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Hydrogeological Conditions and the Necessity for Sanitary Protection of the Norinska River - Prud Spring, Metković, Croatia

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Abstract

A detailed description of the hydrogeological relationships in karst aquifers from this part of the Dinarides, together with the recommended conditions for their protection are given. The Norinska river spring is recharged by groundwater flow from the northwest, mainly from the Jezerac polje region, the northern part of Rastok polje and the middle course of the Trebižat river. On the basis of geological, hydrogeological, hydrological and hydrogeochemical studies, it was determined that part of the water is lost to the subsurface in the region between the Ljubuško polje and the Kravice waterfall and is later discharged at the Norinska river spring. Due to the presence of sulphate, the chemical composition of waters from springs along the Trebižat river basin (and its headwaters), is similar to waters from the Norinska river spring. The sulphate in some springs along the north and north-east valley side of the Tihaljina river is the principal anion, and since these waters contribute to the waters in the Norinska river catchment they also affect its water chemistry. Turbidity and the occurrence of fine sand at the Norinska river spring confirms the existence of developed underground channels, conduits and siphons, along which groundwater flows at velocities greater than 5 cm/s during high pluvial periods. The origin of the sulphate is attributed to the presence of gypsum and anhydrite deposits in the deeper parts of the karstic aquifer. The groundwater protection zones were determined on the basis of the groundwater flow velocities, groundwater retention, urban development and the types of industries present within the areas covered by the Ljubuški and Vrgorac municipalities. Presented map is the basis for micro-zoning and the determination of locations for future mercantile (industrial) facilities. The study was focused towards surface karst phenomena and their protection from anthropogenic influence.

1. INTRODUCTION

The geological, tectonic and morphological features of the Norinska river spring drainage basin define the catchment area and the groundwater flow conditions. The main framework of the catchment area is formed by Upper Cretaceous and Palaeogene limestones. Dolomites are less abundant, together with Upper Cretaceous dolomitic limestones and Eocene flysch deposits. The later (flysch deposits) usually function as "hanging" or complete barriers to groundwater flow. Fault and plicative tectonics have played a major role in determining groundwater flow directions towards the Norinska river spring. As a consequence of karstification in the catchment basin, fast infiltration rates are present with practically no surface runoff, and water rapidly flows towards the lowest base level of erosion, the Norin spring (-6 m a.s.l.).

This paper presents not only the hydrogeological, tectonic and geomorphological relationships of the Tihaljina and Norinska river springs, but also the chemical composition of their waters which indicate groundwater flow from the Tihaljina river to the Norinska river spring. Also, hydrological measurements on the section of the Trebižat river between the Ljubuško polje and the Kravica waterfall, indicates water loss in the drainage basin and its reemergence at the Norinska river spring. This must be verified by tracing experiments from ponors in the Ljubuško polje. The groundwater levels measured in piezometers and sink-holes in the Ljubuško polje varied from 50 to 70 m a.s.l., and in the Jezerac polje from 25 to 35 m a.s.l. while the groundwater level in the sinkhole from which water is discharged at the Norin spring is 1.6 m a.s.l. The flow rate from the "hanging" Tihaljina river in the section between Ljubuško polje and the Kravica waterfall has not yet been determined, due to the lack of hydrological measurements. Since tracing has not been performed, it is not possible to give an accurate estimation of water loss from the Trebižat drainage basin towards the Norinska river spring. The estimation made on the basis of hydrogeological, geochemical, and hydrological studies is that approximately 1 - 1.5 m^3/s of water is drained from the middle course of Trebižat river towards the Norinska river spring during the mean minimum.

2. GEOLOGY

The hinterland of the Norinska river spring consists of Upper Cretaceous and Palaeogene carbonate rocks and Eocene flysch sedimentary rocks (Fig. 1). Quaternary deposits are widespread in the middle course of the Tihaljina (Mlada) river and in the Ljubuško, Rastok and Jezerce poljes. Along the course of the Trebižat river from Ljubuško polje to the Kravica waterfall and fur-

