions. The catchment area of the Vipava seems to be more changeable at different hydrological conditions.

The hydrochemical analyses of weekly samples in the period of three years and the analyses of daily samples taken during six-month period gave very similar characteristics. The results of the weekly sampling during one year period would be satisfactory as well.

4.2.2. Water pulse of the Vipava spring - Pod Lipo 4/2

(J. KOGOVŠEK)

After a medium-sized water pulse in the second half of September the Vipava discharge was decreasing through the whole of October. On November 11, 1995 the discharge increased (the occurrence of the first water pulse) and reached its maximum of 9.6 cubic meters two days later. During the following two days it decreased to a half. On the next day, November 16, the discharge increased again and reached its maximal value of 51.9 cubic meters on November 17, 1995 at 3 p.m., thus forming the second water pulse (see Fig. 4.20). In this time we manually sampled Vipava at the spring Pod Lipo, No. 4/2 for physico-chemical analyses. We measured the temperature, specific electric conductivity and pH and we determined carbonate, calcium and total hardness, and chloride, sulfate, nitrate and phosphate levels.

During the first, smaller, water pulse a slight increase of carbonates, calcium and SEC was recorded, probably due to replacement of old water from a recharge area, for there was no considerable change in discharge in the last 45 days. The second water pulse was followed by a rapid increase reaching the maximal value of discharge in 27 hours. The first sample was taken 7 hours after the minimal discharge at the beginning of water pulse when the discharge reached twice the minimum. The carbonate and calcium levels were lower by 0.3 meq/l than at the first lower water pulse. Unfortunately we did not sample in the intermediate time between the two water pulses.

The discharge increase in the second wave was followed by a slight increase of carbonates and calcium, but when the maximal discharge rapidly decreased they decreased also. Later, when the discharge decrease was slower the hardnesses were in slight increase (Fig. 4.20). Minor deviation was recorded in calcium level, as at the initial decrease its concentration decreased slightly less and during continuing slower discharge decrease remained higher compared to

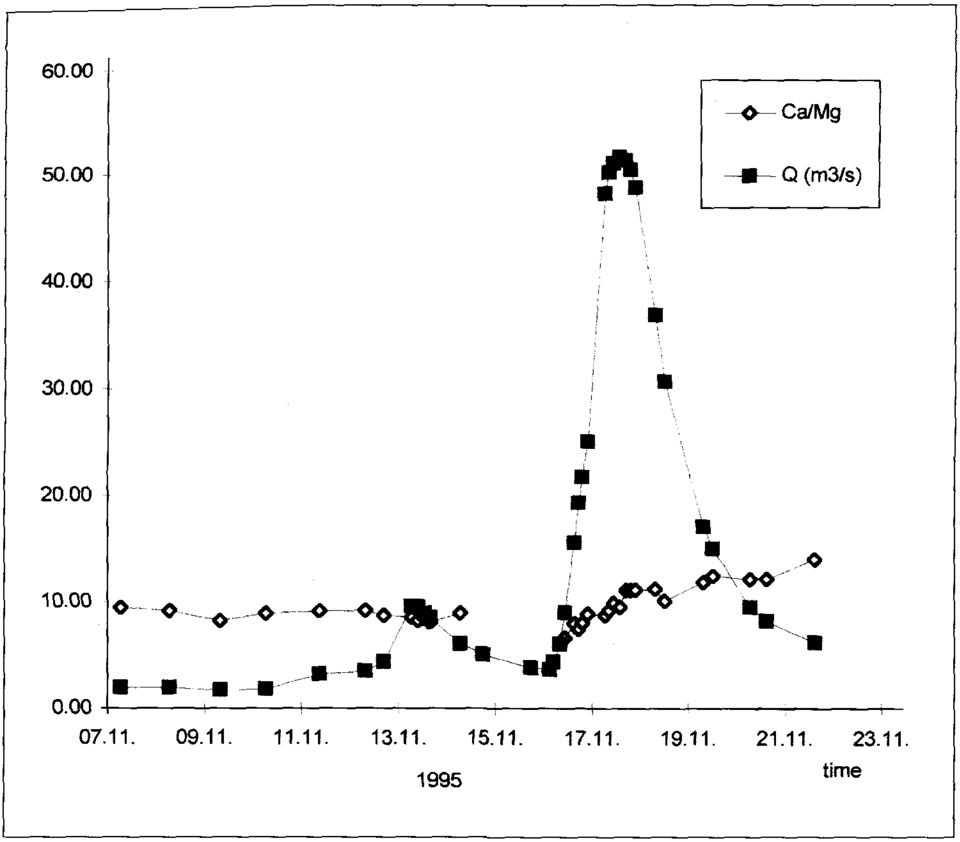


Fig. 4.20: The water pulse (Q) and the Ca/Mg ratio the Vipava spring in November 1995.

carbonates and total hardness during the beginning of the water pulse, although the increase of all three hardnesses was proportionate.

Specific electric conductivity (SEC) is proportionate to total hardness. Dependence of SEC on discharge is seen in Fig. 4.21. Well seen is the difference of SEC dependence on discharge during its increase and decrease. During the first smaller water pulse also SEC increased together with carbonates and calcium. During the second water pulse the SEC firstly slowly decreased when the discharge was in increase, and when it reached the value of 50 cubic meters SEC rapidly decreased until maximal discharge was attained and at that time the minimal value of SEC was recorded. During the discharge decrease SEC at first increased slowly, but when the discharge reached the value of about 10 cubic meters, SEC started to increase faster). The changes in SEC are relatively small, being the difference between the minimal and

maximal value within a water pulse 20 to 25 μS/cm, similar to that recorded at carbonates and calcium. In any case all these measurements and statements must be checked and confirmed by observation of greater number of water pulses and by isotopic analyses and other approaches.

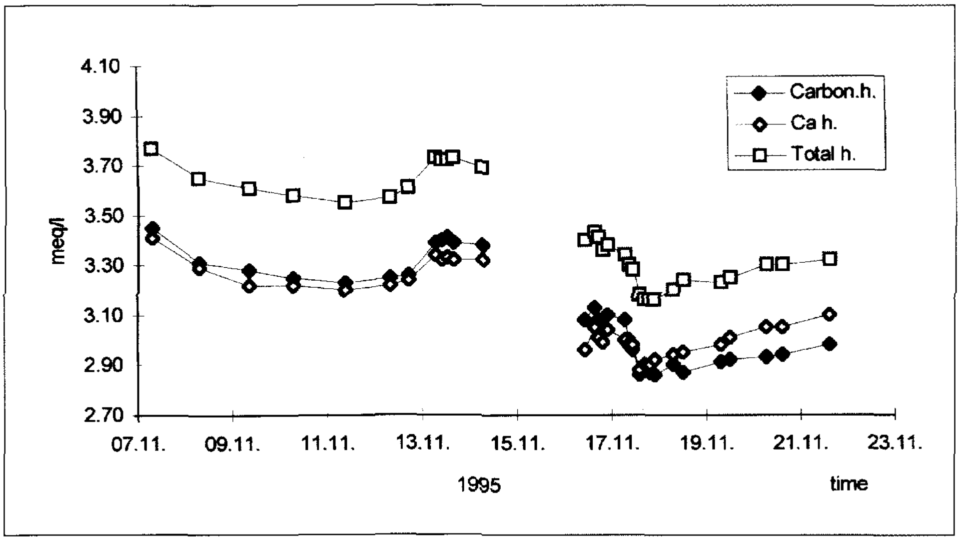


Fig. 4.21: Variations of the carbonate and the calcium levels as well as of the total hardness in the Vipava spring during the water pulse in November 1995.

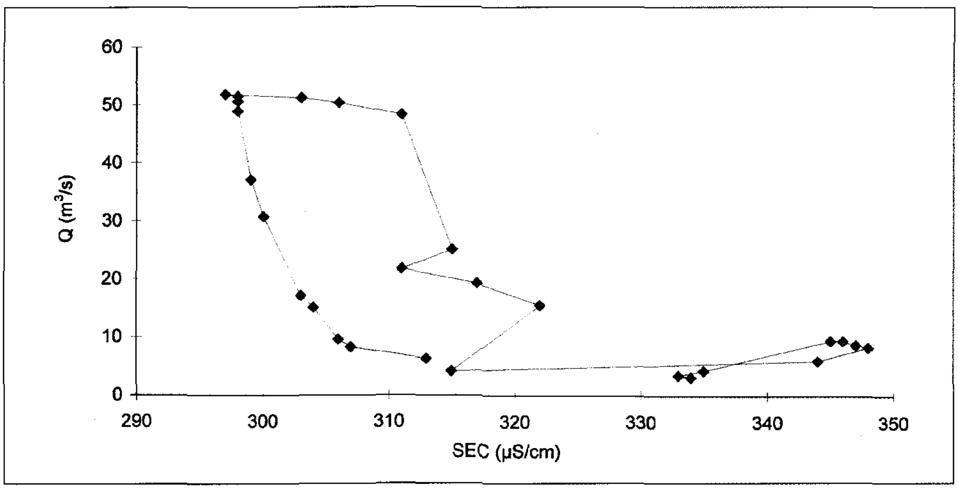


Fig. 4.22: Dependence of the conductivity (SEC) from the discharge during the Vipava water pulse in November 1995. Level contents during the Vipava water pulse in November 1995.

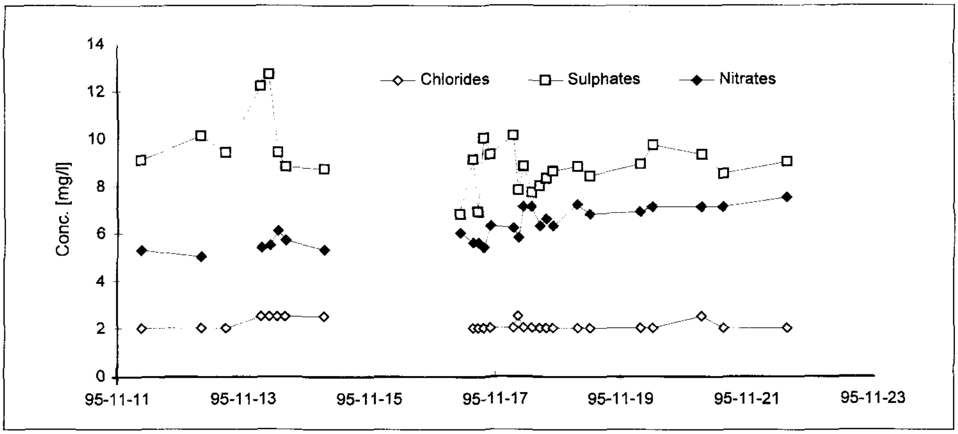


Fig. 4.23: Variations in the chloride, nitrate and sulfate contents during the Vipava water pulse in November 1995.

Determination of phosphate and chloride levels did not display any changes during the two water pulses, or, maybe they were so small that we did not register them. The phosphate concentration was at the limit of detection (0.01 mg PO_4^{3-}/l), and the chloride concentration 2 mg Cl^-/l (Fig. 4.22).

In the first water pulse we recorded a slight increase in nitrate levels of 1 mg NO_3^-/l. During the second water pulse the values only oscillated slightly. During both water pulses a small, but permanent increase in nitrate level was recorded.

The initial value of sulfate level, 9.5 mg SO_4^{2-}/l at the beginning of the first water pulse increased to 12.5 mg SO_4^{2-}/l during the maximal discharge and later it decreased. Similar increase was recorded at the beginning of the second water pulse (Fig. 4.23). When a discharge approached the starting value also the level of sulfate reached the starting value before both water pulses.

4.2.3. The Use of Silica to characterise the allogenic Flysch Component in Vipava Springs during the observation of Single Events

(V. ARMBRUSTER, C. LEIBUNDGUT)

4.2.3.1. Introduction

The Vipava springs show some characteristics of a karst spring, that is influenced by an allogenic flow component. Its catchment borders on Eocene flysch in the East, where sinking streams drain parts of the flysch area and probably have a connection towards Vipava springs.

The soils and the bedrock of the flysch area around Postojna release considerably more silica than those of the karst plateaux of Nanos and Hrušica. As a consequence, silica could be used as a natural tracer to make hydrograph separations of Vipava springs' water into karst water and allogenic flysch water during a runoff event. The dynamics of the allogenic flysch component could be characterized and a rough estimation of the Vipava catchment area, which is made up by flysch, could be given.

4.2.3.2. Methods

The kinetics of silica release are fast and thus, silica contents hardly depend on residence times, but almost exclusively on different flowpaths of water. Nevertheless, time dependent silica contents have been determined for the flysch as well as for the karst component. To obtain a representative silica content of the flysch component, the water of Lokva river on the flysch area has been sampled at Predjama Castle, where it sinks underground at the karst flysch border and has a proofed connection to Vipava springs. To obtain a representative silica content of the karst component, Hubelj karst springs has been sampled, which is uninfluenced by flysch areas. The samples of the two components and the samples of Vipava springs during a heavy precipitation event in April 1996 were analyzed photometrically for dissolved silica. A two component mixing model has been used for the hydrograph separations.

4.2.3.3. Results

During the sampled period from March the 27th until April the 12th 1996, the karst plateaus were partly snow-covered, and the discharge of Hubelj and Vipava springs was relatively high, as snowmelt was taking place. During a heavy precipitation event on April the 1st and 2nd about 90 mm of rain were falling on the Vipava catchment (Fig. 4.24: (A)) and caused strong rises in the discharge of the karst springs. During the precipitation event the rain turned into snow and covered the karst plateaus completely. On the lower neighboring flysch area near Postojna, no snow was deposited and the rainfall amounted to 110 mm, causing extreme floods in the flysch streams. After the precipitation event the discharge of Hubelj and Vipava springs decreased until April the 5th. Then warm and sunny weather caused a strong snowmelt runoff event with daily discharge fluctuations in the karst springs (Fig. 4.24: (C)-(D)).

Flysch Water

Fig. 4.24 (B) shows the assumed discharge of water from the flysch area, drained by sinking streams, and its silica content during the observed period. On the basis of the peak discharge of the two biggest sinking streams Lokva and Belščica and the water level record of the Belščica the discharge was

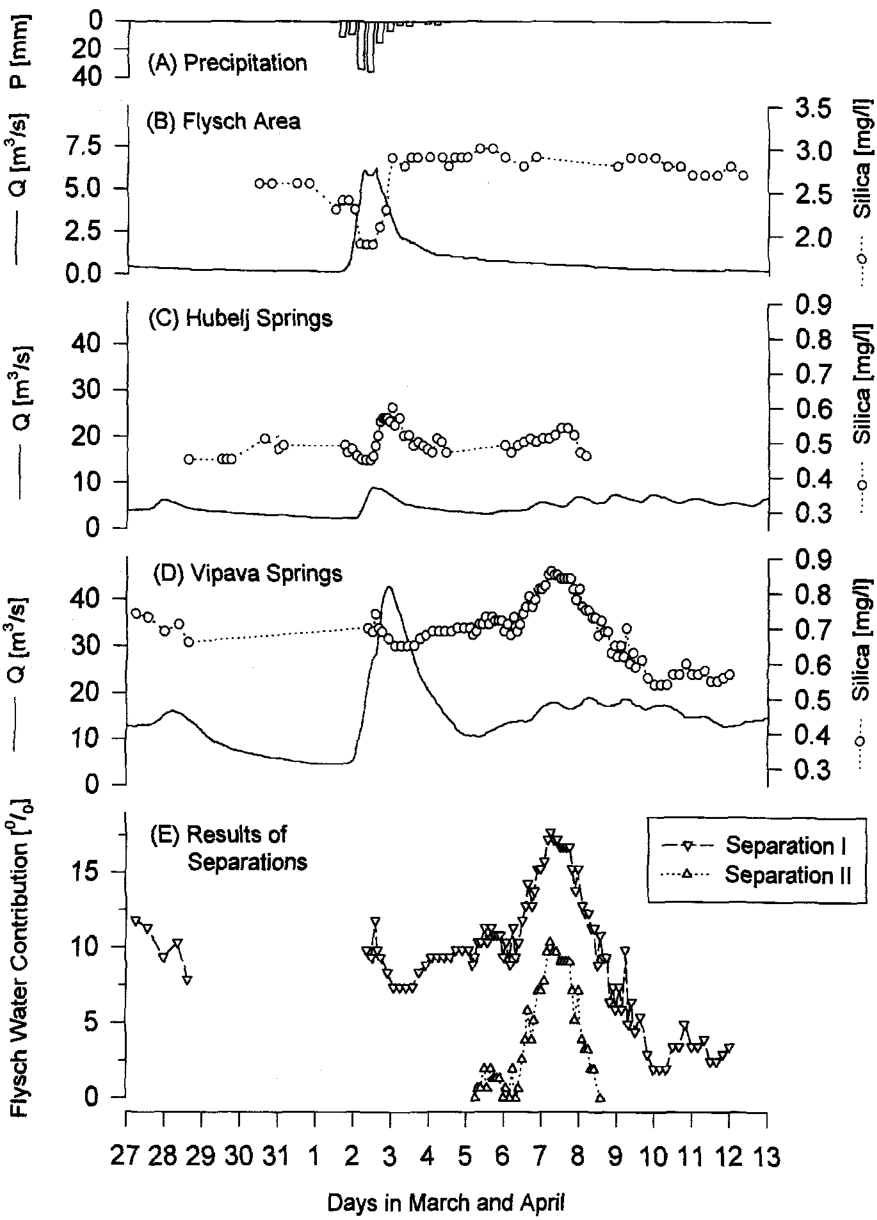

P [mm]
0
20
40
(A) Precipitation
(B) Flysch Area
Q [m³/s]
7.5
5.0
2.5
0.0
3.5
3.0
2.5
2.0
Silica [mg/l]
(C) Hubelj Springs
Q [m³/s]
40
30
20
10
0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
Silica [mg/l]
(D) Vipava Springs
Q [m³/s]
40
30
20
10
0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
Silica [mg/l]
Flysch Water Contribution [%]
(E) Results of Separations
Separation I
Separation II
15
10
5
0
27 28 29 30 31 1 2 3 4 5 6 7 8 9 10 11 12 13
Days in March and April

Fig. 4.24: Data of a single precipitation event in the period from March the 27th till April the 12th 1996: (A) Precipitation heights of 6 hours intervals of precipitation station Podkraj. (B) Silica content and assumed discharge of water from the flysch area near Postojna, drained by sinking streams towards Vipava springs. (C)/ (D) Silica content and discharge of Hubelj and Vipava springs. (E) Contributions of flysch water in Vipava springs, according to two different separations (I and II).

calculated, while the silica content was measured in the Lokva river. The flysch water shows a slight dilution effect during the runoff event, and the silica content ranges from 1.9 mg/l to 3.0 mg/l.

Two different representative silica contents were calculated for the flysch water:

- The discharge weighted mean of the silica contents during the whole period. This is considered to be the best estimation of the silica content in general. It amounts to 2.53 mg/l.
- The discharge weighted mean of silica contents during a 35 hours period of highest silica load. This is considered to be the representative silica content of the flysch flood. It amounts to 2.25 mg/l.

Karst Water

Fig. 4.24 (C) shows the discharge and the silica content of Hubelj springs during the observed period. The silica content of karst water is on a much lower level and ranges from 0.45 mg/l to 0.6 mg/l. Two separate slight rises in silica can be observed, one during the precipitation and the other one during the snowmelt. Possible reasons might be:

- Soil water, being higher in silica, is pressed out by infiltrating event water.
- Deposited sediments within the karst system are mobilised by higher water levels and are releasing silica.
- Deep phreatic water is activated by higher pressure. This water is higher in silica, due to the contact with the flysch basis.

With the available information it was not possible to favour one of the possibilities. The discharge weighted mean of silica contents of all samples amounts to 0.50 mg/l and is used as the representative silica content of karst water, uninfluenced by an allogenic flysch water component.

Vipava Springs' Water

Fig. 4.24 (D) shows the discharge and the silica content of Vipava springs during the observed period. The silica content of the Vipava springs is on a level between those of the karst and the flysch water and ranges from 0.54 mg/l to 0.86 mg/l. It can be seen, that there is no silica rise during the strong precipitation event. Thus, the above listed mechanisms, that might cause a silica rise, seem not to be active in the Vipava system. The high silica peak

from April the 6th until the 8th happens to coincide with the snowmelt event, but has no causal connection to it, as all driving forces of the above mentioned mechanisms are weaker than during the precipitation event.

As a consequence, this peak is attributed to an allogenic flysch component, appearing at Vipava springs and bringing flysch water. Following points support this interpretation:

- In Vipava springs much higher concentrations of silica occur than in Hubelj springs, indicating that other mechanisms are active.
- The overall course of the silica content in Vipava springs can be plausibly explained, assuming that a flysch water component exists. Before the precipitation event a mixture of karst and flysch water in the Vipava aquifer is discharging. During the precipitation event recharge to the aquifer from the flysch area is very high, since there precipitation falls exclusively as rain. As it has a long distance to pass, it arrives at the springs with a big time lag and causes the silica rise. The discharge time series show, that a strong snowmelt event follows. During this event, the only sources of recharge are the higher, snow-covered karst plateaux, causing a decrease in silica to a very low level.
- The travel time of the flysch component was calculated with the time of peak silica load in the Lokva river and the time of peak silica concentration in Vipava springs and amounts to 4 days and 12 hours. This time is well comparable to results from the Uranine tracing experiment from April 1994. There, the tracer, that had been injected in the Lokva stream, arrived at Vipava springs after 6 days and 14 hours. The longer travel time can be plausibly explained by the less extreme hydrological conditions during the uranine experiment (HQ: 25 m^3/s).

Hydrograph Separations

It can be evaluated, how much of the Vipava springs' water comes from the actual flysch flood on the flysch area. The rest of the water, discharging at Vipava springs, is a mixture of water from karst recharge areas and 'older' water from flysch recharge areas. Thus, it further can be evaluated, how much of the Vipava springs' water comes from the karst recharge areas and how much from the flysch recharge areas. Consequently, it is distinguished between two different separations:

- separation I:
  into flysch recharge water (any age) and karst recharge water (any age)
- separation II
  into 'young' flysch flood water and water, that has been in the karst system before the arrival of the flysch flood water (karst water + 'old' flysch water)

For separation I a silica content of 0.5 mg/l is used for the karst water component, while a silica content of 2.53 mg/l is used for the flysch water component. For separation II a silica content of 0.7 mg/l - the mean of the silica contents in Vipava springs before the arrival of flysch flood water - is used for the water in the karst system, while 2.25 mg/l is used for the flysch flood water component. Fig. 4.24 (E) shows the results of both separations.

The results of separation I show, that before the arrival of the allogenic component the flysch recharge water contribution is on a level of about 9%. This is the best estimation of the mean flysch recharge water contribution, that is available from the short observation period. Due to the extreme hydrological conditions, this contribution varies between 3 % and 18 %.

The results of separation II show, that the contribution of the actual flysch flood water rises up to 10 % and that it mainly discharges during a short time of about 2 days. It has to be considered, that the contributions are probably low limits, since snowmelt water from the karst plateaus (lower in silica) was probably already contributing.

4.2.3.4. Conclusions

It could be shown, that during a precipitation runoff event silica could be well used as a natural tracer to detect the allogenic flysch water component in the Vipava karst springs. The rise of the silica content in Vipava springs could be plausibly attributed to the arrival of allogenic flysch water from the flysch area near Postojna. Silica helps to describe the dynamics of the flysch water component, which comes during a relatively short time period and has a travel time of 4 days and 12 hours. This is one third less than the travel time of uranine from the artificial tracer experiment in April 1994, but still comparable, since the hydrological conditions were extreme.

In the single event analyses from November the 16th 1995, there were no hints of an allogenic flysch component though. Unfortunately, silica has not been analyzed. It is possible, that the used parameters were simply not suitable to detect the allogenic flysch component or that the different meteorological conditions were responsible for the different results. During the precipitation event in April, there was snow deposition beside rain on the karst plateaus, resulting in a relatively heavier recharge to the karst aquifer from the flysch area compared to the karst plateaus. The November event was a pure rainfall event.

A hydrograph separation showed, that during the time of peak flysch water contribution, at least 10 % of Vipava springs' discharge was made up by water from the actual flysch flood on the flysch area. Another hydrograph separation into karst recharge water and flysch recharge water showed, that before the arrival of concentrated allogenic flysch water the contribution of flysch recharge water is on a relatively constant level of 9 %. This might give a very

rough estimation of the part of the Vipava catchment, that is made up by flysch. Thus, about 9 % or about 13 km^2 of the Vipava catchment would be on flysch areas. It is critical to draw conclusions on long term conditions on the basis of an observation period of only two weeks, but the results are in realistic ranges.

For further investigations in karst systems with an allogenic flysch component, it might be promising to make long term silica observations (at least one year), in order to obtain information on the part of the catchment, that is made up by flysch. With the same network of automatic samplers a short term sampling during single runoff events could be done, in order to characterize the dynamics of the allogenic flysch component under different hydrological conditions.

5. ISOTOPIC INVESTIGATIONS

5.1. ENVIRONMENTAL ISOTOPE INVESTIGATIONS

(W. STICHLER, P. TRIMBORN, P. MALOSZEWSKI, D. RANK,
W. PAPESCH, B. REICHERT)

5.1.1. Introduction

The environmental isotopes deuterium (^2H), oxygen-18 (^{18}O) and tritium (^3H) are suitable for tracing the origin of the water in the hydrological cycle because they are constituents of the water molecule. Therefore, the use of environmental isotope techniques may, in addition to conventional investigation methods, provide further insight into the storage properties of natural hydrological systems. Information can be derived about the mean altitude of catchment areas and mean residence times (transit times) of subsurface water by applying specific models. As a major part of this study, the ^{18}O content is presented in time series of precipitation and runoff samples. The investigation of single hydrological events (e.g. storms, snow melt) was one of the main targets of the use of isotope methods within the karst research program 1993-96 in Slovenia. The location of the sampling points (precipitation stations, springs and sinkholes) are documented in Figure 5.1.

The ^3H and ^{18}O analyses were performed at the Geotechnisches Institut, Bundesforschungs- und Pruefzentrum Arsenal, Vienna and at the GSF Institute of Hydrology, Neuherberg. The measuring accuracy (2σ criterion) of ^3H values corresponds to 8 % and the detection limit is ca. 0.5 TU. The $\delta^{18}O$ values are given as relative ‰ -deviation from the international standard water V-SMOW. The measuring accuracy (2σ criterion) is equal to 0.1 ‰ in the $\delta^{18}O$ scale.

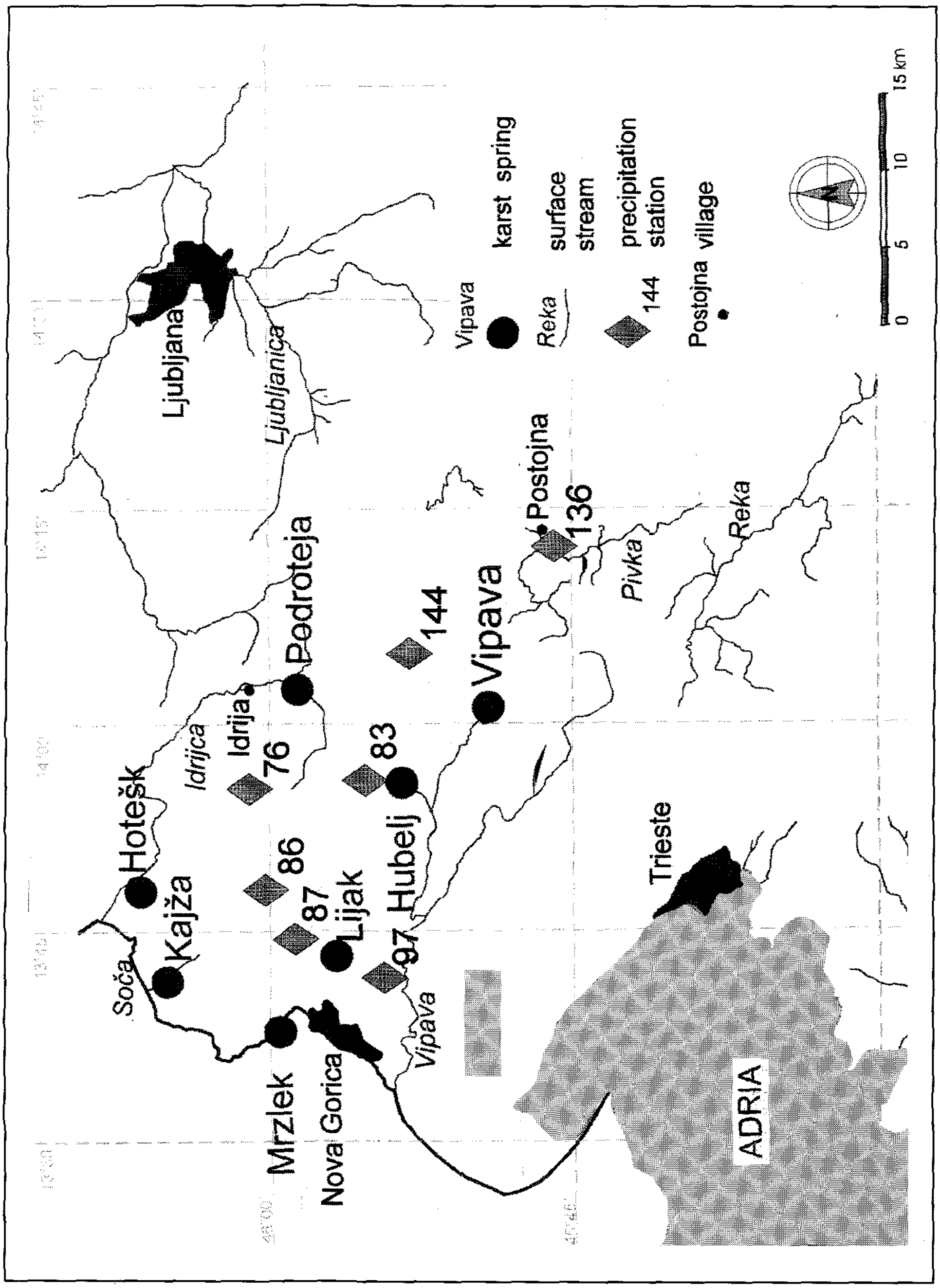


Fig. 5.1: Location map of the precipitation stations, springs and sinkholes of the area under investigation sampled for isotope measurements.

5.1.2. Precipitation

The precipitation was collected at six stations, usually in monthly intervals. The stations are spread over the research area at different altitudes. In Table 5.1, the locations of the precipitation sampling points are listed together with the altitude above sea level.

Tab. 5.1: Precipitation stations.

Name of the station	Code No.	Altitude [m]
Vojsko	76	1070
Lokve	86	965
Trnovo	87	789
Bilje	97	50
Postojna	136	555
Podkraj	144	799

5.1.2.1. Seasonal variation

The $\delta^{18}O$ contents of the monthly precipitation samples are documented in Figure 5.2. The expected seasonal variations can be seen, but are overlapped by irregularities in single months.

At one station (Lokve) the twofold running mean over three months is used to visualise the sinusoidal wave of the isotopic content in precipitation (Fig. 5.3). The relative high $\delta^{18}O$ -values in the summer months are followed by lower $\delta^{18}O$ -values in the winter months. Considering the whole observation period of three years, a general trend towards lower $\delta^{18}O$ -values is obvious.

Using the isotope content as the input function, the precipitation amount has to be taken into account. As an example, Figure 5.4 shows the $\delta^{18}O$-values as an input function recalculated by the following equation:

$$\delta^{18}O_{cal} = \left(\delta^{18}O_i - \delta^{18}O_{mean}\right)\frac{P_i}{P_{mean}} + \delta^{18}O_{mean} \quad [‰] \qquad (1)$$

with $\delta^{18}O_{cal}$: calculated monthly $\delta^{18}O$-value

$\delta^{18}O_i$: measured monthly $\delta^{18}O$-value

$\delta^{18}O_{mean}$: weighted mean $\delta^{18}O$-value

P_i : monthly precipitation amount

P_{mean} : mean monthly precipitation amount

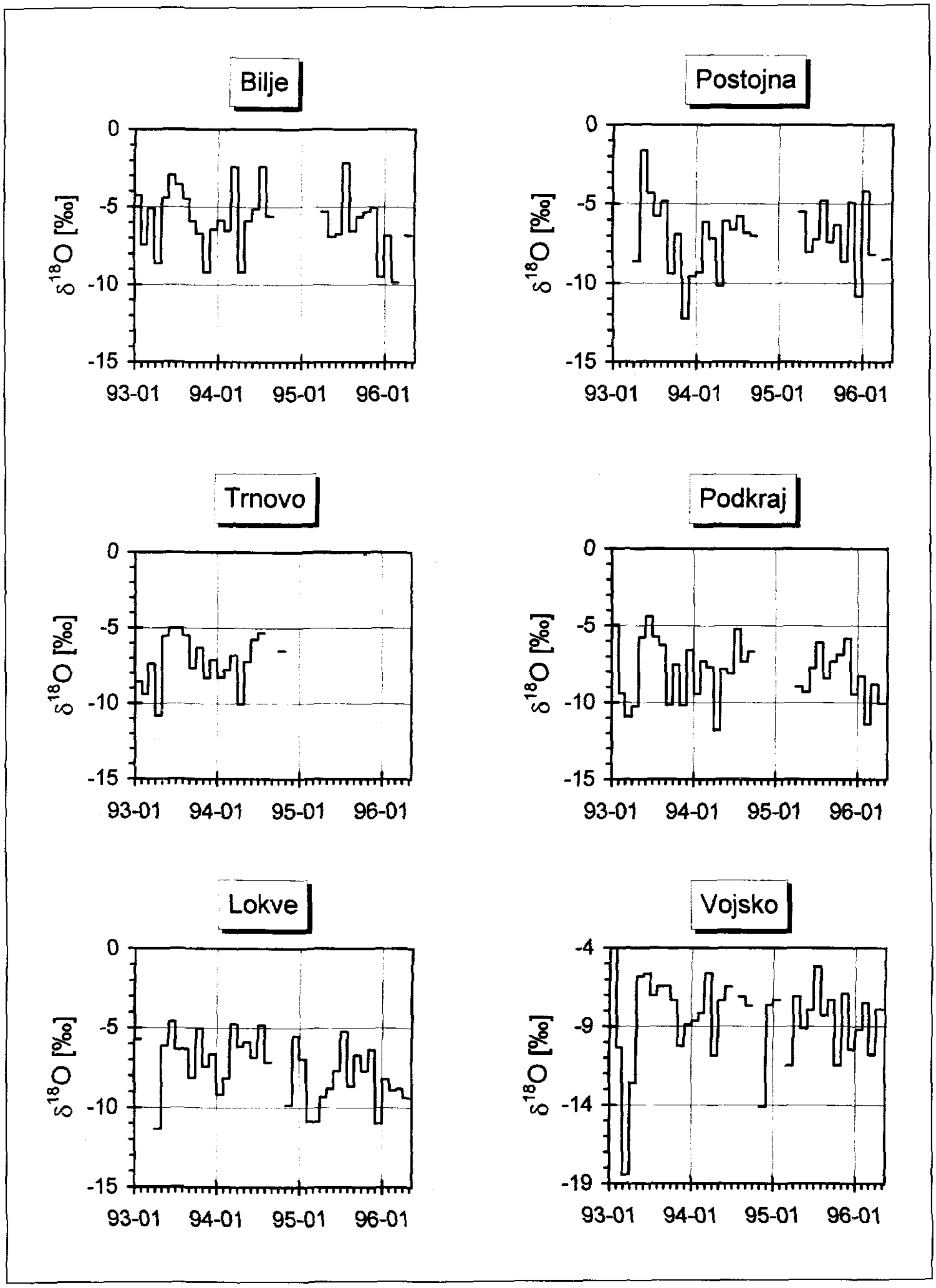


Fig. 5.2: Seasonal variation of $\delta^{18}O$-contents (monthly means) in precipitation from Slovenian meteorological stations.

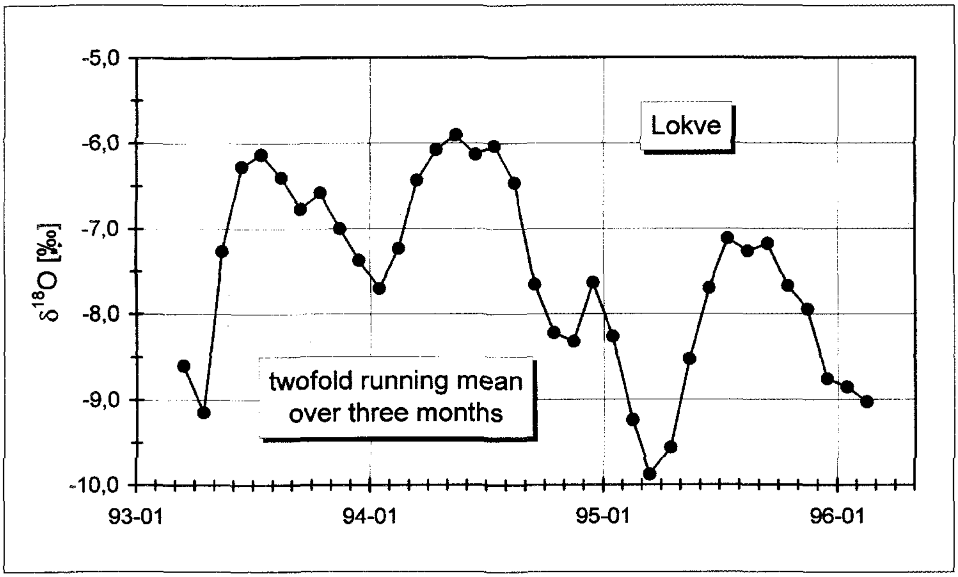


Fig. 5.3: Twofold running mean over three months of $\delta^{18}O$-contents in precipitation from the meteorological station Lokve.

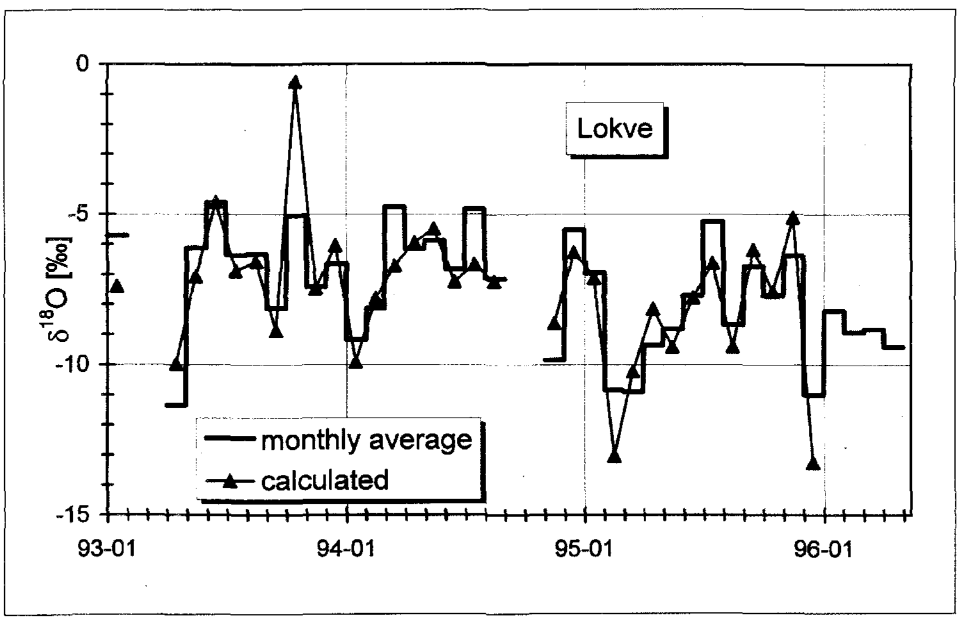


Fig. 5.4: Comparison of $\delta^{18}O$-contents in precipitation of monthly average and calculated after Eq. 1 from the meteorological station Lokve.

Besides the precipitation amount, Eq. (1) also considers the difference between the $\delta^{18}O$ content in the precipitation of a single month and the mean weighted $\delta^{18}O$-value estimated over the whole observation period. It can be seen that relatively higher $\delta^{18}O$-values occur at the beginning of the investigation (1993) in comparison with the $\delta^{18}O$-values towards the end of the observation period (1995).

5.1.2.2. Short term variation

A prerequisite for successful isotope investigations of single hydrological events are variations in the isotope content of the input - the precipitation. The deviation of the $\delta^{18}O$ -values for single precipitation events from the average yearly course depends on the origin of the humid air masses, as well as on the respective climatic conditions during the precipitation events.

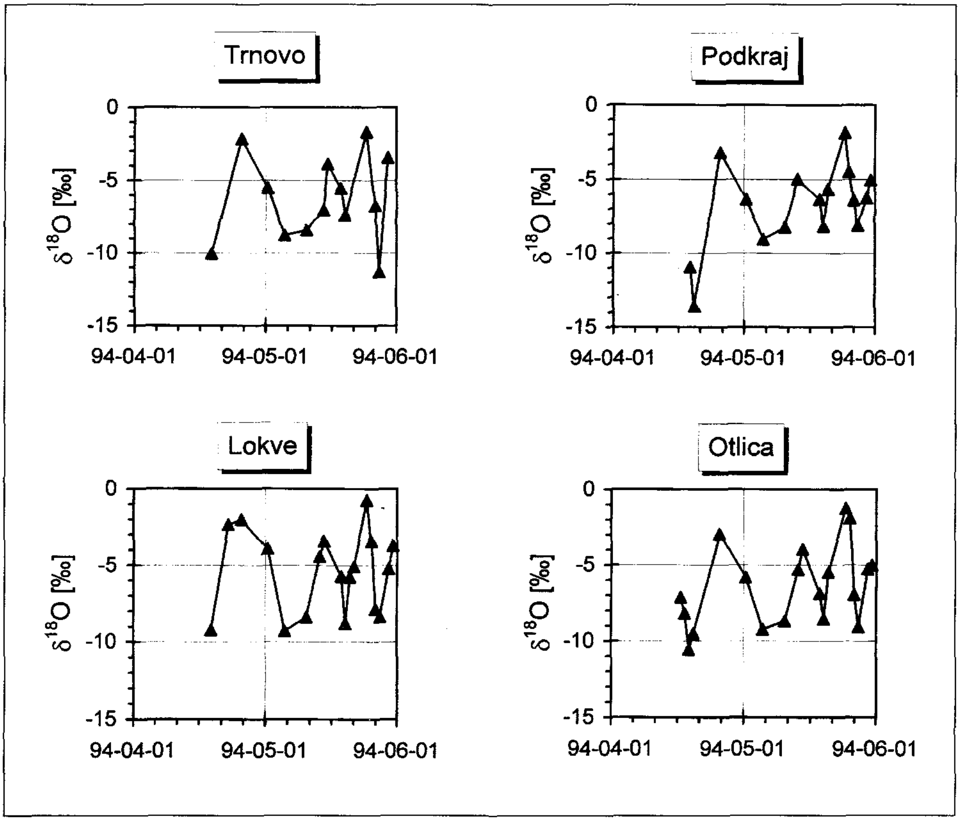


Fig. 5.6: Variation of $\delta^{18}O$-contents in daily precipitation from Slovenian meteorological stations (observation period April to May 1994).

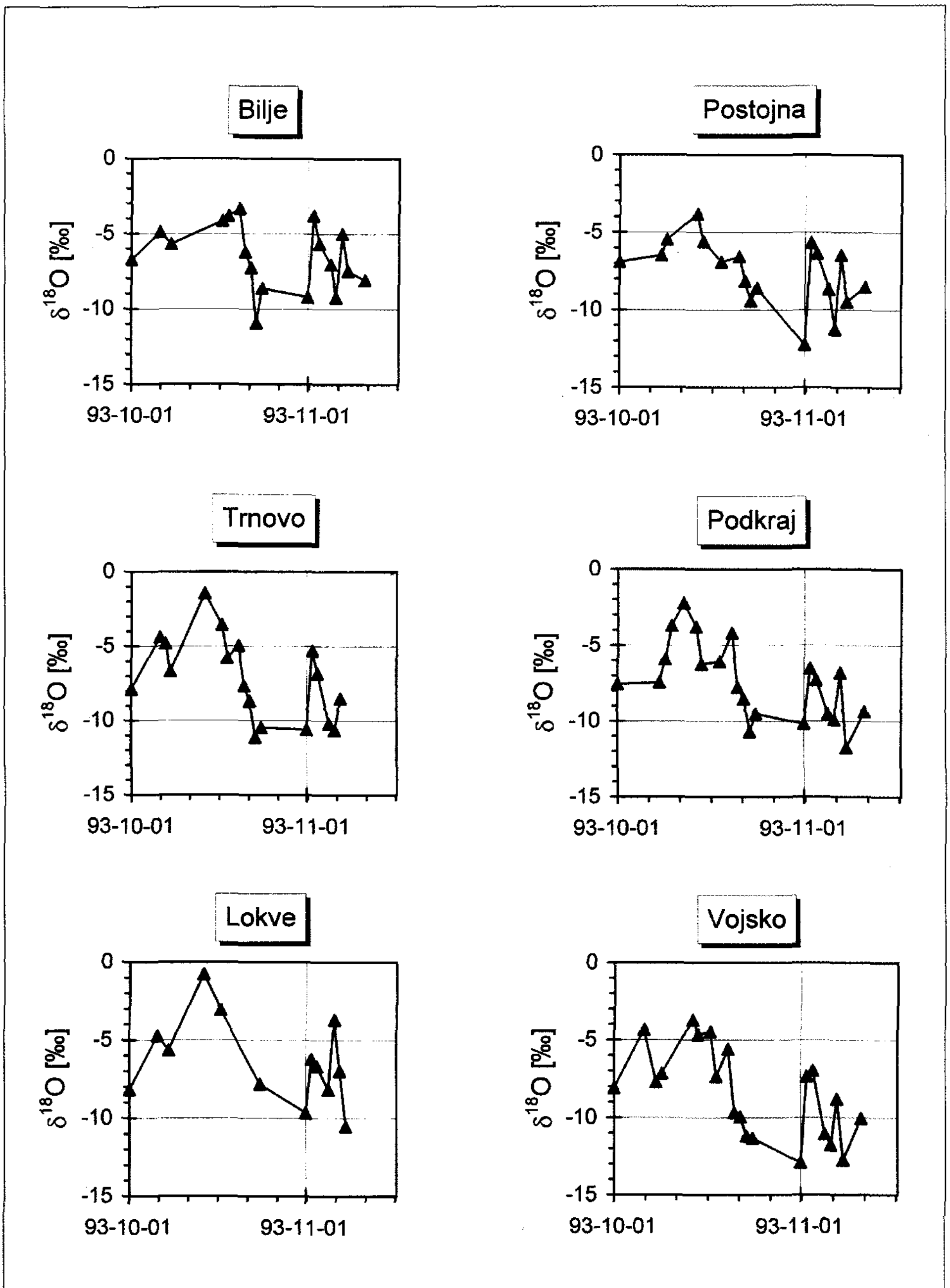


Fig. 5.5: Variation of $\delta^{18}O$-contents in daily precipitation from Slovenian meteorological stations (observation period October to November 1993).

Figure 5.5 depicts the variations in the $\delta^{18}O$ content of daily precipitation at the six sampling stations during the period of October/November 1993. Significant precipitation events occurred with $\delta^{18}O$ content, which differed considerably from one another. These events normally provide useful input signals, which can be followed within the hydrological system. Furthermore it can be recognised that a general pattern is given in the $\delta^{18}O$ variation at all stations. This demonstrates the possibility of using this precipitation data as a regional input. In Figure 5.6, the $\delta^{18}O$ contents of single precipitation events from three sampling stations are plotted together with the results from the precipitation station Otlica. The observation period was from middle of April to the end of May 1994. The $\delta^{18}O$-values, specially in May, scatter up to 10 ‰ from one event to the following. Therefore, the use of these events as a pronounced isotopic input signal is limited.

Further examples are given in chapter 5.1.4 together with the $\delta^{18}O$-values of the discharge of the karst springs Vipava, Hubelj and Lijak.

5.1.3. Altitude Effect

Figure 5.7 shows the correlation between the weighted annual average of the $\delta^{18}O$-values in the precipitation and the altitude (Tab. 5.1) of the corresponding sampling stations for different years. For the stations Bilje, Postojna, and Podkraj, the results of each of the three years could be used, for Vojsko two years and for Lokve only one year. The isotope results obtained from the

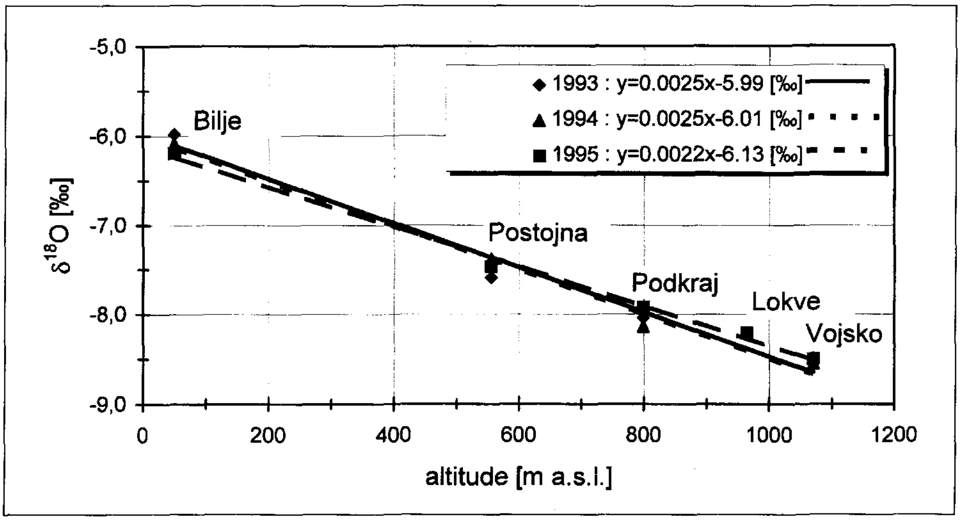


Fig. 5.7: Correlation of $\delta^{18}O$-contents in precipitation from Slovenian meteorological stations and altitude for the years 1993, 1994, and 1995.

precipitation at Trnovo did not fit the ^{18}O content - altitude correlation at all.
Calculating the mean value from the three years, an altitude correlation which will be used for further calculations, is obtained as follows:

$$\delta^{18}O = -0.0024\,A - 6.03 \quad [‰] \qquad (2)$$

with A = altitude in meter above sea level.

5.1.4. Long-term observation

The observation period for the isotope investigations was on the order of three years for most of the selected karst springs. The main objectives were to estimate the mean altitude of the catchment areas of the springs and to calculate the transit time of the water.

5.1.4.1. Altitude of the catchment

For the estimation of the mean altitude of a catchment area, the average $\delta^{18}O$-value was calculated over the whole observation period and Eq. (2) applied. In particular, two sinkholes and seven springs were investigated. The uncertainty of the calculated altitude of the catchment areas results from the 2σ criterion of the $\delta^{18}O$-values.

Sinkholes

Figure 5.8 shows the $\delta^{18}O$ variation of the water from the sinkholes Banjšice and Čepovanski Potok. These two sinkholes are located at an altitude of 667 m a.s.l. and 608 m a.s.l., respectively. The resulting altitudes of their catchment areas are listed in Table 5.2.

Tab. 5.2: Estimated mean altitude of the catchment area of two sinkholes

Name of the sinkhole	$\delta^{18}O$ [‰]	Altitude [m]
Banjšice	-7.76 ± 0.17	720 ± 70
Čepovanski Potok	-8.28 ± 0.14	940 ± 60

Taking the altitude of the sinkholes themselves into account the following can be concluded:
The catchment area of the water disappearing in the sinkhole Banjšice covers an altitude range from 670 m up to 770 m. In contrast, the catchment area of the water in the sinkhole Čepovanski Potok ranges from 600 m up to

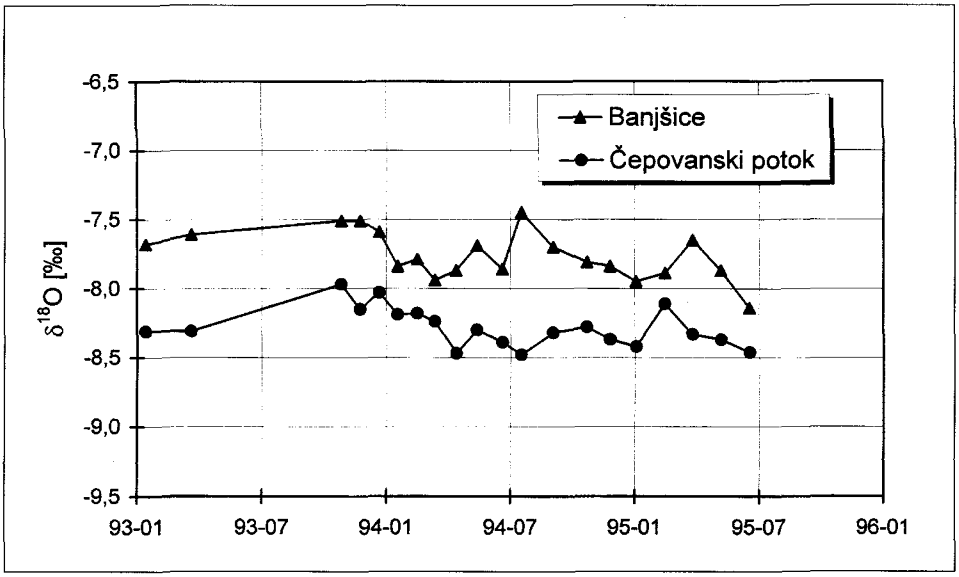


Fig. 5.8: Seasonal variation of $\delta^{18}O$-contents of water from the sinkholes Banjšice and Čepovanski Potok.

nearly 1200 m. This estimation presupposes that the altitude of the catchment area starts at the location of the sinkhole. With these altitude ranges the catchment areas of the waters of these two sinkholes can be geographically fixed.

Karst springs

In Figure 5.9 the seasonal variations of the $\delta^{18}O$ content of the water from the springs Kajža, Hotešk, and Podroteja are plotted. Besides the corresponding sinusoidal fluctuations of the $\delta^{18}O$-values, a difference in the absolute values can be recognised.

The seasonal variations of the $\delta^{18}O$ content of the water from the springs Hubelj, Mrzlek, and Vipava are documented in Figure 5.10. In comparison to the curves in Figure 5.9, the seasonal fluctuations of the $\delta^{18}O$ content of the water are similar, meanwhile the absolute values vary roughly between -8 and -9 ‰ . During 1995, a continuous increase of the $\delta^{18}O$-values in the water of all three springs is obvious. This was caused by an increase in the $\delta^{18}O$-values in the precipitation, documented e.g. in Figure 5.4 for the Lokve precipitation station.