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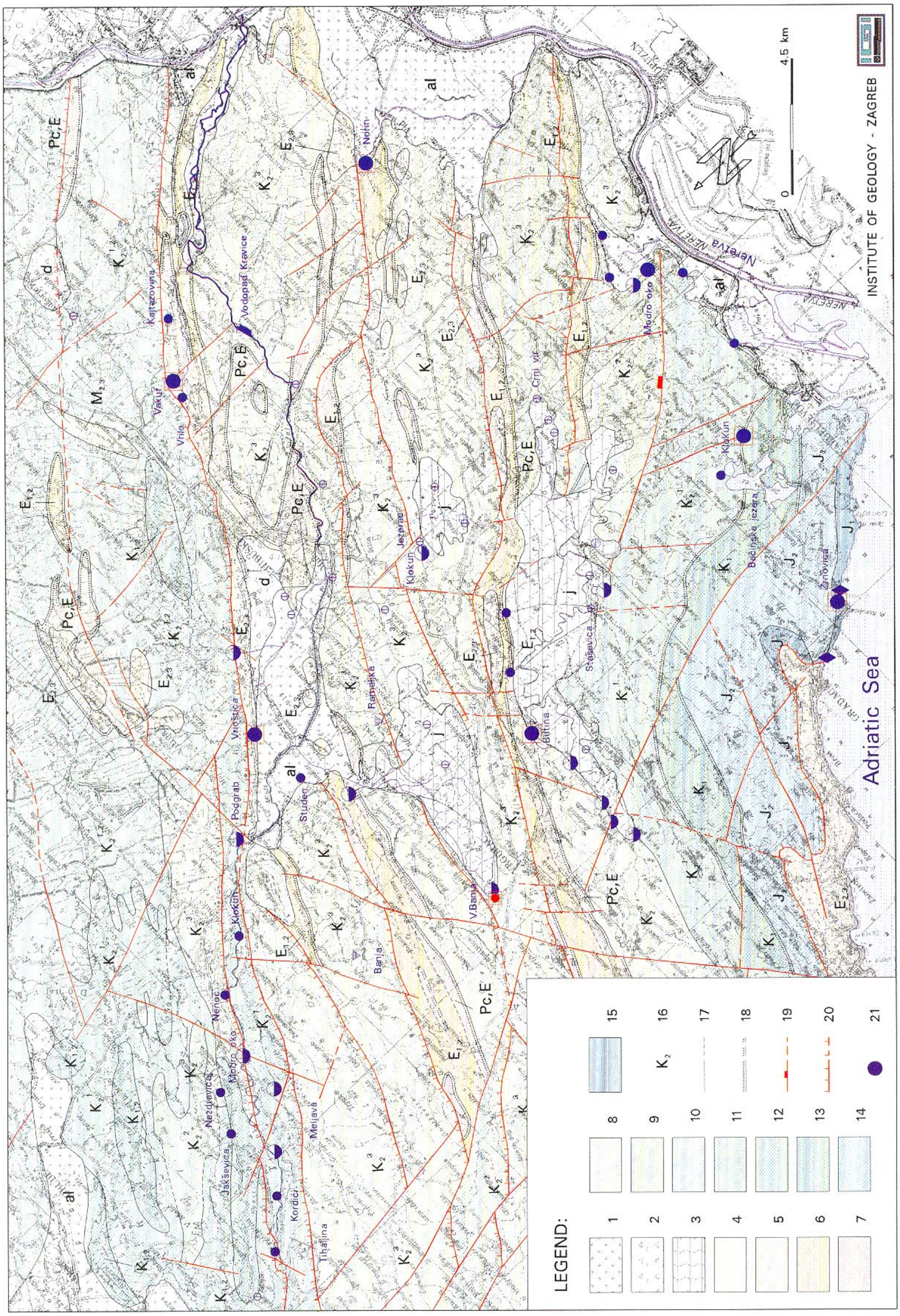

Fig. 1 The regional geological map (after RAIĆ et al., 1975 and MARINČIĆ et al., 1977 - simplified). Legend: 1) alluvial deposits; 2) deluvial deposits; 3) lake and marsh sediments; 4) Miocene marls and conglomerates; 5) Eocene flysch deposits; 6) Eocene foraminiferal limestones; 7) Palaeocene-Eocene marly limestones; 8) Upper Cretaceous limestones; 9) Upper Cretaceous limestones and dolomites; 10) Upper Cretaceous limestones with chondrodonts; 11) Cretaceous limestones and breccia; 12) Lower Cretaceous dolomites, limestones and breccia; 13) Lower Cretaceous dolomites and breccia; 14) Upper Jurassic limestones; 15) Lower Jurassic thin-bedded limestones; 16) stratigraphic symbol; 17) geological boundary; 18) unconformity; 19) normal fault; 20) overthrust; 21) karst spring - see legend on Fig. 2.

ther down the course where it joins the Neretva river, the river bed is "coated" with tuffa deposits which function as a partial barrier.

The studied area is located within a thick complex of Cretaceous and Palaeogene limestones, limestone breccia and dolomitic limestones. The clastic sedimentary deposits of Eocene, Oligocene, and Quaternary age are less abundant. The oldest deposits determined are Albian-Cenomanian dolomites and dolomitic limestones, which form the crest of a recumbent fold, situated northeast from Ljubuški, and which have the positive hydrogeological function of a footwall and lateral barrier.

Structurally, the studied area represents a small section of the Outer Dinarides tectonic unit (RAIĆ et al., 1975; MARINČIĆ et al., 1977). The principal characteristics of this unit, are the carbonate shelf development of Mesozoic deposits, and the high degree of tectonic disruption. The structural and tectonic features were shaped during the Alpine orogeny with a maximum during the Pyrenean phase (Eocene-Oligocene). The structures are often overturned and recumbent with the typical Dinaric strike. The faults that have a northwest-southeast strike are usually reverse in character and have a northeasterly dip. The axial planes of the folded structures also have Dinaric strike direction as a consequence of tangential stress from the northeast. A second less pronounced fault system intersects the strike direction of the folded structures, both perpendicularly and diagonally. However these faults are more important in a hydrogeological sense, since they intersect the groundwater flow directions from higher western Herzegovina horizons.

The younger Oligocene and Neogene tectonic movements have not considerably altered the structural framework formed by tangential stress. During these periods, radial movements predominated and the uplift of land surfaces occurred together with the formation of Neogene freshwater basins. The youngest tectonic movements were very intensive and caused the reactivation of some faults, the formation of new ones, and folding of the Neogene sedimentary rocks and the shaping of recent morphology.

The studied area is a part of the Svitava-Ljubuški tectonic unit characterized by the NW-SE Dinaric fault strikes, as well as transverse and diagonal faults, which often act as flow paths for groundwater from the Trebižat drainage basin towards the Norin spring catchment (Fig. 1).

To the northeast of this tectonic unit lies the Stolac-Čitluk tectonic unit. This unit is characterized by numerous normal, plunging and recumbent folds, together with radial and reverse faults. The most conspicuous is the "Klobučko-Ljubuški" overthrust the crest of which strikes from Klobuk in the west, through Ljubuški towards Čapljina. Along this overthrust a number of springs are present at Klokun, Vrioštica and Studenci, and also a series of smaller permanent and intermittent karst springs can be found.

3. GENERAL HYDROGEOLOGICAL RELATIONSHIPS

The studied area forms part of the Dinaric karst (i.e. the middle belt) and it has all the features of deep karst terrains. Specific hydrogeological relationships dominate in these settings as a consequence of their tectonic and geomorphological evolution. These relationships are viewed as dynamic and changeable in space and time. The hydrogeological map shown in Fig. 2 outlines the rock types according to their hydrogeological functions. The division is based on lithological characteristics, tectonic relationships, geomorphology and hydrogeological phenomena. Terrains with high, medium and low permeability were separated from terrains which are either impermeable or partly hinder groundwater flow (SLIŠKOVIĆ, 1991).

A subsurface composed of permeable well karstified Cretaceous and Tertiary carbonate rocks underlies most of the studied area. The Cretaceous limestones, Palaeocene-Eocene limestones with their alveolina and nummulite fauna are considerably karstified, and as such have a cavernous and fissure type of porosity. These rocks exhibit all the surface and subsurface morphological features that characterize karst areas. They are rocks of high permeability which function as hydrogeological collectors. The region lacks permanent surface flows except for the Trebižat river, which owes its permanent flow to the numerous high-yielding springs along its course on the north-northeast bank and the clogging caused by the deposition of Quaternary sediments. Also, all of the registered ponors and zones of suffosion percolation, i.e. areas characterized by water loss from the water bed are connected with the occurrence of Upper Cretaceous and Palaeocene-Eocene limestones.

Dolomites and dolomitic limestones are mainly characterized by the cavity-fissure type of porosity, while cavernous type is rarely found. These are rocks of general low permeability and are rarely characterized by good permeability. Some anticline structures (e.g. the structure north of Ljubuški) have lower permeability when compared to neighbouring rocks and therefore act as relative barriers in the near surface regions, and as a full barrier in deeper horizons. Upper Cretaceous dolomites with limestone lenses which are found on the north-northeast valley side of the Tihaljina river, from Podgrab to the Tihaljina spring do not practically function as a barrier, because water is drained through these rocks and emerges at the Klokun, Modro Oko, Nenoć, Nezdravica, Jakšenica and Kordići springs. These dolomites do not weather as typical karstified limestones but have a crumbly sucrosic dolomites appearance.

Impermeable rocks are composed of a complex of Eocene flysch and Miocene clayey marl rocks. These rocks are also characterized mainly by cavity-fissure type of porosity, while cavernous type is rarely found. They often act as either lateral and/or footwall barriers within overthrust structures. The Eocene flysch deposits