The calculated altitudes of the catchment areas of the individual springs are listed in Table 5.3.

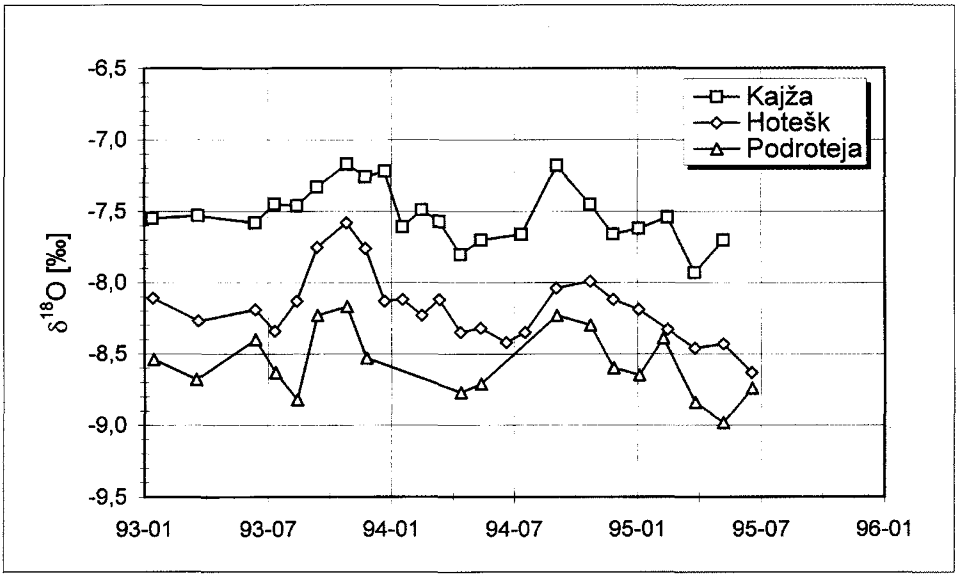


Fig. 5.9: Seasonal variation of $\delta^{18}O$-contents of water from the karst springs Kajža, Hotešk, and Podroteja.

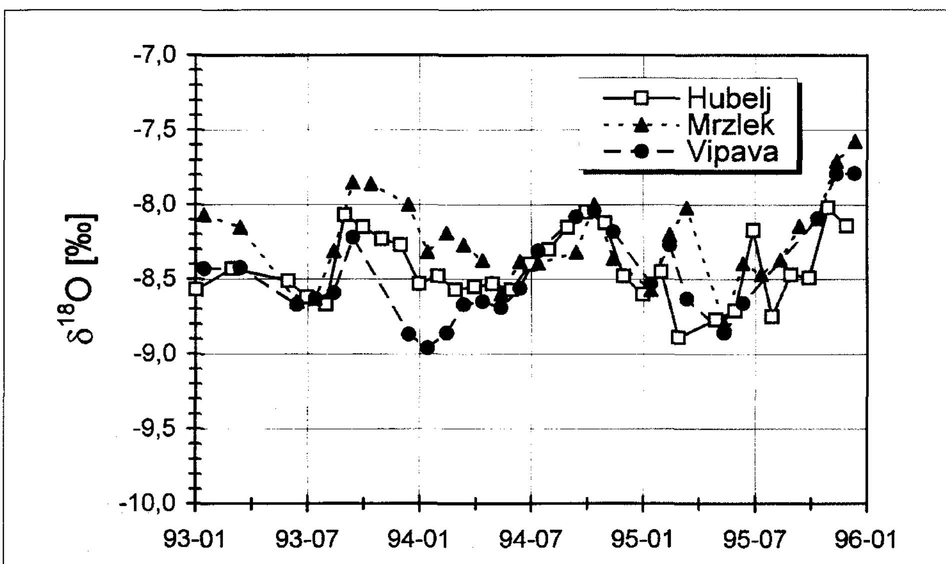


Fig. 5.10: Seasonal variation of $\delta^{18}O$-contents of water from the karst springs Hubelj, Mrzlek, and Vipava.

Tab. 5.3: Estimated mean altitude of the catchment area of the six springs.

Name of the spring	$\delta^{18}O$ [‰]	Altitude [m a.s.l.]
Kajža	-7.52 ± 0.20	620 ± 80
Hotešk	-8.18 ± 0.24	900 ± 100
Mrzlek	-8.24 ± 0.29	920 ± 120
Hubelj	-8.43 ± 0.23	1000 ± 100
Vipava	-8.46 ± 0.33	1010 ± 140
Podroteja	-8.57 ± 0.24	1060 ± 100

Soča River

The $\delta^{18}O$-values of the water from the Soča river shows the analogue seasonal variation as observed in the water of the springs (Fig. 5.11). From the average $\delta^{18}O$-value (-8.46 ± 0.30 ‰), the mean altitude of the catchment area was estimated to 1010 ± 130 m a.s.l.. The general trend over the whole observation period, which was mentioned for the $\delta^{18}O$ content of precipitation samples, is also obvious in the $\delta^{18}O$-values of the river water with a delay of the winter precipitation possibly caused by a temporal storage of the snow cover.

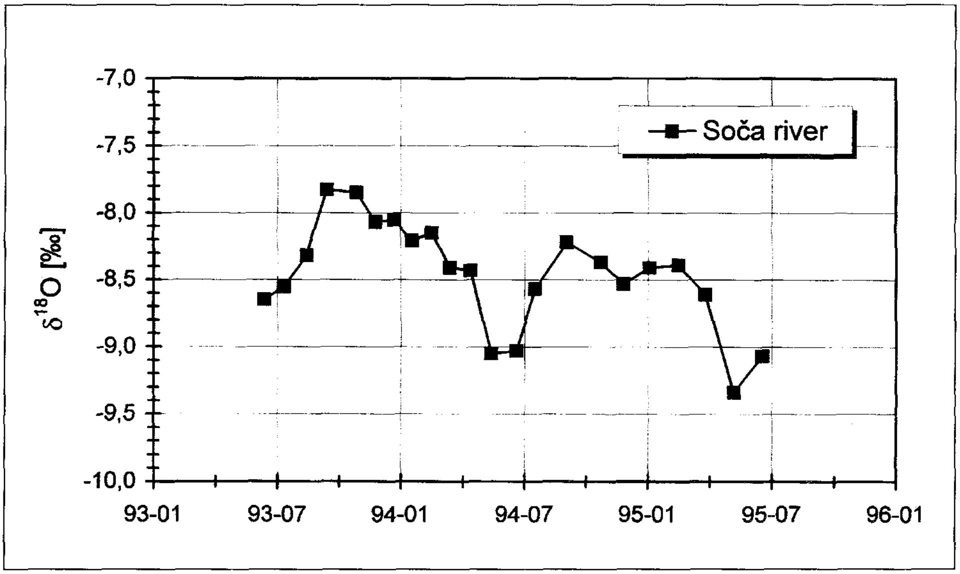


Fig. 5.11: Seasonal variation of $\delta^{18}O$-contents of water from the Soča river.

5.1.4.2. Mean residence time

In the literature, several mathematical models known as so-called Black-Box-Models are used to estimate the mean transit times from long term isotopic observations (MALOSZEWSKI & ZUBER 1982, 1996). Considering the hydrological situation in the area under investigation, the dispersion model (DM) seems to be applicable for the interpretation of the isotope data obtained during base flow conditions. Since the groundwater system is under steady state conditions, the relation between input and output concentration of the nonradioactive tracer is given by the following convolution integral:

$$C_{out}(t) = \int_0^t C_{inp}(\tau)\, g(t-\tau)\, d\tau \qquad (3)$$

where C_{inp} and C_{out} are the input and output concentrations as functions of time, t, respectively, and $g(t)$ is the weighting function defining the transit time distribution in the system. The $g(t)$ function for the dispersion model is defined as follows (MALOSZEWSKI & ZUBER 1982):

$$g(t) = \frac{1}{\sqrt{4\pi P_D (t/T)}} \frac{1}{t} \exp\left[-\frac{(1-t/T)^2}{4P_D(t/T)}\right] \qquad (4)$$

The main parameter of this model is the mean transit time of water (T), which is defined as

$$T = \frac{V}{Q} \qquad (5)$$

where Q is the mean volumetric flow rate through the system and V is the volume of water in the system. P_D is the dispersion parameter, which describes the variance of the transit time distribution.

With stable isotopes, a simpler procedure can be applied, if the isotopic input curve can be approximated as a sinusoidal function with the period of one year (see chapter 5.1.2.1):

$$C_{inp}(t) = A_n \sin(\omega t) \qquad (6)$$

where w = 2p / (year), and A_n is the mean amplitude of the input function.
Introducing Eq. (6) in Eq. (3) yields:

$$C_{out}(t) = B_n \sin(\omega t + \varphi) \qquad (7)$$

where B_n is the mean amplitude of the output function, and φ is the phase shift, which in the case of the dispersion model is equal to:

$$\varphi = T\left[(1+3P_D) - \sqrt{1+(3P_D)^2}\,\right] \qquad (8)$$

The mean transit time can be calculated from the amplitude ratio $f = B_n / A_n$ as:

$$T = \frac{1}{\omega}\sqrt{-\frac{\ln f}{P_D}} \qquad (9)$$

The values of parameters φ and f are determined directly from experimental data. By using the Eqs. (8) and (9) iteratively, the mean transit time of water (T) and the dispersion parameter (P_D) can be calculated.

The amplitude A_n (input function) was estimated from the $\delta^{18}O$ variation in precipitation at representative stations shown in Figure 5.2. The $\delta^{18}O$ output function of the selected karst springs are plotted in Figures 5.9 and 5.10. These data are the basis for the estimation of the amplitude B_n of the karst springs under investigation.

Tab. 5.4: Mean transit time (T) and dispersion parameter (P_D) calculated for selected springs.

Name of the spring	T [months]	P_D [-]
Kajža	5.4	0.28
Hotešk	5.5	0.30
Podroteja	5.5	0.29
Hubelj	5.8	0.25
Mrzlek	5.0	0.25
Vipava	4.4	0.30

The evaluation of the ^3H data gives similar results. The ^3H values of monthly samples from the Vipava spring correspond with the actual ^3H content of precipitation, thus may indicate a relatively short mean residence time of the spring water in the underground (Fig. 5.12). There is no significant increase/decrease of the ^3H content even during low water periods. Only the seasonal variations of the ^3H content in precipitation (see also Fig. 5.12) are reflected in the ^3H graph of the Vipava spring. A mean transit time of about 0.4 years may be estimated from the comparison of the ^3H amplitudes of precipitation and spring water. This corresponds with the results above concluded from the $\delta^{18}O$-values.

However the mean transit times of around 5 months (see Tab. 5.4) seem to be too low considering the hydrogeological situations. Therefore a mixture of two water components, having mean transit times of weeks (karstic channels) and mean transit times of years (outflow from the karst massif) could not be excluded. While, to separate these two components a longer observation period is necessary.

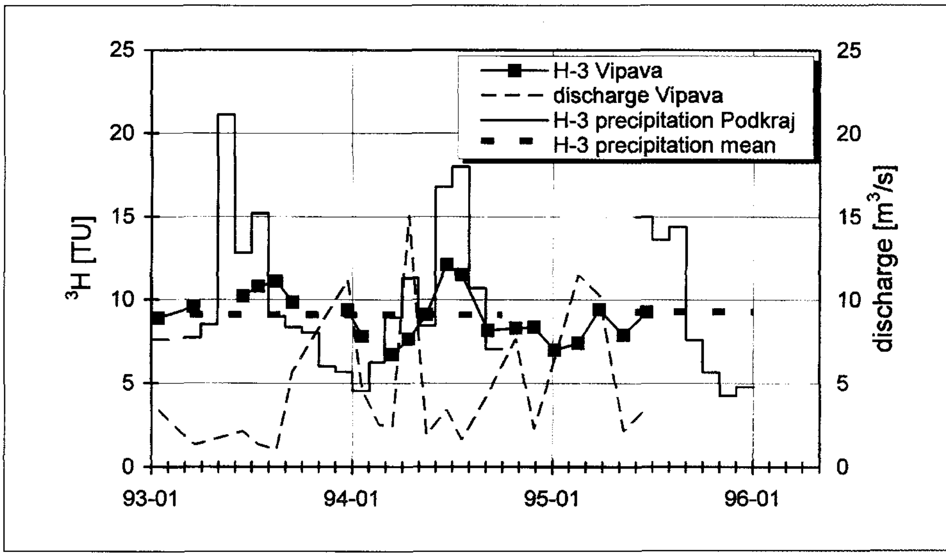


Fig. 5.12: Discharge and ³H content of monthly samples from Vipava spring together with the monthly and weighted mean ³H-values of precipitation at the meteorological station Podkraj.

5.1.5. Short term observation

In addition to a quantitative approach to the course of hydrological events, isotopic investigations also provide insight into the age structure of waters. Such knowledge helps in drawing conclusions on storage processes in hydrological systems and on the composition of the runoff; that is on the relative shares of base flow, direct runoff following storm events, and interflow. Distinguishing the components of runoff is an important basis for hydrological assessment of potable water reserves in a particular region.

To apply this method, an adequate amount of precipitation is necessary as well as a distinct difference in the isotope content of the water components mentioned above. Considering the seasonal variations in the ^{18}O content in precipitation, major deviations in the ^{18}O content from single precipitation events from the mean value of the system can be expected in winter and in summer. In the area under investigation, precipitation in winter generally takes the form of snow, and does not directly reach runoff. Therefore, mid-summer would be the most favourable period for such research.

As mentioned above, isotope data can be used to estimate the portion of water flowing directly through the karstic channels. To do this, the isotope content has to be monitored in the karstic springs before and during a discharge event and in the precipitation producing this event.

The travel time through the karstic system of the fast-flow portion of a precipitation event can be estimated from the time delay between the respective peaks in precipitation and discharge, assuming a piston flow model. The percentage of direct flow water (d) is obtained by calculating the simple mixing equation using the $\delta^{18}O$-values of precipitation and discharge as follows:

$$d = \frac{C_{DE} - C_{BF}}{C_{PE} - C_{BF}} \qquad (10)$$

with: C_{DE} = weighted mean $\delta^{18}O$ content in discharge event
C_{PE} = weighted mean $\delta^{18}O$ content in precipitation event
C_{BF} = mean $\delta^{18}O$ content in discharge before the event at base flow conditions

5.1.5.1. Vipava spring

For the Vipava spring, the determination of the direct water component was only possible from the isotopic data obtained during the event on 17 November 1995.

The discharge measurements of the Vipava spring from October 1995 until March 1996 are plotted in Figure 5.13 together with the precipitation amount of the meteorological station Podkraj. The precipitation and discharge are in phase, only with the low values a shift of some days can be recognised. Isotope data from the single precipitation events are shown in Figure 5.14. Unfortu-

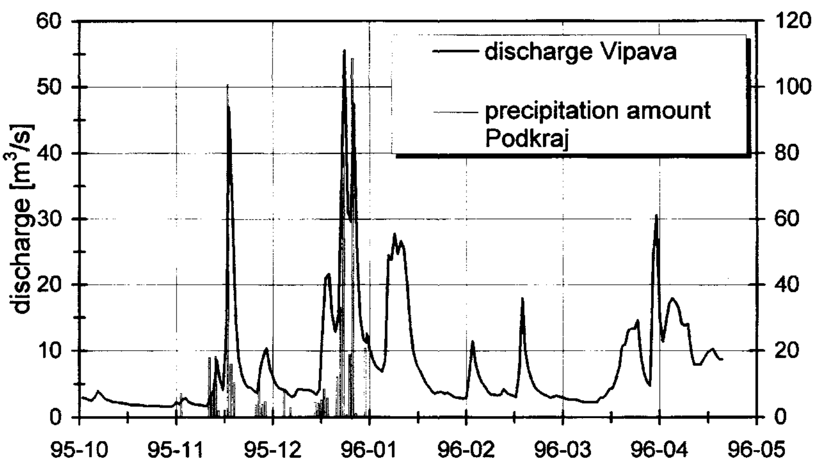


Fig. 5.13: Monthly precipitation amount from the meteorological station Podkraj and daily discharge of the Vipava spring (No. 4/7).

nately no precipitation samples are available from 1996. As can be seen in Figure 5.14, the rain event on the 17 November 1995 with 101 mm has a $\delta^{18}O$-value of -4.86 ‰. The percentage of the direct water component was calculated for this event (see Tab. 5.5). The ^{18}O content of the heavy rainfalls on 24 and

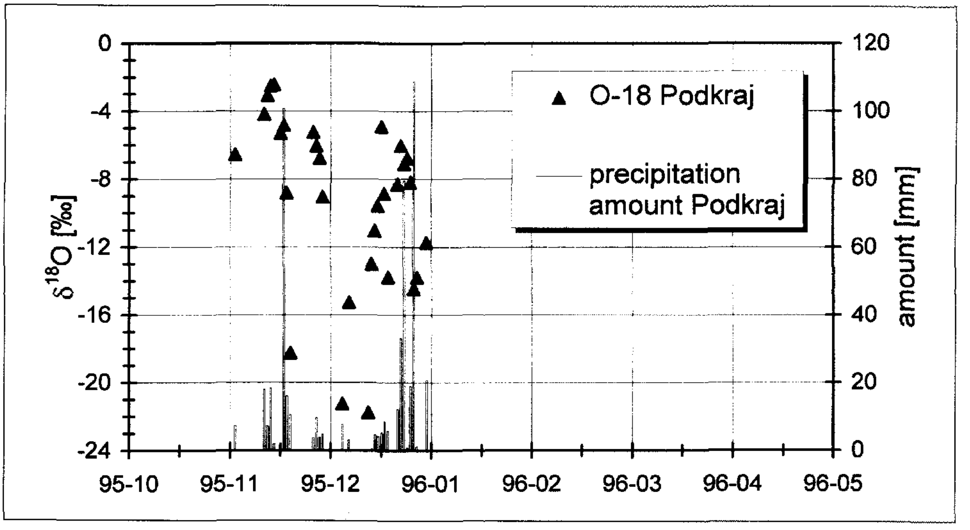


Fig. 5.14: Monthly precipitation amount and $\delta^{18}O$-content of precipitation from the meteorological station Podkraj.

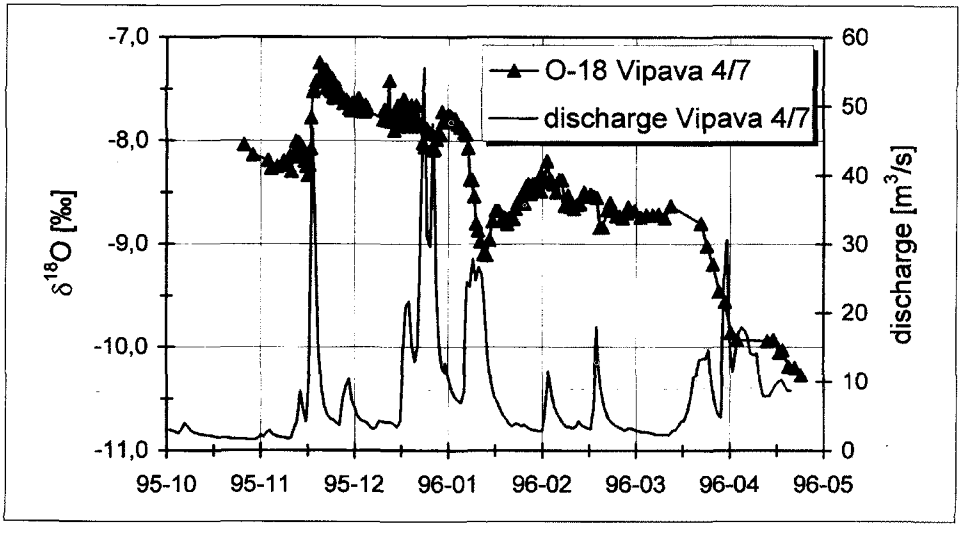


Fig. 5.15: Variation of $\delta^{18}O$-content of water and discharge from Vipava spring No. 4/7.

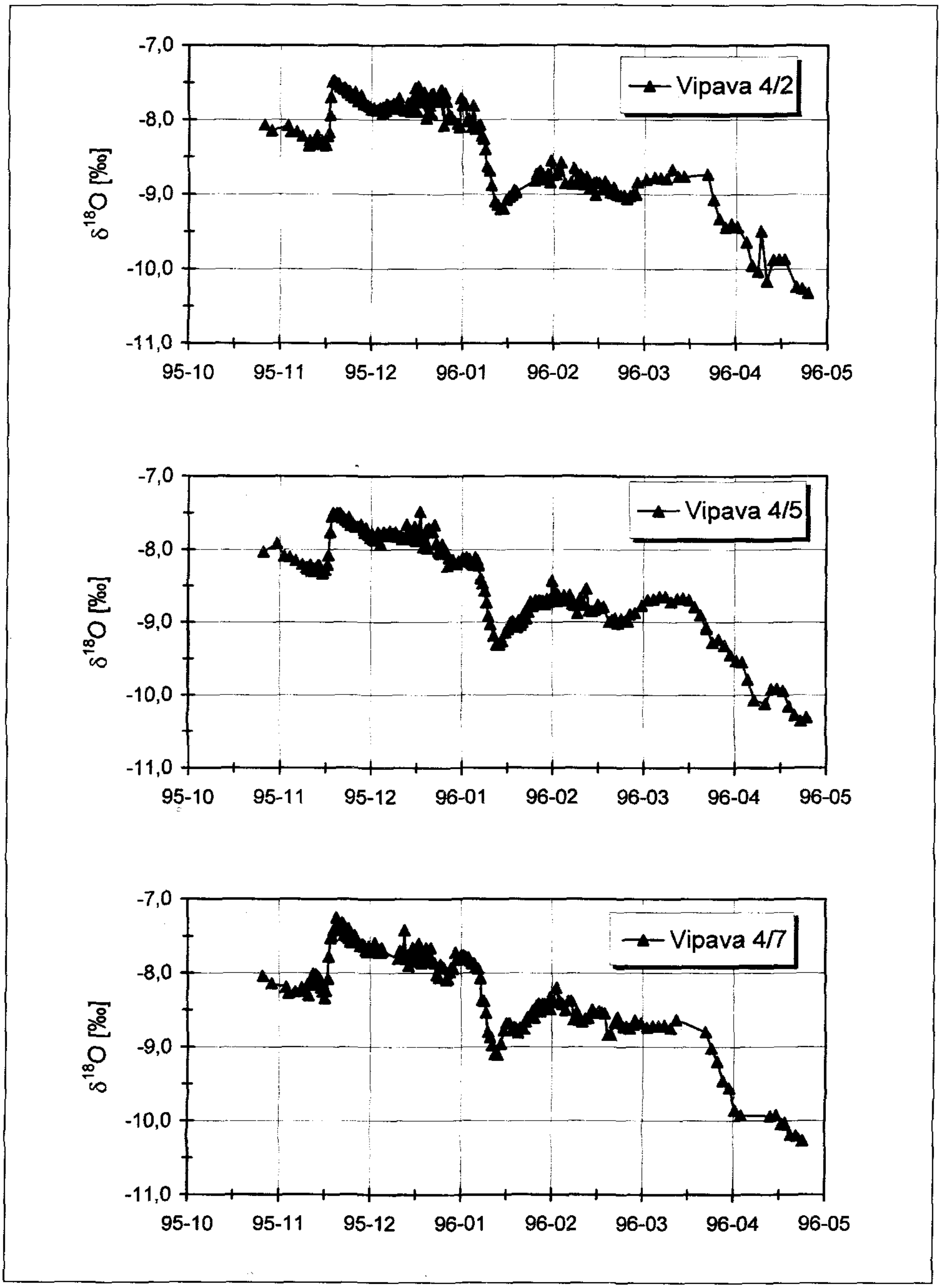


Fig. 5.17: Daily variation of $\delta^{18}O$-content of water from Vipava springs at sampling points No. 4/2, 4/5 and 4/7 (see Fig. 4.12).

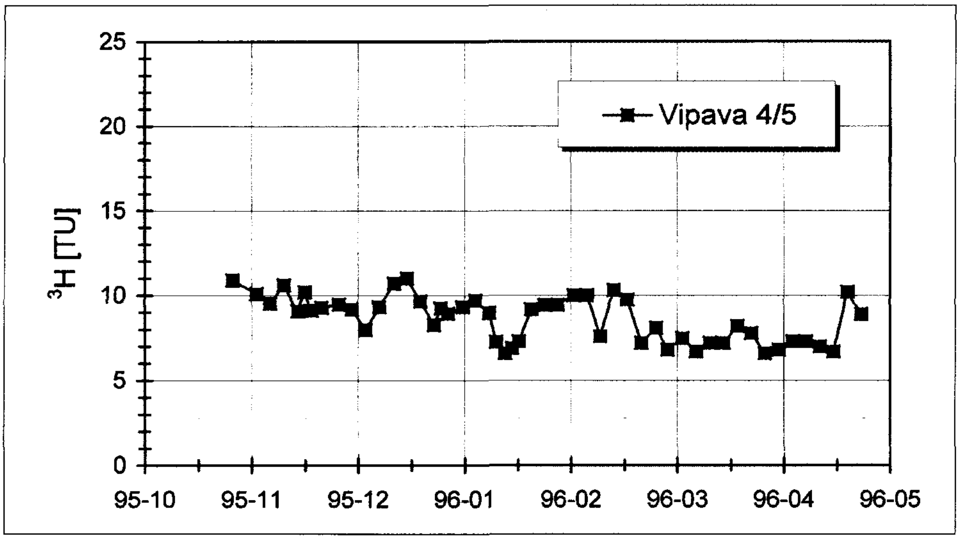


Fig. 5.18: Daily variation of the ^{3}H content of water from the Vipava spring.

27 December 1995 are scattered around the δ^{18}O-values of the discharge and therefore no separation is possible here. In Figure 5.15 the ^{18}O content and the discharge of the Vipava spring at sampling point 4/7 are shown. Measurable changes in the ^{18}O content correspond with high discharge values, except those at the end of December, which is explained above.

During the observation period October 1995 to April 1996 three individual springs of the Vipava system were sampled. The δ^{18}O-values for these spring waters are shown in Figure 5.17. The temporal curves of the ^{18}O content demonstrate the general spatial distribution pattern. The average values of the ^{18}O content of the three springs (4/2, 4/5 and 4/7) differ only slightly over the observation period. Using the altitude relation (see chapter 5.1.3) one can estimate that the mean altitude of the catchment area of Vipava spring 4/7 is ca. 50 m lower in comparison to the two other springs.

Also the ^{3}H data of the Vipava spring 4/5 values (Fig. 5.18) exhibit some variations during the period November 1995 - April 1996, but these changes are not as significant as those of the δ^{18}O-values.

5.1.5.2. Hubelj spring

For the Hubelj spring, two events could be taken into account: 28 August 1995 and 20 September 1995.

As input function, concerning the Hubelj spring, the meteorological station Otlica was used for the hydrograph separation. The precipitation amount

(Otlica) and the discharge measurements (Hubelj) are illustrated in Figure 5.19. Again there is a good correlation with an obvious shift of one day during heavy precipitation events. Taking the mean $\delta^{18}O$-value of the Hubelj spring water into consideration, the precipitation events (Fig. 5.20) from 26 to 28 of August 1995 (166 mm) and from 20 to 22 of September 1995 (73 mm) with $\delta^{18}O$-values of -6.67 ‰ and -7.40 ‰, respectively, were used for runoff

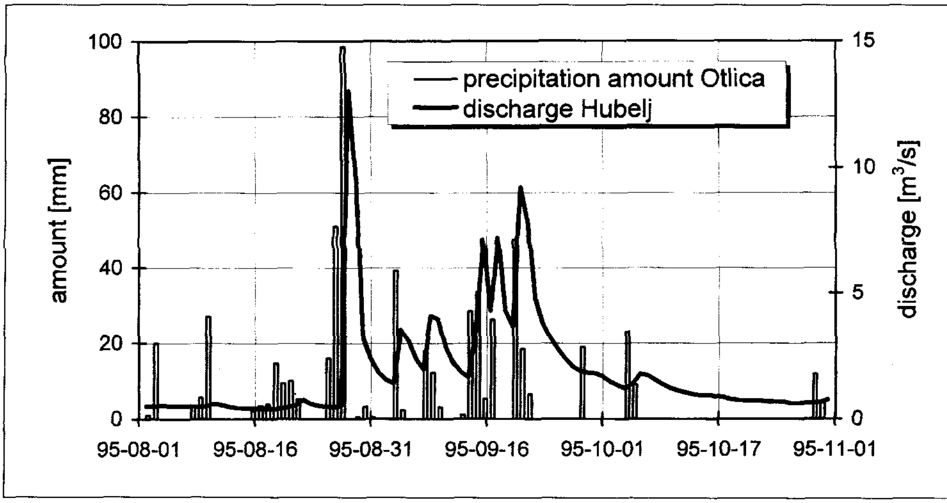


Fig. 5.19: Monthly precipitation amount from the meteorological station Otlica and daily discharge of the Hubelj spring.

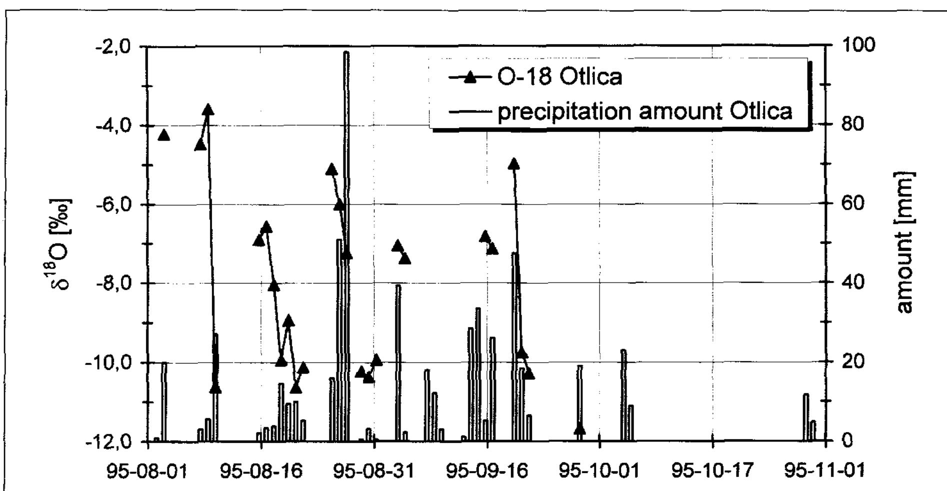


Fig. 5.20: Monthly precipitation amount and $\delta^{18}O$-content of precipitation from the meteorological station Otlica.

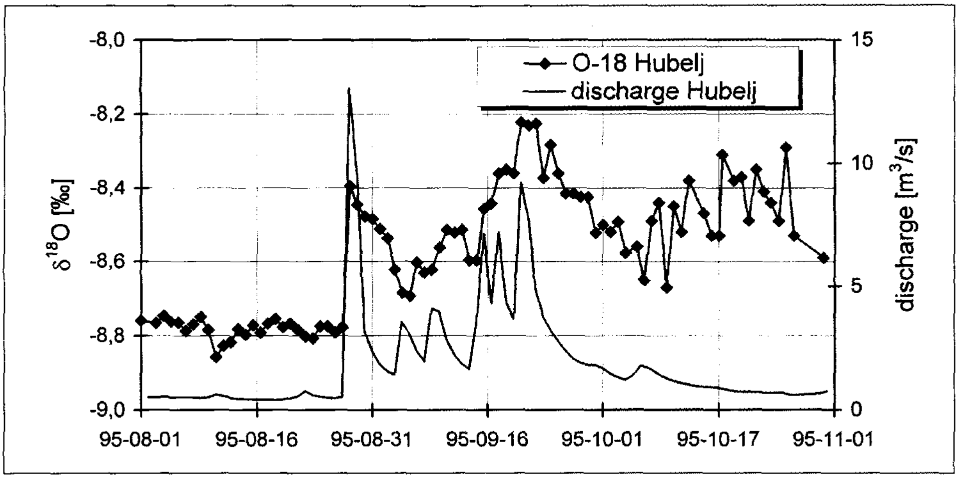


Fig. 5.21: Daily variation of $\delta^{18}O$-content of water and discharge from the Hubelj spring.

separation. The reaction in the ^{18}O content of the discharge in the Hubelj spring is given in Figure 5.21 and the results are summarised in Table 5.5.

5.1.5.3. Additional karst springs

Besides these two main spring systems Vipava and Hubelj, five additional karst springs were sampled on a daily basis during the spring of 1994.

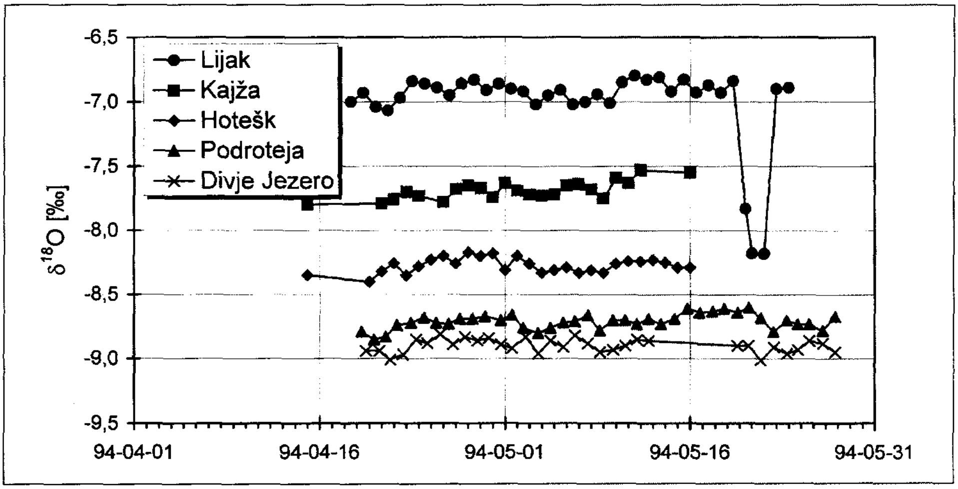


Fig. 5.22: Daily variation of $\delta^{18}O$-contents of water from the karst springs Lijak, Kajža, Hotešk, Podroteja, and Divje Jezero.

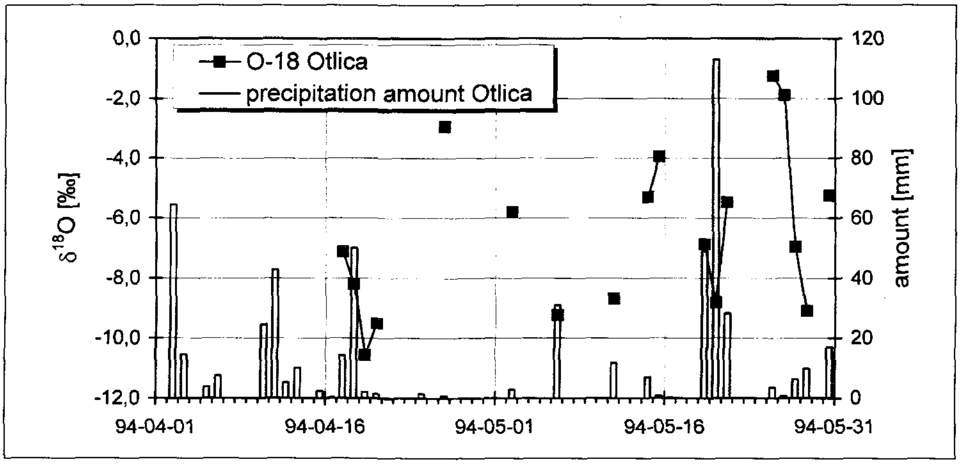


Fig. 5.23: Daily precipitation amount and $\delta^{18}O$-content of precipitation from the meteorological station Otlica.

The temporal variations of the $\delta^{18}O$-values are shown in Figure 5.22. It was only possible to calculate the direct runoff portion with the data obtained from the Lijak spring water during the 19 May 1994 event (see Tab. 5.5). The precipitation amount and the discharge values are documented together with the corresponding isotope data in Figure 5.23 and 5.24.

For the springs Podroteja and Divje Jezero, the ^{18}O content of precipitation and discharge were too close together and Eq. (10) could not be applied. The karst springs Kajža and Hotešk were not sampled during the mentioned precipitation event.

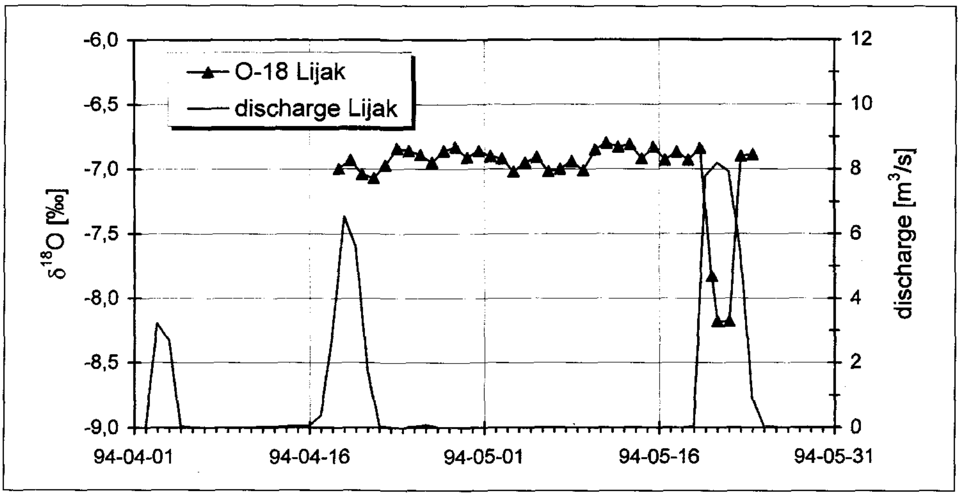


Fig. 5.24: Daily variation of $\delta^{18}O$-content of water and discharge from the Lijak spring.

5.1.5.4. Results

The results obtained by calculating the portion of direct water component during single events of selected springs using ^{18}O contents are summarised in Table 5.5. The travel time between precipitation event and discharge response are on the order of one to two days (see Fig. 5.13 and 5.19).

Tab. 5.5: Portion of direct water component during single events of selected springs calculated using ^{18}O contents.

Name of the spring	Date of event	C_{BF} [‰]	C_{PE} [‰]	C_{DE} [‰]	d [%]
Lijak	1994-05-19	-6.85	-8.63	-8.15	73
Vipava	1995-11-15	-8.20	-4.90	-7.50	21
Hubelj	1995-08-28	-8.78	-6.67	-8.42	17
Hubelj	1995-09-20	-8.36	-7.40	-8.22	15

The portions of direct runoff in Hubelj and Vipava spring range between 15 % and 20 %, with slightly higher values indicated for the Vipava spring. In contrast, the water of the Lijak spring shows a pronounced portion of precipitation water.

The $\delta^{18}O$-values of the karst springs shown in Figure 5.22 could also be used to calculate the mean altitude of the catchment areas of these individual springs. This is due to the fact that the discharge was very low during the observation period, as shown by the discharge measurements of the Podroteja spring (Fig. 5.25).

The average $\delta^{18}O$-content was calculated for the period of 15 April to 15 May 1994. The uncertainty of the calculated altitude of the catchment areas results once more from the 2σ criterion of the $\delta^{18}O$-values.

Tab. 5.6: Estimated mean altitude of the catchment area of the five springs

Name of the spring	$\delta^{18}O$ [‰]	Altitude [m a.s.l.]
Lijak	-6.92 ± 0.08	370 ± 30
Kajža	-7.69 ± 0.07	690 ± 30
Hotešk	-8.27 ± 0.06	930 ± 25
Podroteja	-8.72 ± 0.05	1120 ± 20
Divje Jezero	-8.89 ± 0.05	1190 ± 20

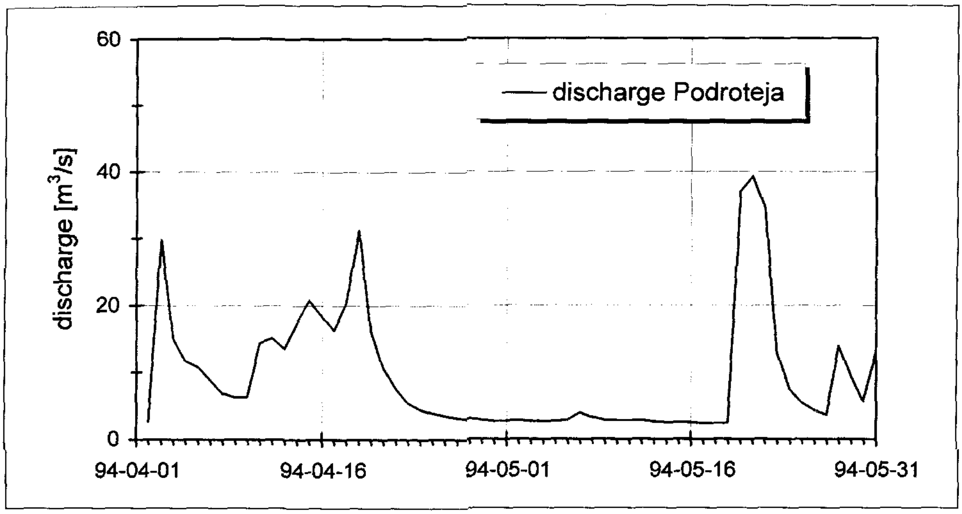


Fig. 5.25: Daily variation of discharge from the Podroteja spring.

The estimated mean altitudes of the catchment areas of the given springs are in agreement with the altitudes calculated by the $\delta^{18}O$-values of the yearly variation (see chapter 5.1.4).

5.2. DISSOLVED INORGANIC CARBON ISOTOPE COMPOSITION OF WATERS

(J. URBANC, B. TRČEK, J. PEZDIČ, S. LOJEN)

The objective of this research is to determine whether the isotope composition of TDIC in water and the chemical composition of water in the outflow from a karst aquifer can be used to interpret the carbon isotope composition and partial pressure of soil CO_2 in the aquifer's recharge area. Further, an attempt was made to establish which model of carbonate rock dissolution in water can be applied to interpret initial conditions and define the degree of accuracy with which the initial conditions can be described if the only data available are those of the isotopic and chemical composition of water in the outflow from a carbonate aquifer. Thus, in our research, the carbon isotope composition and partial pressure of soil CO_2 measured in the recharge area of a karst aquifer were compared to the values, calculated from the isotopic and chemical composition of water in the outflow from aquifer.

Previous observations have shown that the formation of soil CO_2 is to the greatest extent conditioned by soil temperature (BILLES et al. 1971; DORR & MUNNICH 1980; KIEFER & BROOK 1986; WOOD et al. 1993), by the

quantity of organic matter in the soil (WOOD et al. 1993) and by soil moisture (KIEFER & BROOK 1986). Most of soil CO_2 passes into the atmosphere, only a minor part of the total CO_2 is washed into the ground by precipitation (WOOD & PETRAITIS 1984; QUADE et al. 1989; HENDRY et al. 1993). Soil CO_2 can originate from the decomposition of organic matter or root respiration (WOOD & PETRAITIS 1984; HENDRY et al. 1993; DUDZIAK 1994).

Some investigations indicate that during carbonate dissolution in soil, the solution equilibrates with soil CO_2. Thus this is an open system of carbonate dissolution (REARDON et al. 1979; QUADE et al. 1989), while indications for the closed system of carbonate dissolution in the soil were also present (DEINES et al. 1974).

5.2.1. Carbon Isotope Composition In Individual Parts Of The Researched System

The carbon isotope composition of water in the outflow from aquifer can be influenced by the carbon isotope compositions of soil CO_2, carbon isotope composition of the carbonate rock, and by potential changes of carbon isotope composition of water resulting from isotope exchange between the carbon from atmospheric CO_2 and the carbon degassing from water CO_2.

5.2.1.1. Characteristics of carbon isotope composition of soil CO_2

Several sampling points underlying different vegetation covers and at different altitudes were chosen for the measurement of isotope composition and partial pressure of soil CO_2. Three probes for the sampling of soil CO_2 were placed in a forest with prevailing beeches: in the Belca valley (sampling point with the lowest altitude), near Podkraj, and data obtained at Obli Vrh at an altitude of about 1000 m were also included in the investigation. The probes at Col and Grgar were located in soil underlying grass. The probe for the sampling of soil CO_2 in a spruce forest was located near Podkraj.

Samples of soil CO_2 were taken using metal capillaries with an inside diameter of 1 mm, which were dug about 50 cm deep into the ground. Samples of soil atmosphere were transferred into preevacuated 0.7 l glass ampoules. In the laboratory, atmospheric CO_2 was isolated according to the usual procedure (CRAIG 1953) and its isotope composition was measured on the Varian Mat 250 mass spectrometer. From the quantity of isolated CO_2 and the volume of the ampoule the concentration of CO_2 in the gas sampled was calculated.

Dissolved inorganic carbon from water was extracted by adding concentrated H_3PO_4 acid to the water in vacuum (MOOK 1970).

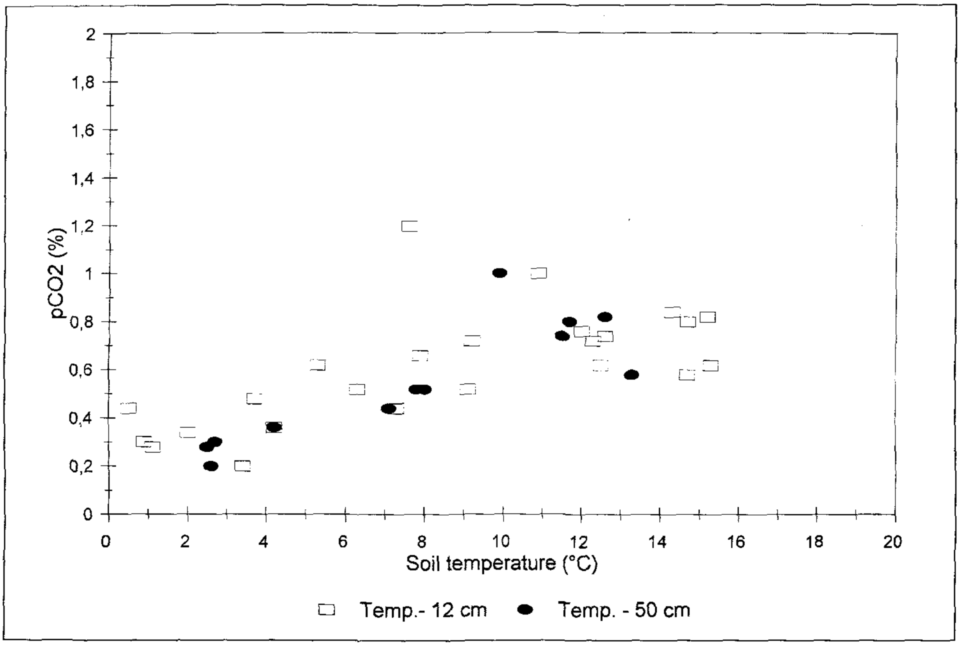


Fig. 5.26: Relation between soil temperature and partial pressure of soil CO_2 in beech forest.

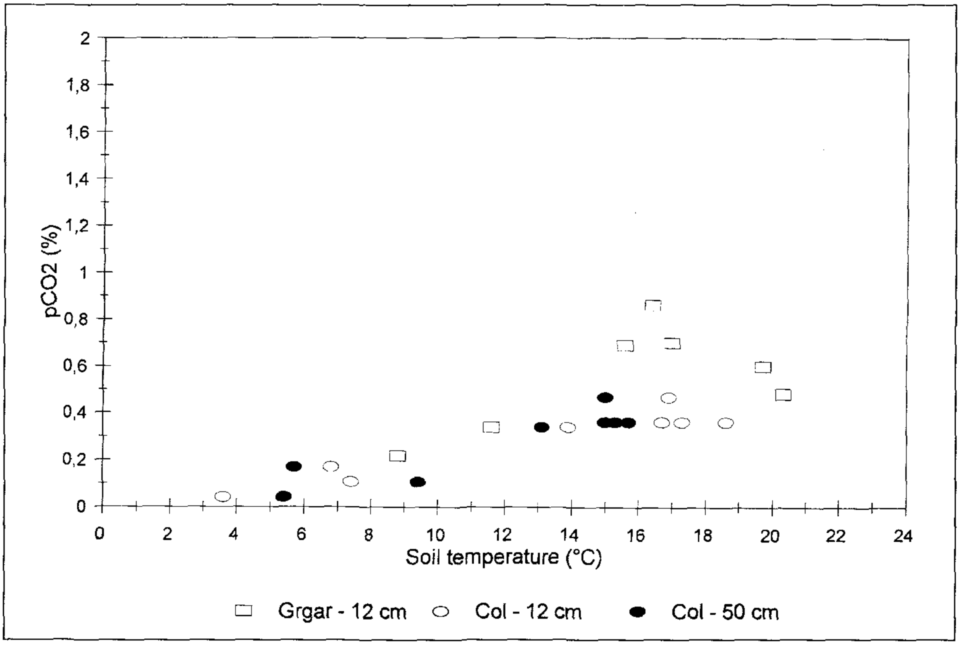


Fig. 5.27: Relation between soil temperature and partial pressure of soil CO_2 in soil under grass.

A linear correspondence between temperature and partial pressure of soil CO_2 can be clearly observed (Fig. 5.26, 5.27). Compared to the soil underlying beech forest, the soil overlaid with grass has lower partial pressures of soil CO_2. The smaller generation of CO_2 is of course conditioned by a smaller transition of organic matter into the soil overlain with grass.

Fig. 5.28 shows average partial pressures measured at individual locations, compared to the average soil temperature. Values measured at sampling points located under the same type of vegetation lie along the same line, and the inclination of P_{CO2}-T correlation lines for beech and grass is also similar.

Beech forest is the prevailing vegetation in the research area, therefore the majority of carbon isotope composition values and partial pressures of CO_2 were measured in soil underlying beech forest. Monthly measurements of soil CO_2 carbon isotope composition showed that most of the $\delta^{13}C$ values lie between -17 and -23 ‰ (Fig. 5.29), while partial pressures of CO_2 range between 0.07 to 1.2 % of the total atmospheric pressure.

A certain interdependence between the carbon isotope composition and partial pressure of soil CO_2 is evident from Fig. 5.28. Such correlation could result from the mixing of biogenic carbon, originating from the decomposition of organic matter in the soil, with the carbon from atmospheric CO_2. In this case, the ratio between biogenic carbon and atmospheric carbon can be expressed by the mixing equation:

$$\delta^{13}C_t = \frac{\delta^{13}C_b \cdot P_b + \delta^{13}C_a \cdot P_a}{P_t} \qquad (11)$$

P ... partial pressure
a ... atmospheric
b ... biogenic
t ... total

In the mixing model, the following $\delta^{13}C$ concentrations were adopted: -23 ‰ for organic carbon, -8 ‰ for atmospheric carbon (KEELING et al. 1979), and 0.03 % for the partial pressure of atmospheric CO_2. The curve of the mixing model is given in Fig. 5.29, indicating that modelled results are in good correlation with the values measured. Equation 11 was statistically proved, the test statistic $F = 3.7+10^{-9}$ (TRČEK 1996). Thus it can be concluded that fluctuations in carbon isotope composition of soil CO_2 can be to a great extent attributed to the mixing of biogenic and atmospheric carbon.

In the above case, sampling points were located under the same type of plant, namely under beech. A different carbon isotope composition of biogenic carbon is to be expected in soil zones underlying other types of vegetation. Figure 5.30 shows the relation between the carbon isotope composition and

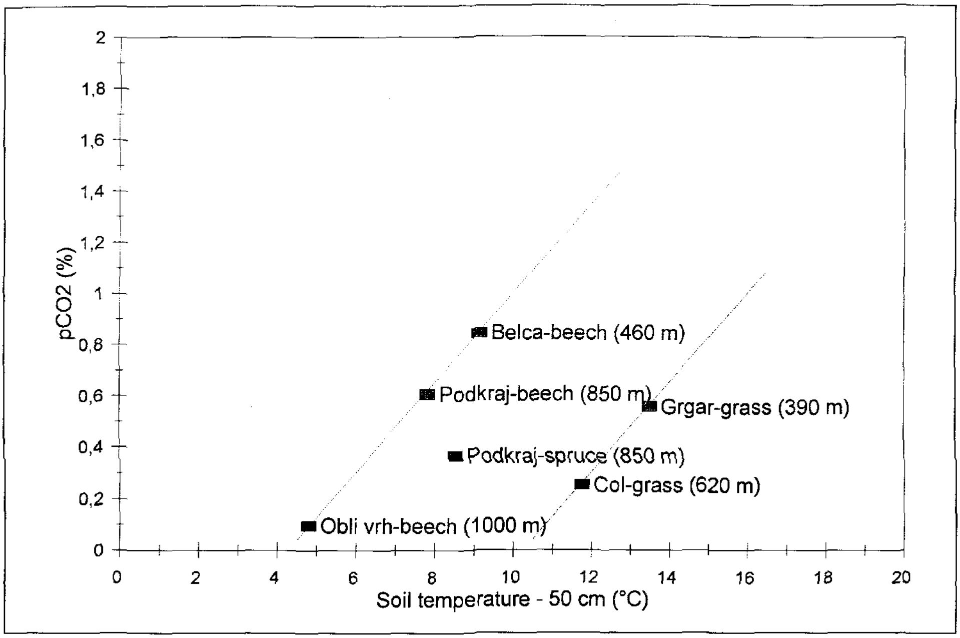


Fig. 5.28: Mean soil temperatures of different locations related to the mean partial pressure of CO_2.

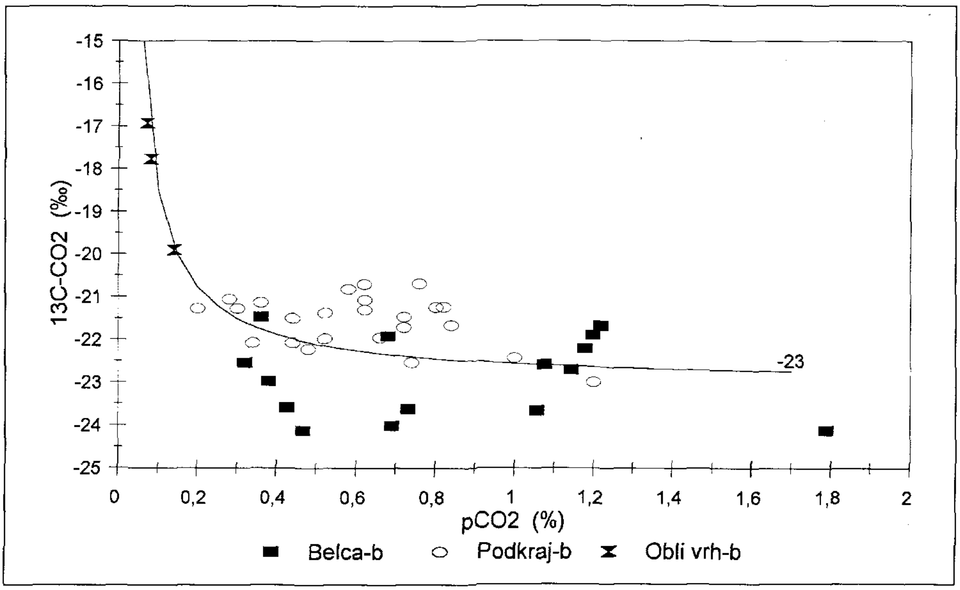


Fig. 5.29: Relation between partial pressure of soil CO_2 and its carbon isotope composition for soil in beech forest.

partial pressure of soil CO_2 for all types of vegetation covers sampled. It can be seen that samples from spruce forest show no significant deviation from the properties of CO_2 in beech forest, while more considerable differences are observed in soils under grass covers. The samples taken from soil underlying grass near Col have a more negative isotope composition of biogene soil CO_2 of about -24 ‰, while the samples from Grgar show a distinctly more positive isotope composition of the biogene component, about -21.5 ‰. This difference in the carbon isotope composition of soil CO_2 under the same type of vegetation is attributed to the different altitude and the different mean soil temperatures. The sampling point near Grgar is situated at an altitude of 390 m in rather Mediterranean climatic conditions, and that near Col is at 620 m above the sea level, where climatic conditions are much harsher. The prevailing types of grass in warmer areas are those with the Hatch-Slack (C4) cycle which generates more positive $\delta^{13}C$ values in plant tissues. On the other hand, the Calvin cycle (C3) prevails in grass from colder areas, giving more negative $\delta^{13}C$ values of plant tissues (CERLING 1984).

Thus it can be concluded that in the area of the Trnovsko-Banjška Planota, CO_2 with varying isotopic properties enters the ground: the most negative values of biogenic carbon isotope composition are to be expected in CO_2 from soil underlying grass and from higher-lying and colder areas (about -24 ‰), soils underlying beech or spruce forests tend to have somewhat more enriched $\delta^{13}C$ values of biogenic carbon (about -23 ‰), and grass from warmer and lower areas give the most positive initial isotopic signal (about -21.5 ‰).

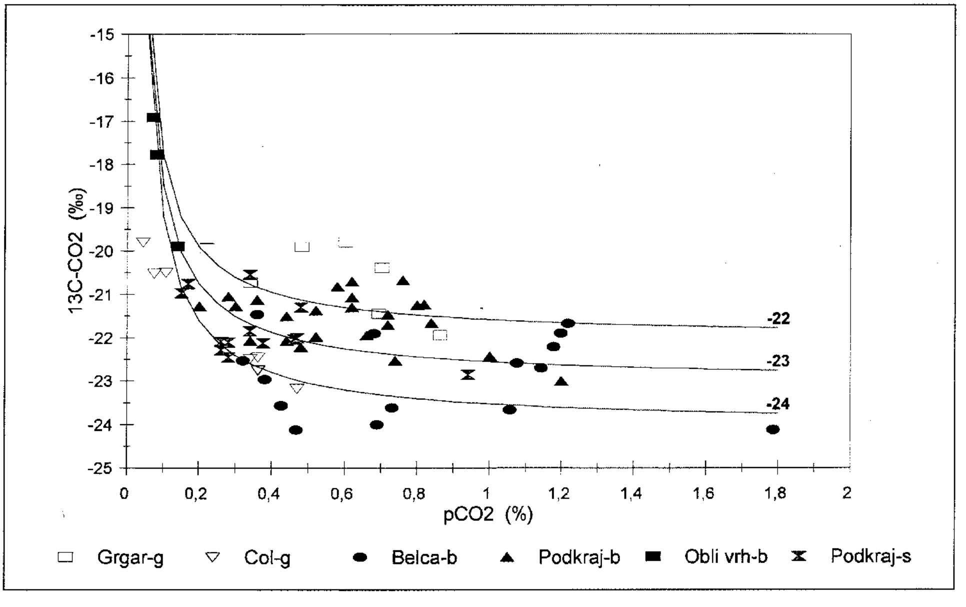


Fig. 5.30: Relation for all investigated soil types.

5.2.1.2 Carbon isotope composition of carbonate rocks

The research area is for the most part composed of Mesozoic limestones and dolomites and flysch rocks. In all, 24 rock samples were taken for isotopic analyses. Measurements of carbon isotope composition of observed samples showed a range in $\delta^{13}C$ values between 0 and +4 ‰ (Fig. 5.31). It can be observed on the graph that dolomites have mostly more enriched $\delta^{13}C$ and $\delta^{18}O$ values compared to limestones or flysch.

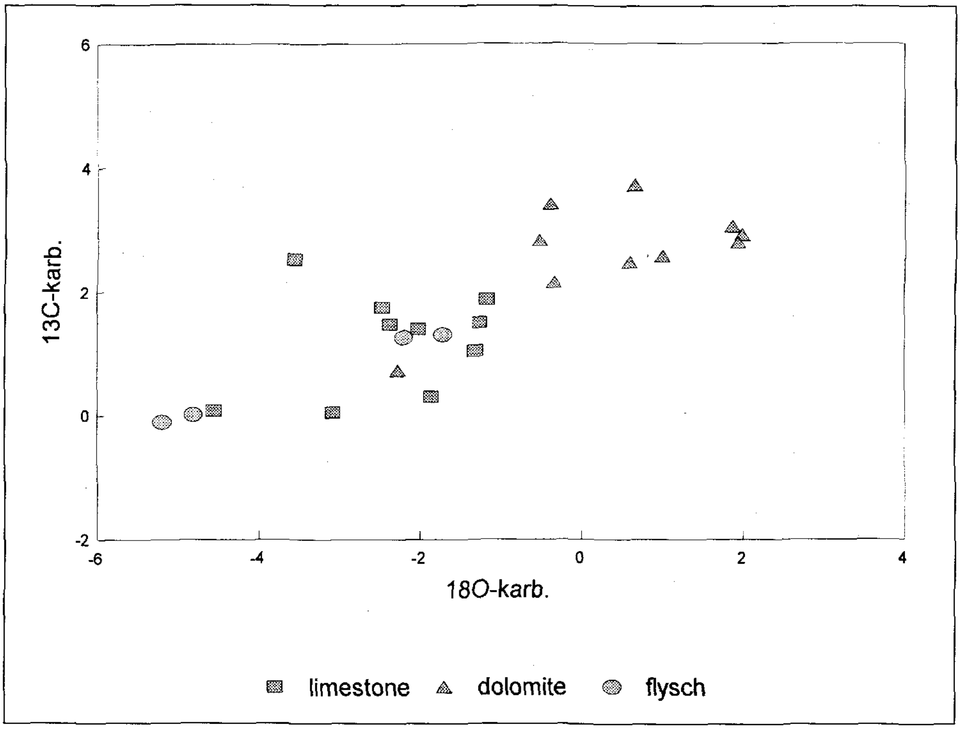


Fig. 5.31: Carbon and oxygen isotope composition of the rocks on investigated area.

5.2.1.3. Isotope composition of the total dissolved inorganic carbon in the outflow

The yearly curve of $\delta^{13}C$ values in the outflow shows certain seasonal variability (Fig. 5.32 to 5.39). General characteristics are most clearly evident from the spring Hotešk (Fig. 5.32). The Figure shows that the most depleted $\delta^{13}C$ values of DIC in the outflow are detected in late fall, usually in November. Then a rather rapid change towards more positive $\delta^{13}C$ values takes

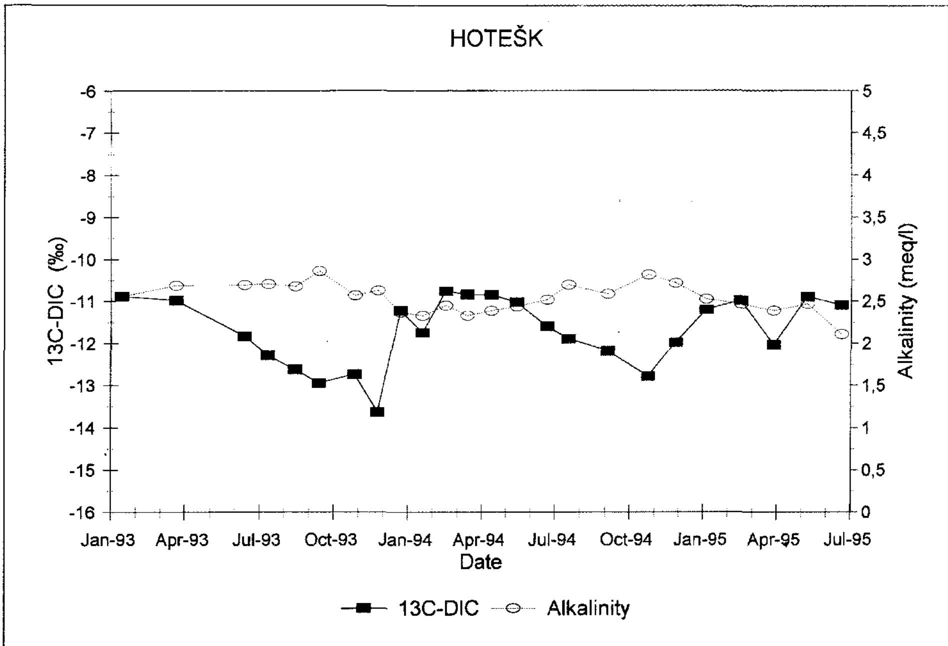


Fig. 5.32: Carbon isotope composition and alkalinity of Hotešk spring.

place until spring, and a gradual depletion in $\delta^{13}C$ values follows over the entire year to the late fall minimum.

Such seasonal isotopic variability can be explained in the following way: Due to the correlation between pedotemperature and partial pressure of soil CO_2, the gradual increase of soil temperature over the year results in an increased production of soil CO_2. In the fall, soil temperatures are the highest, organic matter enters the ground due to lost leaves, which results in a maximum in soil CO_2 partial pressure. A higher content of the biogenic component in soil CO_2 is reflected also in the carbon isotope composition, which reaches its most depleted $\delta^{13}C$ values, and in the DIC isotope composition in the outflow, where the most depleted $\delta^{13}C$ values were also detected.

Lower soil temperatures in winter considerably hinder the processes of soil CO_2 generation, consequently the soil atmosphere contains a higher percentage of atmospheric CO_2 with more positive $\delta^{13}C$ values. When the water from melted snow penetrates the soil in spring recharge area, a larger quantity of atmospheric carbon enters the system, resulting in enriched $\delta^{13}C$ values in the outflow.

A similar pattern of seasonal fluctuations can be perceived also in the other springs, except in the Hubelj, which shows a distinctly different $\delta^{13}C$ isotopic curve (Fig. 5.33).

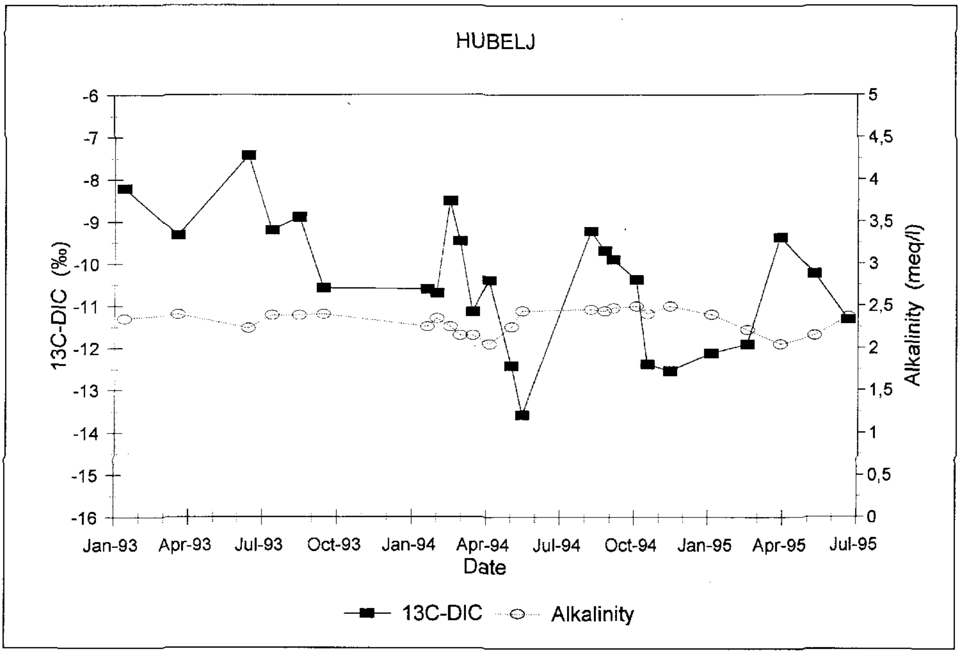


Fig. 5.33: Carbon isotope composition and alkalinity of Hubelj spring.

A comparison of carbon isotope composition variation amplitudes in the outflow is also very interesting. The springs Vipava (Fig. 5.34), Podroteja (Fig. 5.35), Hotešk (Fig. 5.32) and Prelesje (Fig. 5.38) show a fairly similar range of yearly $\delta^{13}C$ values at about 2.5 ‰ . Yearly fluctuations of the carbon isotope signal are much larger in the Hubelj, where the amplitude of $\delta^{13}C$ values from spring 1993 to spring 1994 was over 6 ‰ (Fig. 5.33). This indicates that Hubelj has a higher aquifer water exchange rate, resulting in a less pronounced dampening of the isotope signal. A fairly large range in the isotope signal was measured also in samples from Mrzlek spring, however, the large variability can in this case be attributed to a stronger influence of the Soča river and the fact that Soča river water is more enriched in the heavier carbon isotope (Fig. 5.36).

During surface flow, isotope exchange between the DIC and atmospheric carbon takes place. Because atmospheric carbon is enriched in the heavier carbon isotope, a change towards the more positive $\delta^{13}C$ values can be expected.

Most of the samples for the 7th SWT project were taken from springs, yet some of them were also taken from lower course of surface flow, e.g. from streams on flysch rocks and from river Soča. In order to evaluate the scope of isotope exchange, sampling was carried out along the Bela stream above

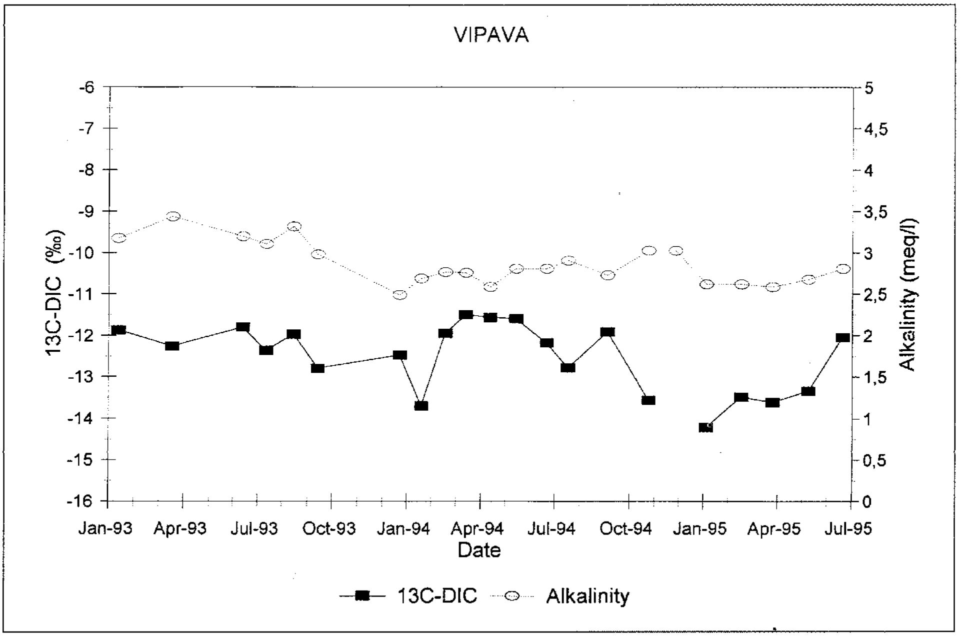


Fig. 5.34: Carbon isotope composition and alkalinity of Vipava spring.

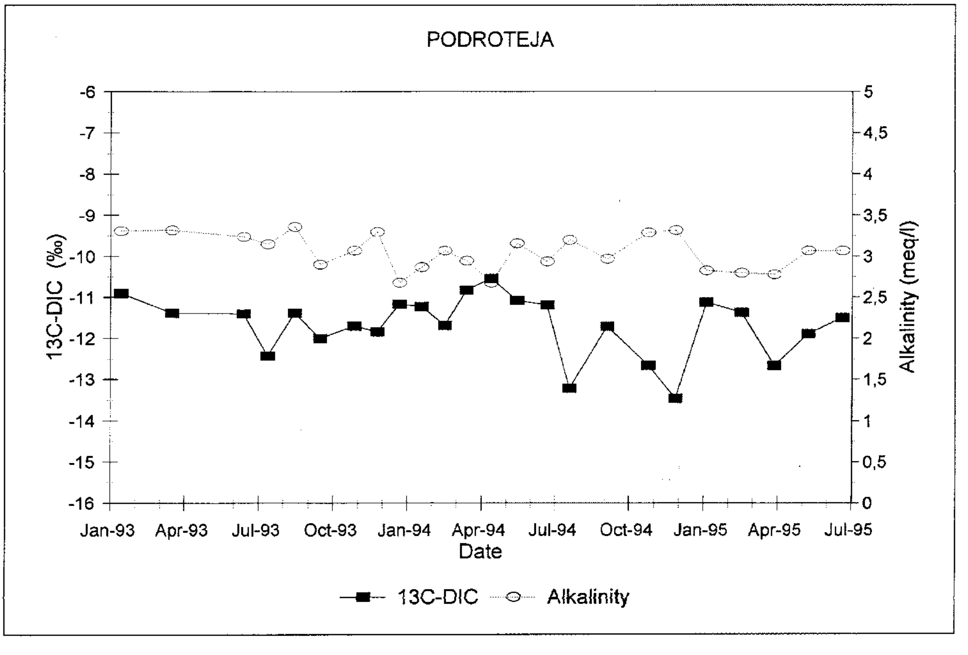


Fig. 5.35: Carbon isotope composition and alkalinity of Podroteja spring.

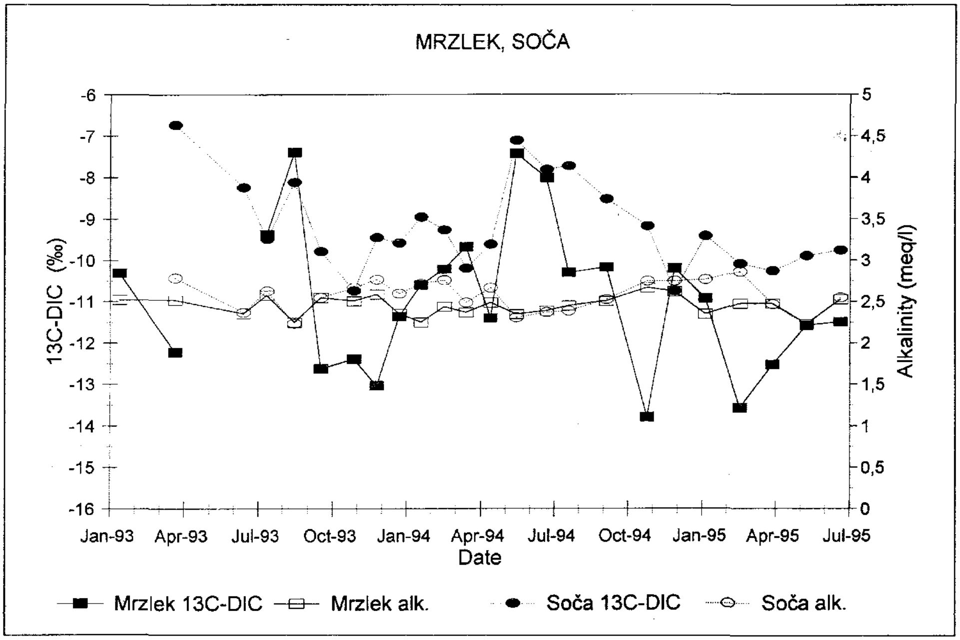


Fig. 5.36: Carbon isotope composition and alkalinity of Mrzlek and Soča springs.

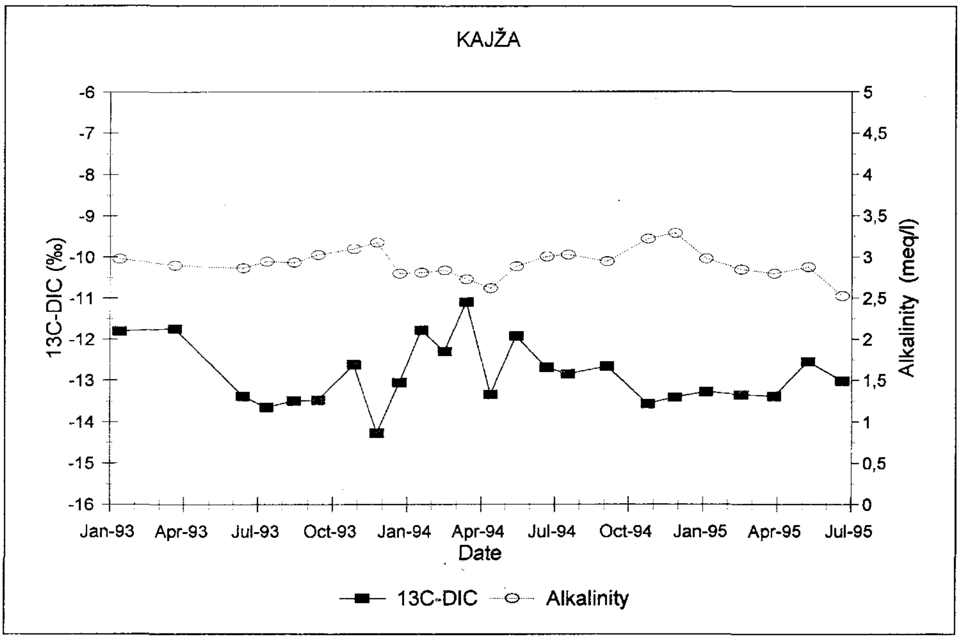


Fig. 5.37: Carbon isotope composition and alkalinity of Kajža spring.

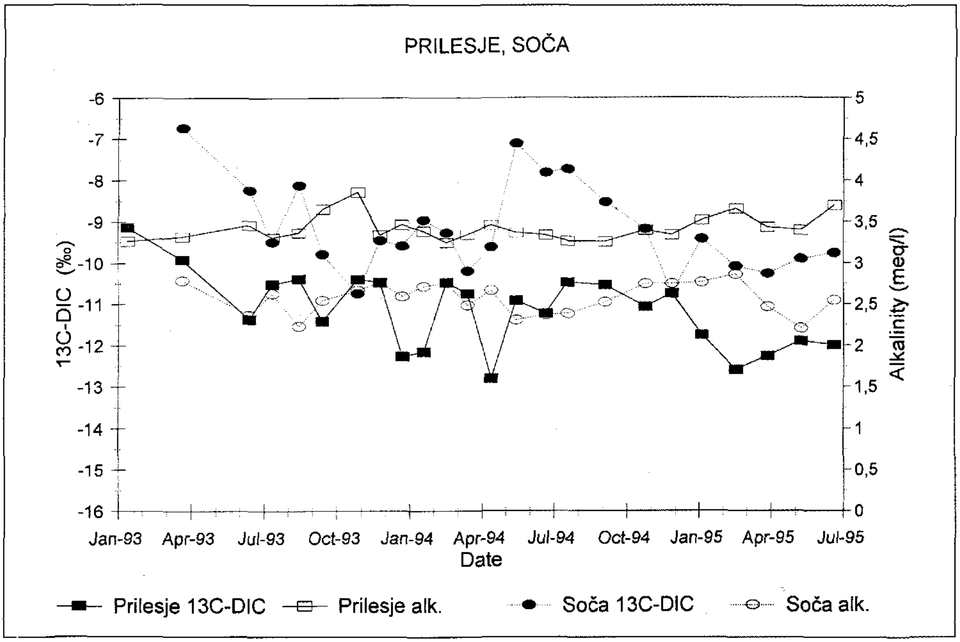


Fig. 5.38: Carbon isotope composition and alkalinity of Prelesje and Soča springs.

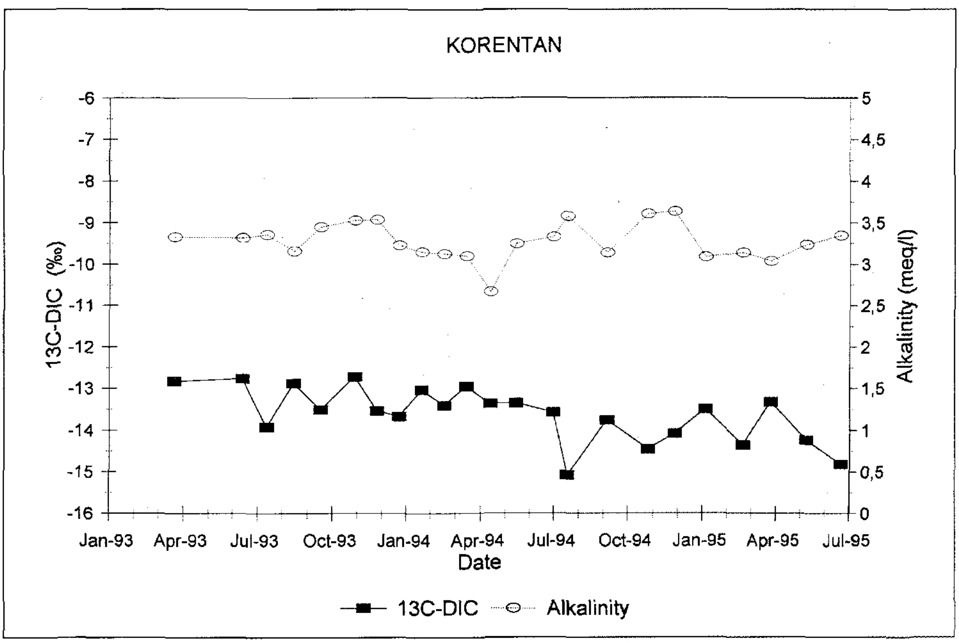


Fig. 5.39: Carbon isotope composition and alkalinity of Korentan spring.

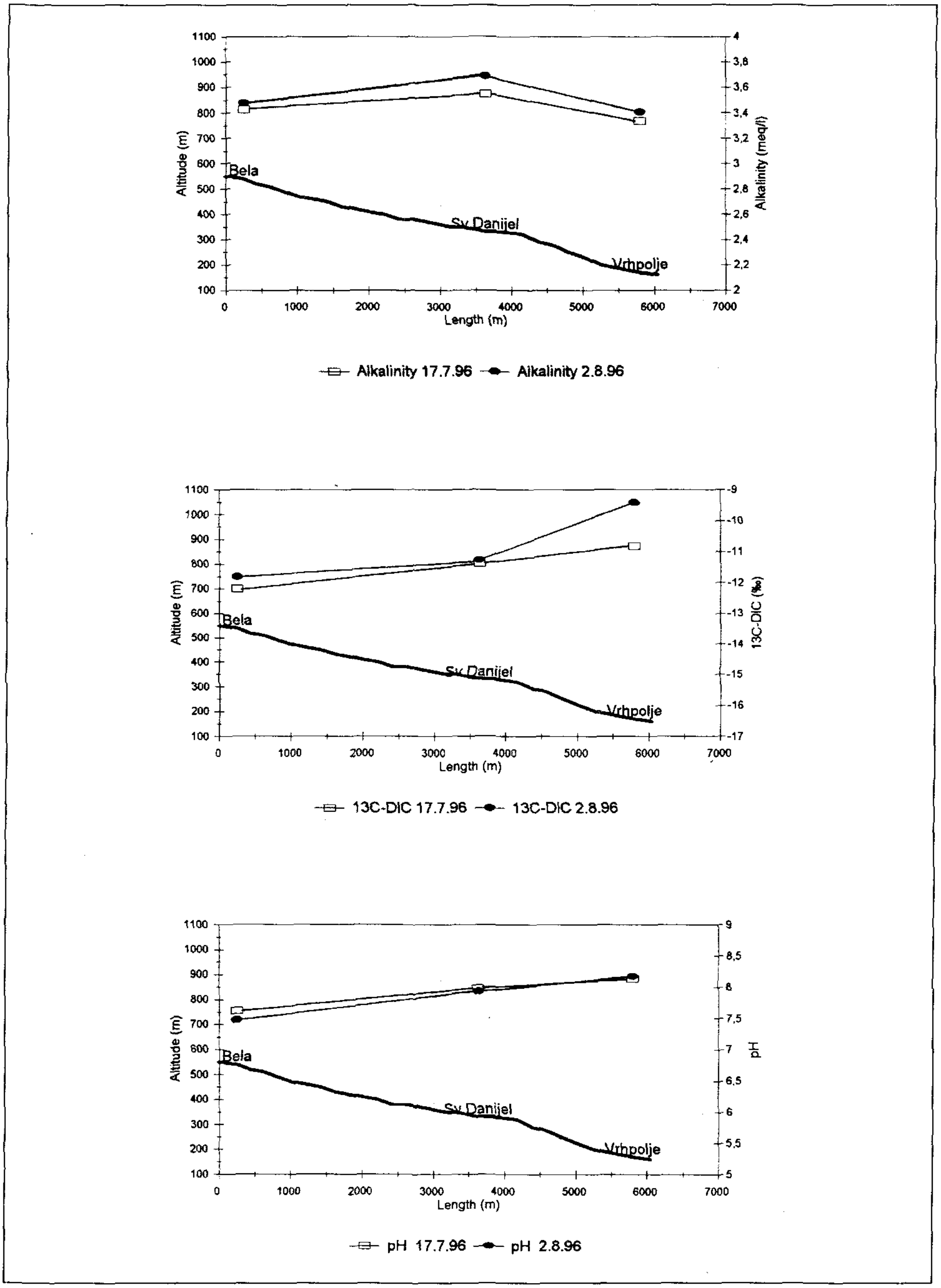


Fig. 5.40: Changes of alkalinity, $\delta^{13}C$ DIC and pH along the surface flow course of the Bela.

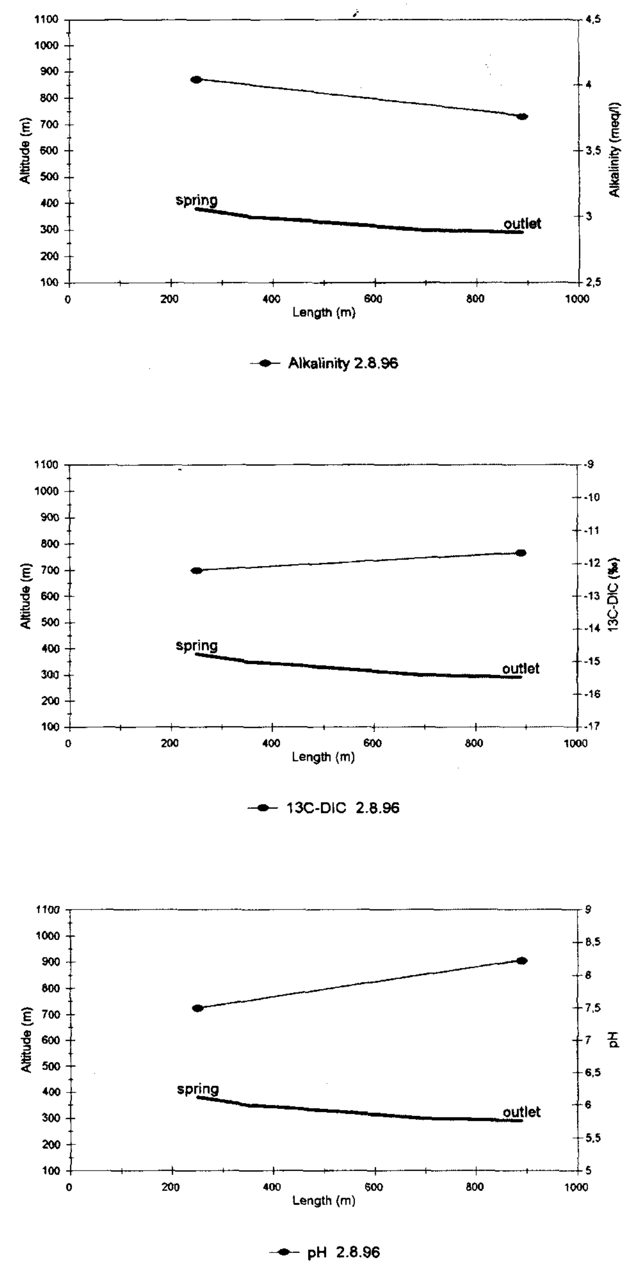


Fig. 5.41: Changes of alkalinity, $\delta^{13}C$ DIC and pH along small stream near Sveti Danijel.

Vipava. Three sampling points were selected: at the village Bela, at Sv.Daniel and at the village Vrhpolje. Fig. 5.40 illustrates the changes in the carbon isotope composition, pH and alkalinity of water along its surface flow course. Indeed, an increase in $\delta^{13}C$ values was observed along the course of the surface flow, which indicates isotope exchange between the carbon from atmospheric CO_2 and the carbon from DIC. A more distinct influence of isotope exchange was measured at low water level on 2.8.1996, when the isotope composition of water between the villages Bela and Vrhpolje changed by as much as 2.4 ‰ The same isotope effect was measured also in the stream flowing into the Bela above Sv. Daniel, which was monitored along its entire course (Fig. 5.41). Thus it can be concluded that significant increases in $\delta^{13}C$ values can take place in surface streams, due to the isotope exchange between atmospheric carbon and the carbon from hydrocarbonate. This is a fact to be taken into account in the interpretation of isotope measurements.

The relationship between alkalinity and the isotopic content of the DIC is very interesting (Fig. 5.42). The majority of results are distributed in the form of a long cloud; higher alkalinity corresponds to DIC depleted in ^{13}C. Such distribution of results can be explained by the fact that higher alkalinity of water requires higher initial partial pressures of soil CO_2, and the concentration of $\delta^{13}C$ depleted carbon in the soil air is increased at higher partial pressures of soil CO_2.

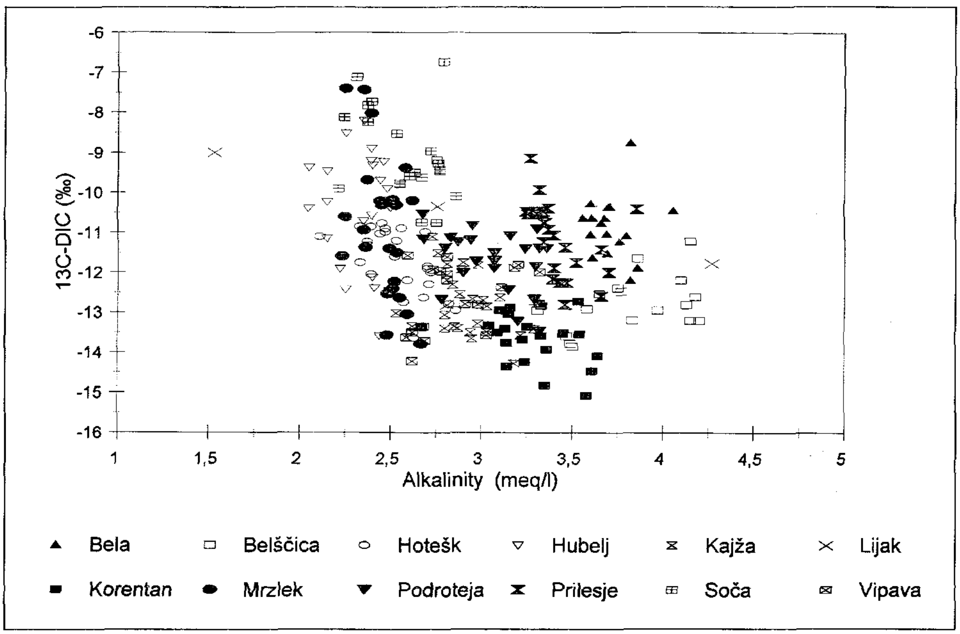


Fig. 5.42: Relationship between alkalinity and $\delta^{13}C$ DIC of the waters from investigation area.

It is also evident from Figure 5.42 that the Bela and the Prelesje distinctly deviate from the basic principle. Bela stream is recharged in flysch rocks, thus this deviation of the $\delta^{13}C$ values towards more positive values can be explained by the effect of isotope exchange between the DIC and atmospheric carbon during surface flow. We assume that water with partially changed $\delta^{13}C$ values due to surface flow enters also into the Prelesje water supply well.

5.2.2. Reconstruction of Initial CO_2 Isotope Composition

The carbon isotope composition of DIC reflects isotopic processes during the dissolution of atmospheric and soil CO_2 in water and in the neutralisation of aggressive water with the carbonate rock. These processes are described with the open and closed system models.

a) The Open System Model

According to the open system model, the carbon isotope composition of an equilibrated solution can be described with the equation (HENDY 1971):

$$\delta^{13}C_t \cdot [DIC] = \delta^{13}C_{H2CO3} \cdot [H_2CO_3^*] + \delta^{13}C_{HCO3} \cdot [HCO_3^-] + \delta^{13}C_{CO3} \cdot [CO_3^{2-}] \quad (12)$$

The carbon isotope composition of individual ion species can be expressed also:

$$\delta^{13}C_{HCO3} = \delta^{13}C_{CO2} + \varepsilon_{HCO3} \quad (13)$$

ε... isotope enrichment of a species with regard to CO_2.

From equations 12 and 13 the isotope composition of initial soil CO_2 can be derived:

$$\delta^{13}C_{CO2} = \frac{\delta^{13}C_t \,.\, [DIC] - \varepsilon_{H2CO3} \,.\, [H_2CO_3^*] - \varepsilon_{HCO3} \,.\, [HCO_3^-] - \varepsilon_{CO3} \,.\, [CO_3^{2-}]}{[H_2CO_3^*] + [HCO_3^-] + [CO_3^{2-}]} \quad (14)$$

b) The Closed System Model

According to the closed system model, the carbon isotope composition of a solution can be expressed by the closed system mass balance equation (DEINES et al. 1974):

$$\delta^{13}C_t \,.\, [DIC] = \delta^{13}C_{CO2} \,.\, [CO_2\ o] + \delta^{13}C_C \,.\, [C_c] \quad (15)$$

CO_2 o ... the concentration of CO_2 in water before reaction with the carbonate rock
c ... carbon from the carbonate rock

$$\delta^{13}C_{CO2}\ o = \frac{\delta^{13}C_t \cdot [DIC] + \delta^{13}C_C \cdot [C_c]}{[CO_2\ o]} \qquad (16)$$

$$\delta^{13}C_{CO2} = \delta^{13}C_{CO2}\ o - \varepsilon_{CO2(g)\ -\ CO2\ (aq)} \qquad (17)$$

The concentrations of carbon ion species in a carbonate solution were calculated using the geochemical program PHREEQE (PARKHURST et al. 1985).

Figure 5.43 gives a comparison of $\delta^{13}C$ values with partial pressures of input CO_2: values obtained from field measurements were compared with values calculated by means of the open and closed system models from data on the chemical and isotopic composition of water in the outflow from a karst aquifer. The $\delta^{13}C$ values calculated according to the open system model

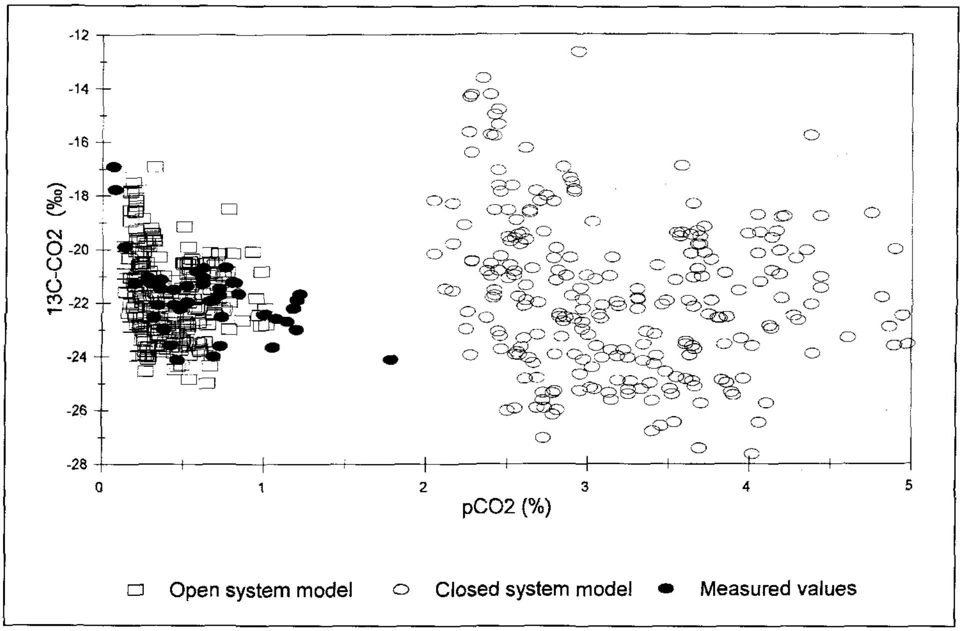


Fig. 5.43: Comparison of calculated and measured values of $\delta^{13}C$ CO_2 and partial pressure of soil CO_2 in the recharge area of observed karst springs.

correspond relatively well to the $\delta^{13}C$ values and partial pressures of soil CO_2 obtained in measurements in karst aquifer recharge areas. We can see, that modelled results are fairly well comparable to the results obtained from measurements, making an interpretation of initial data on the basis of the chemical and isotope composition of water in the outflow generally possible. The dissolution of carbonates in the cases studied proceeds by open-system processes, where the solution during the neutralisation with the carbonate rock remains in contact with the soil CO_2. In this process, the carbon isotope composition of soil CO_2 is equilibrated with that of the solution.

Fig. 5.44 gives a more detailed interpretation of the carbon isotope composition and the partial pressures of soil CO_2, calculated according to the open system model from the DIC isotope composition and the water alkalinity of individual springs. The interpreted $\delta^{13}C$ values of soil CO_2 in the recharge areas mostly range between -17 and -25 ‰, and the interpreted partial pressures of initial CO_2 lie between 0.1 and 1% of the total atmospheric pressure. It has to be taken into account in the interpretation of results that water in the outflow is mostly highly homogenised, which can result in a considerably larger fluctuation of initial isotope compositions and partial pressures of soil CO_2.

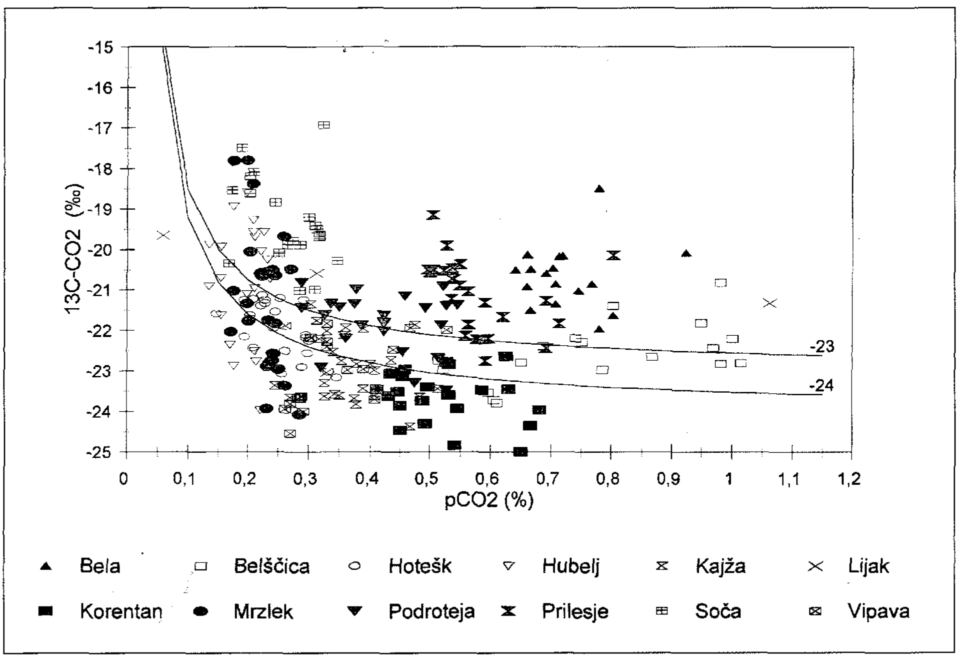


Fig. 5.44: Interpretation of $\delta^{13}C$ CO_2 and partial pressure of soil CO_2 on the basis of water $\delta^{13}C$ DIC and alkalinity.

Fig. 5.44 illustrates also considerable differences among individual springs as regards their carbon isotope compositions and initial CO_2 partial pressures. Similarly as in the $\delta^{13}C$ DIC-alkalinity graph (Fig. 5.42), most of the data are distributed in the form of a cloud. This distribution can be relatively well explained by the mixing equation between the biogenic and atmospheric carbon in soil atmosphere (equation 11), where the adopted isotope composition of biogenic component of soil CO_2 is -24 ‰. In the majority of the results, the biogenic component isotope composition is in good accordance with the measurement results of soil CO_2 isotope composition, where the isotope composition of soil CO_2 biogenic component was estimated at about -23 ‰, using the mixing model.

The general trend in Fig. 5.44 is again not followed by the Bela and the Prelesje. This can be attributed to the effect of isotope exchange between the DIC and the carbon from atmospheric CO_2. Slight deviations from modelled values towards more positive values are present also in samples from the Belščica, Soča and Mrzlek. Due to the surface flow of the Soča and the Belščica, this deviation can be explained in the same way as in the Bela and the Prelesje. Deviations in the samples from the Mrzlek are caused by the presence of the Soča water in the Mrzlek samples at times of low water level.

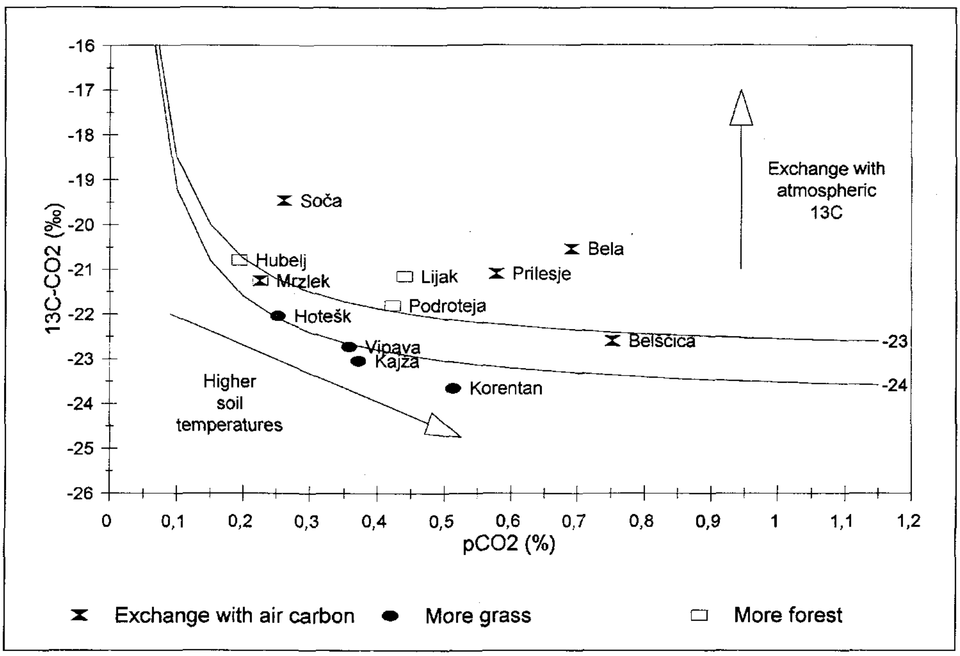


Fig. 5.45: Average values of $\delta^{13}C$ CO_2 and partial pressure of soil CO_2 on the basis of water $\delta^{13}C$ DIC and alkalinity.

Isotopic properties of individual springs are even more clearly evident from the graph of interpreted mean $\delta^{13}C$ values of soil CO_2 and its partial pressure (Fig. 5.45). The greater part of average values lie along theoretical curves of biogenic carbon -23 and -24 ‰ . It is remarkable that springs with mainly forested recharge areas have average $\delta^{13}C$ values closer to the -23 ‰ curve, while the springs which recharge in areas underlying mainly grass, lie closer to -24 ‰ . According to the data obtained from the regional forest management unit, grass areas amount to about 35 % at Banjščice, 25 % in the Nanos area, while they are negligible in the areas of Trnovski Gozd and Hrušica. The differences in the isotope composition of biogenic carbon therefore present a possibility of drawing conclusions about the vegetation properties of recharge areas. Adequate confirmation of these indications would of course require additional investigations.

On the basis of correlation between measured soil CO_2 partial pressure and soil temperature, and between the measured carbon isotope composition of soil CO_2 and soil temperature, and also on the basis of the influence of various types of vegetation on the measured carbon isotope composition and partial pressures of soil CO_2, an attempt was made to approximately estimate mean values of soil temperature in recharge areas of individual springs (TRČEK 1997).

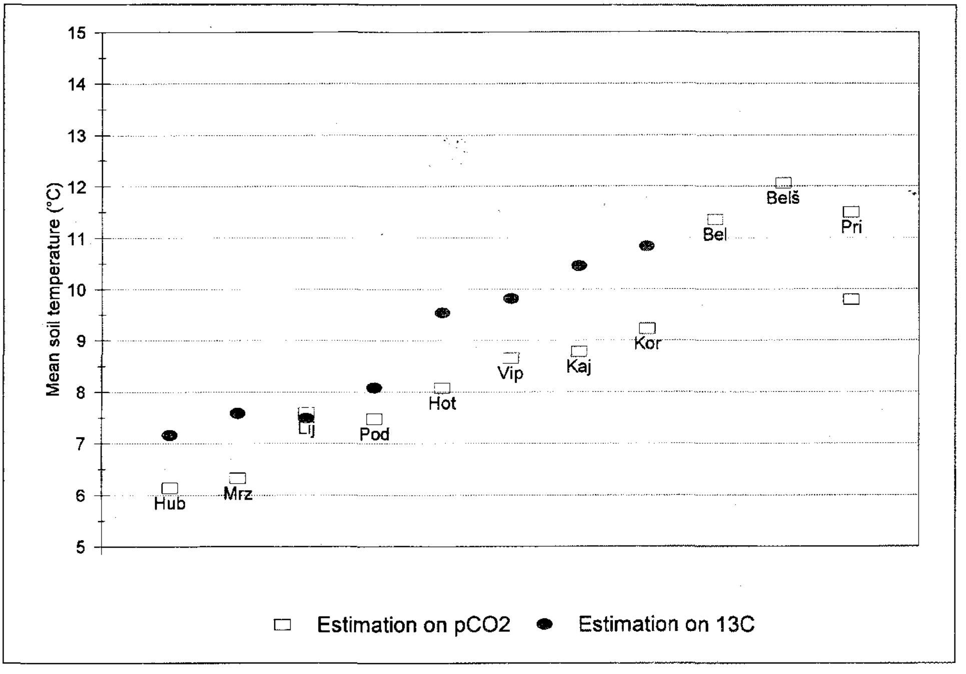


Fig. 5.46: Estimated mean soil temperatures of recharge areas on the basis of $\delta^{13}C$ CO_2 and partial pressure of soil CO_2.

Calculations were made by two methods:

1. Average pedotemperatures were calculated on the basis of CO_2 partial pressure, obtained from the alkalinity of individual springs and taking into account the correlation between the measured partial pressure of soil CO_2 and soil temperature for approximate vegetation structure of the recharge areas.
2. Average temperatures were calculated from the DIC isotope composition, where the correlation between the measured carbon isotope composition of soil CO_2 and soil temperature for approximate vegetation structure of the recharge areas.

The estimated pedotemperatures are shown on Fig. 5.46. The effect of isotope exchange with atmospheric CO_2 was observed in the springs: Bela, Belščica and Prelesje, therefore their mean soil temperatures could only be estimated on a basis of CO_2 partial pressures.

5.3. SHORT-TERM INVESTIGATIONS DURING A HEAVY SNOWMELT EVENT (V. ARMBRUSTER, C. LEIBUNDGUT)

5.3.1. Introduction

A hydrograph separation of Hubelj and Vipava springs into event and pre-event water was done with the stable isotope ^{18}O for a heavy snowmelt event in April 1996. The lighter meltwater made a hydrograph separation possible.

5.3.2. Methods

A two component mixing model was used for the hydrograph separation. In order to determine a representative isotope content of the snowmelt event water, a network of 10 snow lysimeters was put up in the catchment areas of Hubelj and Vipava springs in different altitudes. On the basis of the dependence of snowmelt water heights and isotope contents on altitude a weighting calculation was done and representative isotope contents for the two catchments were obtained.