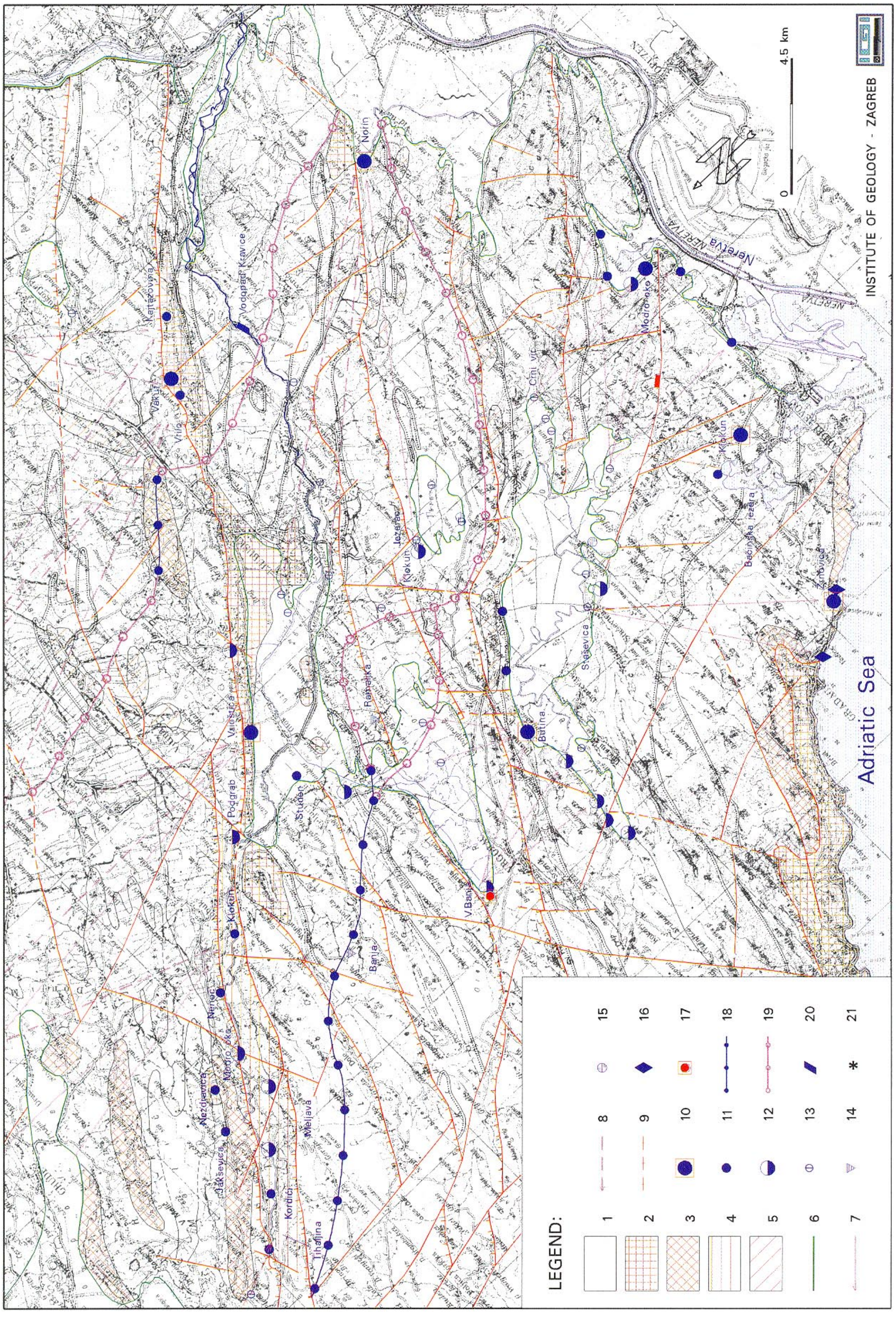

Fig. 2 The regional hydrogeological map (simplified). Legend: 1) permeable area; 2) complete topographic barrier; 3) complete subsurface barrier; 4) relative barrier; 5) partial "hanging" barrier; 6) karst polje; 7) groundwater flow direction - proven; 8) groundwater flow direction - supposed; 9) drainage tunel; 10) spring >1000 l/s - water supply site; 11) spring 10-1000 l/s; 12) intermitent karst spring; 13) swallow hole; 14) pit with water; 15) estavelle; 16) brackish coastal spring; 17) drilled production well; 18) subsurface water divide; 19) subsurface water divide zone; 20) waterfall; 21) geological features - see legend on Fig. 1.

clearly exhibit the features of a lateral barrier along the Studenci-Ljubuški-Klobuk Upper Cretaceous limestone overthrust. As a consequence of its structural and morphological position and its hydrogeological features, all the waters from the far northern and northwestern areas overflow at the contact between the impermeable flysch deposits and the karstified limestones.

The complexity of the hydrogeological function of the Eocene flysch is best manifested by the existence of karstified limestone areas at Humac southeast of Ljubuški. These are probably thin basal deposits which overlie the karstified Lower Eocene or Upper Cretaceous limestones (Fig. 2). Disrupted and uplifted Eocene flysch deposits along the traverse from Vrgorac through Polog, Pozla gora and Nova sela to Vid, act as a hanging barrier for the neighbouring groundwater and are also the zone divide in this part of the drainage basin. The Eocene flysch deposits northeast of Norin spring in Crnići and Duboka draga direct the groundwater that flows from the northwest.

The Quaternary deposits are characterized by intergranular porosity except for calcareous tuffa which has a sponge-like structure. It is possible to distinguish very permeable gravel deposits in Gabelsko polje, alluvial deposits with good permeability around the river bed area of Trebižat river, and deposits of low permeability such as colluvial, deluvial and lake sediments composed of debris, clay, lake lime and sand-silt sediments in the Ljubuški, Vrgorac (Rastok) and Jezerce poljes. Their thickness is small, on average 5-10 m, which allowed the frequent lake water to develop cone ponors through which water is lost.

The calcareous tuffa "padding" and cascades on the Trebižat river are permeable, but are less permeable compared to the rudistid limestone forming the riverbed, therefore the calcareous tuffa slows down the infiltration rate of the water from the "hanging" river into the karstified limestone.

4. THE CATCHMENT BASIN

Detailed analysis of the lithological, tectonic, hydrogeological and hydrological relationships, allowed an provisional delineation of the Norinska river spring catchment area. The divides outlined should be considered with reservation as the position of groundwater divides in karst terrains can change as consequence of the groundwater dynamics. This fact causes problems in the determination of the exact zones for sanitary protection. Besides the waters from the immediate catchment area, the Norin spring is recharged by waters from the northwest, from Rastok polje, the Jezerce drainage basin, and also from part of the ponors in the Vitinsko-Ljubuški polje, and from the Šipovača, Varašovići, Humci and Bijača karst plateaux. Ponor tracing in the southern rim of the Rastok and Jezero poljes determined the connection from Potpolog towards the springs at the northern end of the Jezero polje. This allowed the groundwater divide to be outlined south of Vrgorac through Jezerce and the structure Nova Sela-Vid (PAVIČIĆ & IVIČIĆ, 1997). The northeastern boundary of the catchment basin has not yet been determined as a part of the waters from the Trebižat and Tihaljina recharge the Norinska river spring (SLIŠKOVIĆ, 1994).