5.3.3. Results and Interpretation

The field observation period lasted from March the 27th until April the 12th1996. At the beginning of the period the karst plateaux were partly snow-covered. During a heavy precipitation event on April the 1st and 2nd (Fig. 5.47

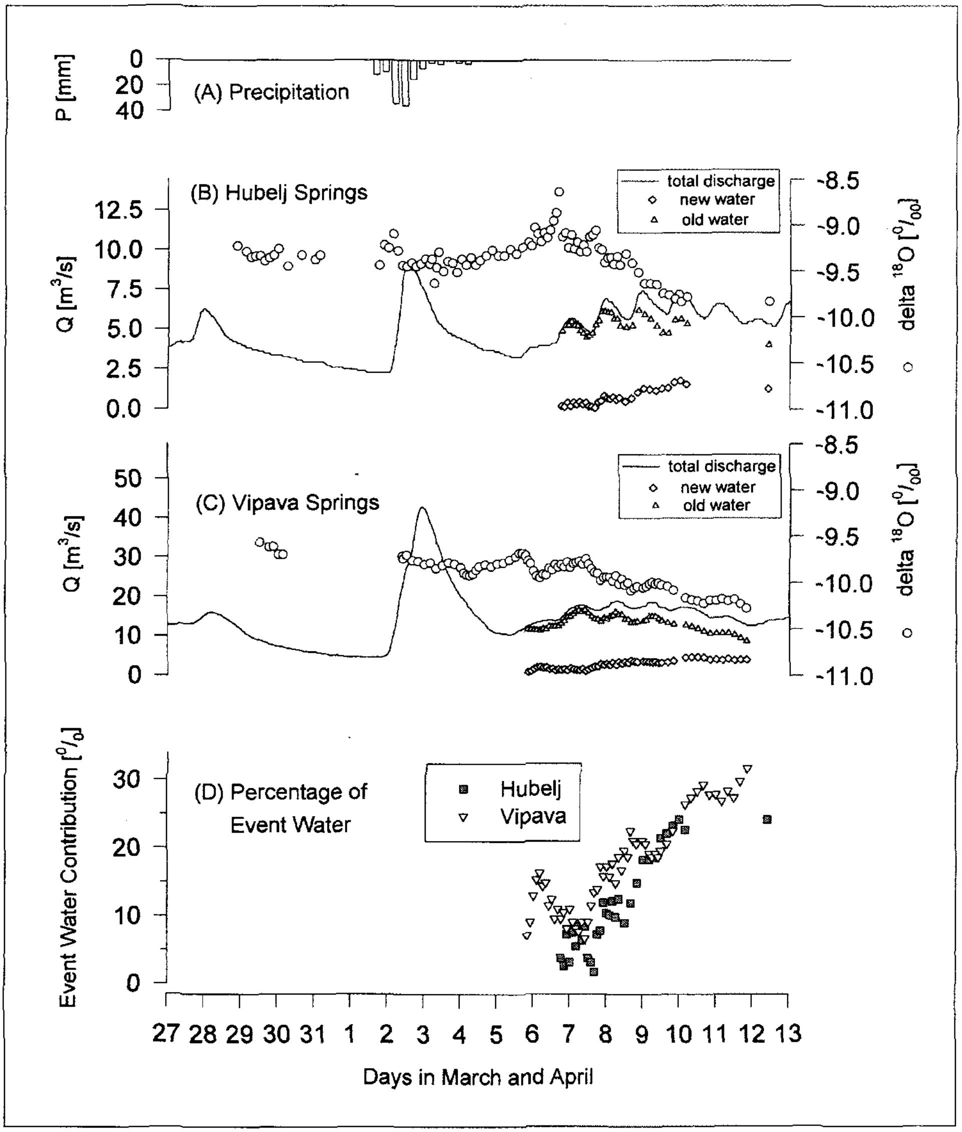


Fig. 5.47: Data of a single snowmelt event in the period from March the 27th till April the 12th 1996: (A) Precipitation heights of 6 hours intervals of precipitation station Podkraj. (B) $\delta^{18}O$ values and total discharge of Hubelj for the observed period; discharge of new and old water of Hubelj for the snowmelt event, starting the 5th of April. (C) Smoothened $\delta^{18}O$ values and total discharge of Vipava for the observed period; discharge of new and old water of Vipava for the snowmelt event. (D) Percentages of event water contributions (new water) of Hubelj and Vipava for the snowmelt event.

(A)), where initial rain turned into snow later, the karst plateaux were completely covered with snow. This precipitation caused the peak discharges of the observed period. Isotope contents of the rain did not differ sufficiently to make a hydrograph separation possible. The deposited snowpack started to melt intensively from the 5th of April onwards, when the weather became very warm and sunny. Mean snowmelt rates amounted to 27 mm/day for the Hubelj and 20 mm/day for the Vipava catchment until the 12th of April. The snowmelt event is represented by daily discharge fluctuations of Hubelj and Vipava springs (Fig. 5.47 (B)/(C)). The snowmelt event water isotope contents are -11.75 ‰ for the Hubelj and -11.69 ‰ for the Vipava catchment for the whole melting period.

Fig. 5.47 (B) shows the discharge and the isotope content of Hubelj springs during the observed period. The isotope content does not show a clear reaction to the precipitation event. After the precipitation event, the isotope content is continuously increasing, until the snowmelt event starts. A possible interpretation might be, that as well heavier older water as lighter event water were activated by the precipitation event and that the contribution of event water decreased faster than that of the older water. When lighter snowmelt event water starts to arrive at the 6th of April, isotope contents decrease. The mean of the isotope contents before the precipitation event amounts to -9.3 ‰ and is used as pre-event water isotope content. The results of the hydrograph separation can be seen in Fig. 5.47 (B) and (D). The event water contribution slowly rises and reaches maximum values of 24 %.

Fig. 5.47 (C) shows the discharge and the smoothened isotope content of Vipava springs. The fluctuating original isotope values were smoothened with the running mean of five values, in order to better visualise the reaction of the Vipava springs. The mean of the isotope contents before the precipitation event amounts to -9.61 ‰ and is used as pre-event water value. The results of the separation can be seen in Fig. 5.47 (C) and (D). The event water contribution slowly rises and reaches maximum values of 31 %.

The snowmelt event was probably still influenced by the preceding precipitation event. Thus, the application of a two component mixing model is a simplification. The snowmelt water was sampled during two periods, and the samples showed, that meltwater became heavier during the ablation. This could not be accounted for in the separation, because a further time.

Discretization of sampling was not practicable. Isotope contents of meltwater varied considerably with the altitude and showed the difficulties of determining a representative isotope content of snowmelt event water in catchments with big altitude differences.

5.3.4. Conclusions

During a heavy snowmelt runoff event the event water contribution to spring discharge of Hubelj and Vipava springs is slowly rising. The contribution is still rising, when discharge is already decreasing. The maximum determined event water contribution 6 days after the snowmelt start is 24 % and 31 % for Hubelj and Vipava springs respectively (actual maxima might be higher, as sampling stopped too early). Only a small part (< 8 %) of the snowmelt water input to the aquifers leaves the karst systems with a short time lag. The hydrograph separation has been done under very specific hydrological conditions and the results can only be rough estimations, as many simplifications are implied.

6. TRACING EXPERIMENTS

6.1. ORGANISATION, INJECTION AND SAMPLING

(A. KRANJC, J. KOGOVŠEK, R. BENISCHKE, B. REICHERT, M. ZUPAN, M. HEINZ-ARVAND)

Within the three years of the research program 4 combined water tracing experiments with the classical hydrologic tracers were carried out to define the hydrodynamic behaviour of the karst systems as well as to localise underground connections. An overview of the tests performed is given in Tab. 6.1, the distribution of the various injection places and the main observation points is depicted in Fig. 6.1. One main focus of the research carried out was to define the variations in the hydrodynamic behaviour by means of repeated tracing experiments under different hydrological conditions. Details on the discharge behaviour of the main springs during the experiments performed are given in chapter 6.2. An overview of the basic data of the main sampling sites is given in Tab. 6.2. In the framework of chapter 6 the following abbreviations for the various laboratories conducting analyses will be used:

Abbreviations:

AGK: Applied Geology, University of Karlsruhe, Germany
GSF: Institute of Hydrology, GSF-Research Center, Germany
HMZ: Hydrometeorological Survey, Slovenia
IHG: Institute for Hydrogeology and Geothermics, Joanneum Research, Austria
IZRK: Karst Research Institute, Scientific Research Center, Slovenian Academy of Sciences and Arts
KÄSS: Laboratory Dr. habil. W. KÄSS, Germany
UBA: Federal Environmental Agency, Austria.

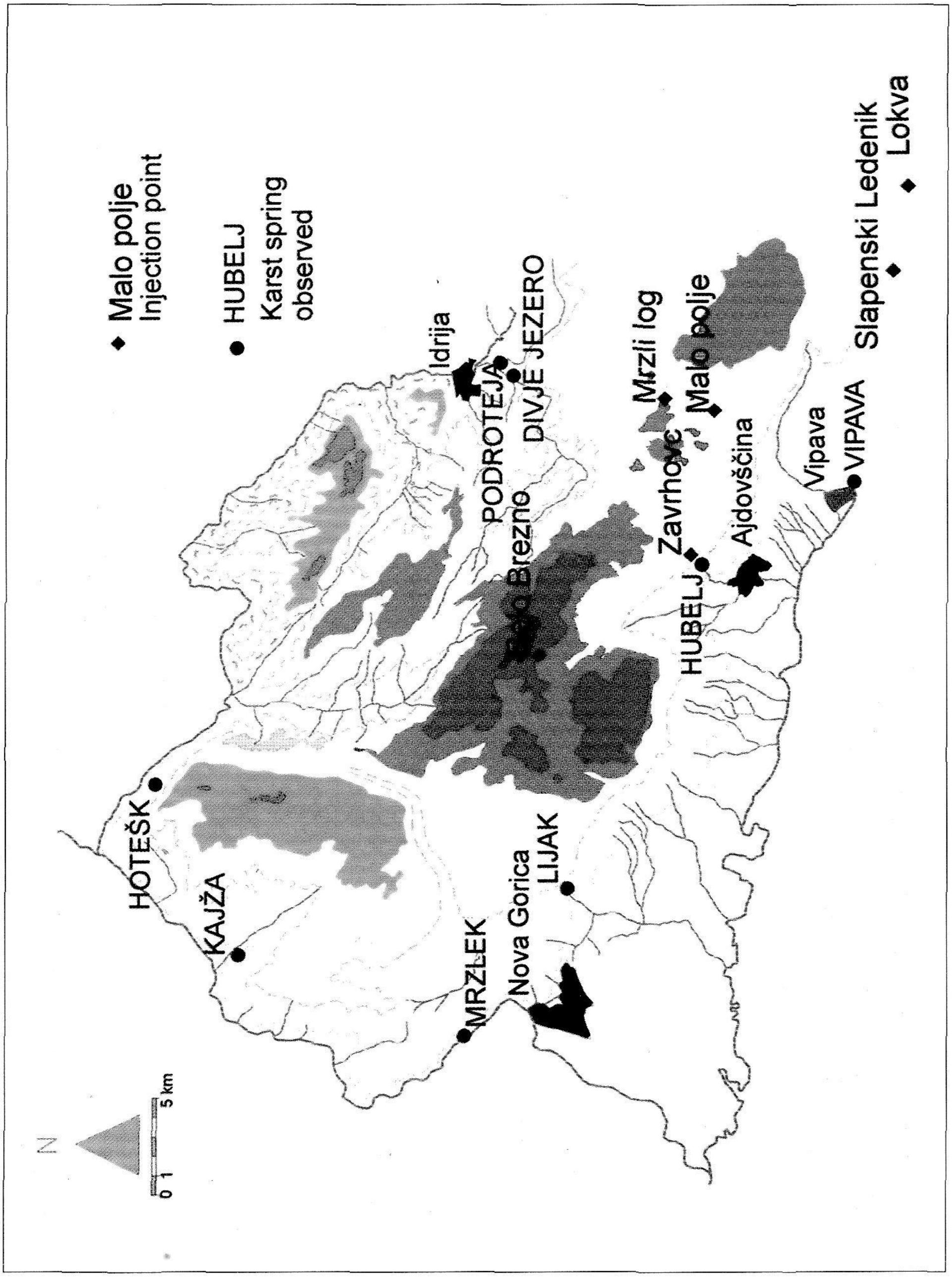


Fig. 6.1: Location map of the injection places and main observation points of the tracing experiments performed in the framework of the ATH research project from 1993 to 1996.

Tab. 6.1: Tracing experiments performed in the framework of the 7th SWT investigations in chronological order: date and time of injection, injection points with altitude, tracer type and amount, amount of pre and after flushing.

No.	date	time	injection place	altitude [m a.s.l.]	Tracer	amount /solution	Flushing pre [m³]	Flushing after [m³]
1	93/10/14	13:10	Belo brezno	1,200	uranine	5 kg / 30 l	*1)	7.0
		14:25	Zavrhovc	790	bacteriophages	$4.1 \cdot 10^{15}$ pfu / 16.5 l	1.5	3.5
2	94/04/16	10:25	Zavrhovc	775	lithium chloride	30 kg / 110 l	3.5	1.0
		10:30	Zavrhovc	775	bacteriophages	$8.0 \cdot 10^{15}$ pfu / 20.5 l		3.5
		13:10	Belo brezno	1,200	uranine	5 kg / 20 l	1.0	7.0
		11:00	Mrzli log	784	strontium chloride + pyranine	50 kg / 120 l + 5 kg / 40 l	1.0	6.0
		12:45	Lokva	464	uranine	7 kg / 100 l	*2)	
3	95/08/01	11:37	Belo brezno	1,200	uranine	7 kg / 30 l	2.0	3.0
		10:25	Zavrhovc	775	bacteriophages	$6.6 \cdot 10^{15}$ pfu / 26.0 l	3.5	3.5
		10:33	Malo polje	615	pyranine	8.5 kg / 120 l	1.5	4.5
4	95/10/26	11:45	Lokva	464	pyranine	8 kg / 100 l	*3)	
		11:45	Slapenski Ledenik	980	uranine	5 kg / 50 l	2.0	4.0

*1) *injection into a natural trickle stream of 0.2 l/s*
*2) *injection into the Lokva stream with an inflow of approx. 166 l/s*
*3) *injection into the Lokva stream by a gauged water level of 1.22 m*

Tab. 6.2: Basic data of the main sampling sites: altitude, distance from the relevant injection places (m) and the altitude differences (m). All data are taken from the official topographic maps.

Spring / Injection place altitude in m a.s.l.	Belo brezno 1,200	Zavr-hovc 1993: 790	Zavr-hovc 1994, 95: 775	Mrzli Dol 784	Malo Polje 615	Lokva 464	Slapen-ski Ledenik 980
Hubelj 240	6,880 / 960	890 / 550	1,000 / 535	9,250 / 544	8,340 / 375		
Lijak 100	13,290 / 1,140						
Mrzlek 58	19,770 / 1,180						
Kajža 198							
Hotešk 195							
Podroteja 330				7,630 / 454	10,710 / 285		
Divje Jezero 350							
Vipava 99						12,490 / 365	7,600 / 881

6.1.1. First Combined Tracing experiment in October 1993

The two injection places of the first tracing experiment are located in the central part of the Trnovski Gozd plateau (ice cave Belo Brezno) and on the steep plateau border below Sinji Vrh close to the spring Hubelj (doline Zavrhovc) (Fig. 6.1). Injection was carried out on October 14 1993. The hydrologic conditions in the catchment area prior, during and shortly after the injection was characterised by a heavy precipitation event with a height of 60

mm on October 9 and 10, 1993 measured in the precipitation station Otlica. The next abundant rainfall was from October 21 to 25, with a maximum of 112.6 mm on October 22, hence altogether 247 mm of rain. At the time of injection the Hubelj discharge was 2.79 m^3/s. It started to increase on October 21 and attained its maximum the next day at 27.6 m^3/s. While the described hydrologic conditions are characteristic for the injection in Belo Brezno, for the tracing test in the doline near Zavrhovc (Fig. 6.1) low water conditions are prevailing.

Injection in the doline near Zavrhovc, October 14 1993

In the bottom of the doline at the farm Zavrhovc, 790 m a.s.l., distance from Hubelj 890 m, 16.5 l of phages solution (4.1 x 10^{15} pfu) were injected.

The selected doline is one of the series of deep dolines situated parallel to the steep plateau border below Sinji Vrh. In the grassy bottom of the doline a 5.5 m deep borehole was drilled through yellow-brown loam, mixed with some rubble in the lower part of the borehole. At the depth of 5 m, close to the rock, the borehole reached a 20 cm wide empty space. Experimentally, 1.5 m^3 of water was poured into the borehole and in 5 minutes it swallowed all the water. The phages solution was poured in at 14.25, injection lasted 3 minutes. Later 3.5 m^3 of water was added and all this water was promptly drained, after flushing lasted about half an hour.

Injection in Belo Brezno, October 14 1993

Belo Brezno is a smaller pothole, 40 m deep, lying south of the Golaki ridge in the area called Kozja Stena (compare chapter 2.5). The entrance of Belo Brezno lies at about 1240 m a.s.l., the pothole's bottom is at 1200 m a.s.l. The injection point is in 6880 m distance to the Hubelj spring, the altitude difference is about 910 m. The tracer was poured at the end of an oxbow passage continuing from the entrance part of the pothole towards the east. Over the oxbow passage wall about 0.2 l/s of water trickled down. The water disappeared among the rubble on the flat bottom. 5 kg of uranine were dissolved in 30 l of water. A closed barrel containing the solved tracer was lowered into the pothole and carried to the injection point. The dye was poured out at 13.10 and immediately disappeared among the rubble. By hoses the tracer was thoroughly washed by 7 m^3 of water. All the water disappeared by 13.45 giving the discharge of 3.9 l/s. The water drained off simultaneously.

Sampling

On the TBP the following main karst springs were sampled: Vipava, Hubelj, Lijak, Mrzlek, Hotešk, Kajža, Podroteja and Divje Jezero (Fig. 6.1). In the

vicinity of the Hubelj spring some smaller karst springs were included into the observation network: Skuk (520 m a.s.l.), Studenec near Gorenje (520 m a.s.l.). Using automatic samplers, partly put at disposal by the Federal Environmental Agency, Vienna, Austria, the Hubelj was sampled up to November 5, 1993 every two hours; later sampling was every 4 hours, and still later every 6 or 12 hours. Till the end of the observations one sample per day was taken. The springs Lijak and Mrzlek were sampled once per day. Unfortunately no sampling of the Mrzlek spring directly in the Soča river was possible due to technical reason. Therefore only samples of the Mrzlek pumping station are available. While water samples from the springs Hotešk, Kajža, Studenec near Gorenje and Skuk were only taken once per day at the beginning of the observation time, main observation was carried out by active charcoal detectors changed once per week. Observation of a possible tracer recovery in the springs Podroteja and Divje Jezero was solely done by activated charcoal adapters.

6.1.2. Second Combined Tracing experiment in April 1994

Injection was carried out on April 16, 1994 at four points: Belo Brezno, the doline near Zavrhovc, in Mrzli Log and in the Lokva stream below Predjama Castle (Tab. 6.1 and Fig. 6.1). In respect to evaluate the variability of the hydrodynamic behaviour under different hydrologic conditions the two injection points used in the first combined experiment (Belo Brezno, Zavrhovc) were chosen again.

Abundant rainfall appeared on April 10 and 11 (67.3 mm - Otlica) and April 17 and 18 (64.2 mm). During the injection the Hubelj discharge was measured as 5.41 m^3/s and Vipava 11.9 m^3/s. Due to rainfall in the catchment areas the Hubelj and Vipava discharge increased the following two days up to a maximal value and then gradually decreased during the whole month. The next precipitation event occurred in May 19 to 21 with a height of 190 mm. Caused by those rainfall, and as described in detail in Chapter 3, both the Vipava and even more the Hubelj discharge increased. After two days the discharge already started to decrease and it was decreasing up to September.

Injection in the doline near Zavrhovc, April 16 1994

Unfortunately, the drilling efforts into the doline's bottom at the same place such as in October 1993 were not successful. The water used for the preflushing did not flushed away. Therefore the tracer was injected into the bottom of a nearby, rocky doline covered with vegetation below the Zavrhovc farm house (775 m a.s.l). Testing of the swallow capacity was done with 3 m^3 of water poured onto the rocks in the border of the doline bottom at 10.00.

The water drained off. On the preceding day 30 kg LiCl were dissolved in 110 l of water and at 10.20 to 10.25 poured on the same spot. It was washed by 1 m^3 of water. At 10.30 20.5 l of phages solution (8 x 10^{15} pfu) were poured and washed by 3.5 m^3 of water. The water drained off promptly.

Injection in Belo Brezno, April 16 1996

The injection was carried out at the same place as in 1993. At the time of the injection the surface was covered by 30 - 60 cm of snow, melting intensively. All over the cave the drippings were strong. 5 kg of uranine were dissolved in 20 l of water. A closed barrel with tracer was lowered into the pothole and transported to the point planned for the injection. The tracer was poured out at the bottom of the cave at 13.10, at the end of an oxbow continuing from the entrance part of the pothole towards the east. Over the oxbow passage wall some 0.5 - 1 l/s of water trickled down. The water disappeared among the rubble. The majority of the dye washed by 7 m^3 of water was drained off within 15 minutes.

Injection in Mrzli Log, April 16 1996

Mrzli Log is a big karst depression, about 1 km long and 70 m deep, partly formed in limestone and partly in dolomite (Fig. 6.1). The bottom is flat, covered by dolomitic debris in which the shallow bed of a periodical stream is incised. The riverbed overgrown by grass ends in shallow alluvial dolines. In one of them a swallow-hole is opened. The tracers were poured into that.

The tracer, 50 kg of $SrCl_2$ was dissolved in 120 l of water quickly and completely. The second tracer, 5 kg of pyranine, was dissolved separately in 40 l of water and later added to the $SrCl_2$ solution. In the swallow-hole the water from a fireman tanker was poured for 5 minutes (about 1 m^3) at the beginning and at 11.00 both tracers were poured in it. The solution quickly drained off. The remains were washed by the remaining quantity of water (about 6 m^3). Water disappeared promptly.

Injection in the Lokva below Jama Cave (Predjama), April 16 1996

The uranine tracer was injected into the ponor of Lokva stream, which sinks at the northern border of the Pivka basin below the Predjama Castle. The ponor lies at 464 m a.s.l. and is 12990 m distant from the Vipava springs. The water level on the gauging site at the time of the injection was 129 cm, the discharge established by the curve 0.166 m^3/s (validity of the curve until 31.3.1994). Uranine was dissolved in about 100 l of water. The tracer was poured into the flow from 12.45 to 12.50. 15 minutes after the injection all the dye was washed off the riverbed.

Sampling

Hubelj was sampled for two weeks every two hours, for one week every four hours, then every 6 hours, and since May 25 two times per day. Studenec near Gorenje and Skuk, Podroteja and Divje Jezero were sampled until the end of April twice per day, and later daily. Hotešk and Lijak were sampled daily, Mrzlek 4 times per day in April and later 2 times per day.

The 7 main sampling locations of the Vipava (compare Fig. 4.12) have been equipped with automatic samplers and with data logger as far it was technically possible (compare Chapter 3.6). The sampling stations are listed in the Tab. 6.3.

Tab. 6.3: Sampling stations at the Vipava spring group with their logging equipment and the different laboratories responsible for their sampling site. Abbreviations refer to the list given in chapter 6.1.

No.	Name	Fluorimetric Analysis	Chemical Analysis	Datalogger
Vipava 4/1	Pri Kapelici	UR (KÄSS)		HMZ: Cond, T
Vipava 4/2	Pod Lipo	UR (HMZ)	CHEM (HMZ)	
Vipava 4/3	Perhavčeva Klet	UR (IHG)		IHG: Cond, T
Vipava 4/4	Vipavska Jama	UR (GSF)		HMZ: Cond, T
Vipava 4/5	Pod Skalo	UR (GSF)		HMZ: Cond, T
Vipava 4/6	Pod Farovžem A	UR (GSF)		HMZ: Cond, T
Vipava 4/7	Pod Farovžem B	UR (HMZ)		IHG: Cond, T, P
Vipava 4/8		UR (IHG)		IHG: Cond, T

All the springs and the common flow of Vipava were observed. The springs Pri Kapelici 4/1, Pod Lipo 4/2, Perhavčeva Klet 4/3, Pod Farovžem 4/7 and common flow 4/8 were sampled for 9 days every two hours and then for 10 days every 4 hours; subsequent sampling was every 6 hours. The springs Pod Skalco 4/5, Pod Farovžem 4/6 and Vipavska Jama 4/4 were at first sampled three times per day and later once per day.

The sampling interval was established individually for distinct periods of time from April 16 to 26 every 2 hours, April 26 to May 3 every 4 hours, from May 3 to May 13 every 6 hours and from May 14 to June 6 every 12 hours. After June 6 1994 the sampling was daily or according to the progress in the breakthrough process at longer intervals.

6.1.3. Third Combined Tracing Experiment, August 1995

Injection

While the water tracing tests in 1993 and 1994 were carried out at medium or high waters, the tracing in 1995 was done at prevailing low water conditions. Since the last half of June and up to the last week in August only little rain fell. The discharge of the Hubelj was rather constant, exhibiting a slow decrease. At the time of injection, the discharge was 0.514 m^3/s. On August 16, 1995 the minimal annual discharge was reached (compare Chapter 6.2). Also the Vipava discharge constantly decreased from the first week in July up to the last days in August; the minimal annual discharge was measured on August 8, 1995. In such conditions on the 1st of August repeated injection was carried out at ice cave Belo Brezno as well as in the doline near Zavrhovc (the same as in 1994). As an additional injection place the doline Malo Polje was selected (Tab. 6.1, Fig. 6.1).

Injection in the doline near Zavrhovc, August 1 1995

The tracer was injected, as in 1994, into the bottom of a rocky doline, covered with vegetation below the Zavrhovc farm, 775 m a.s.l. From 10.21 to 10.25, 3.5 m^3 of water from a fireman tanker was poured in the rocky bottom of the doline. At 10.25 26 l of phages dilution (6.6 x 10^{15} pfu) was injected. The injection was finished in 3 minutes. The remaining quantity of water (3.5 m^3) was poured in the doline in 6 minutes until 10.34.

Injection in Belo Brezno, August 1 1995

The injection point was the same as in the years 1993 and 1994 (Photos 14 and 15). From 11.18 to 11.32 2 m^3 of water from the fireman tanker was

Photo 14: Tracer injection at Belo Brezno, 1995 (Photo by J. Kogovšek).

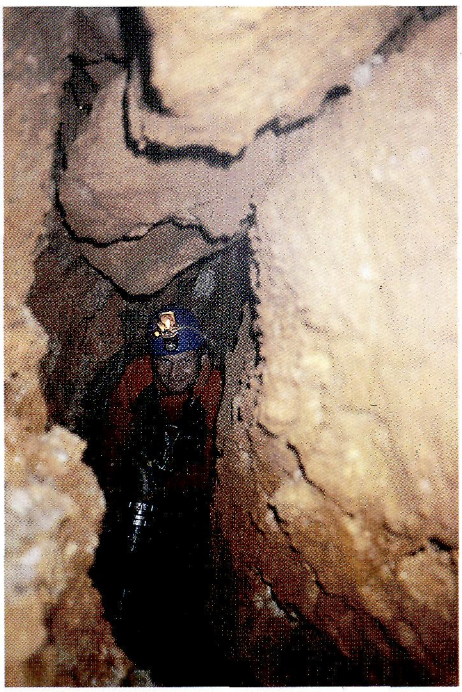


Photo 15: Tracer injection at Belo Brezno, work in the shaft (Photo by A. Mihevc).

poured in the pothole. At 11.37 7 kg of uranine dissolved in 30 l of water was poured at the bottom of the cave at the same point as in 1993 and 1994. The remains were washed by remaining water (3.5 m^3) till 11.55.

Injection near Malo Polje, August 1 1995

This injection point was used for the first time. The village Malo Polje lies 2 km NE from Col. It is in the northern edge of an almost 1 km long karst depression. The injection point was in the middle of the depression in a doline located some metres E from another doline filled with rubbish (Photo 16). The injection doline lies about 660 m a.s.l.

8.5 kg pyranine was dissolved in about 120 l of water. The tracer dissolved quickly and completely. From 10.05 to 10.30 1.5 m^3 of water from a fireman tanker was poured in the swallow-hole, which was artificially enlarged some days prior the day of injection. At 10.35 the tracer was poured into the swallow-hole. The remains of the solution were washed with water at 10.55 and at 11.05 all the remaining water (4.5 m^3) was emptied in the swallow-hole.

Photo 16: Swallow-hole, point of tracer injection at Malo Polje, 1995 (Photo by J. Kogovšek).

Sampling

At the beginning Hubelj (Photo 17) was sampled four times per day for analyses of tracer and isotopes (see Chapter 5). Later it was sampled twice per day and at the end of sampling once per day. In the smaller karst springs Studenec near Gorenje and Skuk in vicinity of the Hubelj water samples were taken once per day for one month and later activated charcoal adapters were changed once per week.

Activated charcoal adapters were changed in Kajža and Hotešk at the beginning of the observation twice per week and later once per week. Podroteja and Divje Jezero were observed by taking water samples either once or two times per day; later the sampling was two times per week. Sampling of Vipava was at springs Pod Lipo 4/2 and Pod Farovžem 4/7 once per day.

This time it was possible to sample the karst spring Mrzlek in both the pumping station and directly in the spring on the right bank of the Soča river. Mrzlek pump station was sampled from July 27, 1995, up to January 4, 1996, by an automatic sampler WTW PB 10/T. Mrzlek spring was sampled from July 27, 1995, up to January 4, 1996, by an automatic sampler Endress+Hauser asp-port. The sampling frequency and missing samples of Mrzlek spring and pump station are given in the Table 6.4. In principle momentary samples should be taken. Due to technical problems for two time intervals only average daily samples were available.

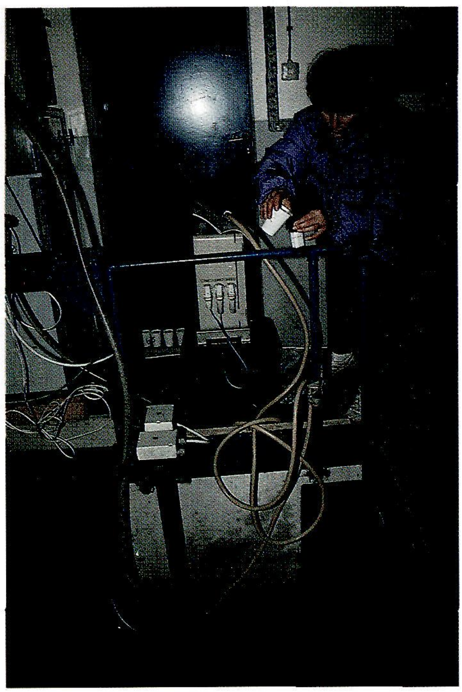


Photo 17: Water sampling devices at Hubelj spring (Photo by J. Kogovšek).

Tab. 6.4: Sampling schedule for the Mrzlek spring and the Mrzlek pump station during the third combined tracer test in 1995.

Sampling point	Date	Sampling intervals
Mrzlek spring	27.7.-29.7.95	1 per day
	8.8-18.8.95, 24.8.-7.9.95	4 per day
	19.8-23.8.95	average daily samples
	8.9.-30.9.95	2 per day
	3.10.-4.1.96	1 per day
	29.7.- 8.8.95, 19.- 26.10, 23.-28.11., 5.- 5.12., 18.- 21.12., 30.12.95 - 1.1.96	automatic sampler out of function
Mrzlek pump station	27.7.-7.8.95	average daily samples
	8.8.-18.8.95, 28.8.-7.9.95	4 per day
	8.9.-10.9.95	2 per day
	19.-27.8., 11.-29.9., 1.10., 9.10., 24.10.-31.1.95	1 per day
	26.8., 30.9., 2.-8.10., 10.-23.10., 26.10., 5.11., 27.11., 2.12., 3.12., 16.12., 21.12.95	automatic sampler out of function

6.1.4. Fourth Combined Tracing experiment, October 1995

Injection

In October 26, 1995 an additional tracing test was done at the Lokva near Predjama repeating the experiment performed during high water flow conditions in spring 1994 and in the pothole Slapenski Ledenik on Nanos (see Chapter 2.5) at prevailing low waters (Tab. 6.1, Fig. 6.1).

Injection in the Lokva below Jama Cave (Predjama), October 26 1995

8 kg of pyranine was injected into the Lokva stream like in 1994. The swallow-hole lies at 464 m a.s.l. and its distance to the Vipava springs amounts up to 12,990 m. The water level on the gauging station was at the time of the injection 122 cm. 8 kg of pyranine was dissolved in about 100 l of water. The tracer was poured in the stream in the time from 10.05 to 10.15. Water only slowly flushed the tracer.

Injection in Slapenski Ledenik on the Nanos plateau, October 26 1995

Slapenski Ledenik is a shaft, 112.4 m deep, lying on the east side of the Nanos plateau. The entrance is located about 1000 m a.s.l. At the depth of 35 m, the shaft divides into two branches (see Chapter 2.5).

5 kg of uranine was dissolved in about 50 l of water. The tracer dissolved quickly and completely. 2 m^3 of water from the fireman tanker was poured in the western branch of the shaft, at the depth of 45 m. At 11.45 the tracer was injected. 10 minutes after the injection all the dye was washed off in the hole. The remaining quantity of water (4 m^3) was washed in the hole until 12.30.

Sampling

In the spring Vipava 4/2 and Vipava 4/7 automatic sampler WTW PB 20/S was installed and in the spring Vipava 4/5 the sampler WTW PB 10/T. All springs were sampled from October 25 1995, up to June 2 1996. Sampling for such a long period of time was performed due to the expectation of a long duration of the uranine concentration wave. Additional, possible tracer recoveries after the snow melt or during the spring high waters can give valuable information on the hydrodynamic characterisation of the Vipava. The sampling frequency and missing samples of Vipava springs are given in the Tab. 6.5.

Tab. 6.5: Sampling in the Vipava springs during the forth tracing experiment in 1995.

SAMPLING POINT	DATE	SAMPLING METHOD
4/2, 4/5, 4/7	25.10.95 - 21.12.95	4x per day
4/2, 4/5, 4/7	22.12.95 - 01.03.96	3x per day
4/2, 4/5, 4/7	02.03.96 - 02.06.96	1x per day
4/5	28.10.95 - 30.10.95	automatic sampler out of function
4/2, 4/7	29.10.95 - 03.11.95	automatic sampler out of function
4/5, 4/7	06.12.95 -11.12.95	automatic sampler out of function

6.2. DESCRIPTION OF THE HYDROLOGICAL SITUATIONS DURING THE TRACING EXPERIMENTS

(N. TRIŠIČ & J. POLAJNAR)

6.2.1. The Hubelj Spring in the Time of the First Tracing Experiment (October 14 to December 31, 1993)

The values of discharges of the Hubelj were above average in the time of tracing experiment, if compared to the average over many years for the same period (October, November, December 1961-90). The mean discharge was by one third higher in the time of the tracing experiment than the mean discharge of the period. The highest discharge in the time of tracing experiment was higher by 2-times than the mean of extremes of the maximum high discharges in the period, and the lowest discharge was equal to the mean of extremes of the minimum low discharges in the period.

At the injection of the tracer on October 14, 1993, the initial discharge of 2.786 m^3/sec was only one half of the average mean discharge in the time of tracing experiment. On October 22, the high water wave followed with the highest discharge of 29.13 m^3/sec, which is more than the mean of extremes of the maximum high discharges in the period. By the end of October, the discharge of the Hubelj decreased below the value of discharge at the time of injection of the tracer, and on November 9, the second minor high water wave occurred with the highest discharge which was lower than the mean of extremes of the maximum high discharges in the period.

The discharge kept decreasing by December 6, when the lowest value was registered in the time of tracing experiment and was equal to the mean of extremes of the minimum low discharges in the period. In mid-December, the last high water wave occurred, with the highest discharge of 34.59 m^3/sec, which is almost by 2-times higher than the mean of extremes of the maximum high discharges in the period. The discharge of the Hubelj decreased by the end of December and was approx. equal to the discharge at the time of injection of the tracer (Fig. 6.2).

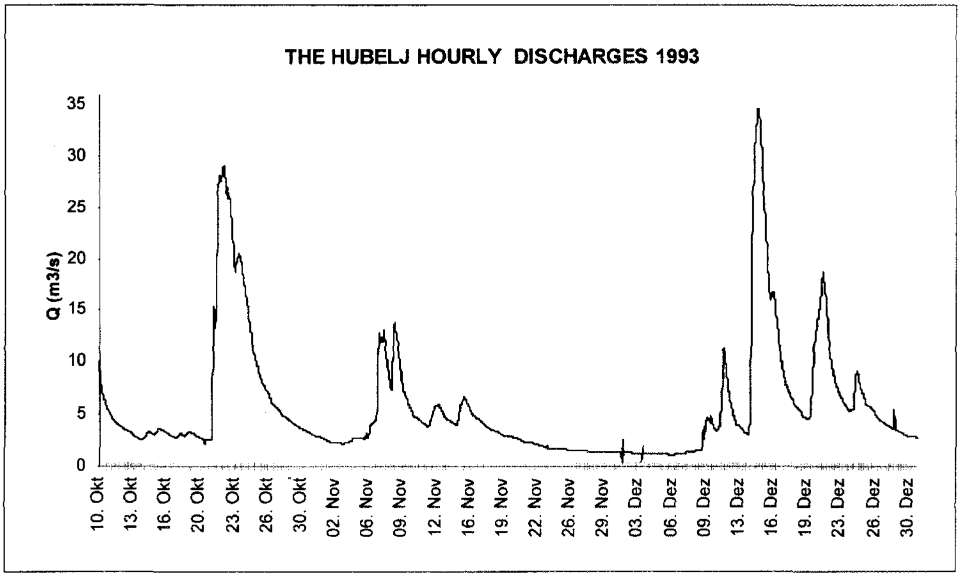


Fig. 6.2: Comparison of the Hubelj discharge behaviour during the second tracing experiment in April 1994 with the characteristic discharges (gauging profile Hubelj - Ajdovščina). Measured Hubelj discharge at the time of injection in Belo Brezno(October 14, 1993, 13:00) was Q.= 2.786 m^3/s. The following discharge data (Q in m^3/s) was evaluated:

	Q_{min}	Q_{mean}	Q_{max}
Oct 14 to Dec 31, 1993	*1.085*	*5.73*	*34.59*
Oct 14 to Nov 13, 1993	*2.11*	*6.77*	*29.14*
long-time (1961-1990)	*0.382*	*3.03*	*59.50*

	Oct	Nov	Dec	average
Q_{mean} *1993*	*10.1*	*7.64*	*5.11*	*7.6*
Q_{mean} *1961-1990*	*3.58*	*4.19*	*3.51*	*3.76*

6.2.2. The Hubelj Spring in the Time of the Second Tracing Experiment (April 16 to July 31, 1994)

The values of discharges of the Hubelj were below average in the time of tracing experiment, if compared to the average over many years for the same period (April, May, June, July 1961-90).

The mean discharge amounted to 2.08 m^3/sec in the time of tracing experiment and was by one third lower than the mean discharge of the period.

The lowest discharge of 0.29 m^3/sec was only one quarter of the mean of extremes of the minimum low discharges in the period, and the highest discharge of 31.27 m^3/sec exceeded by 2-times and a half the mean of extremes of the maximum high discharges in the period.

At the injection of the tracer on April 16, 1994, the initial discharge of 5.409 m^3/sec was higher than the mean discharge of the period and it was higher by 5-times than the mean discharge in the time of tracing experiment.

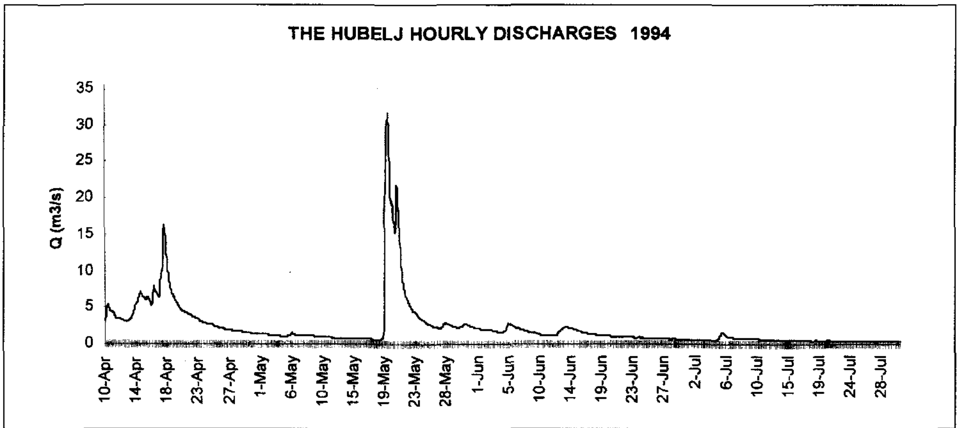


Fig. 6.3: Comparison of the Hubelj discharge behaviour during the second tracing experiment in April 1994 with the characteristic discharges (gauging profile Hubelj - Ajdovščina). Measured Hubelj discharge at the time of injection in Belo Brezno(April 16, 1994, 13:00) was Q.= 0.514 m^3/s: the following discharge data was evaluated:

	Q_{min}	Q_{mean}	Q_{max}
Apr 16 to May 12, 1994	*0.86*	*2.80*	*16.28*
Apr 16 to Jul 31, 1994	*0.29*	*2.09*	*31.65*
long-time (1961-1990)	*0.38*	*3.03*	*59.50*

	Apr	*May*	*Jun*	*Jul*	*average*
Q_{mean} *1994*	*4.17*	*3.17*	*1.37*	*0.54*	*2.31*
Q_{mean} *1961-1990*	*4.91*	*3.20*	*2.70*	*1.52*	*3.08*

In the days that followed the injection, the discharge increased to 16.27 m^3/sec and exceeded the mean of extremes of the maximum high discharges in the period.

By May 18, the discharge of the Hubelj decreased to 0.67 m^3/sec, which is only a half of the mean of extremes of the minimum low discharges in the period, and immediately after, on May 20, followed the high-water wave with the highest discharge of 31.64 m^3/sec which is higher by 2-times and a half than the mean of extremes of the maximum high discharges in the period. By July 31, the discharge of the Hubelj decreased to 0.29 m^3/sec, which is only one quarter of the mean of extremes of the minimum low discharges in the period (Fig. 6.3).

6.2.3. *The Hubelj Spring in the Time of the Third Tracing* Experiment (August 1 to December 31, 1995)

The values of discharges of the Hubelj were above average in the time of tracing experiment, if compared to the average over many years for the same period (August, September, October, November, December 1961-1990).

The mean discharge amounted to 3.24 m^3/sec in the time of tracing experiment and was higher by one tenth than the mean discharge of the period.

The lowest discharge of 0.24 m^3/sec was only one third of the mean of extremes of the minimum low discharges in the period, and the highest discharge of 40.74 m^3/sec exceeded by 3-times the mean of extremes of the maximum high discharges in the period.

At the injection of the tracer on August 1, 1995, the initial discharge of 0.514 m^3/sec was lower than the mean discharge of the period and it was lower by 6-times than the mean discharge in the time of tracing experiment. Towards the end of August, the discharge increased to 17.47 m^3/sec. This is a typical discharge in October as to the mean of extremes of the maximum high discharges in the period. In September, the discharge increased five times above the average value of the mean discharge in the time of tracing experiment, and by the end of this month, it decreased below this value. By mid-November, discharges decreased below the mean of extremes of the minimum low discharges in the period, and on November 18, it increased intensely and reached the value of 40.47 m^3/sec which is the highest value in the time of tracing experiment. The discharge decreased again by mid-December, and in the second half of the month, it increased two times above the mean of extremes of the maximum high discharge in the period (Fig. 6.4).

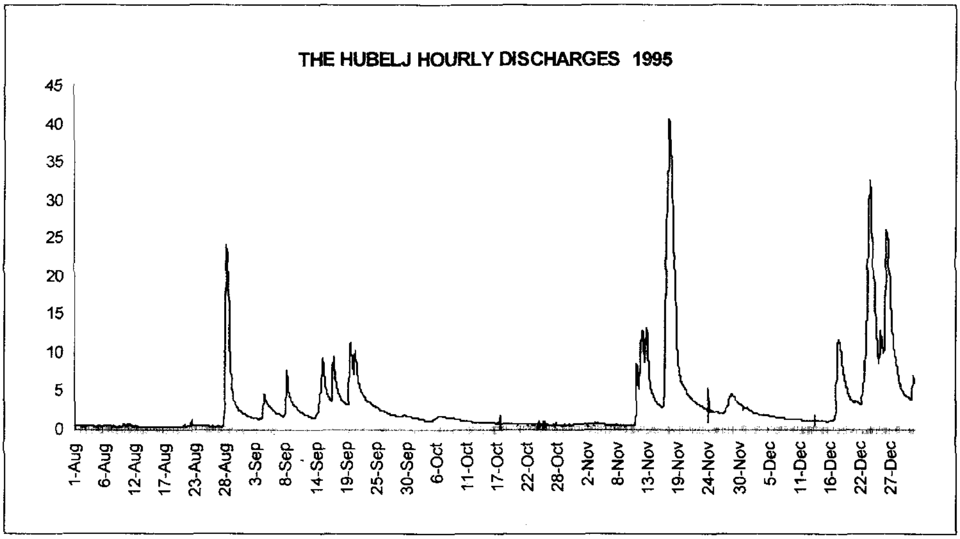


Fig. 6.4: Comparison of the Hubelj discharge behaviour during the third tracing experiment in August 1995 with the characteristic discharges (gauging profile Hubelj - Ajdovščina). Measured discharge at the time of injection in Belo Brezno (Aug 1, 1995 11:37) was Q.= 0.514 m³/s. The following discharge data (Q in m³/s) was evaluated:

	Q_{min}	Q_{mean}	Q_{max}
Aug 1 to Aug 28, 1995	*0.30*	*0.60*	*17.47*
Aug 1 to Dec 31, 1995	*0.24*	*3.24*	*40.74*

	Aug	*Sep*	*Oct*	*Nov*	*Dec*	*average*
Q_{mean} *1995*	*1.24*	*3.44*	*1.01*	*4.80*	*5.43*	*3.18*
Q_{mean} *1961-1990*	*1.32*	*2.18*	*3.58*	*4.19*	*3.51*	*2.96*

6.2.4. The Vipava Spring in the Time of the Fourth Tracing Experiment (October 26 to December 31, 1995)

The values of discharges of the Vipava river at gauging station. Vipava were little lower in the time of tracing experiment, if compared to the average over many years for the same period (October, November, December 1961-1990).

The mean discharge amounted to 9.99 m³/sec in the time of tracing experiment and was higher by 1.95 m³/sec than the mean discharge of the period.

At the injection of the tracer on October 26, 1995, the initial discharge of 1.702 m^3/sec was lower than the mean discharge of the period and it was lower by 6-times than the mean discharge in the time of tracing experiment. On November 17, it increased intensely and reached the value of 52.0 m^3/sec which is the second highest value in the time of tracing experiment. The discharge decreased again by mid-December, and in the second half of the month, it increased two times. On December 24, reached the value of 61.60 m^3/sec which is the highest value in the time of tracing experiment (Fig. 6.5).

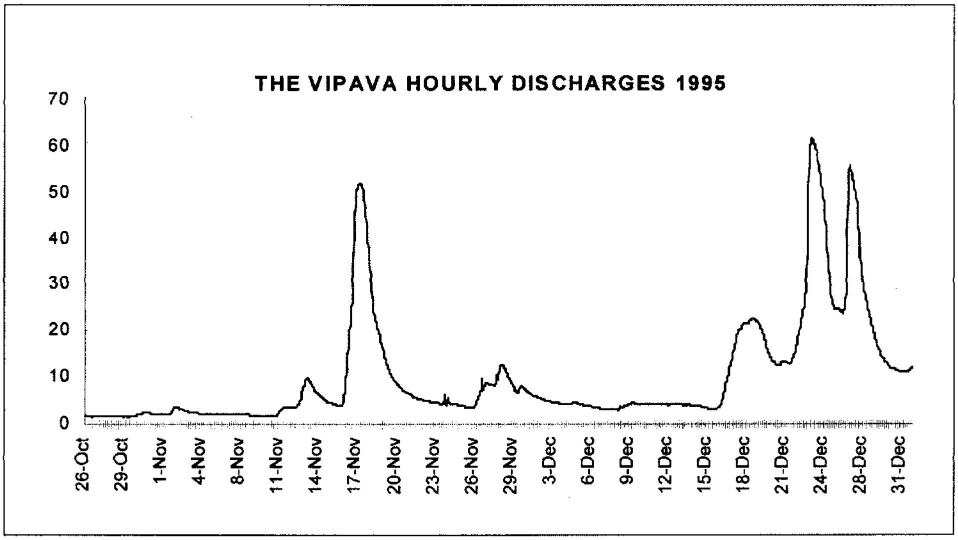


Fig. 6.5: Comparison of the Vipava discharge behaviour during the forth tracing experiment in August 1995 with the characteristic discharges (gauging profile Vipava - Vipava). Measured discharge at the time of injection in Slapenski ledenik (Nov 26, 1995, 12:00) was Q.= 1.702 m^3/s. The following discharge data (Q in m^3/s) were evaluated:

	Q_{min}	Q_{mean}	Q_{max}	
Oct 26 to Dec 31, 1995	*1.51*	*9.99*	*61.60*	
	Oct	*Nov*	*Dec*	*average*
Q_{mean} *1995*	*2.22*	*7.46*	*13.8*	*7.83*
Q_{mean} *1961-1990*	*6.85*	*9.13*	*8.13*	*8.04*

6.3. RESULTS WITH FLUORESCENT TRACERS

6.3.1. Analytical Procedures

(R. BENISCHKE, B. REICHERT, M. ZUPAN)

Analyses in the HMZ laboratory, Slovenia

The concentration of uranine was determined by scanning the emission spectra on the fluorescence spectrophotometer HITACHI F-4500. The samples had been kept in a dark place at room temperature before the analysis took place. Scanning of the emission spectra was performed by the method of simultaneously changing excitation and emission wavelengths with the constant difference of 25 nm for uranine analyses (BEHRENS 1971, 1973) and the constant difference of 105 nm for pyranine. All spectra were scanned by the same conditions: scan speed 240 nm/min, slit EX/EM 10 nm/10 nm, photomultiplier voltage 950V. The uranine concentrations were measured at pH 10, after addition of EDTA, while the pyranine concentrations were measured at pH 4.5-5.0 after addition of acetate buffer solution (BEHRENS, 1986, 1988). For the preparation of standard solutions with the reference samples unchlorinated tap water was used. Wavelengths of emission maximums and detection limits of fluorescent dyes are given in Tab. 6.6.

Tab. 6.6: HMZ Laboratory: Emission maximum and detection limit of the fluorescent dyes applied in the framework of the 7th SWT.

Tracing experiment	Dye	Emission maximum (nm)	Detection limit (ppb)
1993 - October	uranine	512 ± 4	0.0008
1994 - April	uranine	512 ± 4	0.0008
	pyranine	494 ± 3	0.03
1995 - August	uranine	512 ± 4	0.001
	pyranine	494 ± 3	0.01
1995 -October	uranine	512 ± 4	0.0009
	pyranine	494 ± 3	0.02

The obvious variation of the detection limits for the various experiments was caused either by the variability of the injected tracers, which have been provided by several members of the ATH or by the status of the instrument.

In the HMZ the collected samples were measured almost immediately after they arrived in the laboratory. Depending on the delivery of the samples the time after sampling ranges between 1 and 14 days.

Analyses in the AGK, IHG and GSF Laboratories

As described in the above chapters the tracer samples were mostly taken by automatic samplers provided either by HMZ, by UBA, or by IZRK. The service of the samplers was carried out by IZRK, the samples have been transported at first to the Karst Institute in Postojna, stored and then sent to the individual institutes for further analysis. The Tab. 6.7 may serve as an example for a detailed documentation, which seems to be necessary to collect as much information as possible for the following evaluation. This is important in all cases where results are suspicious to be not correct, because of possible bad storage conditions and adsorption or decay processes during storage.

Comparable to the described methodology of HMZ all the other laboratories got a small amount of reference material as a standard for the calibration of analytical instruments. How to handle the reference material was the responsibility of each laboratory according to common agreement on the used analytical procedure. But there was no previous interlaboratory testing of the used methods and their procedural details.

All three laboratories analysed the samples by fluorescence spectrometry with synchronous-scan-method. For uranine a $\Delta\lambda$ of 25 nm was used after alkalising samples and standards with EDTA for establishing a constant pH-value of the testing sample combined with appropriate complexing of carbonates to avoid their possible precipitation. Pyranine was measured with a $\Delta\lambda$ of 105 nm procedure after adding an acetate buffer solution to establish a pH value of 4.5.

Beside water samples about 400 charcoal bags were used to observe a possible tracer recovery. The processing of the charcoal bags was solely performed in the AGK laboratory. The charcoal bags are processed by extracting the fluorescent tracers with mostly organic solvents. The used mixtures were pH-controlled for an optimum performance. After the extraction the samples were analysed in the above mentioned synchronous-scan method.

Tab. 6.7: Example (second experiment, sampling at the Vipava springs) for delivery of samples and the time delay between sampling and analysis. As the time delay grows a possible alteration of sample properties should be taken into consideration. From this point of view it is recommended to document date and time of sampling, delivery and analysis.

Lab	Storage Conditions	Sampling Period	Delivery to Lab	Analy sis
IH G	dark, room temp.	4/3 (940416-940420)	940424	94042 5
IH G	dark, room temp.	4/3 (940420-940503)	940505	94050 9
IH G	dark, room temp.	4/3 (940503-950513)	940518	94051 9
IH G	dark, room temp.	4/3 (940513-940626)	040712	94071 3
IH G	dark, room temp.	4/3 (940630-940728)	date missing	94082 4
IH G	dark, room temp.	4/8 (940416-940420)	940424	94042 5
IH G	dark, room temp.	4/8 (940420-940425)	940505	94051 1
IH G	dark, room temp.	4/8 (940425-940503)	940505	94051 6
IH G	dark, room temp.	4/8 (940503-940513)	940518	94051 9
IH G	dark, room temp.	4/8 (940513-040628)	940712	94071 2
IH G	dark, room temp.	4/8 (940630-940728)	date missing	94082 4

6.3.2. Results of the Hubelj - Mrzlek- Podroteja Area

(M. ZUPAN, B. REICHERT)

6.3.2.1. First Tracing Experiment in October 1993

Uranine injected in the ice cave Belo Brezno was detected in the springs Hubelj, Lijak and Mrzlek after the heavy rain events from October 21 till October 25, 1993 (compare Chapter 6.2.1). The uranine breakthrough curves for the three karst springs are given in Fig. 6.6, 6.7 and 6.8. Tab. 6.8 presents an overview of the relevant curve parameters.

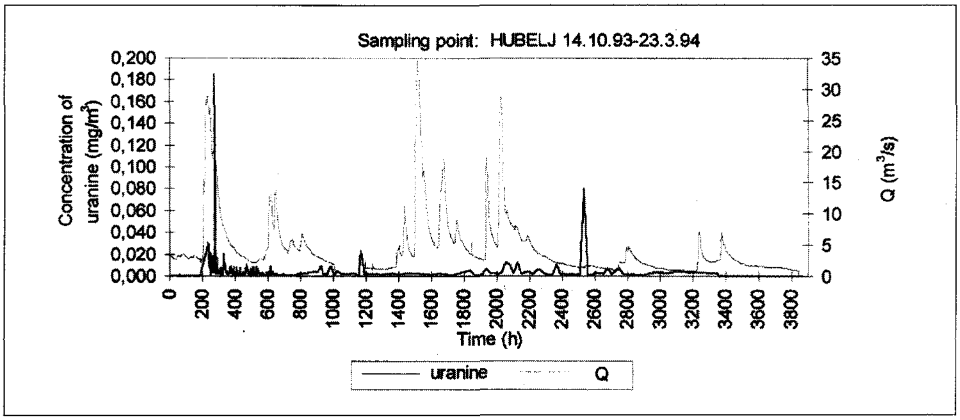


Fig. 6.6: Results of the first tracing experiment, Oct 1993: Breakthrough of uranine in the Hubelj spring and the discharge of the Hubelj during the observation period of 3900 hours.

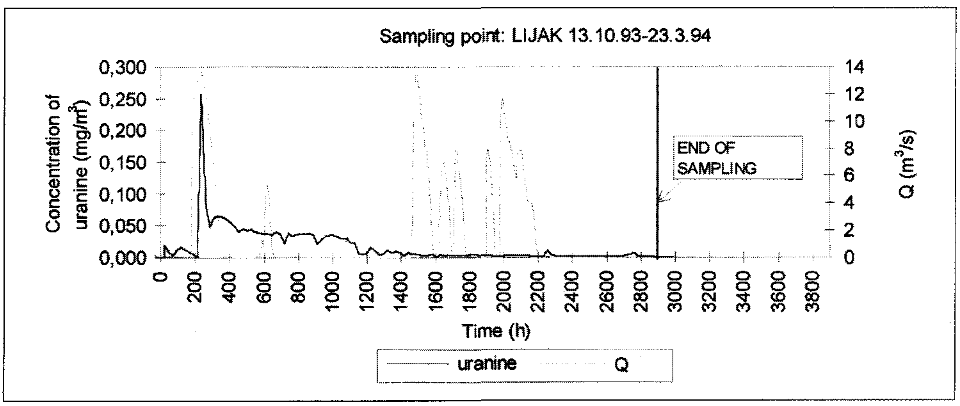


Fig. 6.7: Results of the first tracing experiment, Oct 1993: Breakthrough of uranine in the Lijak spring and the discharge of the Lijak measured at the Lijak -Šmihel gauging station during the observation period of 3900 hours.

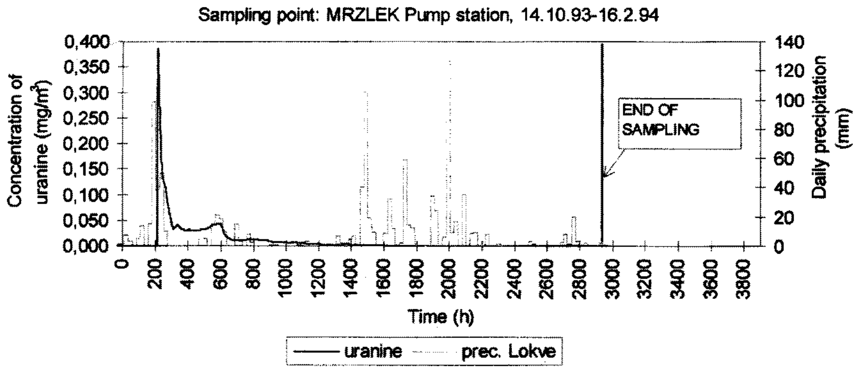


Fig. 6.8: Results of the first tracing experiment, Oct 1993: Breakthrough curve of uranine in the Mrzlek spring (sampling in the pumping station) during the observation period of 3900 hours. Hence the spring is situated in the Soča river no discharge measurements are available. To describe the hydrologic situation the daily precipitation heights of the station Lokve is depicted.

Tab. 6.8: Overview of relevant parameters derived from the uranine breakthrough curves in the springs Hubelj, Mrzlek and Lijak in the first tracer test, Oct 14, 1993: time(t_{max}), concentration (C) and velocity (v_{max}) of the first appearance, time of maximal concentration (t_{max}), maximal concentration (C_{max}) and dominant velocity (v_{dom}) in the springs and the recovery (R).

Spring	C [mg/m³)	t_{max} [h]	v_{max} [m/h]	C_{max} [mg/m³]	t_{dom} [h]	v_{dom} [m/h]	R [kg]	R [%]
Hubelj	0.0300	196	35.1	0.1850	234	29.4	0.107	2.14
Mrzlek pumping station	0.3850	216	92.4	0.3850	216	92.4	2.0 (1.45)*	40 (29)*
Lijak	0.0009	214	63.0	0.2570	238	56.6	0.507	10.10
Hotešk	0.0027	309	67.9	0.0027	309	67.9	*1)	

2.00 = recovery rate for the Mrzlek estimated on the basis of Q_{mean} for 1961 to 1990
(1.45)* = recovery rate for the Mrzlek estimated on the basis of Q_{mean} for 1993 to 1995
*1) = only a singular peak, no recovery estimation

Hence the spring Lijak is only temporarily active (compare Chapter 2.6.2) in the framework of former investigations a borehole was drilled nearby to enable a regular monitoring of the karst groundwater. The regular sampling during the tracing experiment for the sampling point Lijak was not in the spring itself but in this nearby borehole. Only for the long-term investigation direct samples of spring were analysed. The comparison of the results is striking, but so far explainable. The concentrations in the spring samples were definitely higher than in the borehole samples at the approximately the same time (Tab. 6.9).

Tab. 6.9: Comparison of the uranine concentrations in the Lijak spring and Lijak borehole

	Uranine - mg/m^3	
Date / hour	Lijak borehole	Lijak spring
28.10.93 / 11:30	0.065	
28.10.93 / 10:00		0.112
23.12.93 / 10:45	udl	
23.12.93 / 13:00		0.088
19.01.94 / 11:30	udl	
19.01.94/ 13:00		0.054
udl = under detection limit		

Uranine was not detected in the samples taken from the smaller karst springs Skuk and Gorenje in the vicinity of the Hubelj spring. In the spring Hotešk only one singular uranine peak with a very low concentration (0.0027 mg/m^3) was detected in the sample taken on October 27, 1993. This peak should not be overemphasised; it might represent a background value which ranges up to 0.006 mg/m^3 (compare Chapter 6.3.4)

6.3.2.2. The Second Tracing Experiment in April 1994

Uranine

The repeated injection of uranine in the injection point Belo Brezno in spring 1994 resulted in uranine breakthrough in the springs Hubelj and Mrzlek, but astonishingly not in the spring Lijak (Fig. 6.9 and 6.10). Compared to the first tracing experiment a distinct delay of the breakthrough of the maximal uranine concentration occurred (Tab. 6.10). On the other hand uranine appeared earlier for the first time than in the first tracing experiment.

It has to be taken into account that the appearance of uranine in two samples taken on April, 19, 1993, and April, 20, 1993, could possible originate from the first tracing experiment. In comparison with the first tracing experiment the maximal concentrations were much lower in the Hubelj, but higher in the Mrzlek (Tab. 6.10).

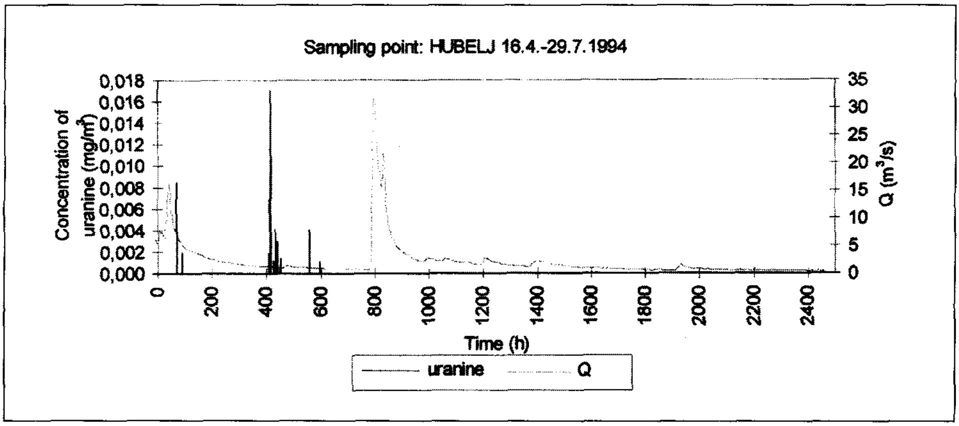


Fig. 6.9: Results of the second tracing experiment, April 1994: Breakthrough of uranine in the Hubelj spring and the discharge of the Hubelj during the observation period of 2500 hours.

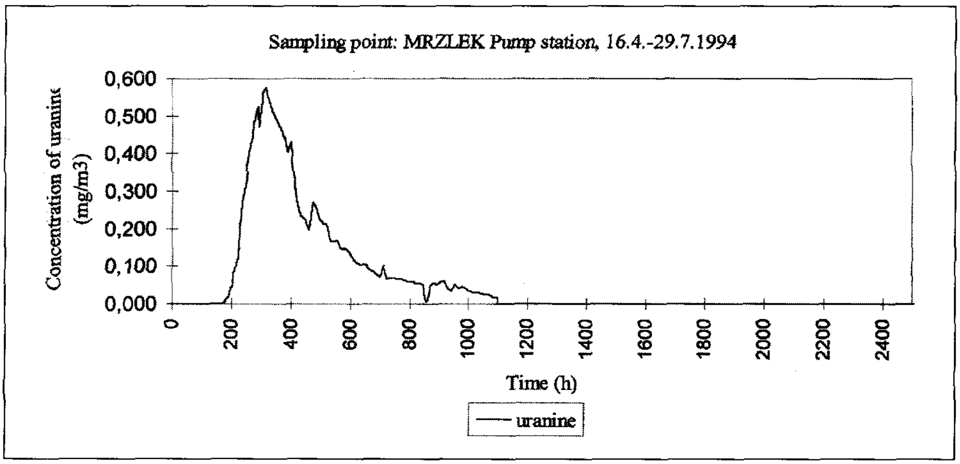


Fig. 6.10: Results of the second tracing experiment, April 1994: Breakthrough curve of uranine in the Mrzlek spring (samples from the pumping station) during the observation period of 2500 hours.

Tab. 6.10: Overview of relevant parameters derived from the uranine breakthrough curves in the springs Hubelj and Mrzlek in the second tracer test, April 16, 1994: time(t_{max}), concentration (C) and velocity (v_{max}) of the first appearance, time of maximal concentration (t_{max}), maximal concentration (C_{max}) and dominant velocity (v_{dom}) in the springs and the recovery (R).

Spring	C [mg/m³)	t_{max} [h]	v_{max} [m/h]	C_{max} [mg/m³]	t_{dom} [h]	v_{dom} [m/h]	R [kg]	R [%]
Hubelj	0.0085	70	98.2	0.017	414	16.6	0.001	0.02
Mrzlek pumping station	0.0009	168	119	0.579	318	62.8	2.98 (2.15)*	59.6 (43)*

2.98 = recovery rate for the Mrzlek estimated on the basis of Q_{mean} for 1961 to 1990
(2.15)* = recovery rate for the Mrzlek estimated on the basis of Q_{mean} for 1993 to 1995

Pyranine

Pyranine, injected in the doline Mrzli Log, was detected in the samples of the karst spring Podroteja and Divje Jezero (Fig. 6.1). While in the spring Podroteja an almost classical pyranine breakthrough curve was observed, only one single pyranine peak occurred, with a much lower concentration in the Divje Jezero (Fig. 6.11). An overview on the determined values gives Tab. 6.11.

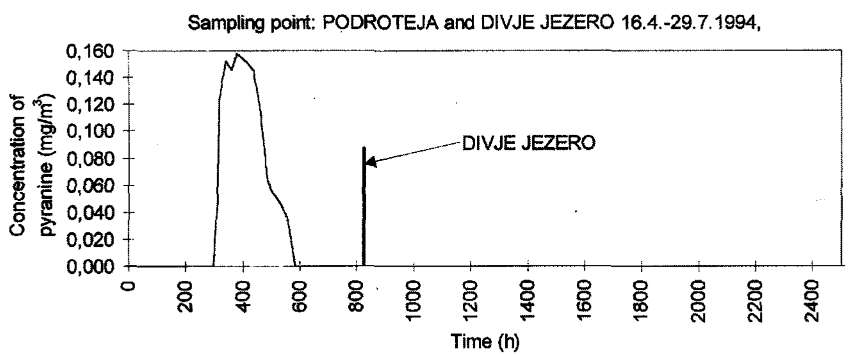


Fig. 6.11: Results of the second tracing experiment, April 1994: Analysed pyranine concentrations in the karst springs Podroteja and Divje Jezero during the observation period of 2500 hours.

Tab. 6.11: Overview of relevant parameters derived from the pyranine breakthrough in the springs Podroteja and Divje Jezero in the second tracer test, April 16, 1994: time(t_{max}), concentration (C) and velocity (v_{max}) of the first appearance, time of maximal concentration (t_{max}), maximal concentration (C_{max}) and dominant velocity (v_{dom}) in the springs and the recovery (R).

Spring	C [mg/m³)	t_{max} [h]	v_{max} [m/h]	C_{max} [mg/m³]	t_{dom} [h]	v_{dom} [m/h]	R [kg]	R [%]
Podroteja	0.0507	309	24.7	0.1579	380	20.1		
Divje jezero	0.0870	822	9.2	0.0870	822	9.2		

6.3.2.3. Third Tracing Experiment in August 1995

Uranine

This tracing experiment was realised at low water conditions (compare Chapter 6.2.3) and the results are quite different from the previous ones. In the Hubelj the first appearance and the maximal concentration of uranine were reached earlier compared to first two tracing experiments. While in the first period of the observation time a continuously breakthrough occurred, later only single samples were uranine positive. At all the uranine concentrations

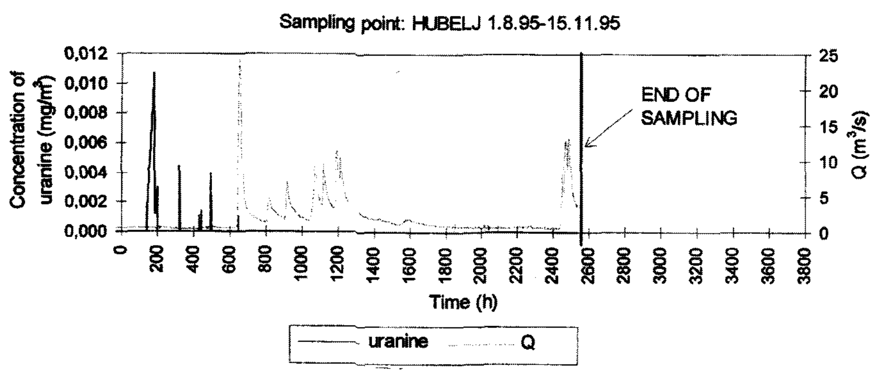


Fig. 6.12: Results of the third tracing experiment, August 1995: Analysed uranine concentrations and the discharge in the karst spring Hubelj during the observation period.

were low (Fig. 6.12). Contrary to the Hubelj the first appearance and the maximal uranine concentration in the Mrzlek pump station was reached much later (Tab. 6.12). While for the first and the second experiment only water samples from the Mrzlek pumping station were available, both, the pumping station and the spring in the Soča river were sampled for the third experiment. The comparison of the result proved the assumption that the karstic flow was practically the same in both sampling points (Fig. 6.13 and 6.14).

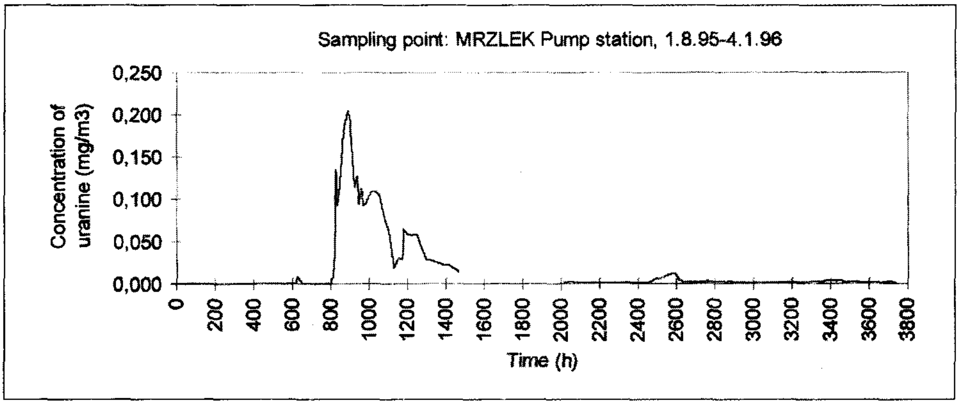


Fig. 6.13: Results of the third tracing experiment, August 1995: Uranine breakthrough curve in the Mrzlek pumping station.

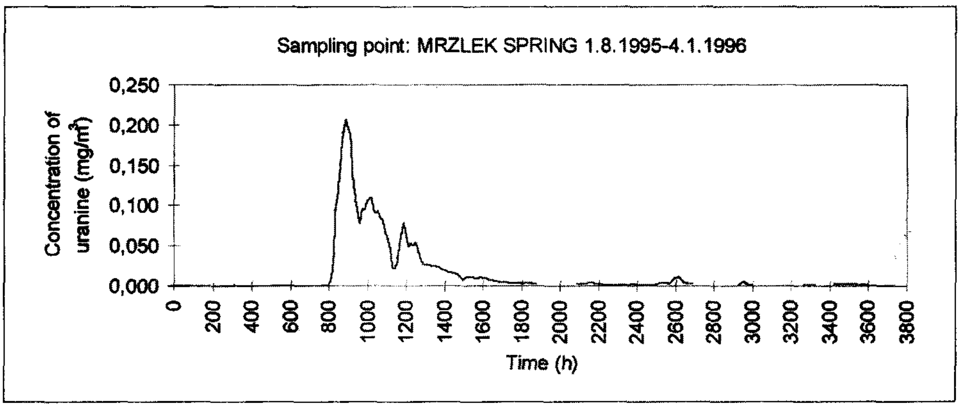


Fig. 6.14: Results of the third tracing experiment, August 1995: Uranine breakthrough curve in the Mrzlek spring itself in the Soča river.

Tab. 6.12: Overview of relevant parameters derived from the uranine breakthrough in the springs Hubelj and Mrzlek (for both the pumping station and the spring in the Soča river) in the third tracer test, August 1, 1995: time(t_{max}), concentration (C) and velocity (v_{max}) of the first appearance, time of maximal concentration (t_{max}), maximal concentration (C_{max}) and dominant velocity (v_{dom}) in the springs and the recovery (R).

Spring	C [mg/m^3]	t_{max} [h]	v_{max} [m/h]	C_{max} [mg/m^3]	t_{dom} [h]	v_{dom} [m/h]	R [kg]	R [%]
Hubelj	0.0019	144	47.7	0.0107	180	38.2	0.0008	0.01
Mrzlek pumping station	0.0028	804	24.6	0.2042	888	22.3	4.6 (3.2)*	66 (45.7)*
Mrzlek Spring	0.0010	798	24.8	0.2057	887	22.3	5.05 (3.6)*	72 (51.4)*

4.6 = recovery rate for the Mrzlek estimated on the basis of Q_{mean} for 1961 to 1990
(3.2)* = recovery rate for the Mrzlek estimated on the basis of Q_{mean} for 1993 to 1995

The Lijak spring was only active for a short period of time. Only two water samples taken on August 28, 1995, and September, 19, 1995 were analysed. The latter had an uranine concentration of 0.023 mg/m^3. Unfortunately no sampling in the borehole was possible due to technical reasons.

Pyranine

Pyranine injected in the doline Malo Polje was detected in the karst springs Podroteja and Divje Jezero (Fig. 6.1). Unfortunately, the pyranine breakthrough took place just in the time period when samples got lost for those two sampling points. Therefore only 5 samples for a time period of in 9 days are available. Despite the missing samples the concentration curves look like a periodical content of the tracer (Fig. 6.15, Fig. 6.16)

Compared to the second experiment by high water conditions the time of first appearance and of maximal concentration in Podroteja was longer as expected by prevailing low water conditions. A direct comparison to the single peak characterising the pyranine breakthrough in spring 1994 is not possible. (Tab. 6.13)

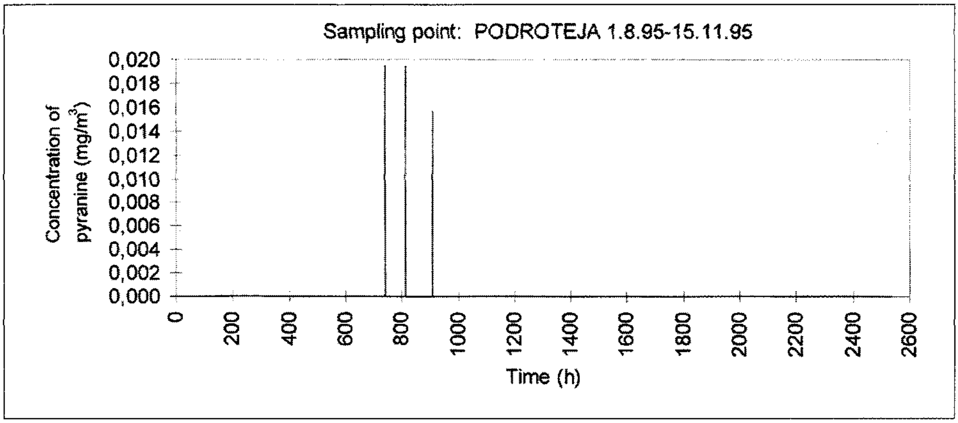


Fig. 6.15: Results of the third tracing experiment, August 1995: pyranine positive water samples in the karst spring Podroteja during the observation period.

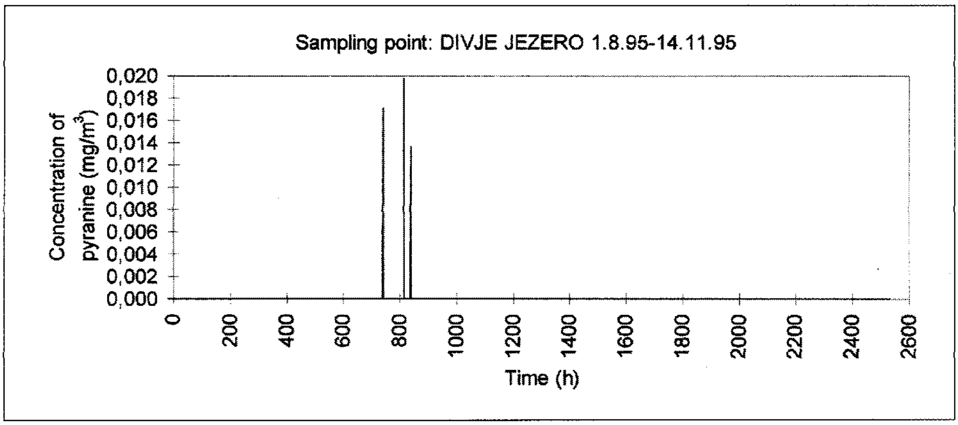


Fig. 6.16: Results of the third tracing experiment, August 1995: pyranine positive water samples in the karst spring Divje Jezero during the observation period.

In the springs Hubelj, Skuk, Gorenje and Vipava 4/7 we analysed neither uranine nor pyranine. In the Vipava spring 4/2 we determined low concentrations (0.001-0.003 mg/m^3) in 5 samples taken from August, 12 till August, 18, 1995. There might be most probably some uranine rest from the previous tracing experiments.

Tab. 6.13: Overview of relevant parameters derived from the pyranine breakthrough in the springs Podroteja and Divje Jezero in the third tracer test, August 1, 1995: time(t_{max}), concentration (C) and velocity (v_{max}) of the first appearance, time of maximal concentration (t_{max}), maximal concentration (C_{max}) and dominant velocity (v_{dom}) in the springs and the recovery (R).

Spring	C [mg/m³)	t_{max} [h]	v_{max} [m/h]	C_{max} [mg/m³]	t_{dom} [h]	v_{dom} [m/h]	R [kg]	R [%]
Podroteja	0.0195	739	14.4	0.0195	739	14.4		
Divje jezero	0.0171	749	14.3	0.0197	829	12.9		

6.3.2.4. Summary

The tracing experiments performed (Tab. 6.1) proved partly the main drainage system given by the structural geological pattern (compare chapter 2.6). The proved flow connections resulting from the combined experiments in the years 1993 to 1995 are depicted in Fig. 6.17.

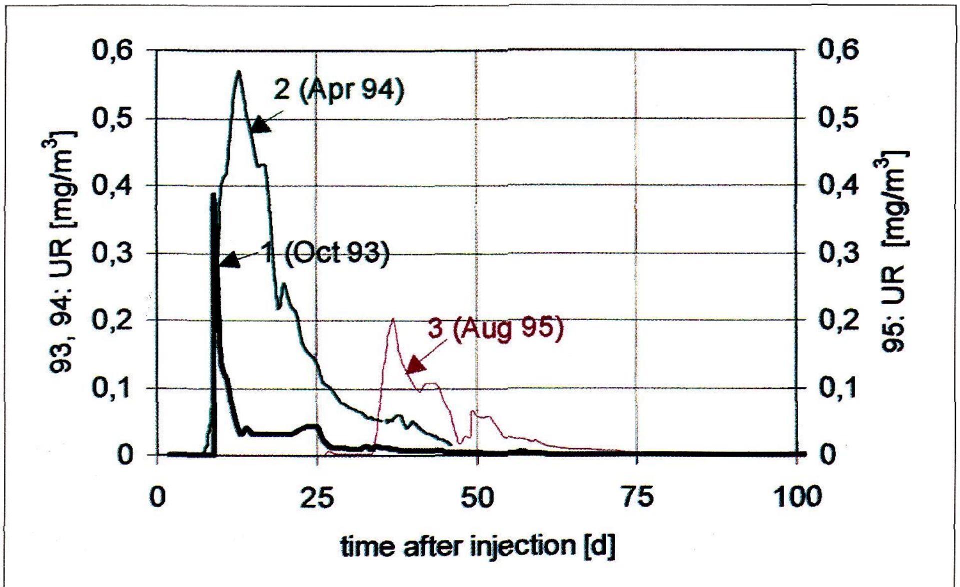


Fig. 6.18: Comparison of the Uranine breakthrough in the Mrzlek spring for the three repeated injections in the ice cave Belo Brezno in autumn 1993, spring 1994 and summer 1995.

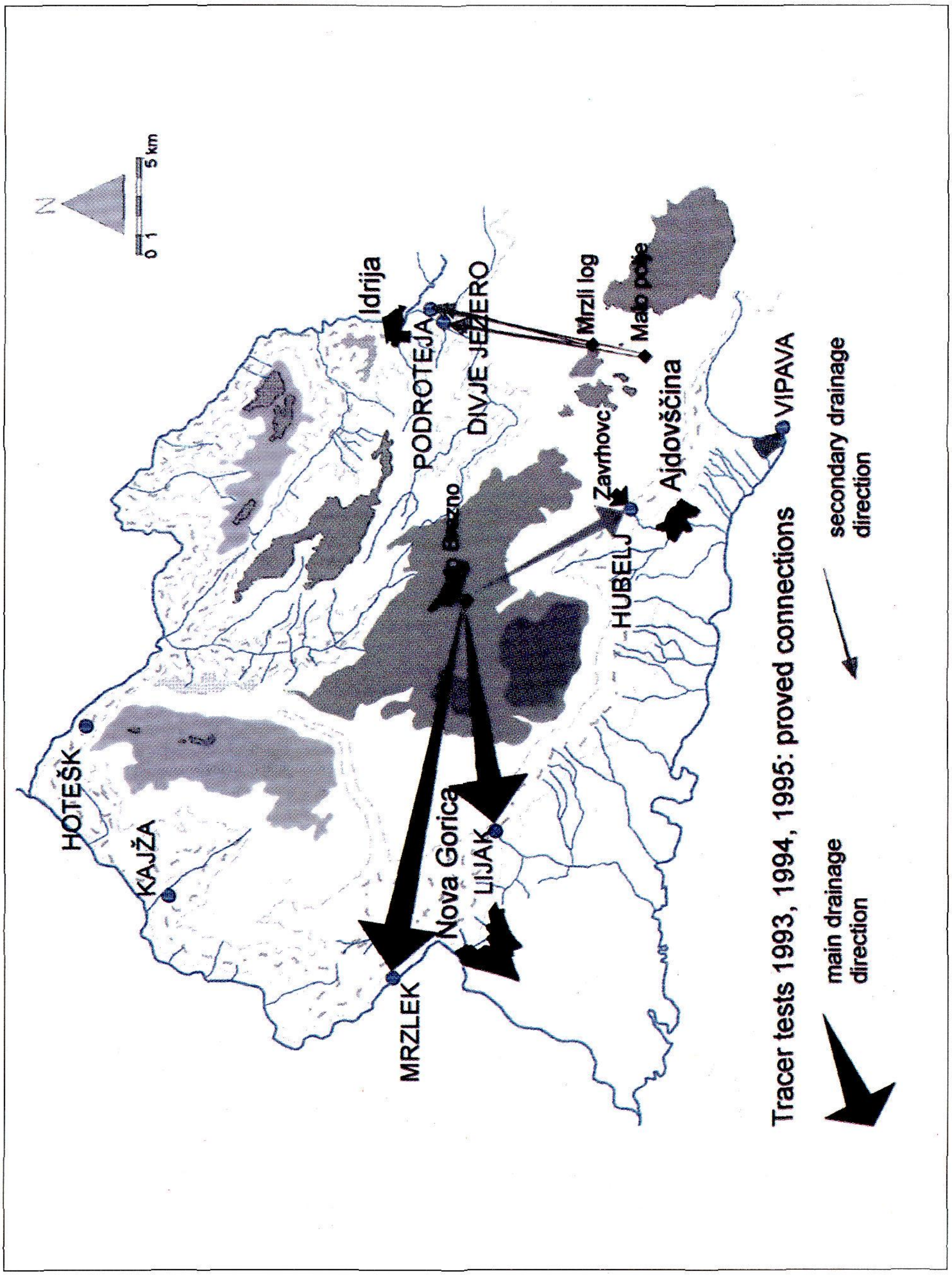


Fig. 6.17: Proved flow connections in the catchment areas of the karst springs Podroteja, Divje Jezero, Hotešk, Kajža, Mrzlek, Lijak and Hubelj resulting from the combined tracing experiments in the years 1993 to 1995.

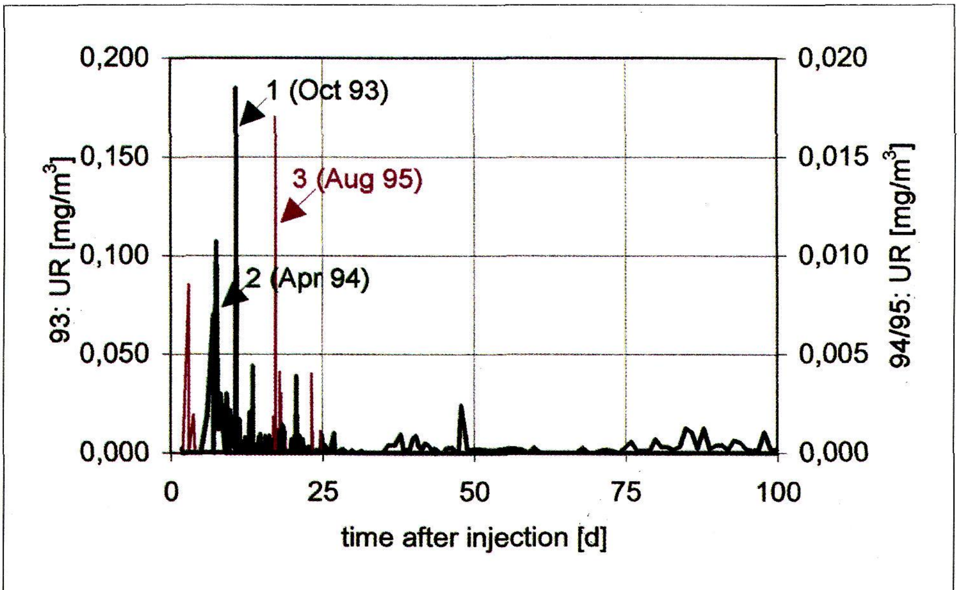


Fig. 6.19: Comparison of the uranine breakthrough in the Hubelj spring for the three repeated injections in the ice cave Belo Brezno in 1993, 1994 and 1995.

The ice cave Belo Brezno, the injection point for repeated uranine tracing under different hydrologic conditions in the central part of the Trnovski Gozd plateau, is developed in the limestones of the Trnovo nappe. Following the general SW dip of the Uppertriassic, Jurassic and Cretaceous carbonate rocks of the Trnovo nappe, directed by the mainly NW-SE striking strike slip faults main reoccurrence of the tracer injected in Belo Brezno is the karst spring Mrzlek at the deepest regional base level of the karst groundwater. During all hydrologic situations tested the Mrzlek spring was the main outlet. A direct comparison of the breakthrough curves resulting from the three uranine injections in experiments is given in Figs. 6.18 and 6.19.

Caused by the flooding of the spring outlet by the Soča river due to the construction of the Solkan hydropower plant, no current discharge measurements are available. Based on a mean discharge calculated from existing long-term observations from 1960 to 1990 the recovery was roughly estimated.

6.3.3. Results of the Vipava Area

6.3.3.1. The Second Tracing Experiment in Spring 1994
(H. BEHRENS, R. BENISCHKE, W. KÄSS, M. ZUPAN)

From the individual sampling stations at the Vipava springs the samples have been delivered in different packages (Tab. 6.5). After analysis of a first series of samples some promising results showed a steep but smooth increase of the concentrations. So it could be expected for the first moment that this was a beginning of a rather classical breakthrough curve. But in the samples of the following series the pattern of breakthrough was quite different and brought concentrations for all sampling stations that could be interpreted in many different ways (influence of biological, chemical or photochemical decay, hydrological events, analytical errors and so on).

The most likely interpretation is, that the samples have been influenced by some decay or adsorption processes. During evaluation and comparison of the results from the different outlets it became apparent, that a component separation based on the data of the artificial tracer would lead to unreliable results, especially for those, where the concentration values of Vipava 4/8 (the total runoff) were higher then those of the individual springs. This is impossible, because any mixing can result at the best in the same concentration as it can be observed in the springs (Fig. 6.20).

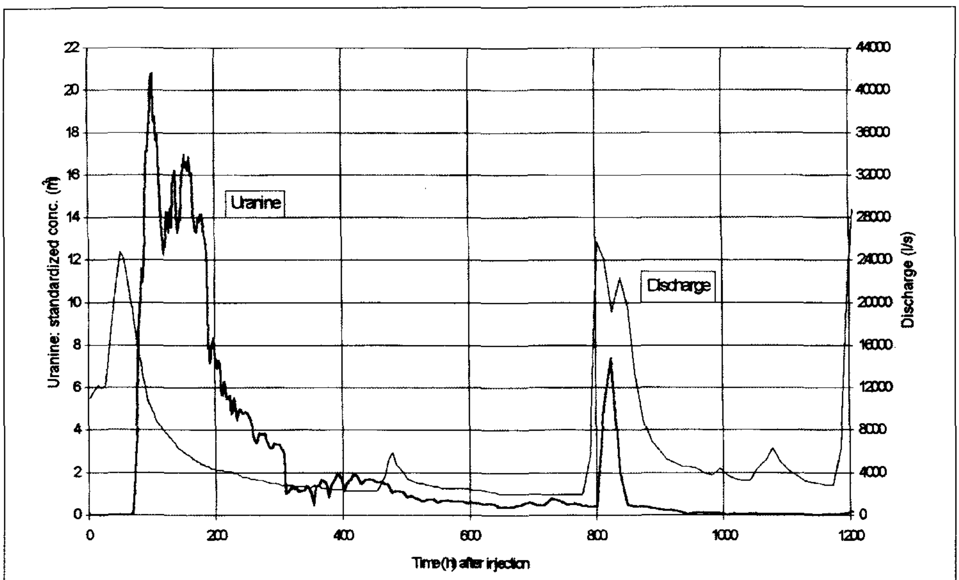


Fig. 6.20: Second experiment, April 1994: Breakthrough of Uranine at the gauging station Vipava 4/8 in comparison with the discharge.

The breakthrough-curve shows in the beginning a normal increase and is not influenced by secondary discharge peaks, also the discharge peak at approx. 500 h after injection had no influence on the concentration. The strong discharge pulse on 19th of May caused a new concentration peak, showing that the tracer which remained obviously in the system until that time has been washed out. From this time on only a decrease in concentration could be observed until the end of the sampling program.

The shape of the first concentration peak cannot be explained by special hydraulic influences from subsystems of the Vipava aquifer, because there is no indication in the discharge curve. Irregular changes or fluctuations in the time-concentration graph a short time after the main peak and a significant concentration dropdown (approx. 300 h after injection) may be a hint on other than hydraulic influences. Possible explanations will be given later in this section.

With exception of station Vipava 4/8 no other spring was equipped for continuous recording of discharge or stage, only Vipava 4/6 and Vipava 4/7 were measured at a bridge of their joint runoff channel about 100 m downstream of the outlets. This was a pity insofar that there was no other possibility to compare the tracer breakthrough curves at the springs with their individual discharge. Before the tracing experiment it was known from hydrochemical analyses and conductivity measurements that the most northern spring

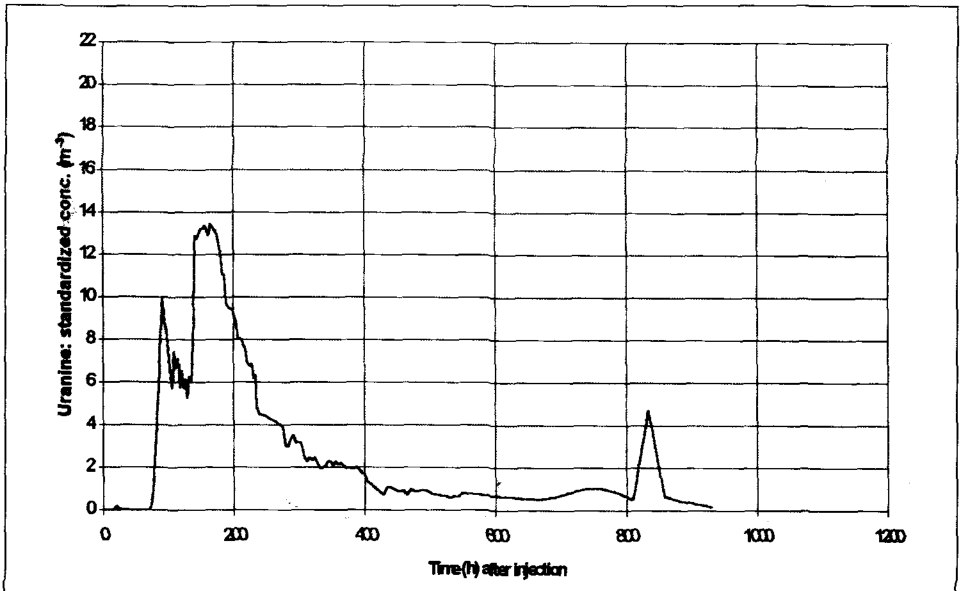


Fig. 6.21: Second experiment, April 1994: Breakthrough curve of Uranine at Vipava 4/1 (Pri Kapelici).

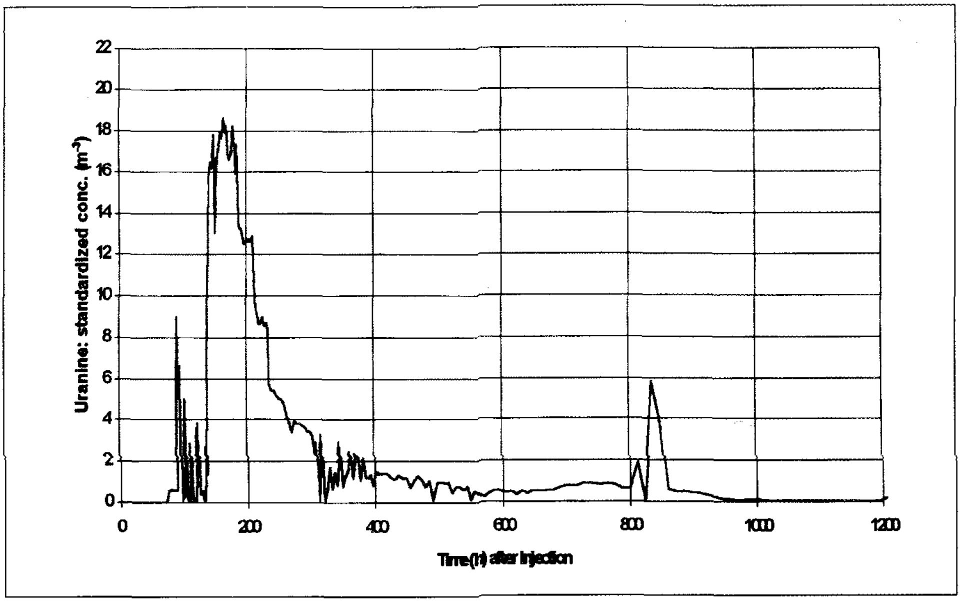


Fig. 6.22: Second experiment, April 1994: Breakthrough curve of Uranine at Vipava 4/2 (Pod Lipo).

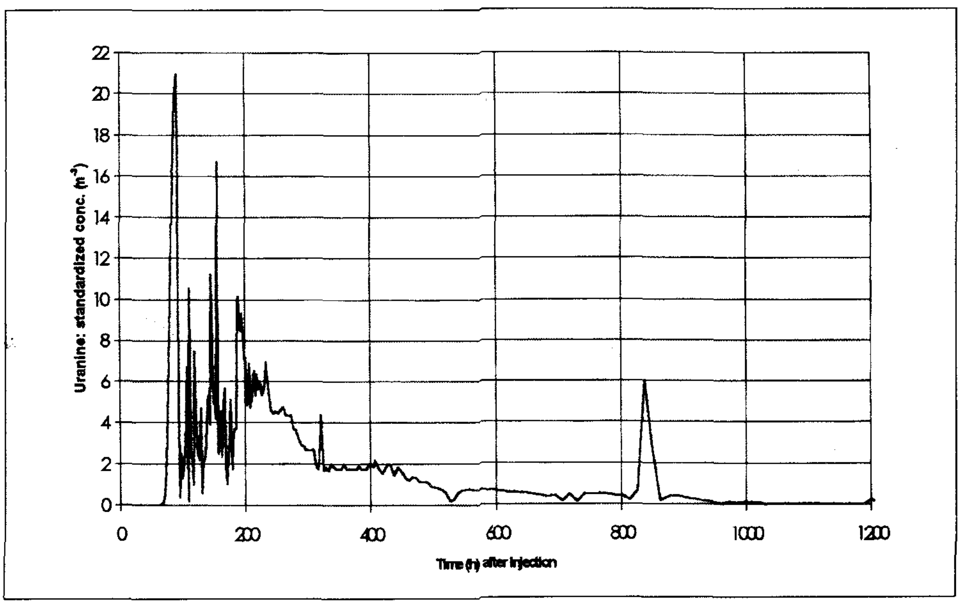


Fig. 6.23: Second experiment, April 1994: Breakthrough curve of Uranine at Vipava 4/3 (Perhavčeva Klet).

(Vipava 4/7 - Pod Farovžem) is probably influenced at certain times by the Bela river which delimits the Nanos massif in the north. The complete different breakthrough curve at this spring may serve as a respective indication.

The figures Fig. 6.21 to Fig. 6.27 show the time-concentration graphs of the individual springs.

The time-concentration graph for station Vipava 4/7 had to be drawn with a concentration scale different from all the other stations, because of rather low values. This station is the only one which showed a possible influence either from the Bela river or from another spring covered by alluvial sediments and with different behaviour. In comparison with the graphs from the other stations (including the total runoff at Vipava 4/8), which are very similar to each other, the discharge of Vipava 4/7 seems to be of no significance. Otherwise the influence on the discharge graph or on the time-concentration graph should be much stronger.

The similarity of the time-concentration graphs from Vipava 4/1-4/6 and Vipava 4/8 shows (despite of not explainable fluctuations) that they represent more or less well mixed water discharging from the springs. The differences between these springs and the station at Vipava 4/7 could originate also from waste water disposal from some houses above and therefore from enhanced biodegradation of the tracer in the samples. Another effect studied by W.

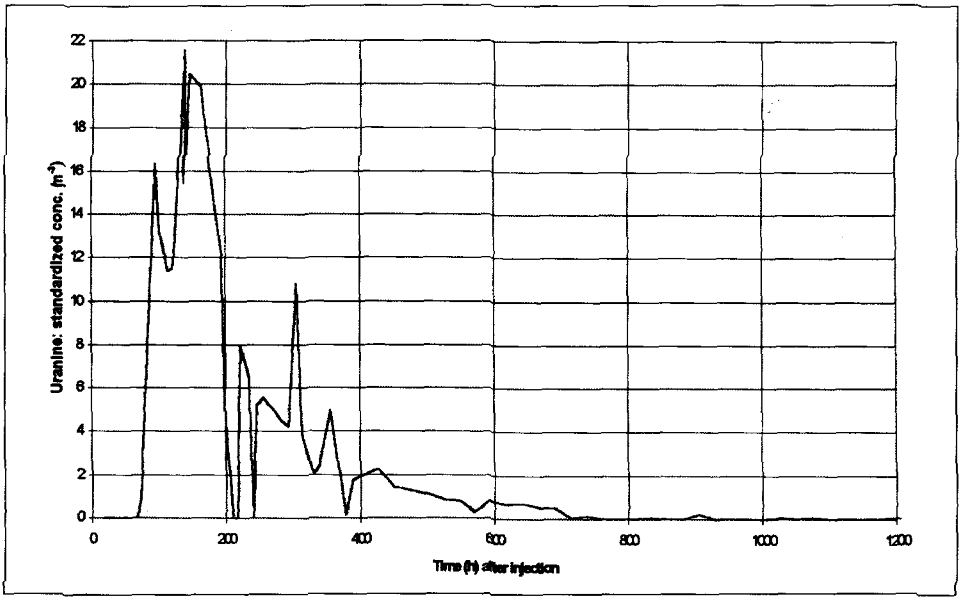


Fig. 6.24: Second experiment, April 1994: Breakthrough curve of Uranine at Vipava 4/4 (Vipavska Jama).

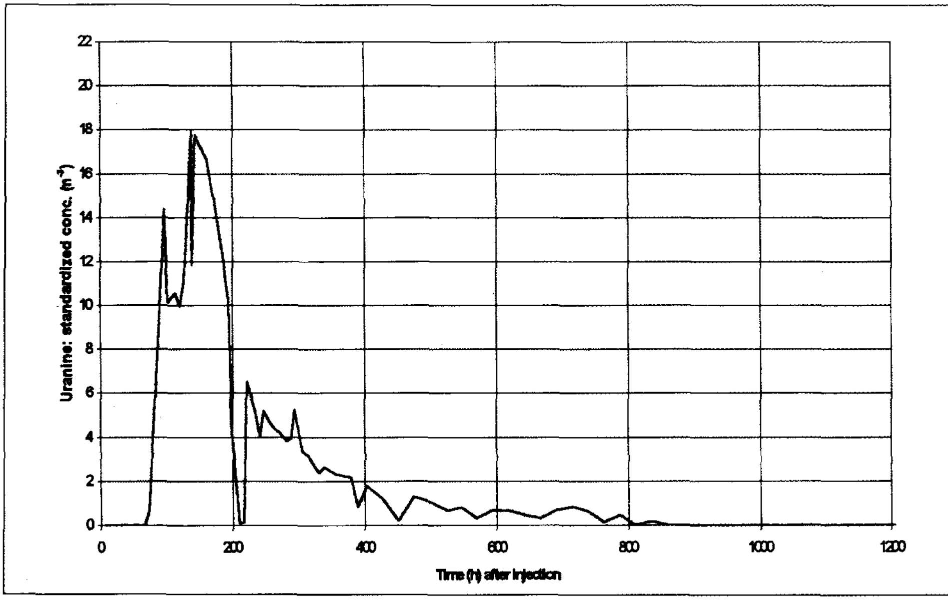


Fig. 6.25: Second experiment, April 1994: Breakthrough curve of Uranine at Vipava 4/5 (Pod Skalo).

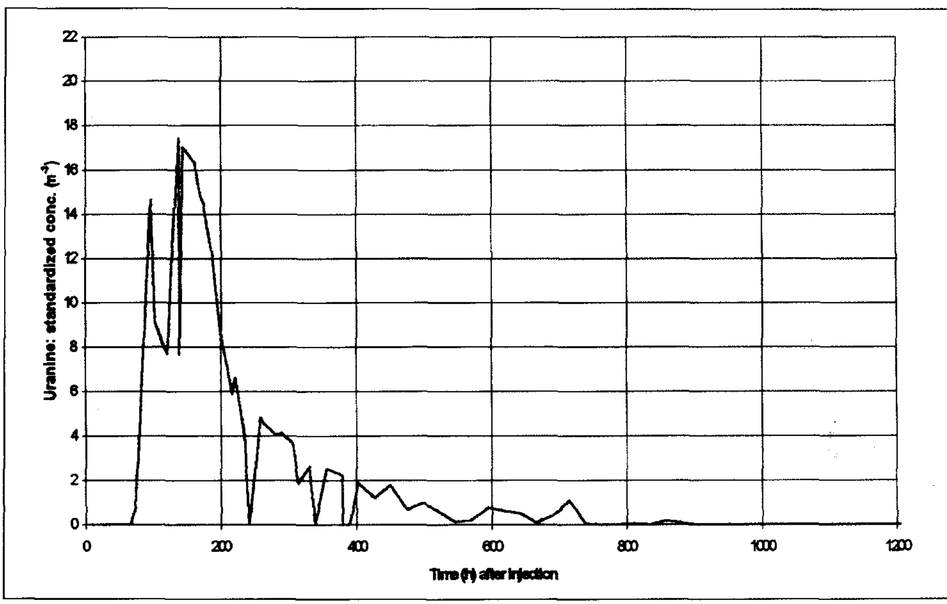


Fig. 6.26: Second experiment, April 1994: Breakthrough curve of Uranine at Vipava 4/6 (Pod Farovžem A).

KÄSS (ref. to chapter 8.1.) could be irregular adsorption at the walls in the sample flasks, or it is a combined influence of both adsorption and biodegradation.

Summarising the characteristic data from all breakthrough-curves it can be said that the first arrival and therefore the maximum flow velocity is quite similar for all stations (Tab. 6.14). The data for peak concentration and the flow velocity calculated for the concentration peak are very influenced by the above mentioned irregularities in the concentrations; they depend on the degree of possible degradation effects.

Despite these influences the calculated recovery for Vipava 4/8 (the only station where discharge data were available) is rather high. But a recovery of about 74 % means that approx. 25 % remained in the system until the end of the sampling program. But taking into account, that the measured concentration values are the result from unknown effects mentioned above, the total recovery could also be nearly 90 or 100 %.

Attempts to separate runoff components only by the uranine data failed. Corresponding concentration values could not be compared in the strong mathematical sense and for separating the discharge of Vipava 4/6 and Vipava 4/7 from Vipava 4/8 was not possible by means of the uranine data, because there was no sampling station at the gauging section for Vipava 4/6 and 4/7.

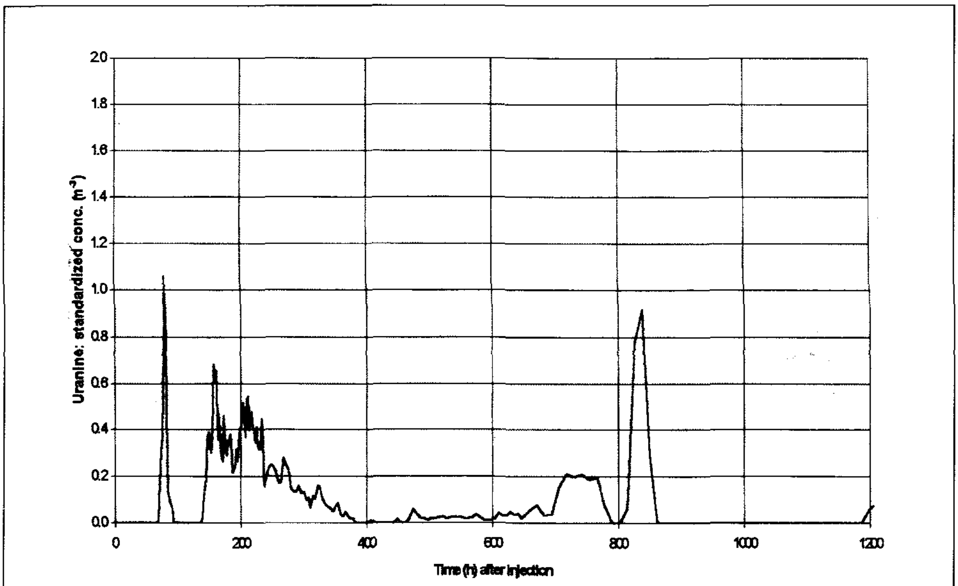


Fig. 6.27: Second experiment, April 1994: Breakthrough curve of Uranine at Vipava 4/7 (Pod Farovžem B).

Tab. 6.14: Summary of tracer data from all sampling stations.