The western boundary of the catchment basin is also zoned and therefore cannot be accurately defined. It can be outlined approximately from Vrgorac, through Kruševica in the direction of the Tihaljina river spring.

The studies show that the position of the divide depends on the groundwater level. During high groundwater levels the water overflows into several catchment basins, while during low groundwater levels the water flows towards the lowest erosion base level, i.e. the Norin spring. The Tihaljina river is a "hanging" river, due to fact that the groundwater levels in the karstified limestones of the lower karst plateaux (Vašarovići and Humci) are at depths of 6 to 50 m a.s.l., and in the karst poljes 0 to 15 m a.s.l. and along the course of the Tihaljina river prior to the Kravice waterfall at the depth of 0 to 20 m. It can be concluded that the Tihaljina river is the major contributor to the recharge of the Norinska river spring. The shallow valley of the Trebižat river is incised into an ancient fluvial landscape. Its flanks consist of karstified limestones, and the river bed of redeposited calcerous tuffa, sand and clay. Along the section between Humac and the Kravice waterfall no springs occur, while low capacity ponors exist along the north and south side of the valley at the contact with limestones. These ponors drain the waters from irrigation channels which do not have concrete linings. Also in this part of the river water is lost via the river bed, and this is especially pronounced during the dry season when the groundwater levels are lower then the river water levels. Hydrological measurements at Humac and above the Kravica waterfall show a water loss of 1.5 m^3/s, which is probably a consequence of a partly permeable river bed. This indicates that the Trebižat river valley is in an evolutionary sense, in the hanging valley formation phase. From this valley, water is lost towards lower erosion base levels in the direction of the Norin spring and the Neretva river.

The groundwater from the aquifers formed in the Šipovača, Varašovići and Humac karst plateaux, and the Rastoka polje and the Jezerce polje, are drained through a complex system of channels, caverns, siphons and fissures and emerge at the Norin spring. The surface is covered by a thin layer of terra rossa soil and debris in a clay matrix. In the karst poljes the thickness of the lake sediments varies from 5-10 m. Intermittent springs occur on the northwestern and northern edges of the poljes (Vrgorska Banja, Šipovačka Banja, Studena and estavellas at Varašovići) and also on the northwestern rim of Jezerce polje (Klokun). Permanent water flow is present along the Perilo-Brza channel which brings water from the Tihaljina river into the Rastok polje. Below the polje and Varašovići a large quantity of groundwater exists even during the dry season. This is confirmed by groundwater levels in the Romaljka sinkhole in which the minimal groundwater levels are at -18 m, and the quantity of water pumped during the extremely dry seasons is 10-15 l/s.

After the high waters from Rastok polje sank they emerged again at the Klokun intermittent spring in Jezerce, flooded the polje, and sank again in the ponor in the middle of the polje at Virina and at the rims of the polje. These waters finally reemerge at the Norin spring. During extremely high water levels the waters also sink in swallow holes at the southern edge of the polje.

Groundwater reservoirs to northwest from the crest of the Čapljina-Studenci-Klobuk thrust are very large and give rise to the occurrence of high yield karst springs (Tahljina, Kordići, Klokun, Podgraba, Vrioštice and Studenački springs) with an average total yield of 12 m^3/s. Only a small fraction of this water sinks again in ponors at Humac and along the course of the Trebižat river.

In a series of karst springs, commencing from Ljubuški polje, the first intermittent spring occurs as Grabovo Vrilo (vrilo = spring) in the Podgrab village. The maximal yield is higher than 5.0 m^3/s, and it is dry 2-3 months annually. The spring is of the overflow type so that water wells can be drilled in the hinterland. At Vitina the Vrioštice spring has the highest yield with Q_{min}=1.25 m^3/s and Q_{max}=16 m^3/s. On the basis of flow differences measured with flowmeters at Grab and Humac an average flow of 6.9 m^3/s has been calculated.

From the Trebižat river water is lost in ponors along its course from the bridge at Humac to the Kravica waterfall. These waters emerge at the Norin spring or in the river bed down-stream from the Kravica waterfall. However, this still has to be confirmed by ponor tracing at Humac.

At the Studenci village, the Trebižat river is joined by waters from its tributary Studenčica which is fed by several major springs: Vrilo with Q_{min}=0,4 m^3/s, Vakuf with Q_{min}=1.9 m^3/s and Kajtazovina with Q_{min}=0.7 m^3/s. These springs are situated along a 2 km interval at the boundary between Upper Cretaceous limestone and Eocene flysch deposits.

The Norinska river spring is an **upward** spring with 1:8 outflow ratio (oscillations Q_{max}=20.0 m^3/s and Q_{min}=2.5 m^3/s). The water outflow occurs from a cone shaped depression 12 m in diameter and 8 m deep. This is the most significant spring in the lower course of the Neretva river, and as such, is the backbone of the regional water supply. The capacity of this spring is such that it can supply half a million people in the central Dalmatian region with potable water, although today only 10% (280 l/s) of its minimal capacity is used. The hydrogeological features of the drainage basin are poorly studied. Only one tracing was performed for the elaboration of the sanitary protection project. The protection of this spring is closely connected with the protection of springs in the Trebižat river catchment basin, because the tracing and the geological predisposition indicate that a part of Rastok polje, Jezerce, Ljubuško-Vitinsko polje and the middle part of the Trebižat river course belong to the Norin spring drainage basin. The catchment surface covers an area of approximately 200 km^2, and further tracing in the Marković ponor at Humac will give a more reliable estimation. The south-western boundary of the drainage basin was determined by tracing in the Rastok polje and Jezerce (Fig. 2). However, the problem of ponors and estavellas remains unsolved in the northern part of Rastok polje (Studena, Konjska, Semetnice and the southern rim of Jezerce near Mali Polog). In the Pozla Gora and Nova Sela the water divide occurs in the subsurface and it is probably zoned.

5. HYDROGEOCHEMISTRY

The chemical composition of waters from the Norinska river spring has been frequently analyzed in the past twenty years. The studies of the lower course of the Neretva river and the Dalmatian surface-waters, also included studies of the Norinska river and its spring (ŠTAMBUK-GILJANOVIĆ, 1994).

Periodic spring water turbidity is a consequence of flooding that occurs in the Rastok and Jezerac poljes and the yield of the Norin spring is above 8 m^3/s. It has been determined that the sand-silt fractions from the Quaternary chalky lake sediments move through ponors and open or siphon channels, and are discharged at the spring and then pass through the water supply system to Pelješac and the island of Korčula. The turbidity is most pronounced when the yields are higher than 8 m^3/s as a consequence of water flow from the Jezerce polje through ponors situated along its edge. The average duration of intensive turbidity is from 5 to 10 days, while less intense turbidity can be noticed for as much as two months after the cessation of flooding of the polje. Sand flow continues even later in the intermediate water period at yields from 4-6 m^3/s. The spring water temperatures range from 12.5 to 13.7 °C, and the pH of the water is near neutral (6.8-7.8). The water is colourless, tasteless and without odour. The total dissolved solids concentration varies from 530 to 750 mg/l. The spring water is geochemicaly a $CaHCO_3SO_4$ type with a total hardness of 20 °dH and carbonate hardness of 10 °dH. The noncarbonate hardness is therefore about 10 °dH, but during low capacity yields it increases considerably. During dry periods, for example, the concentration of sulphate increases to 280 mg/l and chloride to 35 mg/l. During the most recent hydrogeological study hydrochemical analysis of waters was performed. Water samples were collected in November 1995 from selected springs in the Norinska river drainage basin and were analyzed in the INA Naftaplin Laboratory, in the Department for fluid analysis and ecology (Table 1).

The trilinear plot (Fig. 3) indicates that in the studied area two lithologically different aquifers can be delineated. The first geochemical environment is char-

Spring	T °C	pH	CND µS/cm	TDS mg/l	Ca meq/l	Mg meq/l	Na meq/l	K meq/l	HCO^{3-} meq/l	Cl^{-} meq/l	SO_4^{2-} meq/l
Norinska river spring - Prud	12.9	6.96	570	285	6.487	1.152	0.522	0.020	3.781	1.083	3.590
Klokun	12.7	7.08	475	237	5.489	0.658	0.152	0.013	3.780	0.299	2.057
Modro oko	12.9	7.34	532	266	6.238	0.905	0.083	0.023	3.740	0.299	3.204
Butina	12.5	7.45	650	325	8.234	1.070	00696	0.013	3.960	0.299	5.201
Studenci-Kajtazovina	12.5	7.55	580	290	6.986	0.987	0.0174	0.008	4.119	0.240	3.369
Kravica (surface water)	12.3	7.58	786	393	9.232	1.646	0.0435	0.015	3.580	0.260	7.420
Vrioštica	12	7.39	548	274	6.188	1.234	0.087	0.013	3.821	0.200	3.950
Klokun-Klobuk	12.7	7.54	1083	541	14.371	2.304	0.087	0.018	3.719	0.260	13.206
Nezdravica	12.8	7.21	677	338	7.186	2.057	0.065	0.013	3.840	0.200	5.432
Kordići	12.6	7.24	974	487	14.471	3.621	0.078	0.015	3.920	0.299	13.839
Peć-Mlin	12.5	7.41	345	173	3.992	0.428	0.052	0.015	3.821	0.220	0.677

Table 1 Results of hydrochemical analysis of waters from the springs in the Norinska river drainage basin.

acterized by a typical $CaHCO_3$ type of spring water, which is illustrated by the Peć-Mlin spring, indicating that the aquifer is situated within limestone bedrock. The second group of springs contain elevated concentrations of sulphate, the concentrations of which decrease in the direction from Kordići, Klokun-Klobuk, Butina, Nezdravica, Vrioštica, through the Norinska river spring, Studenci-Kajtazovina, Modro Oko to Klokun. The concentration of sulphate decreases as a consequence of the mixing of waters of a $CaSO_4HCO_3$ and $CaHCO_3SO_4$ type with waters of a $CaHCO_3$ type.

The results of hydrochemical analysis were used for calculation of CO_2 partial pressure and the calcite, dolomite, gypsum, anhydrite saturation states of spring waters, with the aid of the geochemical speciation model WATEQ4F (BALL & NORDSTROM, 1991). As a measure of saturation the saturation index (SI) is used, and its positive values indicate saturation (precipitation) in respect to a specific mineral phase, while negative values indicate a nonsaturated state (dissolution) (Table 2).