Injection Start	1994.04.16 / 12:45	Tracer:	Uranine
Injection End	1994.04.16 / 12:50	Amount (gross;kg):	7.000000
		Reference (net;kg):	0.004228
Hor. Distance	12990	Amount (net;kg):	6.995772
Vert. Difference	365		

Spring	Date/Time	Flow time after inj. start (h)	Flow velocity (m/h)	Conc. (mg/m^3)	Std. Conc. (m^{-3})	Load (mg/s)	
Vipava 4/1 (Pri Kapelici)							
1. Arrival	1994.04.19 14:00	73.25	177.3	0.013	0.186		
Peak	1994.04.23 10:00	165.25	78.6	0.939	13.429		
Vipava 4/2 (Pod Lipo)							
1. Arrival	1994.04.19 15:00	74.25	174.9	0.013	0.187		
Peak	1994.04.23 11:00	166.25	78.1	1.305	18.654		
Vipava 4/3 (Perhavčeva Klet)							
1. Arrival	1994.04.19 11:00	70.25	184.9	0.008	0.119		
Peak	1994.04.20 09:00	92.25	140.8	1.467	20.975		
Vipava 4/4 (Vipavska Jama)							
1. Arrival	1994.04.19 14:30	73.75	176.1	0.065	0.929		
Peak	1994.04.22 08:00	139.25	93.3	1.512	21.614		
Vipava 4/5 (Pod Skalo)							
1. Arrival	1994.04.19 14:30	73.75	176.1	0.048	0.686		
Peak	1994.04.22 08:00	139.25	93.3	1.258	17.986		
Vipava 4/6 (Pod Farovžem A)							
1. Arrival	1994.04.19 14:30	73.75	176.1	0.054	0.771		
Peak	1994.04.22 08:00	139.25	93.3	1.219	17.429		
Vipava 4/7 (Pod Farovžem B)							
1. Arrival	1994.04.19 11:00	70.25	184.9	0.001	0.014		
Peak	1994.04.19 21:00	80.25	161.9	0.074	1.059		
Vipava 4/8							
1. Arrival	1994.04.19 10:00	69.25	187.6	0.005	0.067	0.091	
Peak	1994.04.20 20:00	103.25	125.8	1.455	20.796	13.963	
Load - peak conc.	1994.04.20 20:00					13.963	
Peak load at:	1994.04.20 18:00					14.121	
Recovery until:	1994.07.28 09:00						5.14 kg
Recovery until:	1994.07.28 09:00						73.46 %

6.3.3.2. The Fourth Tracing Experiment in Autumn 1995
(M. ZUPAN)

The last tracing experiment in the framework of the program was performed during prevailing low water condition. It was a repetition of the tracing experiment in spring 1994 (Chapter 6.3.3.1) with the injection of pyranine to the Lokva stream below the Predjama castle. Additional a second injection point was chosen on the central Nanos Plateau, the pothole Slapenski ledenik (Chapter 2.5) to get information about the vertical water flow from Nanos towards the Vipava springs. Here uranine was injected (Tab. 6.1).

Pyranine

Astonishingly, the dye tracer pyranine was not at all detected. One possibility could be a dramatic change in the hydrogeological situation, respectively in the flow directions, in the catchment area of the Vipava depending on the hydrologic situation. While by prevailing high water conditions the water from the sinking stream Lokva is directed more or less directly to the Vipava spring as proved by a recovery rate of about 74 % in spring 1994 (compare Chapter 6.3.3.1), the flow direction during low water conditions as in autumn 1995 could change towards Timava. Hence no sampling was carried out which could prove this hypothesis, it is still pure speculation. Beside the hydrogeological conditions of the catchment area the various possibilities of biological, chemical or photochemical decay, which can destroy completely pyranine (KÄSS 1992), have to be taken into account. The tracer amount injected was with 8 kg pyranine almost in the same range as in spring 1994 (7 kg uranine), when dilution was higher due to the high water conditions. Therefore a high dilution of the tracer pyranine below detection limit can be excluded.

Uranine

Uranine appeared in all three Vipava springs, which were chosen for the observation. The times of the first uranine appearing and the time of the maximal concentration are close together (Tab. 6.15). The concentration curves of the Vipava 4/2 (Fig. 6.28) and 4/5 (Fig. 6.29) are very similar, while the curve of the Vipava 4/7 (Fig. 6.30) is periodical different. These results prove once more the assumption that the various Vipava springs have different catchment areas, which are influenced by the hydrologic condition.

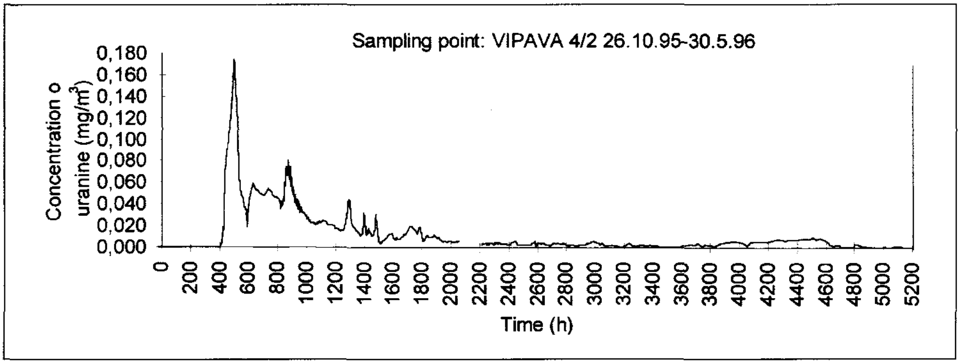


Fig. 6.28: Fourth experiment, October 1995: The concentration curve of uranine in the spring Vipava 4/2.

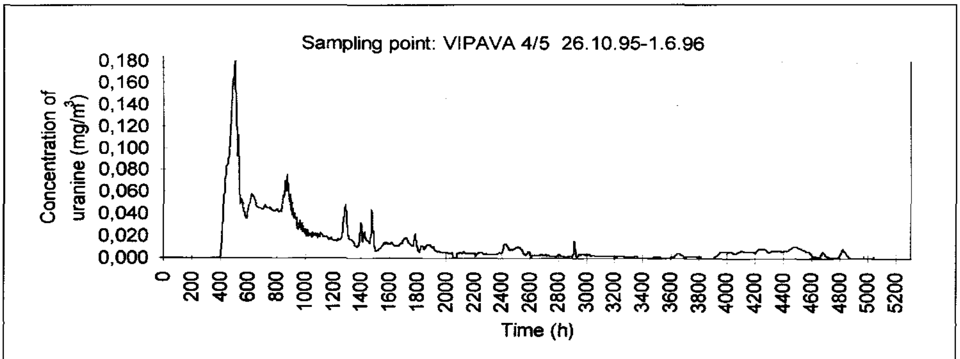


Fig. 6.29: Fourth experiment, October 1995: The concentration curve of uranine in the spring Vipava 4/5

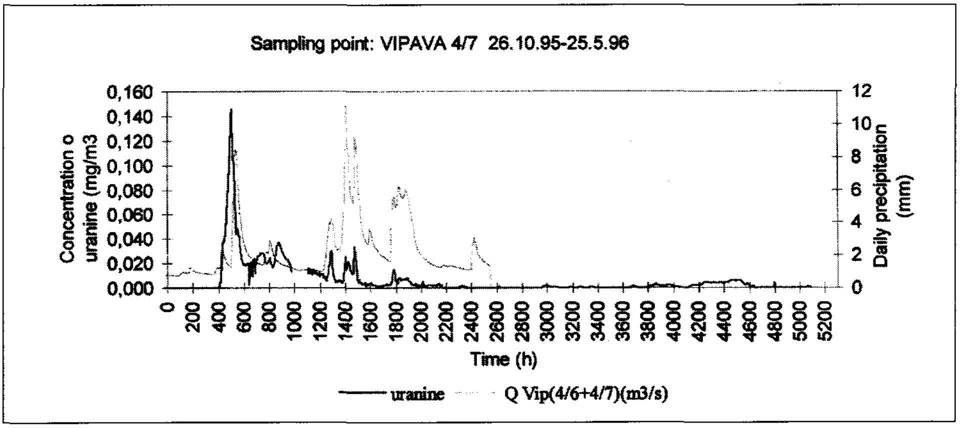


Fig. 6.30: Fourth experiment, October 1995: The concentration curve of uranine in the spring Vipava 4/7 and the join discharge of the Vipava 4/6 and 4/7.

Tab. 6.15: Overview of relevant parameters derived from the uranine breakthrough in the Vipava springs 5/5 and 4/7 in the fourth tracing test in autumn 1995 (injection into the pothole Slapenski ledenik, Oct 10, 1995): time(t_{max}), concentration (C) and velocity (v_{max}) of the first appearance, time of maximal concentration (t_{max}), maximal concentration (C_{max}) and dominant velocity (v_{dom}) in the springs and the recovery (R).

Spring	C [mg/m³)	t_{max} [h]	v_{max} [m/h]	C_{max} [mg/m³]	t_{dom} [h]	v_{dom} [m/h]	R [kg]	R [%]
Vipava-4/5	0,0015	406	19,7	0,1794	502	15,9	1,412*1)	28,2
Vipava-4/7	0,0011	405	19,7	0,1457	503	15,9	0,233*2)	4,66

+1) = recovery rate calculated for 4/1 and 4/5
+2) = recovery rate calculated for 4/6 and 4/7

6.3.4. The decomposition of tracers in the spring waters

(M. ZUPAN)

The decomposition of the uranine is different in different types of water (BEHRENS & ZUPAN 1976; ZUPAN 1991). To estimate this characteristic the analyses of limited number of samples taken in spring Hubelj and Vipava was repeated. The concentration of uranine in the samples taken in the spring Hubelj from October 22, 1993, till October 30, 1993, was determined for the first time from October, 28 till November 16, 1993. We repeated the uranine analysis in 89 of the mentioned samples in February 1994. The differences between the two determinations were in the interval of analytical repeatability and the concentrations of the second determination were practically the same as of the first one.

During the 4th tracing experiment (compare Chapter 6.3.3.2) we stored consecutive samples of the spring Vipava one in a glass flask and the second in a plastic flask. The samples in the glass flasks were analysed in maximal 10 days after sampling. Because of the lack of the time, the samples stored in the plastic flasks were analysed not before January, 25, 1995. The measured concentration of uranine in the consecutive samples was significant lower in the samples stored in plastic flasks then the concentration of the samples stored in the glass flasks. The difference between two consecutive samples decreased 15 to 100 % and in the next sample stored in the glass flask

increased again in the same percentage spread. Repeated analyses of 33 samples of the Vipava spring 4/2 taken from November, 13, 1995 till November, 21, 1995 was performed. The decrease of the uranine concentration of the samples stored in glass flasks ranges between 1 and 9 %, while the decrease in the uranine concentration of the samples stored in the plastic flask was 3 to 100 %.

Therefore in calculating of the tracer recovery for the 4th tracing experiment we considered only the concentrations measured in the samples stored in the glass flasks.

6.3.5. The Background Concentrations of the Used Fluorescent Dyes (M. ZUPAN)

Most of the spring water in the investigation area is used for water supply and therefore the number of appropriate tracers was very limited. Only the use of two fluorescent dyes, uranine and pyranine, was permitted. Additional the time intervals between the tracing tests were relatively short. Therefore we measured a great number of samples to estimate the background concentration in the springs. As background samples we took into account all intermediate samples between two consecutive tracing experiments. In Tab. 6.16 the number of measured samples and the concentrations were shown. Beside the dyes used in the tracing test we determined some signals at the characteristic wavelengths for other fluorescent dyes.

During the first tracing experiment emission peaks with maximal wavelength, significant for eosine appeared in the samples of the Hubelj spring. We evaluated these peaks according to the calibration curves of eosine. It would be possible that they belong to compounds of an unknown source. Eosine we determined in 88 samples taken from November 2, 1993, to February 18, 1994. The measured concentrations were 0.010 - 0.115 mg/m^3.

Tab. 6.16.: Minimal and maximal background concentrations of fluorescent dyes in the springs in the investigation period.

			Minimal and maximal concentration of fluorescent dye - mg/m^3			
Spring	Year	Number of samples	uranine	pyranine	eosine	rhodamine
Hubelj	1993	27	udl*- 0.001 (2)	udl	udl	udl
	1994	52	udl - 0.002 (2)	udl	udl	udl
	1995	50	udl	udl - 0.04 (1)	udl	udl - 0.007 (1)
Vipava	1993	40	udl - 0.001 (2)	udl	udl	udl - 0.002 (1)
	1994	51	udl	udl - 0.04 (2)	udl	udl - 0.005 (1)
	1995	53	udl	udl	udl	udl
Mrzlek	1993	9	udl	udl	udl	udl
	1994	10	udl	udl - 0.04 (1)	udl	udl
	1995	5	udl	udl	udl	udl
Podroteja	1993	9	udl	udl	udl	udl
	1994	10	udl - 0.005 (2)	udl	udl	udl
	1995	5	udl	udl	udl	udl
Bela	1993	3	udl	udl	udl	udl
	1994	10	udl	udl	udl	udl
	1995	5	udl	udl	udl	udl
Belščica	1993	3	udl	udl	udl	udl
	1994	10	udl	udl	udl	udl
	1995	5	udl	udl	udl	udl
Hotešk	1993	8	udl	udl	udl	udl
	1994	10	udl - 0.006 (1)	udl - 0.03 (1)	udl	udl
	1995	5	udl	udl	udl	udl
Kajža	1993	8	udl	udl	udl	udl
	1994	10	udl	udl	udl	udl
	1995	5	udl	udl	udl	udl
Prelesje	1993	9	udl - 0.029 (1)	udl	udl	udl
	1994	10	udl - 0.037 (1)	udl	udl	udl
	1995	5	udl	udl	udl	udl

udl = under detection limit
(1) = number of samples which contained the dye

6.4. RESULTS WITH PHAGES (M. BRICELJ)

6.4.1. Introduction

Phage P22H5 was first introduced in Greece (BRICELJ et al. 1986) in a combined tracing experiment on the Central and Eastern part of Peloponnesus. The phage of mouse typhoid bacterium was chosen because the phages of *Salmonella typhimurium* had been rarely encountered in surface waters (SEELEY & PRIMROSE 1982). In such manner, high background coliphage titres, usually encountered in natural polluted waters, that can interfere with tracer curve, could be avoided (ALTHAUS et al. 1986). Phage P22H5 is clear plaque mutant of transducing phage P22 (SMITH & LEVINE 1967) and produces very discernible clear plaques in the lawn of growing host bacteria. Besides this feature, P22H5 phage (Podoviridae) could be propagated to high titres in controlled growing conditions (BRICELJ 1994). During several tracing experiments in the Slovenian karst region (KRIVIC et al. 1987; KRIVIC et al. 1989; HABIČ et al. 1990) and in a tracing experiment in the Styrian karst near Graz (BEHRENS et al. 1992) in ten tracing experiments only once the background for salmonella phage was positive, but only in some samples. The phage P22H5 proved to be a better tracing agent in comparison to coliphage T7 in several deactivating experiments at the air-water interface (BRICELJ & ŠIŠKO 1992) and in recovery experiments of clay mineral adsorption tests (BRICELJ 1994).

6.4.2. Injection data

The phage tracer - P22H5 virulent mutant of host bacterium *Salmonella typhimurium* LT2 (TL474 w.t.) - was injected, subsequently three times at the location Zavrhovc - Otlica 88, which is a kilometre away from the Hubelj spring on the plateau below Črni Vrh.

In the first tracing experiment a hole with the diameter of 5 cm was drilled in the floor of the doline, 5.5 m deep into permeable strata. Before the injection, 1.5 m^3 of water was poured into the drilling hole, following with 16,500 ml of phage broth that were subsequently washed with additional 3.5 m^3 of water. The injection of phage tracer began at 14.25 on 14 October, 1993 and was continuing for 3 minutes. The total concentration of injected phage particles was 3.0 x 10^{15} pfu (= 1.84 x 10^{11} pfu /ml x 16,500 ml).

The second injection place for the phage tracer lied in other doline next to the place of the first injection. The injection of lithium and phage tracer took place on 16 April, 1994. A fissure at the bottom of the doline, was first washed with 3.5 m^3 of water, from 10.20 to 10.25 lithium chloride in quantity

of 110 l (30 kg) was poured into the fissure, followed by the washing of 1.0 m^3 of water. From 10.29 to 10.30 phage tracer in the quantity of 20,500 ml was poured and then washed with 3.0 m^3 of water. The total quantity of phage tracer was 3.75 x 10^{15} pfu (=1.83 x 10^{11} pfu/ml x 20,500 ml).

The place of the third injection of phage tracer was equal to the second one. On the 1 August, 1995 the phage tracer in quantity of 26,000 ml was poured into the same fissure, at the bottom of the doline. Injection began with the washing of the fissure with 3.5 m^3 of water at 10.21. Between 10.25 and 10.28 phage tracer was poured into fissure, followed by washing with additional 3.5 m^3 of water. The total quantity of phage tracer was 6.6. x 10^{15} pfu (= 2.52 x 10^{11} pfu/ml x 26,000 ml).

6.4.3. Results

The relevant parameters derived from all three experiments with the phage tracer P22H5 are summarised in the tables Tab. 6.17, 6.18 and 6.19.

In the first tracing experiments with phage tracer P22H5 the samples for the determination of phages were taken at sampling points Hubelj, Skuk, Gorenje Studenec, Lijak, Mrzlek and Hotešk. The phage tracer reappeared only in the Hubelj spring (Fig. 6.31). The first positive result was evaluated on October 16, 1993 at 07.02 as 0.6 pfu/ml. Maximum concentration 32.4 pfu/ml was determined in the sample from October 17, 1993 at 11.02. On November 4, 1993 there was the last positive result of 0.4 pfu ml at 23.00. The sampling was stopped on November 13 after several negative results.

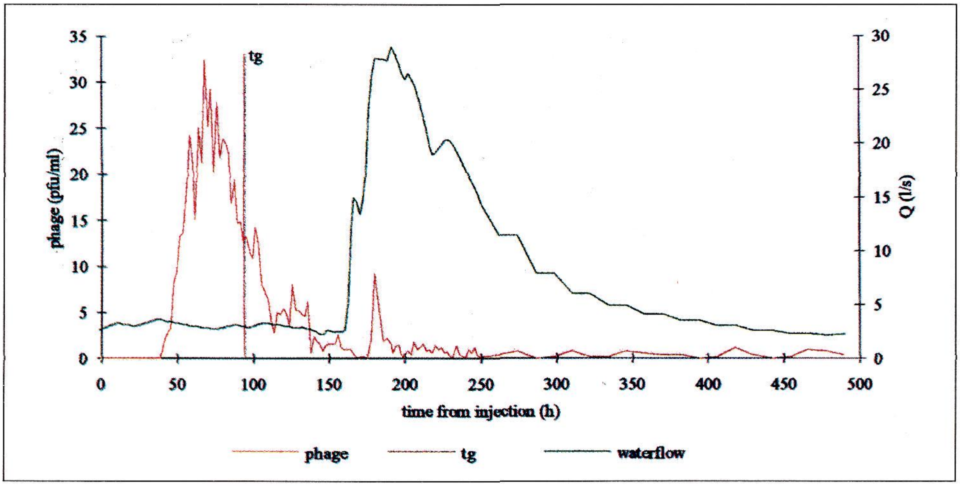


Fig. 6.31: The breakthrough curve of phage tracer P22H5 at the Hubelj spring of the first tracing experiment, in October 1993.

The recovery of tracer was 0.78 %. The gravity centre position of tracer curve t_g was calculated to 94.32 hours. The empirical formula $P_{trac} = a * t_{trac} * Q$ (P_{trac} = quantity of tracer needed in tracing experiment; a = deactivation factor; t_{trac} = time of tracer travel in sec; Q = waterflow in ml/s; Q was taken as average waterflow, including the data from the first appearance of tracer, to the last positive result) was used to calculate the needed quantity of phage tracer for a = 1, Q = 27.79 m3/s and t_{trac} = 94.7 h. The resultant quantity was 9.5 x 10^{12} pfu. The quantity injected was 3.0 x 10^{15} pfu, therefore the calculated inactivation factor is in the magnitude of 316.6. The real inactivation factor calculated from the recovery value 2.43 x 10^{13} was 128.0, that means 2.8 times lower than the calculated one.

Concerning the negative values of control samples, negative background of salmonella phage, sufficient quantity of phage tracer and flowthrough curve of the reappearing tracer, the conclusion could be, that the connection between drill hole in the doline at Zavrhovc and the Hubelj spring does exist.

In the second tracing experiment in spring 1994, the samples for the determination of phage were collected only in the springs of Gorenje Studenec, Skuk and Hubelj. The first positive result was evaluated after 54.30 hours on 18 April, 1994 as 0.5 pfu ml. The maximum value of 1.1 pfu ml 1 was determined on the same day, between 21.00 and 23.00 hours. The last positive result was determined on 25 April, 1994 found in the sample at 01.00 hour (Fig. 6.32).

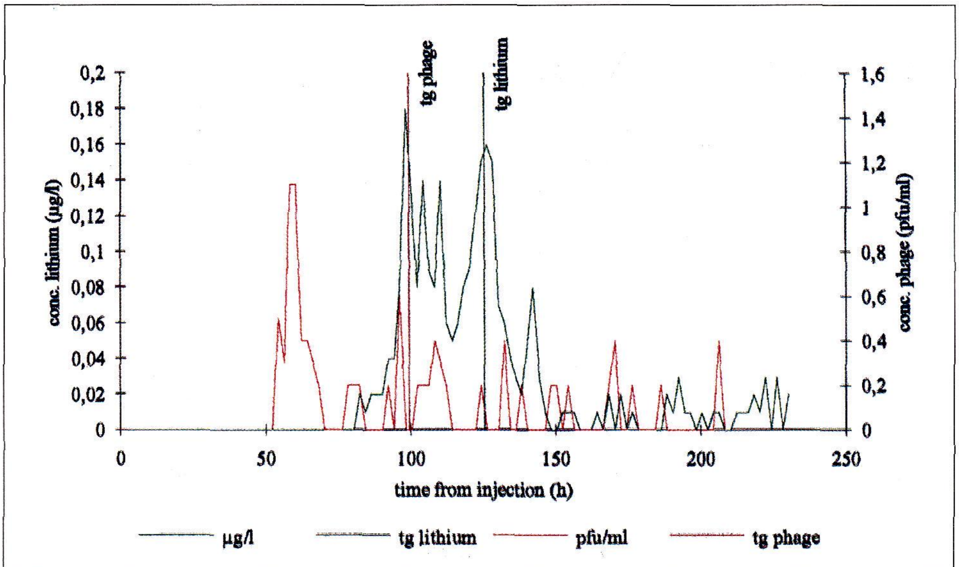


Fig. 6.32: The breakthrough curves of phage P22H5 and lithium tracer in the Hubelj spring during the tracer experiment, in April 1994.

The recovery of tracer was 0.012 %. The gravity centre position of tracer curve t_g was calculated to 99.61 hours. The resultant quantity for empirically calculated tracer quantity that we need in the case of a = 1, Q = 4.38 m^3/s and t_{trac} = 99.61 h was 1.57 x 10^{12} pfu. The injected quantity was 3.7 x 10^{15} pfu, so the calculated inactivation factor is in the magnitude of 2,354.6. The real inactivation factor calculated from recovery value 4.45 x 10^{11} is 8,314.6, that means about 3.53 times greater than the calculated one.

In the third tracing experiment, in the summer of 1995, the samples for the determination of phage were collected only in the spring of Hubelj. The first positive result was evaluated almost after one month, on August 29, 1995 at 00.00 hours as 0.5 pfu/ml. The maximum value of 1.0 pfu/ml was evaluated on the same day at 12.00 hours. The last positive result as 0.1 pfu ml determined on August 31 at 00.00 hours. The additional positive value was recovered from the sample taken on September 11 at 06.00. The value of the determined phage was 0.2 pfu/ml.

The recovery of tracer was 0.001 %. The gravity centre position of tracer curve t_g was calculated as 678.2 hours. The resultant quantity for empirically calculated tracer quantity in the case of a = 1, Q = 3.19 m^3/s and t = 678.2 h was 7.8 x 10^{12} pfu. The injected quantity was 6.6 x 10^{15} pfu, therefore the calculated inactivation factor is in the magnitude of 846.4. The real inactivation factor, calculated from the recovery value 4.62 x 10^{11} is 16.9 times greater than the calculated one.

Tab. 6.19: Measured and calculated data for the three tracing experiments with phage tracer P22H5, injected at the location Zavrhovc, a = deactivation factor calculated from injected and recovery values; av. precipit. = average precipitation in the month period before the injection of phage took place; av. Q inj. = average day's throughflow in the time of injection of tracer; max. con. Q = Q value at the peak concentration of tracer curve; recovery = calculated recovery of the phage tracer from injected and recovered quantity of phage tracer.

.	a	av. precipit.	av. $Q_{inj.}$	max.conc. Q	recovery
October 1993	128.0	15.4 mm	2.81 m^3/s	2.90 m^3/s	0.78 %
April 1994	8314.6	11.8 mm	6.33 m^3/s	9.21 m^3/s	0.012 %
August 1995	1.0 x 10	2.8 mm	0.51 m^3/s	9.50 m^3/s	0.007 %

*Tab. 6.17: The values of the time of appearance of phage tracer and its velocity in the spring of Hubelj for three tracing experiments. The distance between the injection point and the sampling point suits 1000 m for each tracing experiment: t_{min} = time elapsed from injection and the first appearance of tracer, t_{max} = time elapsed from injection and the maximal quantity of tracer; t_g = time calculated from following equation Σ ci*ti / Σ ci; v_{min} = velocity calculated with t_{min}; v_{max} = velocity calculated with t_{max}; v_{tg} = velocity calculated with t_g.*

	t_{min}	v_{min}	t_{max}	vmax	t_g	v_{tg}
October 1993	40.61 h	0.007 m/sec 592.2 m/day	68.62 h	0.004 m/sec 350.5 m/day	94.7 h	0.003 m/sec 253.9 m/day
April 1994	54.50 h	0.005 m/sec 442.9 m/day	59.30 h	0.005 m/sec 405.5 m/day	99.61 h	0.003 m/sec 241.4 m/day
August 1995	661.5 h	0.0004 m/sec 36.4 m/day	673.5 h	0.0004 m/sec 35.7 m/day	678.2 h	0.0004 m/sec 35.5 m/day

Tab. 6.18: Comparison of the determined parameters of the phage and the lithium (Chapter 6.5) breakthrough in the Hubelj during the second tracer experiment in April 1994. (explanation of the abbreviations, are given in Tab. 6.17).

Tracer.	t_{min}	v_{min}	t_{max}	vmax	t_g	v_{tg}
phage P22H5	50.5 h	0.0051 m/sec 442.9 m/day	59.5 h	0.0046 m/sec 405.5 m/day	99.61 h	0.0028 m/sec 241.4 m/day
lithium	82.5 h	0.005 m/sec 442.9 m/day	98.5 h	0.0028 m/sec 244.1 m/day	1265 h	0.0022 m/sec 190.1 m/day

6.4.4. Conclusions

The tracing experiments with phage P22H5 and other tracers on the karst plateau were performed in three different water level situations, low, high and medium. The first tracing experiment was performed in the medium level of water in the spring of Hubelj (compare Chapter 6.2.1). The medium day's water level in the time of injection, was 2.81 m^3/s. The average precipitation in the month period before the injection was 15.4 mm (Tab. 6.19). It is believed, that the underground passages under the permeable strata in the bottom of doline were partly saturated by water, after the steady raining, before the tracing experiment took place. In such conditions the bacteriophage tracer was injected to the permeable strata for the first time instead of directly into the water as was commonly done in preceding experiments in several karst locations (Tab. 6.20). The recovery of tracer in the first experiment was the highest comparison to the recovery values of the two subsequent tracer experiments (Tab. 6.17), although a part of phage tracer was adsorbed to the underground surfaces. This can obviously be seen in the breakthrough curve of phage tracer at the Hubelj spring (Fig. 6.31), where the second peak of phage tracer with 9.2 pfu/ml in 180.6 hours after the injections strictly follows the sudden augmentation of water throughflow at the Hubelj spring.

Second tracing experiment was performed after the melting of the snow, which gave high water with the average day's throughflow of 6.33 m^3/s in the time of the injection. The recovery of the phage tracer was lower than in the first tracing experiments because of the high dilution of phage tracer and possible dispersion of the phage tracer in highly saturated strata, away from the main flow. The difference in the values of deactivation factor in both experiments could be contributed to the dispersion of the phage tracer rather than to the enhanced adsorption. The effect of lithium chloride on phage tracer could not be omitted, but we think that because of the high dilution the effect of lithium tracer on phage is of less importance. Nevertheless, the velocity of phage tracer calculated from the centre of the gravity of tracer curve was a little bit lower than in the first tracing experiment (Tab. 6.17). The gravity values of tracer curves from the both mentioned tracing experiments have a difference about five hours (Tab. 6.17). The difference could be contributed to the different injection locations or different underground water conditions. Comparing the phage reappearance data of the second tracing experiment with the data of lithium that was injected in the same location simultaneously (Tab. 6.18 and Fig. 6.31), we can conclude that the phage tracer preceded the lithium for approximately one day (26.9 h). The first appearance of the phage tracer occurred on 18 April at 17.00 (54.5 hours after injection) and from the smoothed curve of lithium tracer we can conclude, that first appearance of lithium occurred on 19 April. at 17.00 (82.5 hours after the injection). The difference in recovery quantity of both tracers is very high,

comparing 1.69 % of lithium with 0.012 % of phage. This difference could be contributed to water level conditions and velocity of both tracers. The phage that was quicker in moving towards Hubelj area was probably more diluted on April, 18 when the through-flow augmented from 7.5 m sec (17 April) to 12.56 m sec than lithium that appeared on 19 April, when the throughflow at Hubelj lowered to 6.92 m sec.

Completely different conditions were in the time of the third tracing experiment, when the average precipitation in the monthly period before the injection was only 2.8 mm (Tab. 6.19). The phage tracer that was injected on 1st August and washed into the permeable strata with water, remained there immobile, or moved very slowly for nearly a period of a month. The high water level, which is indicated by the sudden augmentation of throughflow from 0.52 m^3/s (27 of August) to 13.03 m^3/s pushed the adsorbed and extremely slowly moving phages into the Hubelj spring., where the peak of tracer curve occurred on 29 August at 12.00. Recovery value of 0.001 % could be contributed partly to the deactivation of adsorption to different underground surfaces and partly to dilution of phage tracer because of the sudden augmentation of the ground water levels. Keeping in mind the time of the passage of phage tracer in first and second tracing experiment, that was 94.7 and 99.6 hours respectively and the day values of precipitation at Otlica in the time of reappearance of phage tracer; we can conclude that the main water which pushed the phages into the Hubelj spring came from other direction than from the background of Otlica, where the precipitation achieved the maximum values on 29 August with 98.5 mm in the time when the peak value of phage tracer in the Hubelj spring was already determined.

The recovery values for phage tracer P22H5 in both three experiments at Nanos plateau are for several magnitudes lower than in the preceding tracing experiments in different karst regions, where bacteriophage was injected directly into flowing waters (Tab. 6.20). Nevertheless, the results of all the three tracing experiments with the phage P22H5 on high karst plateau confirm, that the phage tracer could also be injected into permeable strata with additional washing, where the water flow doesn't occur. The best recovery values for phage tracer can be expected, when permeable strata are sufficiently saturated due to longer rainy periods.

Tab. 6.20: The centre of gravity values (t_g), and average velocity of phage tracer based on t_g value for several tracing experiments with P22H5 phage in karst environment. Recovery values for some tracing experiments are also included.

injection point	sampling point	distance [m]	t_g [h]	v_{tg} [m/day]	recovery [%]
Kapsia	Kiveri	39,000	233.0	4017	-
Smokavska vala	Rižana	3880	348.0	268	0.006
Hotičina	Rižana	12,450	482.0	620	4.5
Lurbach	Hammerbach	3000	53.4	1348	2.5
Kačji potok	Radeščica	19,200	511.4	901	3.0
Kačji potok	Obrh	20,000	704.6	681	-
Bajer	Krupa	6000	99.1	1453	-
Vrčice	Krupa	6000	156.8	818	-
Movražka vala	Ara	800	80.8	237	-
Movražka vala	Mlini	1000	94.6	165	3.4
Movražka vala	Sopot	1043	145.1	173	-
Zavrhovc	Hubelj	1002	94.7	255	0.78
Zavrhovc	Hubelj	1002	99.61	247	0.012
Zavrhovc	Hubelj	1002	678.2	36	0.007

6.5. RESULTS WITH SALTS (W. KÄSS)

6.5.1. Lithium Tracing Test at Zavrhovc (April 16, 1994)

The kation lithium was used as a tracer together with bacteriophages (compare chapter 6.4) in the second tracing experiment in spring 1994. As briefly described in chapter 6.1 (Tab. 6.1) the injection of 30 kg lithium chloride solved in 110 l of water took place on April 16, 1994 at 10:25 and was followed by the injection of 20.5 l phage suspension at 10:30 (compare chapter 6.4) in the rocky doline below the Zavrhovc farm. The salt suspension was rinsed down with about 1 m^3 water. After flushing of both tracer injections was performed with 3.5 m^3 water.

As observation points for lithium the spring Hubelj (altitude: 240 m a.s.l.) and the two smaller karst springs in the vicinity of the Hubelj spring, Gorenje (243 m a.s.l.) and Skuk (520 m a.s.l.) were chosen.

Results

Hubelj

Between April 16, 13:00 and May 25, 1:00 the total of 232 samples were investigated. The extremely low background between 0.01 and 0.04 μg/l allowed a good recognition of influences from the tracing, even when they were very low. Between April 20 and 26 a significant Li-increase above the background could be detected (Fig. 6.33).

For the interpretation the background was subtracted (net-values for the increase above the background) and the breakthrough-curve between April 19, 1:00 and April 27, 23:00 was fivefold smoothed (Fig. 6.34).

The injected 30 kg LiCl only contain 16.4 %, resp. 4.92 kg lithium. By means of the discharge values, made available by Hydrometeorološki Zavod, Ljubljana, a recovery of 70.52 g lithium was calculated for the lithium passage during the period above given. These are only 1.43 % of the injected quantity.

A second Li-passage took place between May 19 and the end of the observation on May 25, 1:00. This passage was aroused by heavy rainfalls which caused a discharge of the Hubelj-spring up to 31,600 l/s (Tab. 6.21):

A rough calculation of this second lithium passage between May 19, 13:00 and May 25, 1:00 resulted in an additional lithium recovery of 81.95 g. Thus 152.7 g lithium, resp. 3.1 % reappeared completely with this test in the spring Hubelj. In Fig. 6.35 the cast-line for the whole observation time is depicted.

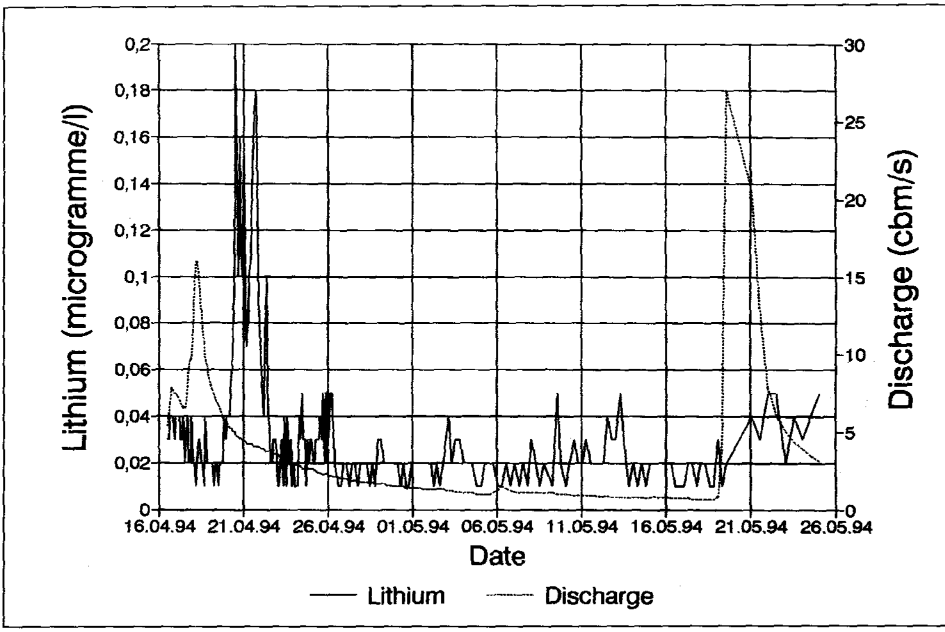


Fig. 6.33: Second tracing experiment: analysed lithium-values in the spring Hubelj in connection with the discharge of the Hubelj (m³/s).

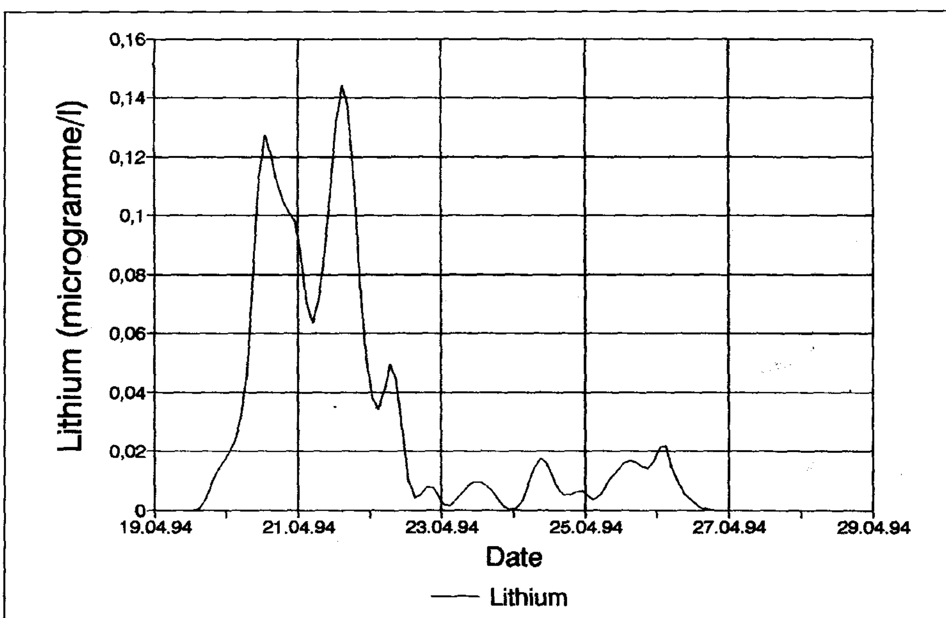


Fig. 6.34: Lithium-netto-values in the Hubelj spring between April 19 and 27.

Tab. 6.21: Lithium passage in the spring Hubelj between May 19 and 25 due to a significant increase in the discharge.

Day	Time	Li (µg/l)	Q (l/s)
18.5.1994	13:00	0.01	677
18.5.1994	19:00	0.01	677
19.5.1994	1:00	0.02	792
19.5.1994	7:00	0.01	4,220
19.5.1994	13:00	0.02	27,000
19.5.1994	17:00	not observed *	31,600
21.5.1994	1:00	0.04	20,500
21.5.1994	13:00	0.03	13,100
22.5.1994	1:00	0.05	7,880
22.5.1994	13:00	0.05	6,130
23.5.1994	1:00	0.02	5,060
23.5.1994	13:00	0.04	4,390
24.5.1994	1:00	0.03	3,910
24.5.1994	13:00	0.04	3,450
25.5.1994	1:00	0.05	3,170
* the sampling was interrupted because of high water!			

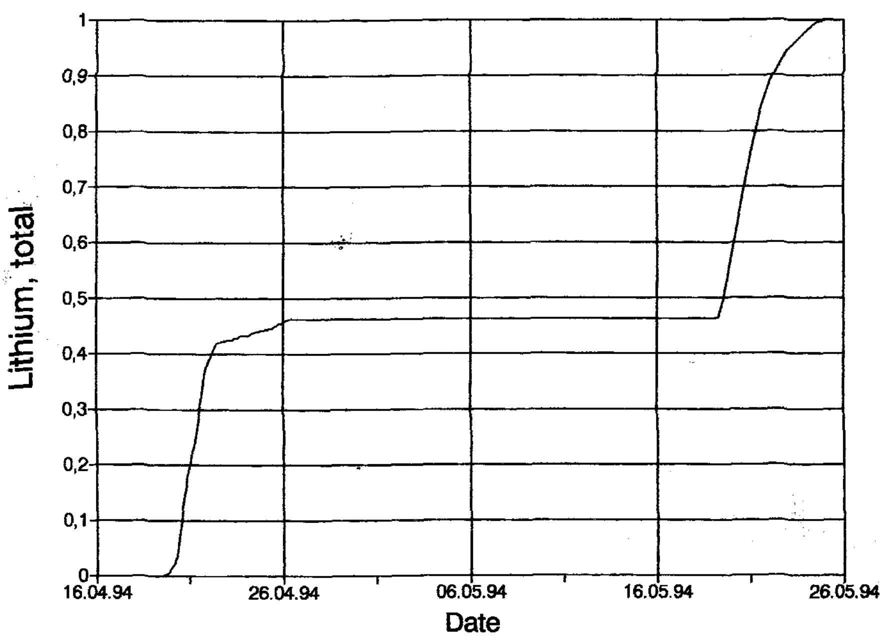


Fig. 6.35: Cast-curve for the Li-breakthrough in the Hubelj spring.

Gorenje and Skuk

No lithium passage was observed at the other two observation points, Gorenje and Skuk.

For the observation of a possible lithium breakthrough in the karst spring Gorenje 50 water samples were analysed for the observation period from April *16, 12:15 to May 24, 13:00. The highest Li-value observed was 0.11 μg/l, the* lowest 0.06 μg/l, with a medium value of 0.0866 μg/l. The standard deviation was 0.013 and the variance 0.00017.

Period of observation: 16.4., 12:00 - 24.5., 13:00 with 51 samples. Highest Li-value: 0,08, lowest value: 0,04, medium value: 0,0586 μg/l. Standard deviation: 0,0088, variance: 0,000078.

6.5.2. Strontium Tracing Test at Mrzli log (April 16, 1994)

A second salt injection was carried out with the kation strontium in the framework of the second combined tracing experiment. As injection point the deepest doline (784 m a.s.l.) of the karst depression Mrzli Log was selected (Fig. 6.1). The tracer solution consisted of 50 kg strontium chloride hexahydrate, resp. 16.3 kg strontium, dissolved in 120 l of water and 7 kg pyranine dissolved in 40 l of water. The injection took place simultaneously at April 16 at 11:00 after a preflushing of the doline with about 1,000 l and was followed by a after flushing of about 6,000 l.

Main aim of this injection was to define the watershed between the Hubelj spring at the one side and the karst springs Podroteja and Divje Jezero at the other side (Fig. 6.1). Therefore 6 karst springs were selected as observation points for a possible strontium breakthrough (Tab. 6.22).

Tab. 6.22: Observation points for a possible strontium recovery for the combined tracing experiment in Mrzli Log (April 16, 1994) with the distance from the injection point, the altitude of the spring outlet and the incline.

Observation points		Distance (m)	Altitude (m a.s.l.)	Incline
1	DIVJE JEZERO	7221	350	0.060
2	PODROTEJA	7630	330	0.0595
3	VIPAVA 4/1	9594	99	0.0713
4	VIPAVA 4/7	9594	99	0.0713
5	GORENJE	10183	243	0.053
6	HUBELJ	9255	240	0.059

Results

Divje Jezero

Observation period: 19.4, 9:20 - 27.5., 18:25
Amount of samples: 44
Highest value: 31 μg/l Sr
Lowest value: 18 μg/l Sr
Medium value: 23 μg/l Sr
Standard deviation: 2,81
Variance: 7,9
Result: No Sr-passage

Podroteja

Observation period: 19.4, 9:25 - 20.7., 12:00
Amount of samples: 51
Highest value: 45 μg/l Sr
Lowest value: 19 μg/l Sr
Result: The Sr-values constantly increased from the beginning to the end of observation (Fig. 6.36). Whether this has been influenced by the tracing, remains open.

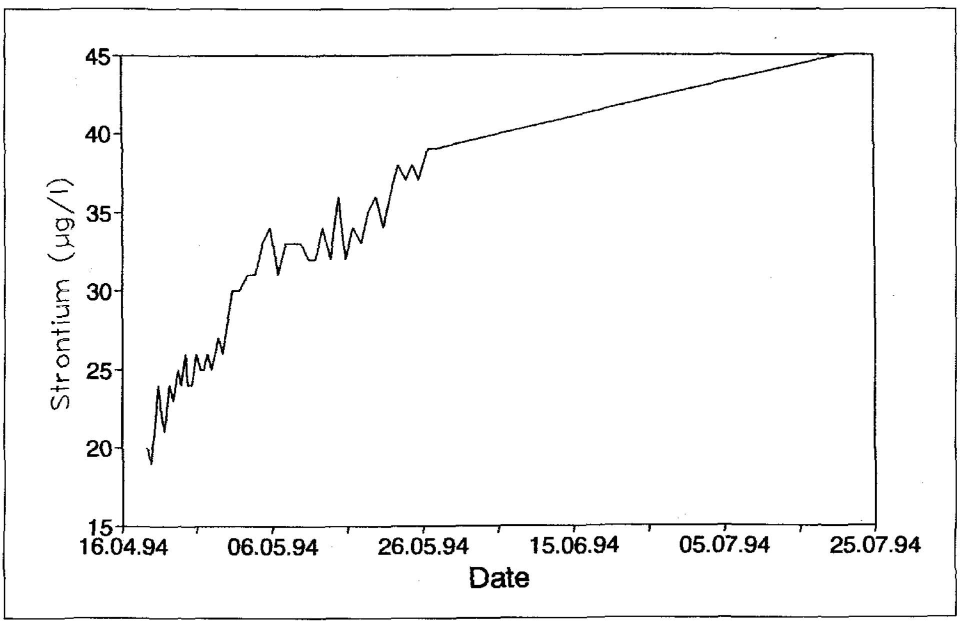


Fig. 6.36: Strontium values in the Podroteja spring.

Vipava 4/1 (Kapelica)

Observation period: 16.4, 10:00 - 28.7.,9.00
Amount of samples: 198
Highest value: 113 μg/l Sr
Lowest value: 27 μg/l Sr
Medium value: 49 μg/l Sr
Standard deviation: 17,8
Variance: 319
Result: The Sr-content constantly increased from the beginning to the end of the observation with some interruptions.

Vipava 4/7 (Pod Farovžem-L.)

Observation period: 16.4, 13:00 - 28.7.,9.00
Amount of samples: 198
Highest value: 113 μg/l Sr
Lowest value: 27 μg/l Sr
Medium value: 49 μg/l Sr
Standard deviation: 14,9
Variance: 221
Result: The Sr-content increased from the beginning to the end of the observation with distinct interruptions (Fig. 6.38).

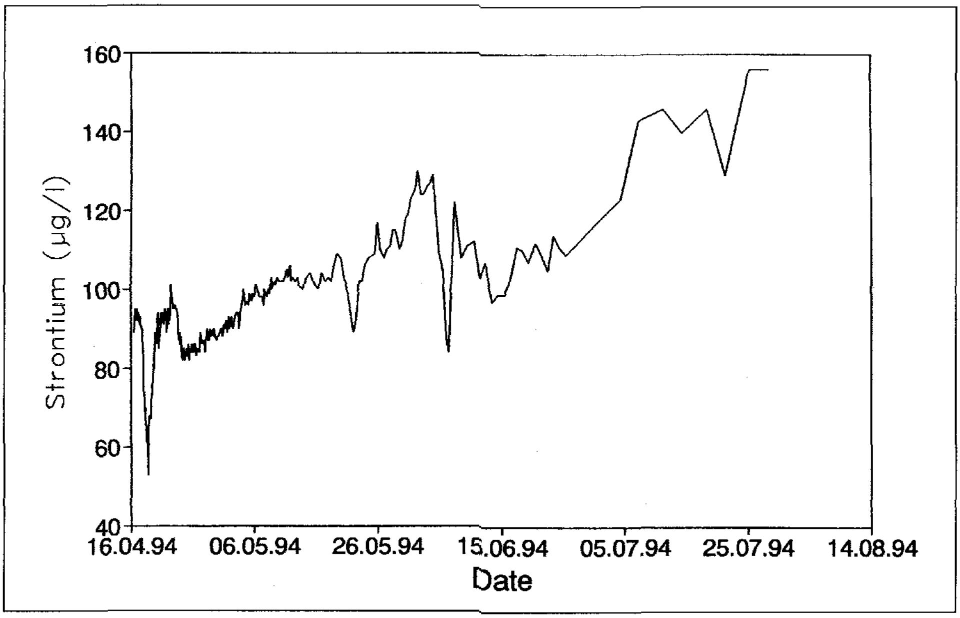


Fig. 6.38: Sr-contents in the spring Vipava 4/7 between April 16 and July 28.

Gorenje

Observation period: 16.4, 12:15 - 24.5., 13:50
Amount of samples: 50
Highest value: 19 μg/l Sr
Lowest value: 9 μg/l Sr
Medium value: 13,5 μg/l Sr
Standard deviation: 1,88
Variance: 3,53
Result: No Sr-passage

Hubelj

Observation period: 16.4., 12:00 - 25.5., 1:00
Amount of samples: 232
Highest value: 9 μg/l Sr
Lowest value: 2 μg/l Sr
Medium value: 4,96 μg/l Sr
Standard deviation: 1,42
Variance 2,04
Result: No Sr-passage

6.6. MATHEMATICAL MODELING WITH THE MULTI-DISPERSION-MODEL (A. WERNER & P. MALOSZEWSKI)

6.6.1. Introduction

Numerous tracer experiments have been carried out within the research program of the 7th SWT on the Trnovski Gozd plateau (Slovenia). The area between the springs Mrzlek, Lijak and Hubelj (Fig. 6.1) formed one main focus of the investigations of the ATH. In the following the mathematical interpretation of the uranine tracer experiments of the input location Belo Brezno (Fig. 6.1, Tab. 6.1) will be described. At this place one tracer test was performed in each of the years 1993, 1994 and 1995 (compare chapter 6.3.2). Therefore it was possible to evaluate mathematically experiments with different hydrological boundary conditions. The main output was the karst spring Mrzlek in a distance of 19.8 km to the injection point and not the nearby located Hubelj spring (6.9 km distance). As described previously current discharge measurements of the Mrzlek spring are not available, due it's outlet in the dammed Soča river.

6.6.2. The Multi-Dispersions-Model (MDM)

The Multi-Dispersion-Model (MDM) was used for the evaluation. This model was developed by MALOSZEWSKI et al. (1992) for the interpretation of tracer tests in Styria. The MDM is an extension of the classical convection-dispersion model after LENDA & ZUBER (1970). The resulting breakthrough curve of a tracer experiment is seen as the outcome of different flow paths. Step by step the breakthrough curves of the individual flow paths and the parameter of convection (mean transit time) and dispersion (dispersivity) processes are determined. The mathematical background of this model was illustrated detailed in the report of the 6th SWT (MALOSZEWSKI et al. 1992). The following solution is valid for every flow path:

$$C_i(t) = \frac{M_i}{Q_i} \frac{1}{t_{0_i}\sqrt{4\pi\, P_{D_i}\left(\frac{t}{t_{0_i}}\right)^3}} \cdot \exp\left[-\frac{\left(1-\frac{t}{t_{0_i}}\right)^2}{4P_{D_i}\left(\frac{t}{t_{0_i}}\right)}\right] \qquad (1)$$

with C_i = tracer concentration
M = tracer mass
Q = discharge
t_0 = mean transit time

$$P_D = \frac{D}{vx} = \frac{\alpha}{x}$$

P_D = dispersion parameter
D = dispersion
v = mean flow velocity
α = dispersivity
i = index of the flow path

The total concentration is the superposition of the individual flow paths:

$$C(t) = \sum_{i=1}^{N} C_i(t) \qquad (2)$$

The discharge Q is normally necessary for a full calculation. Unfortunately this information was not available because of the location of the spring at the bottom of a river. However, it is possible to normalize the solution (1) to the maximal concentration.

In the past the MDM was used for the interpretation of tracer tests in different karst areas (MALOSZEWSKI et al. 1994; BARCZEWSKI et al. 1996; LÖHNERT et al. 1996; WERNER et al. 1997a; 1997b).

6.6.3. The Tracer Tests of the Injection Place Belo Brezno

Three different tracer experiments were selected for the mathematical interpretation. The ice cave Belo Brezno was the injection place for all of these tests. The injection was performed at the lowest point in this cave. An additionally injection of water should ensure that the tracer was flush out direct in the saturated zone.

The experiments were carried out under the following hydrological conditions:

	Karst water level	Number of Rain Events
• 1993	very high	many
• 1994	high	very few
• 1995	very low	no, first after 500 h

The main outcome of the injected tracers was the Mrzlek spring. In the Hubelj spring it was only possible to detect very low concentrations with an episodic behavior (compare Chapter 6.3.2). A further detection of the uranine was only possible in the Lijak spring. The activity of this periodical spring strongly depend on the karst water levels. More details about the performance of the experiments, the sampling and the results are given in the chapters 6.1, 6.2 and 6.3.

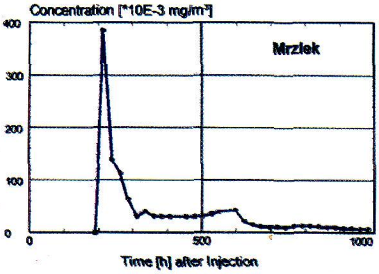
6.6.3.1. The First Tracer Test (1993)

This tracer test was carried out in the autumn 1993. The water level of the karst system was very high due to a longer precipitation period. The resulting breakthrough curve (Fig. 6.39) of the Mrzlek spring could be divided in different single peaks. However, these four peaks were not the result of the individual flow paths but of the multiple flow of one or two paths.

Due to the high karst water level the tracer was transported very fast into the saturated zone. This leads to a quick transport. The less values for the dispersivity (Peak I and II) are typical for the transport in the conduit system of a karstic aquifer. However, a smaller part of the tracers was hold in the unsaturated zone and flush out a short time later by following rain events. The higher values for the dispersivity and mean transit times of the Peak III and IV show this behavior.

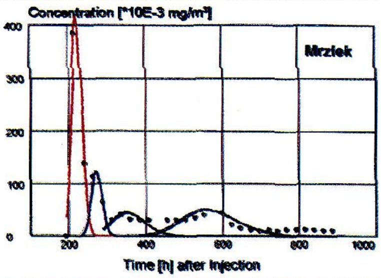
Due to the high karst water level the Lijak spring was active during this tracer test. The determined values are comparable with the results for the Mrzlek spring. Therefore the Lijak drained probably the same part of the karst system.