The occurrence of $CaSO_4HCO_3$ and $CaHCO_3SO_4$ type of waters in karst aquifers is usually attributed to the existence of gypsum and anhydrite in the rocks of the drainage basin. Also, elevated sulphate can be a consequence of the oxidation of sulphide minerals or by H_2S or HS^- derived by decomposition of organic matter. Outcrops of neither gypsum nor anhydrite were detected in the Norinska river spring drainage basin nor in the

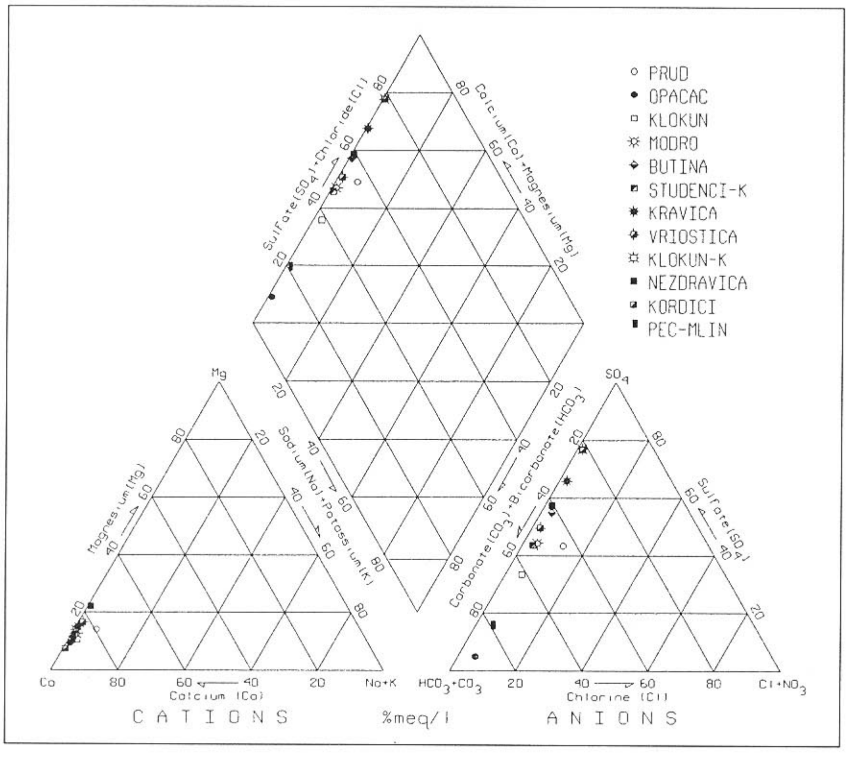

Fig. 3 The trilinear diagram of the spring water composition.

Spring	log pCO_2	SI calcite	SI aragonite	SI dolomite	SI anhydrite	SI gypsum
Izvor Norinska river - Prud	-1.79	-0.377	-0.529	-1.546	-1.409	-1.157
Klokun	-1.884	-0.269	-0.422	-1.506	-1.672	-1.419
Modro oko	-0.144	0.05	-0.103	-0.781	-1.468	-1.215
Butina	-2.201	0.265	0.111	-0.405	-1.206	-0.953
Studenci-Kajtazovina	-2.274	0.35	0.197	-0.199	-1.418	-1.165
Kravica (surface water)	-2.372	0.371	0.218	-0.055	-1.051	-0.797
Vrioštica	-2.159	0.082	-0.072	-0.594	-1.396	-1.149
Klokun-Klobuk	-2.327	0.468	0.315	0.101	-0.73	-0.478
Nezdravica	-1.996	-0.067	-0.22	-0.721	-1.246	-0.993
Kordići	-2.031	0.161	0.008	-0.322	-0.724	-0.471
Peć-Mlin	-2.164	0.007	-0.147	-1.008	-1.968	-7.417

Table 2 Saturation index and CO_2 partial pressures of spring waters.

shallower parts of the aquifer. The measured concentrations of sulphate in the spring waters indicates deep karstification which could allow deep groundwater circulation and possible contact with gypsum and anhydrite deposits. The dissolution of gypsum and anhydrite in karst aquifers (limestone and dolomite) frequently causes calcite saturation and often its precipitation. Since calcite precipitation causes a decrease in CO_3^{2-}, dissolution of dolomite occurs and the concentration of magnesium in the groundwater rises. This also means that the concentration of calcium and magnesium rise as a function of sulphate concentration increase (BACK & HANSHAW, 1970; PLUMMER, 1977; HANSHAW & BACK, 1979, 1985; PLUMMER & BACK, 1980; BACK et al., 1984; PLUMMER et al., 1990). Such conditions were determined in the springs of the Norinska river drainage basin, and as such are evidence that gypsum and anhydrite are present in the aquifer bedrock.

The increase of sulphate concentrations in spring waters displays very high positive correlation coefficients with calcium and magnesium concentrations (Figs. 4 & 5), and the calcite and dolomite saturation states of spring waters are also in accordance with these trends (Fig. 6). These events are well studied in a geochemical sense as the incongruent dissolution of dolomite (PLUMMER, 1977). In this case such a relationship serves as evidence for the presence of gypsum and anhydrite in the deep subsurface of the Norinska river spring catchment area.