MRZLEK
Uranine



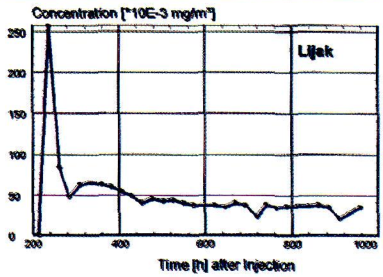
Hydrologic Situation:
- very high karst water levels
- multiple intensive rain events

Tracer Experiment
- Input: Belo Brezno
- Tracer: 5 kg Uranine
- Date: 10/14/1993



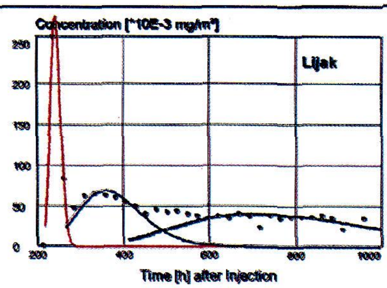
	Peak 1	Peak 2	Peak 3	Peak 4
t_0 [h]	222	272	359	572
v [m/h]	89	73	55	35
α_L [m]	35	28	137	122

LIJAK
Uranine



Hydrologic Situation:
- very high karst water levels
- multiple intensive rain events
- periodic spring

Tracer Experiment
- Input: Belo Brezno
- Tracer: 5 kg Uranine
- Date: 10/14/1993



	Peak 1	Peak 2	Peak 3
t_0 [h]	245	381	823
v [m/h]	54	35	16
α_L [m]	15	49	654

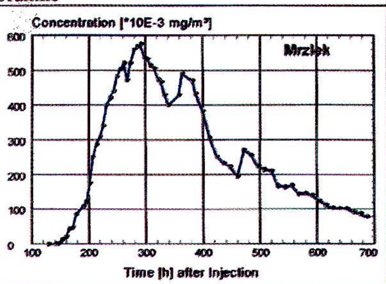
Fig. 6.39: Evaluation of the first tracing experiment from autumn 1993.

6.6.3.2. The Second Tracer Test (1994)

This tracer experiment was also performed during high karst water levels, but after the injection no rain events were observed for the first 470 h (Fig. 6.40). A natural flush out of the tracer by the rain events like 1993 was not possible. The lower flow velocities and the higher values for the dispersivity (Peak II) in comparison to the experiment of 1993 are the result of a delayed entry in the saturated zone. Because of the missing rain events the tracer was hold back in the unsaturated area. The following transport in the conduit system of the saturated zone is also very quickly. The third peak is caused by the rain events after 470 h.

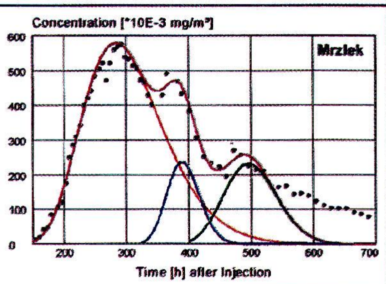
No tracer was detected in the Lijak spring because during the experiment the karst water level was decreased. The discharges of the Lijak spring were in the beginning about 5 ml/s and within two days they were fall down to values of less than 10 l/s.

MRZLEK
Uranine



Hydrologic Situation:
- high karst water levels
- until 470 h: no rain events
- after470 h: several rain events

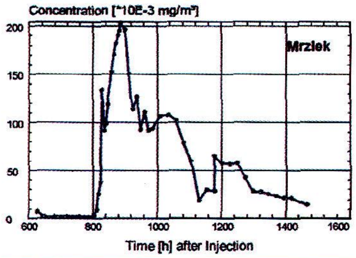
Tracer Experiment
- Input: Belo Brezno
- Tracer: 5 kg Uranine
- Date: 04/16/1994



	Peak 1	Peak 2	Peak 3
t_0 [h]	307	393	502
v [m/h]	64	50	39
α_L [m]	495	44	71

Fig. 6.40: Evaluation of the second tracing experiment from spring 1994.

MRZLEK Uranine		Peak 1	Peak 2	Peak 3	Peak 4

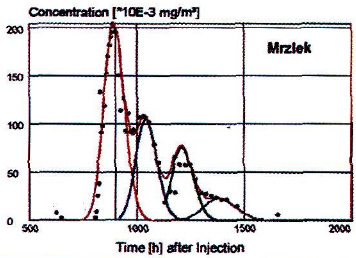


Hydrologic Situation:

- Very low karst water levels
- Till 650 h: no intensive rain events
- after 650 h: intensive rain events

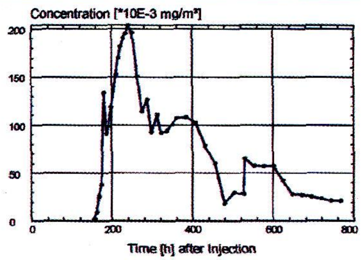
Tracer Experiment

- Input: Belo Brezno
- Tracer: 7 kg Uranine
- Date: 08/01/1995



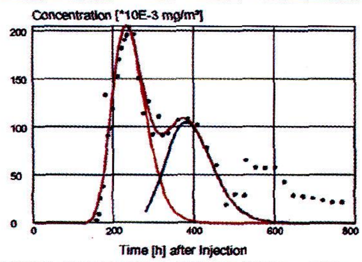
	Peak 1	Peak 2	Peak 3	Peak 4
t_0 [h]	897	1046	1212	1389
v [m/h]	22	19	16	14
α_L [m]	28	22	17	28

MRZLEK Uranine		Peak 1	Peak 2



Corrected Interpretation:

- Effective Input after 650 h



	Peak 1	Peak 2
t_0 [h]	245	395
v [m/h]	81	50
α_L [m]	299	222

Fig. 6.41: Evaluation of the third tracing experiment of summer 1995.

6.6.3.3. The Third Tracer Test (1995)

This experiment was carried out during a dry period in the summer of 1995. (Fig. 6.41)The karst water level was very low during the whole experiment. No larger rain events were detected during the first 650 h of this tracer test.

The evaluation of the experiments (Fig. 6.42 above) shows great mean transit times but only very less dispersivity values. Therefore it can be assumed that the tracer was first hold in the epikarst. The following intensive rain events (after ca. 650 h) flush out the tracer into the saturated zone. The less dispersivity values show then the same transport behavior in the conduit system as in the years before.

A fictive input after 650 h (28.8.) was simulated for comparison. The evaluation (Fig. 6.42 above) shows mean transit times in the order of the other experiments. The high dispersivity values are caused in the distribution of the tracer in the epikarst during the first hours.

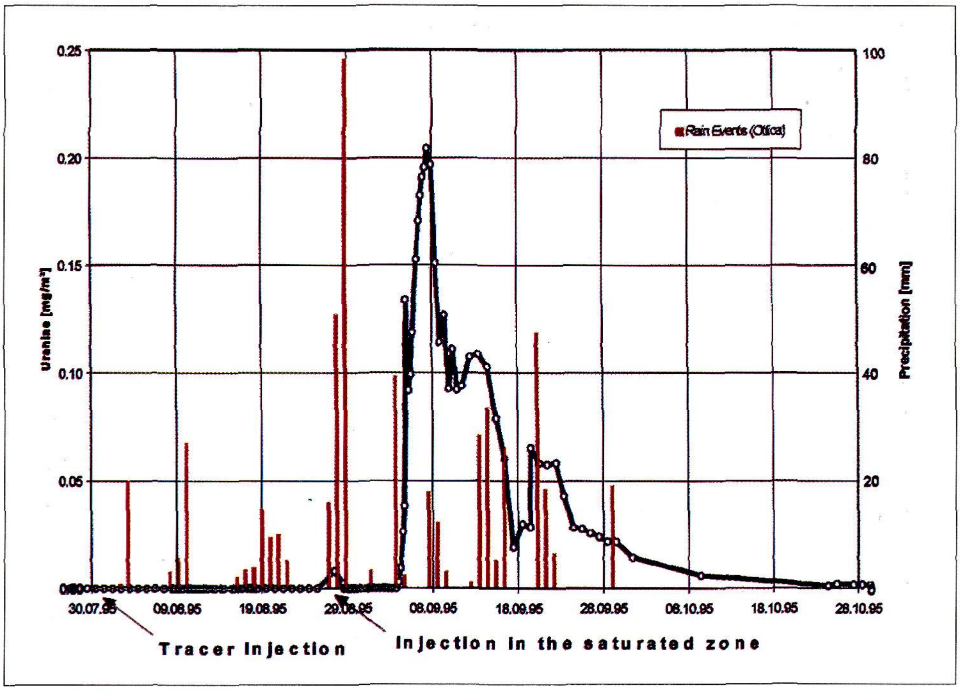


Fig. 6.42: Breakthrough curve of the third tracer experiment (summer 1995) and precipitation heights recorded in the precipitation station Otlica.

6.6.4. Conclusion

The evaluation shows that the transport behavior in the **saturated zone** is mainly independent of the hydrological conditions and the karst water level (Tab. 6.23) The flow velocities are between 60-90 m/h and the dispersivity values are very low (20-30 m). The transport takes place in the conduits of a good developed karst system. The number of flow paths or better flow systems can not determine unequivocal. Due to the rain events the multiple flow of one or two ways is probably.

Tab. 6.23: Overview of the results (for the first two Peaks) determined with the Multi-Dispersion-Model.

Tracer test /Year	Spring	Mean transit time [h]		Dispersivity [m]	
		Peak I	Peak 2	Peak 1	Peak 2
First / 1993	Mrzlek	222	272	35	28
	Lijak	245	381	15	49
Second / 1994	Mrzlek	307	393	495	44
Third / 1995	Mrzlek	897	1046	28	22
	Mrzlek (corrected.)	245	395	299	222

The differences in the breakthrough curve of the tracer experiments are caused in the location of the injection place in the **unsaturated zone**. Depending on the karst water level and/or rain events it was possible that the injected tracer was totally hold back (1995). The additional injection of water was not enough for a full input of the tracers into the saturated zone. The epikarst processes are difficult to understand. They are recognizable on the high dispersivity values (> 100 m) and the long mean transit times. The migration processes in the epikarst are also responsible for the episodic tracer detection in the Hubelj spring.

A further quantitative evaluation is not possible because of the missing discharge values of the Mrzlek spring. The performed normalization can lead to deviations of the determined parameters. However, these differences are normally not very large (WERNER 1997).

7. CONCLUSIONS REGARDING THE INVESTIGATION AREA

7.1. UNDERGROUND CONNECTIONS IN DEPENDENCY TO HYDROGEOLOGICAL CONDITIONS (J. JANEŽ)

Geological cross-section 1-1' (Fig. 7.1) shows the structure, that makes the underground water flow from the western and middle part of Trnovski Gozd to the West, to the springs near the Soča river, possible. The whole area is part of the Trnovo nappe, where the Uppertriassic, Jurassic and Cretaceous carbonate rocks dip towards South-west. There is no hydrogeological barrier between Belo Brezno and the Soča valley. The Uppertriassic dolomite is found in the basis of karstified Mesozoic limestone. The dyeing in Belo Brezno likewise the older tracing test in Čepovan shows that the regional faults (Avče fault, Raša fault) do not influence the general direction of the karst groundwater flow. The horizontal distance between Belo Brezno and the Mrzlek spring is 21 km, and the altitude difference is 970 m.

The position of Uppertriassic and Jurassic beds, that dip towards Southwest enables the groundwater outflow from Belo Brezno to Hubelj. Uppertriassic dolomite is relative hydrogeologic barrier in the grounding of Jurassic limestone. By drawing the lifting of the flysch beds in the nearest hinterland of Hubelj at the Avče fault we try to show that interrupted and periodical appearance of the tracer in the Hubelj spring can be a consequence of the hydrogeological structure, too (Fig. 7.2).

Cross-section 3 - 3' (Fig. 7.3) shows geologic and hydrogeologic conditions between the Vipava spring, injection points Malo Polje and Mrzli Log and the spring Divje Jezero near Idrija. At Malo Polje the dye was injected into the Jurassic limestone. Under the Uppertriassic dolomite of the Trnovo nappe and Čekovnik interjacent slice the dye flowed off towards Divje Jezero. The horizontal distance is 10,0 km and the altitude difference 295 m. Considering the geological conditions it can be expected that Malo Polje also belongs to the catchment area of the Hubelj spring although the tracing test did not confirm that supposition.

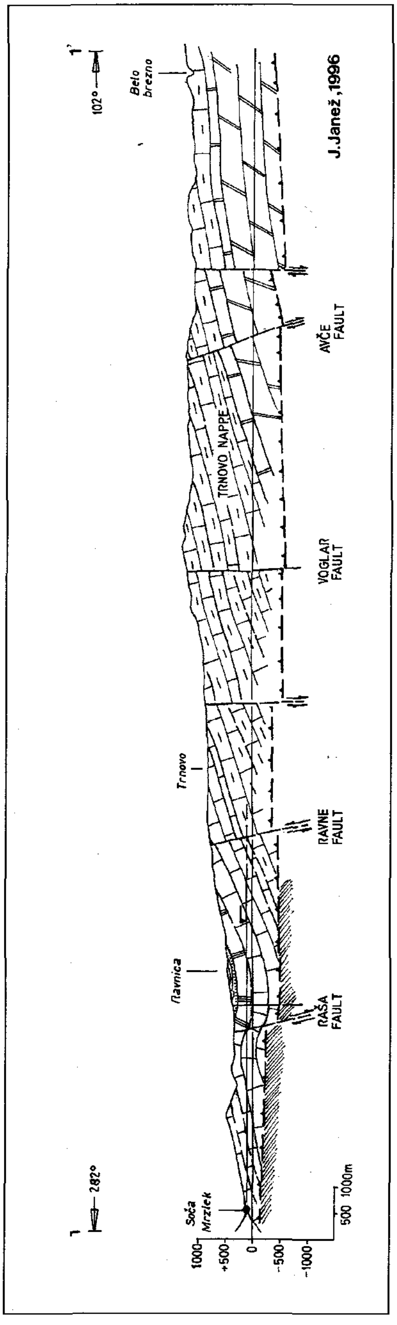


Fig. 7.1: Geological cross-section 1-1'; Belo Brezno - Mrzlek.

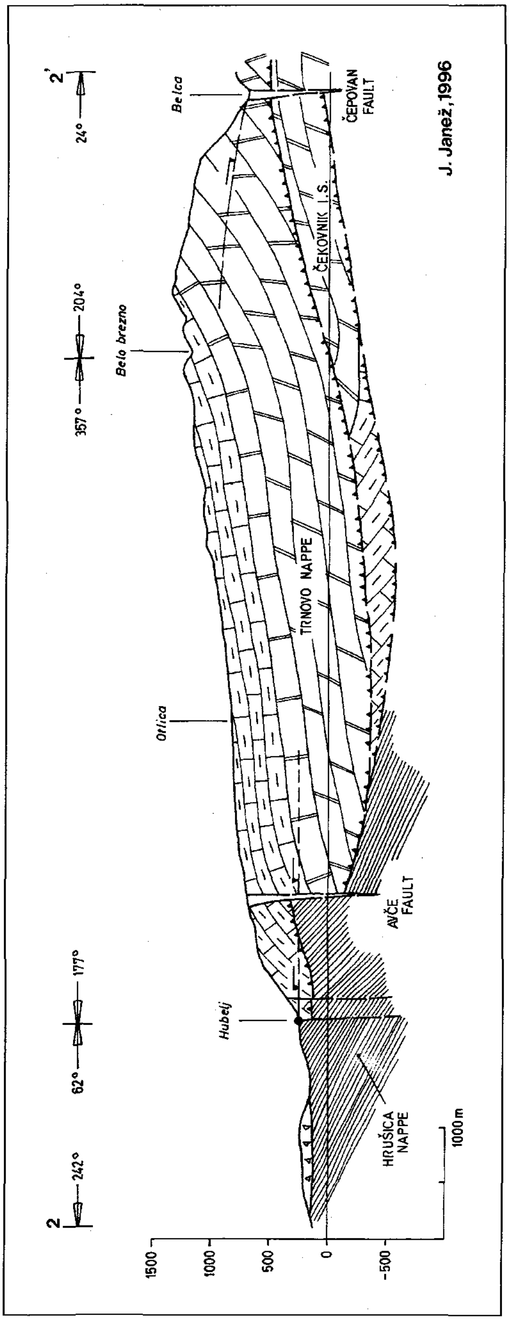


Fig. 7.2: Geological cross-section 2-2'; Belo Brezno - Hubelj.

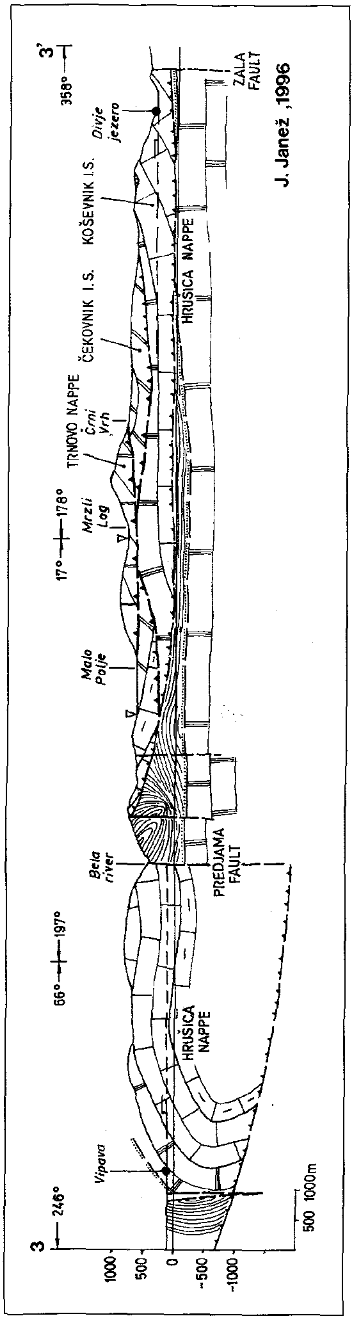


Fig. 7.3: Geological cross-section 3 - 3'; Vipava-Malo Polje-Mrzli Log-Divje Jezero.

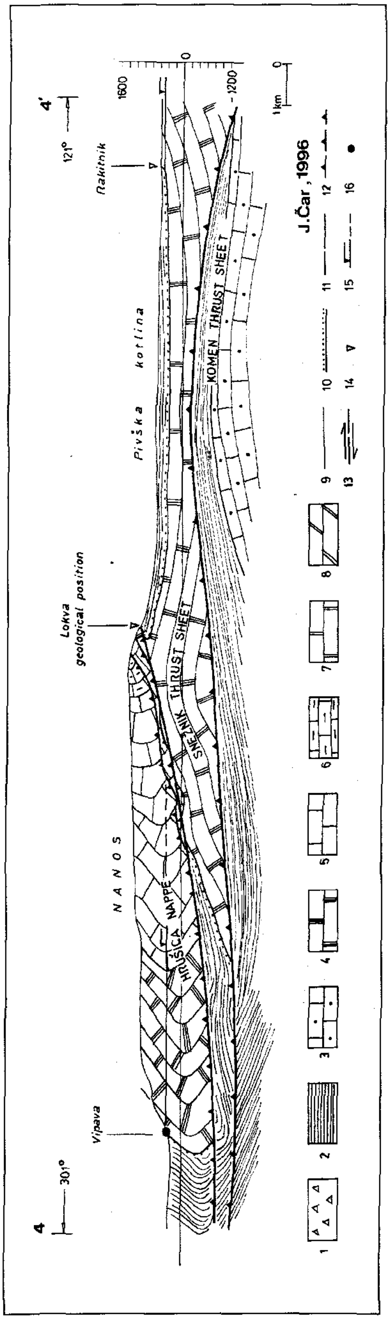


Fig. 7.4: Geological cross-section 4 - 4'; Rakitnik-Lokva-Vipava.

LEGEND 1- Periglacial breccia and rubble, Quaternary and Holocene; 2- Flysch rocks of Upper Cretaceous, Palaeocene and Eocene age; 3 - Limestone, Palaeocene; 4 - Upper Cretaceous organogenic limestone; 5 - Lower Cretaceous bituminous limestone with inliers o f dolomite; 6 - Limestone and dolomites of Jurassic age; 7 - Norian - Rhaetian (Dachstein) limestone; 8 - Norian - Rhaetian dolomite; 9 - Normal geological boundary; 10 - Erosion discordance; 11- Fault; 12 - Thrust; 13 - Direction of tectonic movement; 14 - Sinkhole, Injection point; 15 - Groundwater level; 16 - Karst spring.

Much more difficult is to explain the underground connection between Mrzli Log and Divje Jezero. The dye was injected in the sinkhole formed in the Uppertriassic dolomite of Trnovo nappe. As in the Čekovnik interjacent slice near Črni Vrh a hanging fissured aquifer is proved by a hydrogeological borehole it can be supposed that the dye gets lost through the shallow dolomite lid into the lower limestone of Koševnik interjacent slice, where a normal karstic flow towards Divje Jezero is possible. The horizontal distance between Mrzli Log and Divje Jezero is 7,2 km, while the altitude difference is 455 m.

This geological cross-section (Fig. 7.4) explains the hinterland of the Vipava spring. P. Habič (1989) proved that the sinking stream Stržen near Rakitnik in the Postojna basin flows away in two directions, towards the Timava springs as towards the Vipava. The cross-section shows that the Lokva can have a normal underground karst flow towards the Vipava spring without any hydrogeological barrier. It has to be pointed that Lokva at low water can flow of into the limestone of Snežnik thrust sheet and trough it towards Timava. Although this geological cross-section is only supposed, it gives an explanation for the phenomenon, that the dye injected at low water in the Lokva stream did not appear in the Vipava spring.

7.2. UNDERGROUND WATER CONNECTIONS DEPENDENT ON HYDROMETEOROLOGICAL CONDITIONS (P. HABIČ)

7.2.1. The aim of water tracing by artificial tracers

From 1993 to 1995 combined water tracing tests in the area of Trnovski Gozd and Nanos were achieved mostly at the same points but during various meteorological and hydrological conditions. Using mostly the same tracers provided that tracing results may be well compared one to another. Except in two cases, the tracers were poured into epikarst vadose zone, this is why their travel up to springs highly depended on rainfall, in particular on consecutive showers that washed the tracer from the injection area. The analyses of water and tracer pulses in such cases are specially interesting.

The results of three consecutive water tracing tests in Belo Brezno below Golaki are important to understand water drainage in the area of Trnovski Gozd. Major part of tracer from the injection point at 1200 m a.s.l was flushed by rainwater into Mrzlek near the Soča (77 m a.s.l.), distant 19 km and partly into Lijak (water level between 77 and 116 m); smaller part flowed into near, 6,9 km distant Hubelj spring near Ajdovščina (water level between 220 to 270 m; See Chapter 6 about water tracing). Water tracing in immediate recharge

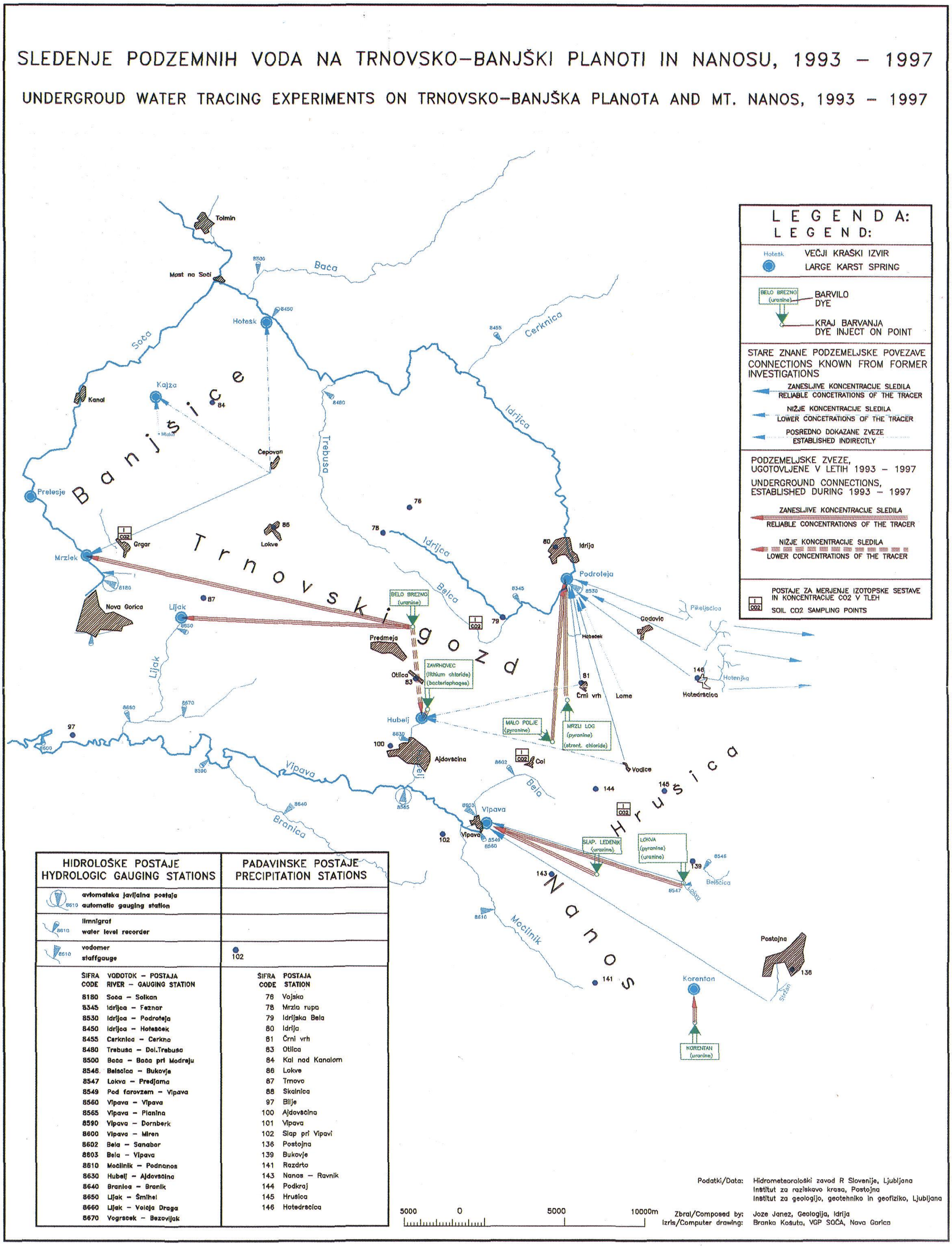


Fig. 7.5: Underground water tracing experiments on Trnovsko-Banjška Planota and Mt. Nanos.

area of Hubelj near Zavrhovc tried to explain the conditions in epikarst and vadose zone close behind the spring. Water tracing tests at Mrzli Log and Malo Polje should define the watershed area between Hubelj at the Vipava and Divje Jezero and the Podroteja at the Idrijca. Water tracing tests of the Lokva near Predjama and in shaft Slapenski Ledenik on Nanos Mt. should allow the comparison of mostly horizontal flow in epiphreatic zone and feeding of delta-shaped outflow from the aquifer into the Vipava springs with vertical drainage in a thick vadose zone.

7.2.2. Hydrometerological conditions during water tracing tests

On October 14, 1993 the first combined water tracing test was achieved after the initial autumn rain in September that followed a long dry period; practically there was no rainfall since January to the end of August 1993 (See hydrogramme of Hubelj and Lijak 1993). A week after the tracer was poured a distinct water pulse appeared after a heavy rain on October 21 to 25 (Otlica received 247 mm of rainfall); in the first half of November a new rain period followed with lower, but longer lasting water pulse up to the beginning of December; in the second half of December another rain and water pulse was recorded (See Chapter 6).

The second water tracing test was performed in spring, on April 16, 1994. The initial discharge of the Hubelj was twice as much as during the first tracing; already one day after the injection heavy rain increased the discharge in the springs; they slowly decreased through mid-May; after next rain from May 19 to 21 a distinctive water pulse occurred.

The third combined water tracing test was achieved during the summer drought on August 1, 1995. Dry weather continued since July to August 28, when in two days there was only 175 mm of rain on Nanos, 165 mm on Otlica and 118 mm on Lokve. The first abundant water pulse was followed by other five consecutive pulses in September, on September 4, 9, 15 and 20.

The fourth water tracing test was achieved during a dry autumn, on October 26, 1995. Slightly higher September waters flowed off, low discharges lasted from September 25 to October 30. After soft rain on October 30 and 31 (16.6 mm) the discharges in springs slightly increased for the first time; heavy autumn rain appeared between November 11 and 14 (188 mm) and between November 16 and 19 (193 mm on Otlica). Water pulses appeared in Lijak on November 12, 17 and 28 and on December 17 and 23, 1995.

Various amount of rainfall recorded at rain-gauge stations on Trnovski Gozd and Nanos differently influenced on height and distribution of water pulses in different springs. Smaller deviations of rain and discharge peaks are due to different permeability of single aquifers and different size of karst background of springs.

Table 7.1 Overview of discharges at the beginning of water tracing tests.

Date	Q Hubelj	Q Vipava	Q Idrijca-Podroteja
October 14, 1993	2.8	8.1	18.1
April 16, 1994	5.4	11.2	13.2
August 1, 1995	0.5		1.7
October 26, 1995	0.6	1.7	2.7
sQp 61-90	3.03	6.78	9.29

7.2.3. Underground water connection Belo Brezno - Hubelj

During the first water tracing test in 1993 the water pulse appeared in Hubelj after 155 hours and dye pulse after 190 hours after the injection. It means that rainfall accelerated the rinsing of tracer from Belo Brezno to Hubelj. Low concentrations and typical jagged concentration curve indicate, although the tracer was present in the spring for at least 1500 hours, partial and unhomogeneous outflow of rain from the area of Belo Brezno into Hubelj. According to our opinion the irregular concentrations are due to injection technique which was performed by separated pouring of dissolved tracer and by later adding of water from a lorry tank; such injection causes a sort of splashes of more or less diluted tracer from vadose to phreatic zone and it is recorded in different hourly or daily tracer concentrations in spring.

Due to low values in concentration curve (Fig. 6.21) it is difficult to read the true washing out, pushing or dilution of tracer by water pulses. It seems, that the very first appearance of tracer in spring together with the highest concentration is mostly due to normal outflow 150 hours after the injection and only partially to accelerated drainage influenced by the first water pulse. The second peak of concentration, after 285 hours, seems to be the result of tracer rinsing out of Belo Brezno after rain at the end of October; this tracer pulse is supposed to need 100 hours from the injection site to the spring (69 m/h); the second water pulse after rain in mid-November surely diluted the tracer in time from 600 to 800 hours after the injection. Increased concentration after 1100 hours might be the result of a new pulse due to rain in mid-November that washed off the tracer. This tracer pulse needed from 300 to 600 hours for its travel to spring (23 - 11.5 m/h). All these assumptions are, as it was said, rather doubtful due to modest secondary peaks of the dye pulse.

The second water tracing test in April 1994 recorded, by twice higher waters, understandably lower concentrations of Uranine in Hubelj but they appear in separated peaks. The first traces after 70 to 90 hours are probably due to previous water tracing as similar last trace was still recorded at the end

of January. More distinctive traces of Uranine appeared after 400 hours at relatively constant low discharge. After 600 hours after the injection there are no traces of Uranine recorded. Also at this second water tracing a higher water pulse flushed a major part of Uranine from Belo Brezno towards Mrzlek. Rate of returned tracer in Hubelj was even hundred times smaller than it was at the first test.

The concentration curves of the third water tracing in Belo Brezno at very low waters in August 1995 do not essentially differ from the previous two. There are separated tracer peaks, only the initial part resembles more to a short pulse, with intermediary dilution; that would be the result of unhomogeneous tracer pouring. The first traces appeared in Hubelj after 140 hours, tracer reached its peak after 180 hours and its end after 204 hours. Some tiny traces were recorded after 320, 440 and 500 hours and after an abundant water pulse after 650 hours all the traces of Uranine practically disappeared. The rate of returned tracer is in this case twice as small as at the second tracing (0.01 %).

Low concentrations and sporadic appearance of Uranine during all the three tracing tests indicate an impeded drainage, some sort of splashing from Belo Brezno towards Hubelj. Apparent velocities of the first appearance and apparent peak of the dye pulse are in this case even less reliable than at other springs. If we do not take into account the first trace at the second water tracing after 70 hours but we consider as the first the appearance after 400 hours then it is shown that the fastest outflow occurs at the lowest waters and at the lowest concentrations, and slower outflow at higher waters when concentrations are higher too. Disproportion in amount of tracer between medium and high waters indicates different drainage in epikarst and maybe even in phreatic zone during different hydrometeorological conditions. In all the three cases the basic drainage was oriented from Belo Brezno towards Mrzlek.

7.2.4. Underground connection Belo Brezno - Mrzlek

As karst waters from Mrzlek spring flow directly into the Soča a direct comparison between dye and water pulses is not possible in this spring. For comparison we used hydrogrammes of Hubelj and partly of Lijak. Hubelj and Lijak hydrogrammes are pretty similar considering the fact that in Lijak overflow pulses were recorded only and lower part of the hydrogramme reflects water table lowering in the borehole near Lijak. Water level in it reacts concordantly to emptying and filling of the common aquifer (JANEŽ 1992; PETRIČ 1993). Differences are partly due to different distribution and quantity of rainfall to the eastern and western side of Trnovski Gozd and partly to different accumulation capacities of both parts of the common aquifer.

At the first water tracing in Belo Brezno a typical dye pulse appeared in Mrzlek with highest concentration at its beginning; after 216 hours a computed velocity was 92.4 m/h; in Hubelj the velocity was 35 m/h. Similar as in Hubelj also in Mrzlek water pulse outran the dye pulse for about 60 hours. Rain after 150 hours since the injection pushed the dye pulse out of underground and thus diluted its initial part; it is seen in conical start of a concentration curve. The second rain after 500 to 600 hours since the injection diluted Uranine in Mrzlek where Uranine outflowed constantly for about 1000 hours in total.

After the second water tracing in Belo Brezno a nice dye pulse appeared in Mrzlek. The concentration curve is regular due to rainfall soon after the Uranine injection that washed the tracer into phreatic outflow zone of the karst aquifer. The first appearance of tracer after 168 hours, which means about 100 hours after the water pulse peak, and dye pulse peak after 318 hours, give rather realistic velocities of underground flow (120 and 60 m/h) at medium high waters. Smaller secondary Uranine concentration peak between May 5 and 6 is probably influenced by soft rain that pushed a part of tracer from underground but did not cause dilution. Without a proper effect to dye pulse was also rain about May 20; smaller dilution appeared only at low waters in the next ten days.

The third water tracing test with Uranine in Belo Brezno at low waters confirmed the results of the previous two tests. Also in this case a major part of used Uranine (60-70 %) flowed into Mrzlek. The first trace appeared after 630 hours together with the beginning of water pulse after more than one month of dry weather. The peak of water pulse outran the peak of dye pulse for about 100 hours; this means that similarly as at the first tracing it was rain that pushed the tracer out of underground. Obviously tracer almost reached spring thus one may reckon with real apparent velocity of low waters in phreatic zone to be from 20 to 25 m/h.

After the first rain at the end of August, another five rainy periods followed in September provoking corresponding water pulses. At the same time they were recorded in Lijak and Hubelj and we suppose that they correspond to water pulses in Mrzlek. After the first dye pulse two secondary peaks appeared; the first after 880 (1000) hours and the second after 1030 (1200) hours since the injection. Both secondary dye pulses are connected with washing and pushing of tracer in Vast karst aquifer. A trace of Uranine was recorded in Mrzlek still after 3600 hours or five months; till now this is the longest water tracing in the High Karst of the western Slovenia.

7.2.5. Underground connection Belo Brezno - Lijak

During the first water tracing test it was still possible to sample the water in the Lijak borehole and near it, later the borehole breached and thus data for comparison are missed. In 1993 Uranine appeared in Lijak after 214 hours

since it was injected in Belo Brezno; it is practically the same time as it was required for Hubelj and Mrzlek and it was undoubtedly influenced by the already known water pulse. The Uranine concentration curve in Lijak is practically identical to the Mrzlek curve, only maximal concentration is slightly lower. Thus already known hydraulic connection of Lijak and Mrzlek was confirmed; in the first one only high waters flow on the surface while the second one permits a permanent outflow from common aquifer. A short lasting water pulse drained about 10 % of Uranine which was present in the karst groundflow of Lijak up to 2800 hours since the injection although five distinctive overflow pulses occurred in this time; in Mrzlek the tracer was present 1400 hours only. Probably a part of low water remains in Lijak, as it cannot flow directly to Mrzlek without an additional hydraulic pressure. At water tracing in 1994 we did not record Uranine in Lijak and in 1995 it occurred only in a sample belonging to the sixth water pulse of September 19, 1995.

7.2.6. Underground connection Zavrhovc - Hubelj

Drainage through 550 m thick vadose karst zone, only 1 km distant from the Hubelj spring, was traced three times by phages (See Chapter 6.4) and once by LiCl (See Chapter 6.5).

After the first tracing on October 14, 1993 at medium waters and after a wet season (See Table 6.14) the tracer travelled by 37,7 m/h (for its first appearance) and 22.3 m/h during the peak. Such drainage was undoubtedly provided by rainfall that previously watered the epikarst zone (from October 7 to 13 there was 75.6 mm of rain); after the injection there was at first a soft rain (October 15-19 28,6 mm) followed by two periods of abundant showers (October 21-25 251,3 mm and November 3-9 388 mm, gauged on Otlica). Concentration curve is jagged, typical of tracing in a vadose zone with unhomogeneous watering, but it indicates a characteristic tracing pulse and also traces of secondary rinsing of phages after an abundant water pulse (See Fig. 6.31)

At the second water tracing test there was still more water. On Otlica 177 mm of rain was recorded from April 1-15, and after the injection, between April 16 and 20, another 85,7 mm. Correspondingly higher were also discharges in the Hubelj spring. Without considering slightly changed injection location, the flow velocities through epikarst zone were very similar. The first trace was 14 hours late, the concentration peak appeared 9 hours earlier giving slightly higher velocity (25,9 m/h) than at the first tracing. The tracer concentration curve is even more jagged, but the concentrations are 25 times lower (See Fig. 6.32) and correspondingly lower is also the rate of returned tracer (0,78 % and 0,012 %).

At the same time as phages also LiCl was poured at the same site into epikarst zone. Rather typical dye pulse appeared in the spring between April 20 and 26; the first appearance was after 80 hours and the peak after 100 hours since the injection giving slightly lower velocity (18,5 to 15,6 m/h). The secondary LiCl pulse was recorded in Hubelj between May 19 to 25; it was due to abundant rain as the discharges in Hubelj increased to 31,5 m^3/s.

The third water tracing with phages at Zavrhovc was achieved during the summer drought when epikarst zone above Hubelj was without rain, worth mentioning, from mid-June to the end of August 1995. From June 16 to August 1 there was only 77 mm of rain on Otlica, it rained only three times (from 10 to 15 mm) in the season, when evapotranspiration is the highest. From August 1 to August 26 there was 105,7 mm of rain, a real rain, 165,5 mm, started from August 27 to 29, having an impact on Hubelj discharge also. The first trace after the injection of phages on August 1, 1995 appeared after 661 hours on August 29, the peak of dye pulse only 12 hours later; apparent velocity is thus 2.3 m/h. Secondary trace appeared on September 11, after rain on September 4 and 8. The phages travel through dried epikarst zone was practically blocked for four weeks, until heavy rain provoked the tracer pulse; concentrations were very low and the rate of returned tracer only 0,001 %. Water tracing in epikarst zone requires special preparation and suitable conditions, the results are important for planning the protection of karst aquifers.

7.2.7. Underground connection Mrzli Log - the Podroteja and Divje Jezero

On April 16, 1994 during the second combined water tracing Pyranin was injected into an ouvala Mrzli Log between Križna Gora and Javornik above Črni Vrh. According to morphological properties this area should belong to the Hubelj recharge area (9,2 km). The water tracing test did not confirm this assumption as Pyranin appeared in a dye pulse of Podroteja (7,6 km) after 300 to 600 hours and after 822 hours it was recorded in Divje Jezero also. The connection corresponds to geological setting. Apparent tracer velocity in Podroteja was 24,7 m/h and the peak of pulse 20,1 m/h. Outflow velocity (9,2 m/h) into Divje Jezero is truly apparent as during low waters Divje Jezero does not drain karst water from a common aquifer; the tracer there was recorded as a short outflow during water pulse on May 19 only. During this water pulse it did not appear any more in Podroteja as Pyranin could not be detected even 200 hours earlier due to dilution.

7.2.8. Underground connection Malo Polje - the Podroteja and Divje Jezero

For the third combined water tracing in summer 1995 Malo Polje near Col was chosen as it lies on would-be watershed between Podroteja and Hubelj; it is 8,3 km far from Hubelj and 10,7 km from Podroteja. This tracing by Pyranin also did not confirm the supposition of the connection with Hubelj; the tracer appeared in three separated peaks in low concentration in Podroteja and Divje Jezero after 740 to 830 hours with apparent velocity from 13 to 14 m/h. The tracer appeared in both springs after 100 hours after the peak of the first high water pulse, while during the second, substantially lower pulse tracer was no more recorded. Probably this case indicates a trace of secondary washing while true base outflow from Malo Polje is not proved. Water tracing in epikarst watershed zone requires more tracer and a more sensitive one.

7.2.9. Underground connection Lokva (Predjama) - the Vipava (P. HABIČ, V. ARMBRUSTER)

In April 16, 1994 during the second combined water tracing test among the others also the sinking stream Lokva near Predjama was dyed. The permanent springs of the Vipava from V-1 to V-7 and common at water gauge station V-8 were monitored. Hydrological conditions were similar as in the catchment area of other springs in the area of Trnovski Gozd. Two days after the injection at relatively high waters (11,2 m^3/s) a water pulse occurred with peak at 25,2 m^3/s. Later water decreased constantly. After 450 to 500 hours on May 6 a low water pulse, peak 6,3 m^3/s, occurred; after 800 hours since the injection a more abundant water pulse occurred on May 20 with first peak at 26.7 m^3/s and on May 21 with 22,6 m^3/s. The first traces of Uranine appeared in the Vipava after 69 to 74 hours, varying in different springs, and the first peak after 80 to 103 hours. The velocities of the first tracer appearance are between 175 to 185 m/h. In some springs the second peak was more distinctive, between 140 to 166 hours since the injection, velocities from 78 to 126 m/h (See Fig. 6.21 - 6.26). Water pulse accelerated the washing of tracer somewhere in the middle between swallow-hole and spring and at the same time it washed off the retained tracer from the ponor area. Thus two tracer pulses appeared in the springs. The first had higher concentrations only at the common gauge station V-8 and in the spring V-3; the first peak in the spring V-7 was rather diluted, although higher than the second one. The springs V-1, V-2, V-4, V-5 and V-6 had higher concentrations in the second pulse which was certainly much more prominent in all the springs.

The differences in the concentration curves between single springs are

partly due to hydrologic connections between feeding channels in common but not entirely homogeneous throughflow system of the aquifer. Jagged concentration curves at some springs, in particular at V-2, V-3 and V-7 are probably due to local hydrological influences and possible pollution and disintegration of tracer in samples (Chapter 6.3). The concentration curves in most springs evenly decreased, only at spring V-4 two separated peaks appeared after 300 and 350 hours probably controlled by different underground flow. Another tracer peak due to water pulse push after 850 hours appr. (May 20 and 21) appeared at lateral springs V-1, V-2 and V-3 and less distinctively at V-7. According to hydrological, physico-chemical and tracing results the main Vipava springs at medium and high water level are V-4, V-5 and V-6 draining the aquifer the most directly exercising the least lateral discharge effects.

During a heavy precipitation event the connection between the sinking Lokve stream on the flysch area near Postojna and Vipava springs could be investigated with the natural tracer silica. On April the 1st and 2nd 1996 heavy precipitation brought 110 mm of rain to the flysch area. The biggest of the sinking streams, Lokve river, showed a very high peak discharge of 4.4 m^3/s. 4 days and 12 hours after the peak silica load in Lokve river, a strong rise in the silica content of Vipava springs was detectable. It occurred long after the peak discharge (HQ: 43 m^3/s) in the Vipava springs. This silica peak could be plausibly attributed to concentrated allogenic water, coming from the flysch area near Postojna. Dispersion has been low and the travel time amounted to 4 days and 12 hours.

7.2.10. Underground connection Slapenski Ledenik (Nanos Mt.) - the Vipava

The fourth combined water tracing test at low waters on October 26, 1995 was aimed to compare the drainage in epiphreatic and vadose zone of Nanos Mt. Pyranin was poured into the sinking stream Lokva near Predjama (13 km far from Vipava), Uranine into a shaft Slapenski Ledenik on Nanos (7,6 km far from the Vipava). Unfortunately Pyranin was not detected in any spring, maybe because of too small an amount; however the drainage towards the nearby aquifer may not be excluded.

Uranine from Slapenski Ledenik appeared after 400 hours in a distinctive tracer pulse, 30 hours before the first, lower and about 100 hours before the high water pulse due to rain on November 16 and 19. Surely the first rain between November 11 and 14 accelerated the outflow of tracer which was already close to the spring in the phreatic zone. The flow velocity up to the first tracer appearance (19,7 m/h) and up to the peak of the pulse (15,9 m/h) are very typical of low waters. After 100 hours tracer concentrations substan-

tially decreased due to dilution because of heavy rain. During the following discharge decrease the concentrations increased accordingly to outflow of less diluted base flow.

Another tracer pulse appeared after 900 hours approximately, between December 1 and 2 slightly after the low water pulse due to rain on November 26 and 29 (20 mm) which was not strong enough to flush the tracer. More probably this is a secondary pulse due to washing off the Uranine from Slapenski Ledenik after the rain on November 19. This pulse required about 300 to 400 hours to reach the spring; this gives the velocity of 20 to 25 m/s and according to higher water level it is slightly higher than was the velocity during the first pulse. The following peaks of the tracer pulse curve appeared in December together with water pulses; they are obviously the result of pushing of dyed water from the underground after 1300 to 1800 hours since the injection. Similar phenomenon was recorded at previous water tracing in August 1995. The last traces after 4600 hours confirmed that water is retained in the Vipava aquifer for at least half a year. Similar conditions were stated during water tracing of the Pivka and Stržen near Postojna in 1988 (HABIČ 1989).

7.3. WATER PROTECTION MEASURES (J. JANEŽ)

7.3.1. Introduction

The first attempts to protect karst water between the valleys of the Vipava, Soča and Idrijca started 25 years ago when the professional foundations and proposition of protection of the recharge area of Podroteja spring near Idrija was being prepared. The decree did not pass. In the early 80' the Karst Research Institute ZRC SAZU, Postojna prepared the professional foundations and the communes Nova Gorica and Ajdovščina passed the communal acts to protect the springs Mrzlek, Vipava and water storage of Čepovan-Lokve water supply. The Mrzlek recharge area was protected by the act issued at Nova Gorica but not at Ajdovščina commune. The Vipava recharge area was protected by the Ajdovščina commune but only the area covered by its own commune while the part that administratively belongs to Postojna was not protected.

Insufficient local and partial measures animated the initiative to prepare a full range of professional foundations for uniform protection of the entire karst aquifer of Banjšice, Trnovski Gozd, Nanos and Hrušica and the recharge areas of all the concerned springs. These foundations were being prepared from 1988 to 1993. The first phase of the project was concluded, including geography,

geology, karst springs, hydrogeology, speleology, surface and underground pollution, threat to waters, plan of protection with proposed protection areas and protection measures. The second phase aimed to the abatement of pollution and future land use management, was not achieved.

7.3.2. Physico-chemical and biological threat to karst superficial and underground waters

7.3.2.1. General criteria

Threat to karst waters depends on ecological burden and natural sensitivity (vulnerability) of the aquifer. The first one is controlled by different forms and varying degree of industry, thus it represents active and latent sources of pollution and may be diminished by better hygienic organisation of the environment. Vulnerability of a karst aquifer depends on superficial infiltration (rate and velocity), hydrogeological conditions of the aquifer that control way and time of underground drainage, quantity of water and rate of dilution and stage of environment deterioration that was already reached (JANEŽ 1995).

Classification of recharge areas according to different degrees of vulnerability is used to determine the protection areas. Definition of the true burden is urgent for a sensible approach and sensible order at sanitation of pollution.

7.3.2.2. Vulnerability

The vulnerability of an aquifer may be defined, without considering the distribution of pollution sources, by hydrogeological properties of terrain; it means that underground water below more permeable areas is more threatened than below less permeable ones. Anthropogeneous factors, as for instance population at a given time or land use of the aquifer surface do not impact on vulnerability except when man and his interventions had essentially changed the natural conditions (for example wood cutting can substantially increase the soil erosion etc.).

The vulnerability of an aquifer or a degree of pollution danger may also be defined by possibilities of intervention in case of pollution. By intervention one may prevent:

- spreading of harmful substances over the surface and their in vasion into aquifer
- preventing the access of accidental spills into water supply system, to user respectively.

We have taken into account only such possibility of intervention in case of pollution that is controlled by natural circumstances and conditions, mostly hydrogeological and not by anthropogeneous impacts as is momentary urbani-

sation/population of karst surface or organisation of water management.

Using the above mentioned criteria we divided the entire region between the Soča, Vipava and Idrijca into areas of catastrophic, great, medium and little vulnerability.

The areas of catastrophic vulnerability are those where there is practically no possibility nor time in case of pollution to prevent the harmful substance access into water supply system. Areas of great vulnerability belong to such regions where there is practically no possibility to prevent the access of harmful substance into aquifer, but there is a certain time to prevent the access into water supply system. They include the entire karst recharge area of a water source having exclusively underground drainage of precipitation. In the areas of medium vulnerability there is more chance to prevent the access of harmful substance either into aquifer or into water supply system. As medium vulnerable areas are treated the regions consisting of medium to bad permeable rocks, dolomitic and some flysch areas in particular. The areas of little vulnerability offer in case of pollution a true time and possibility to react and prevent the access into aquifer. They include the surface on impermeable beds with exclusively surface drainage of the precipitation.

7.3.3. Overview of way and degree of protection

7.3.3.1. General criteria

The extent of protected area is defined for the conditions of high hydrological levels (the fastest discharge, the highest water level, the widest surface of recharge area). Protection measures are totalled - a measure implemented for a wider protection area applies to all the areas within.

1. This protection area includes the surface of the catastrophic vulnerability area where there is in case of pollution practically no possibility to prevent the access of harmful substance into water supply system. It is divided into two parts; zone 1 a means enclosure around the water storage which prevents intentional water pollution; in zone 1 b all the activities that may threaten the water quality and quantity are restricted.
2. This protection area with a severe regime covers the area of great vulnerability where there is practically no possibility to prevent the access of harmful substance into aquifer, however there is a certain time to prevent the access into water supply system. It includes karst recharge area of the water source. The area is aimed to be protected by severe sanitary measures against organic biological pollution.
3. This area with sanitary regime includes the area of medium vulnerability with some time available to prevent the access of harmful substance either into aquifer or into water supply system (rocks of medium or bad perme-

ability). The area is aimed to protection against intensive organic biologic pollution.

4. This protection area bears a soft regime and includes the area of little vulnerability where there is still time and possibility to prevent the access of harmful substance into aquifer in case of pollution (surface on impermeable beds). The area is aimed to be protected against the unconventional pollution by permanent, non-degradable substances.

7.3.4. Verifying the protection areas related to recent water tracing tests

The achieved water tracing tests from 1993 to 1996 show the following:

- the principle of uniform protection of the entire region showed to be correct. The conservation of one area (Belo Brezno and vicinity of Golaki, for instance) remains the same without regard whether the water flows to Mrzlek or Hubelj.
- According to water tracing results the classification of all the limestone terrains in the second protection area with severe regime of protection was correct.
- Water tracing tests in Mrzli Log and Malo Polje showed that it would be probably necessary to protect the area of sinking streams on dolomite and flysch more severely and include them into the second protection area.

8. GENERAL CONCLUSIONS

8.1. METHODOLOGICAL ASPECTS OF WATER-TRACING EXPERIMENTS (H. BEHRENS, R. BENISCHKE, W. KÄSS)

Water tracing methodology consists of different components of which the most important are the availability of suited tracer materials and efficient methods for the tracer detection at observation/sampling points. Besides them, modes of tracer injection, sampling or measurement in-situ, display of data, and interpretation of results are essential features. It is revealing to follow the development of these aspects in the course of the past ATH-events (Graz 1966, Freiburg 1970, Ljubljana/Bled 1976, Bern 1981, Athens 1986, and Karlsruhe 1992).

Among the tracer materials from begin until now fluorescent dyes have played the major role because of their detectability with high sensitivity. Uranine (disodium-fluoresceine) was all time the most efficient candidate. Already 1966 direct measurement in the field with a TURNER filter fluorometer was performed. Laboratory detection at that time was performed on a ZEISS spectrophotometer with fluorescence assessory attachment making it a mixed spectro/filter fluorometer (KÄSS). A breakthrough was achieved in the experiments in Slovenia 1972-1975 with the use of real spectro fluorometers (PERKIN ELMER 203) and application of the new synchronous scanning method which offered higher detection sensitivity by background reduction and more selectivity by optimal spectral resolution. Later also in-situ fluorometers (VARIOSENS, by C. LEIBUNDGUT) were applied particularly in lake-circulation studies. The more recently developed optical-fiber fluorometers (e.g. R. BENISCHKE) which allow in-situ measurements in boreholes and in fissures, however, have not been used in the ATH-experiments until now. Also more advanced analytical techniques using HPLC separation of tracers were not yet applied.

The scale of fluorescent water tracers (eosin, pyranin, sulphorhodamines G and B, rhodamines B and WT besides uranine) was extended to the blue fluorescent region by use of optical brighteners and especially by naphthionate (WERNLI 1986).

Already in Graz 1966 with iodine-131 a radioactive tracer was applied (BEHRENS). In later experiments chromium-51, indium-114, and also stable indium as an activable tracer were used with good success.

Bacteria as tracers were also already applied in 1966 (*Serratia marcescens*, by DOMBROWSKI). Later the scale of microbial tracer methods was extended by use of phages (e.g. BRICELJ, Athens 1987).

Lycopodium spores played an important role since the begin of karst tracing experiments. The method was made more versatile by the introduction of discernible spores which were labelled by colouring with different dyes (DECHANT 1967). More recently fluorescent microspheres have become available for water tracing purposes (e.g. KÄSS 1992).

Collection of water samples for tracer identification has mainly been improved by the introduction of automatic sampling equipment, as well as self-constructed (LEIBUNDGUT) and also commercial (e.g. by BÜHLER, ISCO).

The display of data made profit of the arising availability of efficient personal computers. Comparison of the behaviour and yield of simultaneously injected different tracers was improved by introduction of normalising tracer concentrations to the injected amounts of individual tracers. Mathematical modelling which was not in discussion in the first ATH-events, made the interpretation more and more sound in the following (e.g. MALOSZEWSKI).

Altogether the water tracing methodology has been developed to a high standard. Therefore in the here submitted description of the recent joint experiments in Slovenia a concern on further developments appeared not to be in urgent need. However, the gained successes should not be a reason to rest and efforts should be made to find even more effective techniques (e.g. other types of tracers or advanced analytical procedures). A special demand is the concern on tracer transport properties which until now are not always satisfying with the materials on disposal. Sorption behaviour and stability of tracers are important items, because interfering retardation or full loss of water tracers have been observed in numerous cases where the losses in some events may be attributed to microbial action. From the actual experiments in Slovenia, an example of influence of bottle type for collecting and storing water sample on the results of a fluorescent dye is given.

8.1.1. Degradation of Uranine during tracer tests

On April 16, 1994 7 kg Uranine were injected into the Lokva near Predjama castle (6.3.1). The investigations on Uranine from the Vipava spring 4/3 were carried out in Graz. The samples filled in plastic bottles partly showed conspicuous values. The content of Uranine was too low measured against the other samples.

In Umkirch 2 samples were subjected to store tests:
1. sample from April 20,1994, 7.00 a.m.
2. sample from April 20,1994, 5.00 p.m.

Both samples were again tested on Uranine on October 30, 1994. Conspicuously low values were measured then (Tab. 8.1). The samples were endowed with Uranine on the same day and investigated on Uranine in more or less regular intervals in the following time up to November 13, 1995. On April 15, 1995, approximately in the middle of the observation period about half the content from the plastic bottles was filled into brown-glass-bottles. It appeared that the content of Uranine in the plastic bottles had permanently decreased since the endowment, while the content of Uranine in the glass bottles remained constant (Fig. 8.1 and Table 8.1).

The Uranine test on the Nanos plateau near "Slapenski Ledenik" was carried out with 5 kg Uranine on October 26, 1995. The spectrafluorimetric investigations were done by HMZ in Ljubljana. Here the Uranine concentration values of 33 samples from Vipava spring 4/2 between Nov. 13, 1995, 10.00 a.m. and Nov. 21, 1995, 7.00 a.m. are considered. The samples were alternately

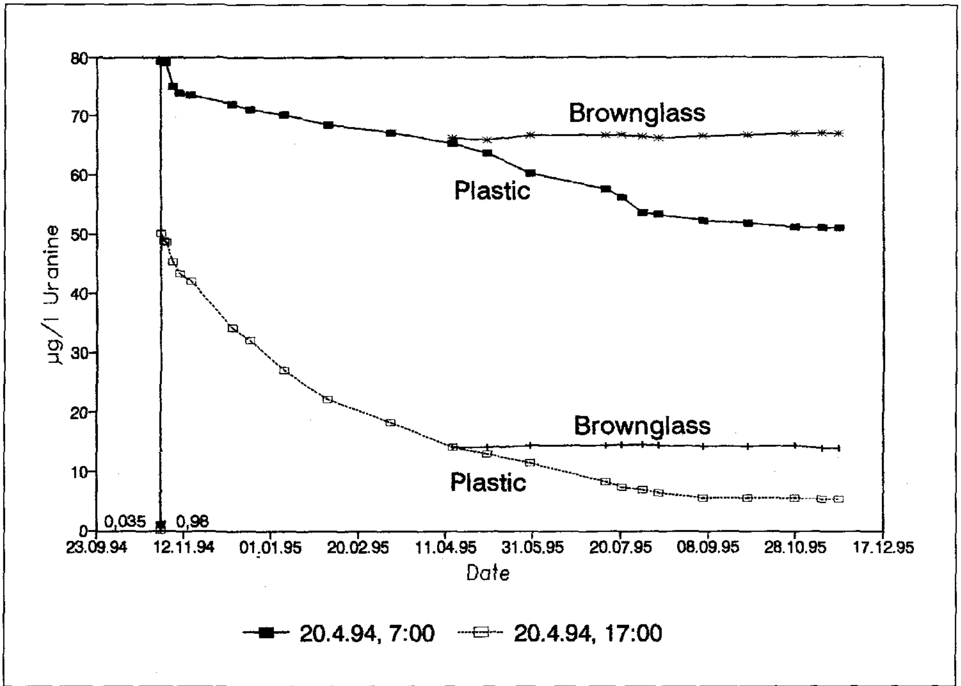


Fig. 8.1: Uranine degradation during a store test in plastic and glass bottles from Vipava spring 4/3.

filled into bottles out of glass (17 samples) and out of plastic (16 samples). The samples in the glass bottles were for the first time tested between Nov. 20 and 22 for the second time on April 18, 1996, at which no noticeable difference of concentration was to be seen. In the diagram of Fig. 8.2 the Uranine values from the glass bottles were interpolated for the between-samples (for the plastic bottles) The concentrations in the plastic bottles were also measured twice: on Jan. 25, 1996, and April 18, 1996.

The decrease of Uranine contents between the sampling and the time of determination can be well recognised in those samples filled in plastic bottles. The diminution lies between 34 and 100 %.

Result: In both described cases there probably exists an adsorption at the sides of the bottles. A microbiological degradation of Uranine would have caused an essentially faster decrease of Uranine (KÄSS 1992).

Recommendation: Uranine investigations from plastic bottles must be finished within a few hours after the sampling.

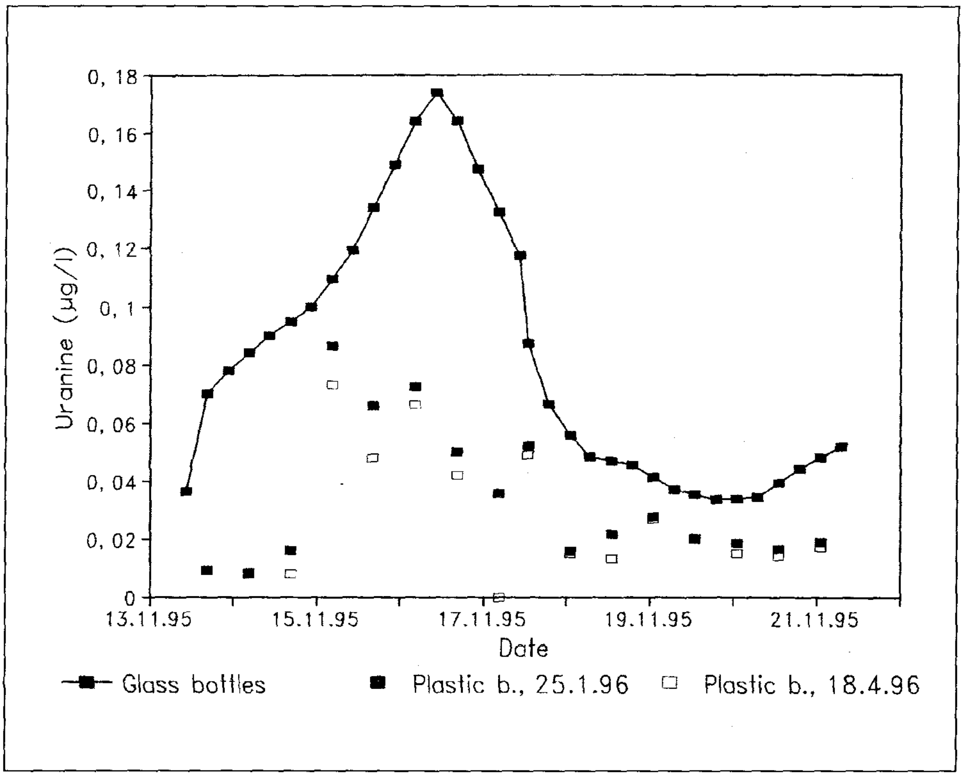


Fig. 8.2: Uranine concentrations in glass and plastic bottles during the tracer test on the Nanos plateau in October 1995.

Table 8.1: Uranine concentrations in the stire test with water samples of Vipava spring 4/3 from April 20, 1994, 7.00 and 17.00. values in µg/l.

Date	30.10.94		15.4.95	13.11.95	15.4.95	13.11.95
Sampling	Uranine endowment		Plastic bottles		Glass bottles	
20.4.94	before	after				
7.00	0.98	79.3	65.3	45.6	65.4	65.6
17.00	0.0035	44.7	13.7	4.4	13.7	12.7

8.2. METHODOLOGICAL ASPECTS OF INVESTIGATIONS OF SINGLE EVENTS - THE USE OF THE NATURAL TRACER SILICA (V. ARMBRUSTER)

With the natural tracer silica it was possible to detect and characterise the arrival of an allogenic flysch component from sinking streams in a karst spring during a heavy precipitation event. Before the arrival of the concentrated flysch water, the level of silica in the karst spring was already higher than in a neighbouring comparable karst spring without such a flysch component. After the precipitation event the arrival of concentrated flysch water in the karst spring was detectable by a strong increase in silica. The travel time of the flysch water could be determined and its dispersion qualitatively described. The travel time corresponds well with results from an artificial tracer experiment. A hydrograph separation of the spring water into flysch recharge water and karst recharge water showed, that it might be promising to determine long term silica contents of spring water, flysch water and mere karst water. With these contents it would be possible to estimate the part of the catchment area of the spring, that is made up by flysch areas.

8.3. FUTURE ASPECTS (P. HABIČ)

After the 6th International Symposium in Karlsruhe in 1992 the Association for Tracing Hydrology (ATH) decided to adopt as an experimental polygon within the preparations for the 7th SWT the area of the High Karst in western Slovenia covering about 700 km^2 of surface that belongs to common background of four big karst springs.

An extensive research programme is being designed which was later adapted to available material, temporal and financial means of the participating institutions from Slovenia, Austria and Germany. As it was impossible to

ensure the contemporaneous intensive studies of numerous hydrogeological, hydrological, physico-chemical and other parameters in the area of the whole karst aquifer, the researches were rationally limited to the Hubelj and Vipava recharge area while practically the consecutive water tracing tests included observations and sampling of other springs, mostly Mrzlek and Lijak, Podroteja and Divje Jezero.

The previous chapters provide the main results. In spite of problems regarding the collection of data, sampling, analyses and processing of gathered information a very important knowledge was acquired about natural conditions of a classical karst aquifer fed prevailingly by precipitation's. The previous hydrogeological knowledge is completed, basic water budget is performed, total water reserves are estimated and it conveys some idea of relation between direct and base outflow. Consecutive water tracing tests during different hydrological conditions allowed to compare the velocity and direction of underground drainage in upper unsaturated and deep saturated zones. However, additional water tracing tests will be required to delineate a spatial relationship of the common aquifer to recharge areas of single springs. By completed hydrological parameters and distribution of natural tracers it would be possible to continue the conceptual and mathematical modelling of hydraulic properties of extensive karst aquifer. The researches within the ATH programme contributed precious knowledge and experiences and also conveyed the possibilities to manage and permanently protect important karst sources. New questions appeared about the use of tracers and about the knowledge of karst aquifer properties which, obviously, could not have been solved in such a short time.

Similar experiences were met by the researchers during all the previous common research projects on international symposia. Unsolved questions provoke the development of new tracer techniques and methods. By common efforts an important progress was achieved in tracer hydrology which allowed solving numerous practical questions at exploitation and protection of superficial and underground waters in particular in hydrogeologically extremely heterogeneous karst aquifers.

Within the sphere of management and protection of karst waters, which is important today and will be decisive in future to provide permanent exploitation of natural resources, tracer hydrology might contribute a lot. Without doubt the main task of ATH is improvement of tracer techniques and selection of the most suitable tracers for quantitative definition of hydraulic parameters, mass transport, feeding and storage of water in karst aquifer and to assess its vulnerability and safeguarding.

Referring to up to now achieved common projects and combined water tracing tests studying karst aquifers we mostly need a reliable and sensitive tracers that may be used in adequate amounts. Unreliable and not enough of tracer does not yield reliable results. The use of artificial tracers is more and

more limited due to sanitary aspects. We must assure the normatives for a concrete use in foreseen concentrations and across limited timespans.

Beside the improvement of tracing techniques by artificial tracers we expect a considerable progress related to use of natural tracers to establish the activities in different hydrological zones of a karst aquifer and also to classify the aquifers themselves.

Monitoring exceptional occurrences, showers, snow melting, accidental spills etc. by intensive sampling and continuous measurements of some parameters enriched the knowledge of hydrodynamics in karst underground. The experiences show that in many cases the extent of researches may be restricted providing that the most important phenomena are monitored intensively. A good example is given by a continuous measurement of conductivity, it is also useful to survey the precipitation and discharge during short lasting showers in an intensive way. The methodology and technology of short run intensive measurement of single parameters and sampling for analyses must be improved. The access, selection of locations, reliability and precise measurements must be taken into account. All the warnings related to standards issued by the previous symposia since 1966 must be considered.

Numerous problems opening during every common research project dictate the need to establish new forms of co-operation and relationship within the ATH. Some efforts were already taken in this direction. Practice showed that co-operation is the best achieved by common research problem and suitable polygon. According to available time and means the problem and space must be realistically limited, well equipped and enough attractive for researchers. Considerate choice of a research field and a good concept of common programme for next symposium is required.

Designing the contents and choice of field all the phases of project achievement must be considered. Interdisciplinary approach, co-operation of various institutions and researchers, management and co-ordination of work regarding the content, time and available means must be taken into account. In any case a certain adapting of programme related to climatic conditions and time of participants during the project itself is necessary. It would be also appropriate to organise a sort of training for students as future research fellows. The equipment must be standardised as well as analyses and synthesis procedures, the field area must be adequately equipped and transport of samples as well as information and documentation facilities well organised.

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10. POVZETEK (J. KOGOVŠEK)

10.1 OSNOVNI PODATKI

Projekt "Širjenje škodljivih snovi v krasu. Sledila in modeli - 7.SWT" je obsegal raziskave Visokega Dinarskega krasa Trnovskega gozda, Banjšic in Nanosa z delom Hrušice. Območje obsega okoli 700 km^2 površja, ki na območju Banjšic dosega nadmorsko višino med 300 in 1100 m, na območju Trnovskega gozda od 600 do 1500 m, na Nanosu od 600 do 1300 m in na Hrušici 800 do 950 m. Prevladujejo zakraseli kredni in jurski apnenci ter triasni dolomiti. Karbonatne kamnine so narinjene na plasti eocenskega fliša. Izviri Vipave, Hublja in Lijaka se pojavljajo na najnižjih točkah meje z neprepustnim flišem.

Trnovsko-Banjška planota (TBP) je z vseh strani obdano z normalnim reliefom, razen na severovzhodnem delu, kjer prehaja v kraško Hrušico, tako da padavine s površja ponikajo neposredno v globoki kraški vodonosnik, ki napaja številne kraške izvire na obrobju: Vipavo, Hubelj, Lijak, Mrzlek, Kajžo, Avšček ob Soči, Hotešk, Divje jezero in Podrotejo (poglavji 2.1 in 2.4). Na območju TBP je znanih 489 jam. Najdaljša je Jama pri Predjami, ki je dolga 7571 m in vanjo ponika Lokva. Kar 17 jam je daljših od 200 m in 18 globljih od 100 m (poglavje 2.5).

TBP je na območju med mediteranskim in alpskim podnebjem, s srednjo letno temperaturo od 7 do 9° C, z dolgimi mrzlimi in sneženimi zimami. *Povprečne količine letnih padavin so v zaledju Vipave okoli 1900 mm*, v zaledju Hublja preko 2100 mm in v zaledju Idrijce okoli 2600 mm. Glavnina padavin pade jeseni oktobra in novembra, najbolj suh mesec pa je julij, ko je najintenzivnejša evapotranspiracija. Pretok Vipave in Hublja (srednje mesečne vrednosti) dosega dva letna maksimuma, višjega aprila ob taljenju snega in drugega novembra; minimum pa je julija in avgusta. Srednji pretok Vipave znaša 6.7 m^3/s, razmerje med minimalnim, srednjim in maksimalnim pretokom (30 letna opazovanja) pa znaša 1 : 9 : 96. Srednji pretok Hublja dosega 3.0 m^3/s, razmerje med minimalnim, srednjim in maksimalnim pretokom pa 1 : 16 : 322 (poglavji 2.2 in 2.3).

Glavni kraški izviri ob visokih vodah odvajajo okoli 280 m^3/s vode. Nivo podzemne vode je opazno višji v zaledju Hublja in severnem delu Banjšic v pri-

merjavi z območjem med Lijakom in Sočo. Podzemna voda TBP s prosto gladino odteka proti jugozahodu in zahodu predvsem zaradi nagnjenosti fliša v podlagi Trnovskega pokrova v to smer. Glavna iztoka sta Hubelj in Mrzlek, Lijak pa preliva le visoke vode. Zaledje Divjega jezera in Podroteje je vezano predvsem na podzemno vodo zakraselih krednih apnencev vmesne luske Črnovrške planote, vendar zapletene litološko tektonske razmere omogočajo tudi povezave s ponikalnicami v širši okolici in drugih tektonskih enotah (poglavje 2.6.2).

Trnovski gozd predstavlja prehodni pas med dinarskim in alpskim fitogeografskim območjem, kar kaže prisotnost velikega števila alpskih vrst. Južno obrobje Trnovskega gozda, proti Vipavski dolini, neposredno meji na submediteransko fitogeografsko območje. Izraziti predel, kjer se mešajo dinarsko - ilirske, alpske in submediteranske vrste, je Čaven. Celotna planota Trnovskega gozda, razen mraziščnih predelov, pokriva združba dinarskega gozda bukve in jelke. Drugi tip vegetacije v Trnovskem gozdu je smrekovje, ki le na zaravneh s tlemi iz rožence in v vrtači Smrekova Draga tvori prave gozdne sestoje. V dinarskem fitogeografskem območju gradi zadnji gozdni pas bukev in sicer v združbi subalpinski bukov gozd (poglavje 2.9).

10.2 CILJI IN POTEK RAZISKAV

Ker so zgoraj našteti kraški izviri edini izdatni viri pitne vode v tem delu Slovenije, kar nekaj jih je že zajetih za oskrbo prebivalstva s pitno vodo, je potrebno njihovo kraško zaledje varovati pred onesnaženjem. Za načrtno varovanje pa je potrebno dobro poznavanje zaledij posameznih izvirov oz. je potrebno vedeti kam in kako odteka padavinska voda, s padavinsko vodo pa tudi onesnaženje, ki je rezultat človekove dejavnosti na tem območju. Cilj projekta je bila poglobitev temeljnega poznavanja osnovnih mehanizmov delovanja kraških vodonosnikov, mehanizmov polnjenja in praznjenja vodonosnih struktur, kar vse pogojuje tudi način prenosa in akumulacije polutantov v teh vodonosnikih. Nova spoznanja bodo pripomogla k optimalnemu gospodarjenju in izkoriščanju vodnih virov na Trnovsko-Banjški planoti, predvsem pa k njihovi ustrezni zaščiti.

V okviru teh zastavljenih ciljev je bil v letih 1993 do 1996 uresničen raziskovalni program, ki je obsegal:

- podrobno geološko in hidrogeološko kartiranje izvirov Vipave in Hublja;
- meritve, vzorčevanje ter izotopske in fizikalno-kemične analize padavin na postajah Vojsko, Trnovo, Podkraj, Bilje, Lokve in Postojna;
- meritve pretokov (limnigrafske postaje) Hublja, Vipave, Belščice, Bele-Sanabor, Idrijce-Podroteja in Korentana ter meritve na vodomernih postajah Lokva, Bela-Vipava in izvir Vipave-Pod farovžem;
- pogoste meritve temperature, specifične električne prevodnosti in pH z elektronskimi zbiralci podatkov na izviru Hublja in izvirih Vipave Perhavče-

va klet 4/3 in Pod farovžem 4/7, kasneje pa še na ostalih izvirih Vipave;
- mesečne fizikalno-kemične (temperature, spec. el. prevodnost, pH, vsebnost karbonatov, kalcija, magnezija, kloridov, nitratov in sulfatov, natrija in kalija) in izotopske analize (devterija ^{2}H, tricija ^{3}H, kisika-18 ^{18}O in ogljika-13 ^{13}C) na 12 točkah na območju TBP;
- tedenske fizikalno-kemične analize Hublja in Vipave in dnevne fizikalno-kemične analize Hublja, Vipave in Mrzleka;
- ugotavljanje kvalitete Vipave, Hublja, Lijaka, Mrzleka in Podroteje s fizikalno-kemičnimi, bakteriološkimi analizami, analizami težkih kovin in organskih snovi v vodi in sedimentu;
- pregled vodne favne v izvirih Vipave, Kajže in Ajbe;
- ugotavljanje vpliva kmetijstva na onesnaževanje kraške vode z mineralno bilanco prsti na območju Dol - Otlica, za občino Ajdovščina in za 16 posameznih kmetij;
- virološke raziskave vode Vipave, Hublja, Podroteje, Hoteška, Mrzleka, Kajže, Prelesja in Bele pri Sanaboru;
- izvedbo 4 kombiniranih sledilnih poskusov ob različnih hidroloških razmerah v letih 1993 (injiciranje v Belem breznu in v vrtačo pri Zavrhovcu), 1994 (injiciranje v Belem breznu, v vrtačo pri Zavrhovcu in v Mrzlem logu ter v Lokvo pri Predjami) in 1995 (injiciranje v mesecu avgustu v Belo brezno, v vrtačo pri Zavrhovcu in pri Malem polju ter oktobra v Slapenski ledenik na Nanosu in v Lokvo pri Predjami). Opravljeno je bilo tudi sledenje Korentana. Uporabljena so bila sledila: uranin, piranin, bakteriofagi, litijev in stroncijev klorid;
- podrobne izotopske in fizikalno-kemične analize vodnih valov Vipave in Hublja.

10.3 REZULTATI RAZISKAV

Podrobno geološko in hidrogeološko kartiranje ožjega zaledja Hublja je pokazalo, da leži ta izvir v dnu izrazite, ozke in visoke strukturne depresije v narivni ploskvi Trnovskega pokrova. Izviri se pojavljajo v nadmorski višini 240 do 265 m. Vode večinoma pritekajo po korozijsko razširjenih lezikah. Hidravlični gradient podzemeljske vode za izvirom je zelo strm, čemur je verjetno vzrok slaba prepustnost jurskih apnencev, oblika flišne podlage pri Hublju in neotektonski premiki, kjer kraška korozija zaostaja za hitrostjo dviganja (poglavje 2.6.3).

Nastanek morfološko izrazite zajede pri Vipavi (usmerjena je od zahoda proti vzhodu) povezujemo s tektonsko pretrtostjo apnenca kot tudi z močnimi tokovi podzemne vode v zaledju vipavskih izvirov. Voda z intenzivnim korozijskim delovanjem odnaša velike količine raztopljenega apnenca. Pri tem ne more ustvariti večjih odprtih jamskih prostorov, saj se kamnina zaradi pretrtosti

sproti sesipa. Zatrep Skalnice je še v nastajanju. Med Vipavo in Vrhpoljem je zahodno pobočje Nanosa reliefno enolično oblikovano z mirnim nagibom proti zahodu, enakim vpadu skladov zgornjekrednega apnenca. Vanje je Bela urezala svojo strugo. Na smer struge ima največji vpliv plastnatost apnenca. Apnenec je nekoliko bolj pretrt južno od Vrhpolja, kjer Bela ponika, v Vipavi pa je apnenec spet kompakten in nepretrt, z redkimi razpokami (poglavje 2.6.4).

Na osnovi meritev pretokov so bile izračunane značilne vrednosti za opazovane izvire v času od 1993 do 1995. Opravljene so bile dodatne meritve za izračun povrnjenih količin sledil v sledilnih poskusih. Z vzporednimi meritvami padavin in pretokov voda ter evapotranspiracije za obdobje, daljše od dveh let, je bila narejena vodna bilanca Trnovsko-Banjške planote, ki je pokazala glavni odtok voda v Sočo (Mrzlek), manj v Idrijco in najmanj v Vipavo (poglavje 3.2). Razporeditev padavin se na Trnovsko-Banjški planoti od kraja do kraja zelo spreminja. Jeseni 1993 je bilo ob padavinah ugotovljeno, da reagira Hubelj na padavine najhitreje, v treh do petih urah, in da se nekaj urne prekinitve že odrazijo v njegovem pretoku. Pretok Vipave reagira s 6-urnim zaostankom, čisto drugače pa reagira Lijak, namreč z znatno večjim zaostankom za padavinami. Ostaja pa nerešeno vprašanje Mrzleka, ki se izliva neposredno v Sočo in zato ni mogoče meriti njegovega pretoka (poglavje 3.3).

Onesnaženje izvirnih voda je še sorazmerno majhno. Večina vodnih vzorcev ni prekoračila normativov glede kemičnih parametrov. Vendar pa so v sedimentih relativno visoke koncentracije živega srebra, kadmija, svinca in bakra. Policiklični aromatski ogljikovodiki in fenolne spojine so pogosto prisotne v vodnih vzorcih Vipave, Hublja in Podroteje. Določene so bile tudi številne spojine v vodi in sedimentih, ki izvirajo iz onesnaževanja zaradi različne človekove dejavnosti na površju. Izvira v Čepovanu sta onesnažena s policikličnimi aromatskimi ogljikovodiki - voda in sediment. Sediment pa je onesnažen tudi s težkimi kovinami. V vseh vodnih vzorcih pa so bili določeni estri ftalne kisline, pri katerih je bil v času treh let ugotovljen trend naraščanja. Kemične analize sedimenta Hublja, Vipave in Podroteje kažejo na onesnaževanje njihovega zaledja, na občasno onesnaženje pa so pokazale tudi mikrobiološke analize vode Podroteje, Hublja in Vipave (poglavje 2.7.1). Virološke analize voda niso dokazale prisotnost katerega koli patogenega virusa iz skupine Picornaviridae niti ob nizkem niti ob visokem vodostaju.

Preiskava favne izvirov Vipave, Kajže in Ajbe je pokazala, da imajo vode, ki se stekajo s TBP, majhno vsebnost organskih snovi in temu primerno sestavo faune - bogato favno z majhnim številom vrst (poglavje 3.8).

Na območju TBP prevladujejo plitva tla, globine 10 do 50 cm, z nizko kapaciteto za zadrževanje vode. V primeru intenzivnih padavin tla niso sposobna zadržati vse vode, zato se lahko pojavi izpiranja hranil. Delež evapotranspiracije v rastni dobi je v letih 1993 in 1994 znašal 40 % deleža padavin. Površinska mineralna bilanca za leto 1991 je pokazala nizke bilančne presežke dušika, ki so pod slovenskim povprečjem. Le posamezne kmetije presegajo to

povprečje, vendar nobena ne dosega 100 kg/ha. Večje presežke dušika pa lahko povzroči intenzivnejša živinoreja. Iz tega sledi, da je potrebna določena stopnja selektivnosti pri uvajanju omejitev rabe gnojil in gostote živali med regijami z različnimi naravnimi potenciali za kmetovanje (poglavje 2.7.2).

Za preučevanje hidrodinamičnega značaja izvirov Hublja in Vipave sta bili uporabljeni metodi korelacije in spektralne analize časovnih serij dnevnih padavin in pretokov za obdobje 1985 - 1995. Rezultati opravljenih analiz so pokazali, da lahko vodonosnika v zaledju izvirov Hublja in Vipave opredelimo kot kraška sistema tipa Aliou z zelo učinkovito drenažno mrežo. Čeprav nekateri drugi hidrološki pokazatelji kažejo značilne razlike med obema sistemoma, je bil z analizo časovnih serij ugotovljen zelo podoben hidrodinamični režim. To podobnost lahko interpretiramo kot nasproten efekt med geološkimi in geomorfološkimi karakteristikami, ki naj ne bi olajševale razvoja učinkovite drenaže, in potencialom zakrasevanja, ki je v obravnavanem primeru zelo pomemben. Količina padavin v povezavi z gosto vegetacijo, ki proizvaja CO_2, dejansko omogoča, da voda ustvari učinkovite drenažne kanale in zelo hitro oblikuje podzemni sistem (poglavje 3.4)

Hidrološka analiza dnevnih pretokov Hublja in Vipave v obdobju 1961-1990 je nakazala tako podobnosti kot tudi razlike v hidrodinamičnem delovanju obeh izvirov. Krivulji srednjih pretokov sta praktično identični, določeno ujemanje režimov pa kaže tudi analiza krivulje recesije ali krivulje praznjenja. Ta ima pri kraških vodonosnikih kompleksno obliko, kjer je vsak odsek na krivulji definiran s svojim koeficientom praznjenja in opisuje različne tipe odtoka od hitrega toka iz velikih kanalov do počasnega iz por in ozkih razpok. Za prvi in drugi odsek krivulje so bile s statistično primerjavo izračunanih koeficientov ugotovljene podobnosti v delovanju Vipave in Hublja. Drugače pa je pri tretjem odseku, ki predstavlja bazni tok, saj je srednji koeficient praznjenja pri Vipavi dvakrat manjši kot pri Hublju. Razlog je lahko manjši hidravlični gradient ali manjša prepustnost vodonosnika, ki napaja izvire Vipave (poglavje 3.5).

Specifična električna prevodnost (SEP) lahko služi tudi kot indikator hidrodinamičnih procesov. Na osnovi meritev SEP vsakih 5 minut in ob shranjevanju povprečne vrednosti vsakih 15 min je bilo za vse izvire Vipave ugotovljeno (poglavje 3.6), da večji del pretoka v vodnem valu predstavlja "starejšo" vodo iz rezervoarja. Delež "mlajše" vode v vodnem valu pa je dosegal največ 27 %. Srednji letni delež "mlajše" vode vodnih valov pa je dosegal preko celega leta 10 % celotnega pretoka. Ob višjih pretokih imajo izviri Vipave 4/1-4/5 večji delež "starejše" vode. Te ugotovitve se lepo skladajo z rezultati raziskav z izotopi (poglavje 5.1), kjer je znašal izračunani delež "mlajše" vode v pretoku izvirov 21 % za izbrane posamezne vodne valove.

Raziskave so pokazale tudi na razlike izvira 4/7 od ostalih izvirov, kar so pokazale tudi fizikalno-kemične analize izvirov Vipave (poglavje 4.1.4). Hidrogrami izvirov Vipave 4/6-4/7 se razlikujejo od izvirov 4/1-4/5, še posebno v vodnih valovih. V opazovanih vodnih valovih jeseni 1994 je delež "mlajše"

vode upadel pri izvirih 4/6-4/7 pod 10% v 2 dneh, pri 4/8 in izvirih 4/1-4/5 pa v 12 dneh. To nakazuje, da nastopata v izviru 4/7 dve komponenti pretoka, prva iz skupnega zaledja z izviri 4/1-4/5 in druga iz območja Bele. Razvidno je, da infiltrirane padavine ne prispevajo direktno k pretoku izvirov, ampak vplivajo nanj posredno, le v večjih vodnih valovih pa vplivajo na pretok delno neposredno.

Mesečne meritve temperature izvirnih voda tekom dveh let so pokazale nihanja v ozkem temperaturnem intervalu. V Podroteji in Vipavi temperatura sezonsko niha, manj izrazito pa v Hotešku in Kajži. Meritve temperature in ostalih parametrov, tudi izotopov Mrzleka na izviru in v črpališču, pa so pokazale, da se v sušnih obdobjih mešanje izvirne vode in Soče premakne globoko v izvir. Pri Podroteji smo zabeležili najnižje vrednosti razmerja Ca/Mg, z najmanjšimi nihanji preko leta, podobno kot tudi pri temperaturi, kar kaže na dolgo zadrževanje vode v zaledju oz. močno dušenje padavinskih vplivov. Podobno smo zabeležili tudi pri Mrzleku in Hotešku. Vipavo označuje višje razmerje Ca/Mg z večjimi nihanji preko leta. Vsebnost kalcija v Vipavi ob naraščanju pretoka preko 10 m^3/s upada, medtem ko v Hublju ni večjih sprememb kalcija, vendar pa upada vsebnost magnezija. Vipava dosega preko leta opazno višje vrednosti celokupne trdote kot Hubelj, kjer smo zabeležili najnižje vrednosti v okviru opazovanj vseh izvirov. Vsebnost kloridov je bila pod 4 mg/l, z izjemo Belščice. Vsebnost nitratov (povprečne vrednosti) je bila pod 6.5 mg NO_3^-/l. Najvišje vrednosti sta imeli Vipava in Belščica (do 10 mg/l), Vipava celo nekoliko višje kot Belščica. Vsebnost sulfatov je bila pod 11 mg SO_4^{2-}/l, višje vrednosti, do 18 mg SO_4^{2-}/l, smo zabeležili v Belščici, Prelesju in Beli (poglavje 4.1.1).

Tedensko spremljanje istih parametrov je pokazalo največjo spremenljivost SEP in vsebnosti bikarbonata; nihanja pa so bila večja v Vipavi kot v Hublju. Z AARDVARK (WRc 1995) sezonskim modelom je bilo ugotovljeno, da se zaledje Hublja v različnih hidroloških razmerah ne spreminja zelo, medtem ko prihaja v zaledju Vipave do večjih sprememb. Izkazalo se je tudi, da zadostuje enoletno tedensko vzorčevanje, saj v triletnem opazovanju ni bilo večjih razlik med leti (poglavje 4.1.3).

Ob nizkih in najnižjih vodah Vipave so bile opravljene fizikalno-kemične analize vseh izvirov za njihovo medsebojno primerjavo. Pokazale so odstopanje izvira 4/7 Pod farovžem od ostalih izvirov. Izvir 4/7 je dosegal višje vrednosti SEP, celokupne trdote, vsebnosti karbonatov, kalcija, nitratov in sulfatov. Nihanja merjenih parametrov so bila v izviru 4/7 preko leta manjša kot v ostalih izvirih, vendar pa so razlike med izviri 4/1 do 4/6 v določenem trenutku minimalne (poglavje 4.1.4).

Za podrobnejši pregled kvalitete vode v izvirih, kot tudi za primerjavo s tedenskim vzorčevanjem, so bili dnevno vzorčevani Hubelj, Vipava in Mrzlek. Pokazalo se je, da bi za ugotovitev teh karakteristik izvira zadostovala že tedenska vzorčevanja preko enega leta. Vzporedno vzorčevanje Mrzleka na

izviru in v črpališču je pokazalo v sušnem obdobju višjo vsebnost magnezija in nižjo kalcija na črpališču, kar kaže na vpliv Soče (poglavje 4.2.1).

Fizikalno-kemične analize vzorcev vodnega vala Vipave - Pod lipo 4/2 novembra 1995 so v prvem manjšem povečanju pretoka pokazale na vzporedno povečanje SEP, vsebnosti karbonatov, kalcija in celokupne trdote. To je v manjši meri izraženo tudi v začetnem delu drugega, izdatnejšega vodnega vala. Sklepamo, da je prišlo najprej do iztiskanja starejše in trše vode iz slabo prepustnega dela zaledja in šele kasneje do mešanja z mlajšo vodo, vendar pa je delež direktne komponente sorazmerno majhen, saj je SEP upadla največ za 25 μS/cm, vsebnost karbonatov, kalcija in celokupne trdote pa za 0.5 mekv/l. Sočasno spremljanje izotopske sestave ^{18}O padavin in izvira Vipave je podala 21 % delež direktne komponente. Ob kasnejšem upadanju pretoka v vodnem valu je prišlo do naraščanja vrednosti vseh omenjenih parametrov, ki se je intenziviralo pri pretoku nekako 10 m^3/s (poglavje 4.2.2).

Ker vode s flišnega območja okoli Postojne vsebujejo znatno višjo vsebnost silicija (Si) kot kraško območje Nanosa in Hrušice, je bil Si uspešno uporabljen kot naravno sledilo v vodnem valu za ugotovitev flišne komponente v izvirih Vipave. Konec marca 1996 so izdatne padavine, ki so na območju Nanosa in Hrušice prešle v sneg, oblikovale izdaten vodni val Vipave, ki mu je sledil položen vodni val zaradi taljenja snega. Povišane vsebnosti Si s flišnega območja so se v izvirih Vipave pojavile šele po 4 dneh in 12 urah, kar je glede na ekstremne hidrološke razmere primerljivo s sledenjem z uraninom leta 1994 (poglavje 6.3.3). Z ločitvijo hidrogramov je bilo ugotovljeno, da se je pojavilo v izvirih Vipave najmanj 10 % flišne komponente. Za obdobje pred vodnim valom je bil ta prispevek zelo konstanten in je znašal 9 %, kar pomeni, da je 9 % ali približno 13 km^2 zaledja Vipave na flišnem območju. Vsekakor pa bi bilo potrebno za podrobnejše opredelitve opraviti še daljša opazovanja Si, najmanj 1 leto (poglavje 4.2.3).

Okoljski izotopi, devterij, tricij in kisik-18, so zelo pomembni za sledenje izvora voda, saj so sestavni deli vode. Za izbrane izvire: Kajžo, Hotešk, Podrotejo, Hubelj, Mrzlek in Vipavo so bili izračunani na osnovi meritev ^{18}O srednji zadrževalni časi od 4.4 do 5.8 mesecev in disperzijski koeficienti (poglavje 5.1.4.2). Meritve mesečnih vzorcev tricija v padavinah in izviru Vipave kažejo na sorazmerno kratek srednji zadrževalni čas vode v podzemlju, ki znaša 0.4 leta, kar sovpada z rezultati na osnovi meritev ^{18}O. Ker se zdi ta čas prekratek, je zelo verjetno, da gre za dve komponenti, prvo z zadrževalnim časom nekaj tednov (kraški kanali) in drugo z zadrževalnim časom nekaj let (iztok iz manj prepustnih delov kraškega masiva). Za določitev teh dveh komponent pa bi bila potrebna daljša opazovanja. Podrobno spremljanje izotopske sestave ^{18}O padavin in izvira v vodnem valu omogoča določitev deleža vode, ki priteka v izvir po prepustnejših kanalih. Za izvir Vipave je bilo to mogoče le v vodnem valu novembra 1995, ko je bilo ugotovljeno, da je vodni delež direktne komponente 21 %. Ta ugotovitev se dobro ujema z ugotovitvijo

na osnovi meritev SEP, da znaša maksimalni delež direktne komponente 27 % (poglavje 3.6.3) in rezultatom meritev ^{18}O v vodnem valu ob taljenju snega, kjer naj bi bil ta delež 31 % (poglavje 5.3). V vodi Hublja je bil delež direktne vodne komponente v vodnih valovih konec avgusta in septembra 17 in 15 %, spomladi, v vodnem valu ob taljenju snega, pa 24 % (poglavje 5.3). Močno [illegible]

Vzporedno z naštetimi raziskavami so potekali kombinirani sledilni poskusi za ugotovitev podzemnih povezav kot tudi za ugotavljanje hidrodinamičnih značilnosti kraških sistemov ob različnih hidrodinamičnih pogojih. Ob prvem sledenju 14.oktobra 1993 je bil injiciran uranin v Belo brezno v osrednjem delu Trnovskega gozda in bakteriofagi v vrtačo pri Zavrhovcu nad Hubljem. Ob sledečem sledenju 16. aprila 1994 je bilo ponovljeno injiciranje pri Zavrhovcu (bakteriofagi in LiCl) in v Belem breznu (uranin), v Mrzlem logu sta bila injicirana piranin in $SrCl_2$, v Lokvo pri Predjami pa uranin. Ker sta bili omenjeni prvi dve sledenji izvedeni ob srednjem in visokem vodostaju (razen sledenje z bakteriofagi pri Zavrhovcu v letu 1993, ko je bil nizek vodostaj) je bilo tretje injiciranje izvedeno 1.avgusta 1995, ko so bili pri Zavrhovcu ponovno injicirani bakteriofagi in v Belem breznu uranin; v bližini Malega polja pa piranin. Dodatno sledenje ob nizkem vodostaju je bilo izvedeno 26. oktobra 1995, ko je bil v breznu Slapenski ledenik injiciran uranin, v Lokvo pri Predjami pa piranin (poglavji 6.1 in 6.2).

10.4 SLEDENJA V ZALEDJU MRZLEKA, HUBLJA IN LIJAKA

V prvem sledenju oktobra 1993 je bilo 29 % uranina (navedene so izračunane vrednosti glede na srednji pretok za obdobje 1993-95) iz Belega

brezna ugotovljenega v Mrzleku, 10.1 % v Lijaku in 2.14 % v Hublju po izdatnem deževju konec oktobra. Povrnjene količine sledil za Mrzlek glede na srednji pretok za obdobje 1961-1990 so v primerih vseh sledenj nekoliko višje. Najhitreje je uranin potoval proti Mrzleku (v_{dom}=92.4 m/h), počasneje v Lijak (v_{dom}=56.6 m/h) in najpočasneje v Hubelj (v_{dom}=19.4 m/h). Ugotovljene so bile večje razlike v koncentracijah Lijaka na izviru in v vrtini (poglavje 6.3.2.1). V nadaljevanju pod pojmom hitrosti pretakanja navajamo dominantne hitrosti, ki so le navidezne, saj so realne hitrosti višje.

V drugem sledilnem poskusu spomladi 1994 se je uranin iz Belega brezna pojavil v Mrzleku in Hublju, presenetljivo pa ne v Lijaku, čeprav je bila injicirana količina uranina enaka tisti v letu 1993. Uranin se je v obeh izvirih pojavil prej kot ob sledenju oktobra 1993, vendar je bila maksimalna koncentracija v Hublju znatno nižja, v Mrzleku pa višja. Hitrost pretakanja v Mrzlek je bila 62.8 m/h, v Hubelj pa 16.6 m/h, torej manjša kot ob prvem sledenju. Tudi povrnjena količina uranina je bila v Mrzleku višja (43 %), v Hublju pa le 0.02 % (poglavje 6.3.2.2). Piranin, injiciran v Mrzlem logu, je bil določen v Podroteji, kjer je oblikoval klasično krivuljo prehoda, v Divjem jezeru pa le kot posamezne povišane vrednosti. Hitrost pretakanja v Podrotejo je bila 20.1 m/h.

Tretje sledenje ob nizkih hidroloških razmerah avgusta 1995 je podalo bistveno drugačne rezultate od prvih dveh sledenj. Uranin iz Belega brezna se je pojavil najprej v Hublju. Prvi pojav uranina, kot tudi maksimalna koncentracija sta se pojavila prej kot ob prvih dveh sledenjih ob višjih hidroloških razmerah. V Mrzleku, kjer je potekalo vzorčevanje v izviru in v vodarni, se je uranin pojavil dosti kasneje in med obema zajemnima mestoma ni bilo bistvenih razlik. Hitrost pretakanja uranina v Hubelj je znašala 38.2 m/h in v Mrzlek 22.3 m/h. Povrnjena količina uranina je v Mrzleku - izvir znašala 51.4 %, v Mrzleku - vodarna pa 45.7 % in v Hublju 0.01 %. Lijaka ni bilo mogoče vzorčevati, ker je bila vrtina zamašena.

Injicirani bakteriofagi v vrtačo pri Zavrhovcu v prvem sledenju oktobra 1993 ob srednjih vodah so se pojavili le v Hublju. Povrnjena količina je znašala 0.78 %. V Skuku in Studencu pri Gorenju se niso pojavili v nobenem sledenju. V drugem sledenju aprila 1994 (bakteriofagi in LiCl) je bila ob višjem vodostaju povrnjena količina bakteriofagov 0.012 % (poglavje 6.4), povrnjena količina LiCl pa 3.1 % (poglavje 6.5). Litij se je pojavil z enodnevno zakasnitvijo za bakteriofagi, potovalna hitrost bakteriofagov pa je bila v obeh poskusih, leta 1993 in 1994, približno enaka. V tretjem sledenju ob nizkem vodostaju so se bakteriofagi dalj časa zadrževali v karbonatnem masivu, v izvir Hublja pa jih je spral šele izdatnejši dež po skoraj enem mesecu. Povrnjena količina je znašala le 0.007 %. Ker so padavine na Otlici padle šele, ko je bil prehod bakteriofagov v Hublju že zaključen, je morala priti voda, ki je sprala bakteriofage v Hubelj, iz neke druge smeri.

V Mrzlem logu sta bila ob višjih vodah aprila 1994 injicirana piranin in $SrCl_2$. Piranin se je pojavil le v Podroteji in Divjem jezeru. V Podroteji je

oblikoval klasično krivuljo prehoda, medtem ko so bile pri Divjem jezeru zabeležene le posamezne povišane vrednosti. V času opazovanj je bilo zabeležena tudi povečana vsebnost stroncija v Podroteji, kjer je koncentracija stroncija stalno in enakomerno naraščala, vendar ostaja odprto vprašanje, ali je bil to vpliv injiciranja v Mrzlem logu.

Pri Malem polju je bil v nizkem vodostaju injiciran piranin, ki se je pojavil v Podroteji in Divjem jezeru v sorazmerno nizkih koncentracijah. Potovalna hitrost je znašala 14.4 oz. 12.9 m/h in je bila nižja kot ob sledenju iz Mrzlega loga ob višjem vodostaju.

10.5 SLEDENJA V ZALEDJU VIPAVE

Sledenje Vipave spomladi 1994, ko je bil v Lokvo injiciran uranin, je pokazalo, da sta bila prvi pojav sledila in s tem maksimalna hitrost potovanja sledila dokaj enaka za vse izvire Vipave. Vzrok za razlike med izviri 4/1 do 4/6 in izvirom 4/7 je morda v biorazgrajevanju uranina zaradi onesnaženja iz hiš, ki leže tik nad izvirom, možnost pa je tudi neenakomerna adsorpcija na stenah stekleničk. Izračun povrnjene količine uranina na točki 4/8 (združen tok vseh izvirov) je pokazal 74 % injicirane količine. Ob upoštevanju omenjenih vplivov biorazgradnje in adsorpcije, pa bi bila ta vrednost višja, blizu 90 ali 100 % (poglavje 6.3.3.1). Po injiciranemu $SrCl_2$ v Mrzlem logu aprila 1994 je bilo ugotovljeno v izvirh Vipave Pri kapelici 4/1 in Pod farovžem-levo 4/7 naraščanje vsebnosti Sr ves čas vzorčevanj z določenimi prekinitvami, vendar ostaja vprašanje, če je to posledica injiciranega $SrCl_2$ v Mrzlem logu, odprto (poglavje 6.5.2).

Jeseni 1995 je bilo v Lokvo ponovno injicirano fluorescentno sledilo, tokrat piranin, ob nizkem vodostaju. Piranin se ni pojavil v izvirih Vipave, zato je možno, da se ob tako nizkih vodah, kot so bile oktobra 1995, podzemeljske vode odtekajo v smeri Timava, saj možnost razredčenja pod mejo detekcije lahko ovržemo (poglavje 6.3.3.2). Ta predpostavka je bila postavljena tudi na osnovi geološkega prereza Rakitnik - Lokva - Vipava (poglavje 7.1). V primeru piranina obstajajo tudi možnosti biološke, kemične in fotokemične razgradnje (Käss 1992) (poglavje 6.3.3).

Vzporedno so potekali tudi poskusi ugotavljanja stabilnosti vzorcev, oz. ugotavljanje razgradnje sledil (uranina) s časom ob hranjenju vzorcev v stekleničkah in plastenkah. Za vzorce Hublja so bile ugotovljene ob ponovni analizi po približno 4 mesecih enake vrednosti v okviru analitske ponovljivosti. Pri vzorcih Vipave so bile ugotovljene večje razlike med vzorci, shranjenimi v stekleničkah, ki so bili analizirani prej in med tistimi v plastenkah. Kasnejše ponovne meritve vzorcev so pokazale v stekleničkah upad koncentracije od 1 do 9 %, v plastenkah pa 3 do 100 % (poglavje 6.3.4). Opravljene so bile tudi meritve 33 vzorcev Vipave 4/2 v času 4. sledilnega poskusa z razponom

koncentracij uranina od 0.04 do 0.18 mg/m^3. Po petih mesecih v vzorcih v stekleničkah niso bile zabeležene večje razlike, pri tistih v plastenkah pa je bilo zabeleženo zmanjšanje koncentracij od 34 do 100 % (poglavje 8.1.1). Te ugotovitve kažejo na velik pomen shranjevanja vodnih vzorcev v primeru fluorescentnih sledil (uranin) v stekleničkah in ne v plastenkah.

10.6 SKLEPI

Ker so si sledilni poskusi sledili vsako leto (dovoljena je bila uporaba le dveh fluorescentnih sledil uranina in piranina), so bile narejene tudi številne meritve za določitev vrednosti ozadja (poglavje 6.3.5). Te vrednosti so na mestih vzorčevanja za uranin nihale do 0.006 mg/m^3, z izjemo Prelesja z vrednostmi do 0.037 mg/m^3, za piranin pa do 0.04 mg/m^3. V času prvega sledenja jeseni 1993 so bili ugotovljeni v Hublju emisijski signali z maksimalno valovno dolžino, ki je značilna za eozin. Določene so bile koncentracije med 0.010 in 0.115 mg/m^3. Pripadajo snovem neznanega izvora in zaenkrat to ostaja še odprto vprašanje.

Za ovrednotenje sledilnih poskusov ob bistveno različnih hidroloških razmerah je bil uporabljen tudi multi-disperzijski-model (MDM) (Maloszewski et al. 1992). Pokazalo se je, da je prenos snovi v nasičeni coni krasa v glavnem neodvisen od hidroloških pogojev in zapolnjenosti krasa z vodo. Hitrosti toka se gibljejo med 60 in 90 m/h, disperzija pa je zelo nizka (disperzijske vrednosti 20 - 30 m). Gre torej za prenos po prevodnikih v dobro razvitem krasu. Razlike v krivuljah prehoda sledila ob različnih sledenjih so posledica injiciranja v nenasičeni coni. Glede na nivo vode ob injiciranju je možno, da je zalivanje sledila z vodo ob injiciranju prešibko, da bi potisnilo sledilo v nasičeno cono. To opravijo padavine, ki sledijo, zato je zelo pomembno, kdaj nastopijo in v kakšni izdatnosti. Procesi v nenasičeni coni so zapleteni. Prepoznamo pa jih po veliki disperziji (več kot 100 m) in dolgem zadrževalnem času (poglavje 6.6).

Metodologija sledenja zavisi od številnih komponent, od katerih sta najpomembnejša primerno sledilo in učinkovita metoda za njegovo detekcijo. Seveda so pomembni tudi način injiciranja, vzorčevanja, hranjenje vzorcev ali pa kar neposredno merjenje na terenu, ovrednotenje rezultatov in njihova interpretacija. Razvoj te metodologije poteka že 30 let v okviru ATH. Fluorescentna sledila so imela glavno vlogo že vse od začetka ugotavljanja vodnih povezav prav zaradi njihove določljivosti z veliko občutljivostjo. Uranin je bil ves čas najpomembnejši. Pomemben korak je bil narejen v času raziskav v Sloveniji v letih 1972-1975 (3.SWT), ko so bile opravljene meritve s pravimi spektralnimi fluorimetri. Najnovejši fluorimetri z optičnimi vlakni, ki omogočajo merjenje insitu, pa še niso bili uporabljeni v ATH-poskusih. Tudi analizna tehnika, ki uporablja HPLC ločitev sledil, še ni bila uporabljena. Uporabljajo pa se tudi

druga fluorescentna sledila: eosin, piranin, sulforodamina G in B, rodamina B in WT, kot tudi optična belila (naftionat), radioaktivna sledila (Cr-51, In-114), bakterije in bakteriofagi. Zajemanje vzorcev poteka večinoma z avtomatskimi zajemalci, dobro obdelavo rezultatov omogočajo osebni računalniki ter uporaba matematičnega modeliranja. Metodologija sledenja je dosegla visok nivo znanja, vendar so tu še vedno odprta vprašanja sorpcije in stabilnosti sledil; v okviru opisanih rezultatov pa se je pokazal kot zelo pomemben faktor tudi izbor primernih stekleničk za hranjenje vzorcev.

Ker je uporaba umetnih sledil omejena zaradi sanitarnih vidikov, se pričakuje znaten napredek na področju izrabe naravnih sledil. Pomembno je redno spremljanje padavin in pretoka, veliko koristnih informacij pa nam da intenzivno opazovanje posebnih dogodkov ob nalivih, taljenju snega in nenadnih izlivih. Zato bi bilo potrebno izpopolniti metodologijo intenzivnega merjenja posameznih parametrov ob vzporednem zajemanju vzorcev za podrobnejše analize. V okviru projekta se je izkazalo za zelo koristno pogostno merjenje specifične električne prevodnosti z elektronskimi shranjevalci z vzporednimi meritvami padavin in pretokov (poglavje 8.3). Raziskovanje pa bo v prihodnosti še uspešnejše, če bomo razpolagali z zanesljivimi merilniki za več parametrov, ki bi ob vzporednem zajemanju vzorcev ob tistih najbolj zanimivih dogodkih omogočali njihovo vsestransko podrobno analizo.

Raziskave TBP so podale obširno znanje o tem delu slovenskega krasa, kar je osnova za njegovo varovanje in ohranitev kvalitetne vode v izvirih na njenem obrobju. Ranljivost krasa zavisi od hidrogeoloških lastnosti območja, od načina pretakanja skozi nezasičeno cono, ki je lahko glede na padavinske razmere zelo upočasnjeno, in od hidrogeoloških razmer globlje v zaledju. Med Belim breznom in dolino Soče ni hidrogeoloških pregrad in vode s tega območja v glavnem odtekajo proti Mrzleku. Položaj spodnjetriasnih in jurskih plasti, ki vpadajo proti SW, omogočajo tudi stranski tok proti Hublju. Občasno pojavljanje uranina v Hublju bi lahko bilo tudi posledica hidrogeološke strukture (dvignjene plasti fliša v ožjem zaledju). Sledenje v Malem polju je pokazalo, da voda odteka pod Trnovskim pokrovom in Čekovniško vmesno lusko proti Divjemu jezeru. Na osnovi geološke zgradbe bi pričakovali tudi zvezo s Hubljem, a je sledilni poskus ni potrdil. Teže je razložiti povezavo Mrzlega loga z Divjim jezerom, kjer mora priti voda v nižji apnenec Koševniške vmesne luske, kjer vlada kraški odtok v smeri Divjega jezera. Geološki prerez Rakitnik-Lokva-Vipava kaže, da ima Lokva normalen podzemni kraški tok v smeri Vipave brez hidrogeoloških pregrad, ob nizkih vodah pa lahko teče skozi apnenec Snežniške narivne grude proti izvirom Timave. Ranljivost bi lahko definirali tudi glede na možnost posredovanja in ukrepanja v primeru onesnaženja. Sledilni poskusi na TBP so potrdili, da se je pokazal princip enotnega varovanja celotnega območja kot pravilen, da pa je potrebno uvrstiti vsa apnenčeva ozemlja v drugo varstveno območje s strogim režimom zaščite. Prav tako bi bilo potrebno bolj varovati okolico ponikalnic na dolomitu in flišu in jih tudi uvrstiti v drugo varstveno območje (poglavji 7.1 in 7.4).

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