High proportions of the sulphate component, the milliequivalent concentration of which is similar to the milliequivalent concentration of calcium in the waters from the Kordići and Klokun-Klobuk springs, shows that the origin of dissolved salts is connected with gypsum and anhydrite deposits. These deposits must be in close proximity to the springs and the possibility of dilution with bicarbonate waters is small.

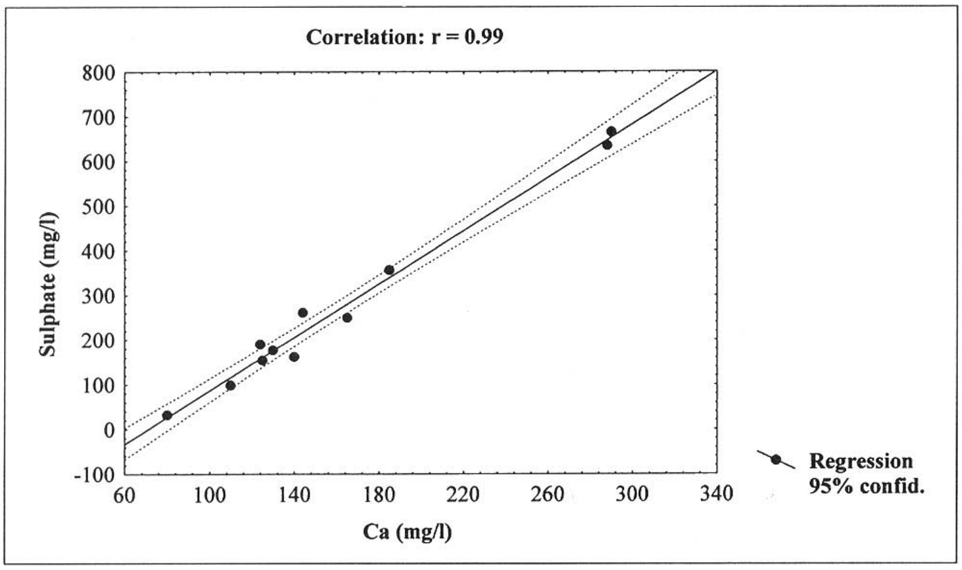

Fig. 4 Regression of Ca^{2+} concentrations to SO_4^{2-} concentrations.

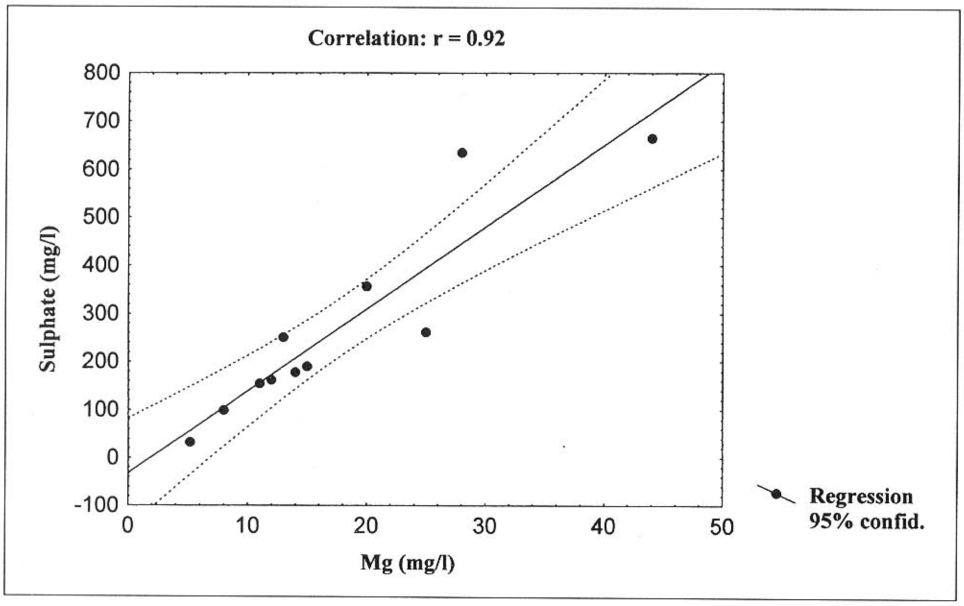

Fig. 5 Regression of Mg^{2+} concentrations to SO_4^{2-} concentrations.

Previous very detailed hydrochemical studies, determined an increase of sulphate concentration during low water levels (ŠTAMBUK-GILJANOVIĆ, 1994). This is due to the fact that the occurrence of gypsum and anhydrite is confined to the deeper parts of the karstified aquifer, and that during the hydrological minimum, percolation through the footwall carbonate rocks is reduced, inhibiting therefore the dilution of sulphate waters with calcium bicarbonate waters. Therefore more detailed mixing effects and evaluation of the contributions of various geochemical water types should be viewed under different hydrological conditions. This would also enable a more detailed definition of catchment areas.

6. THE PROTECTION OF THE NORIN SPRING, AND POLLUTION SOURCES IN THE CATCHMENT BASIN

The first (I) sanitary protection zone is marked by a wire fence along the Norin-Ljubuški road and curves along the path towards the Norin and Crnići villages (Fig. 7). Due to the close proximity of the road, the drainage channel built along its edge should be maintained, since it drains the surface waters from the road and discharges them into the Norinska river down stream from the spring.

Also the construction of sewage drainage facilities for the village above the Norin spring is necessary with

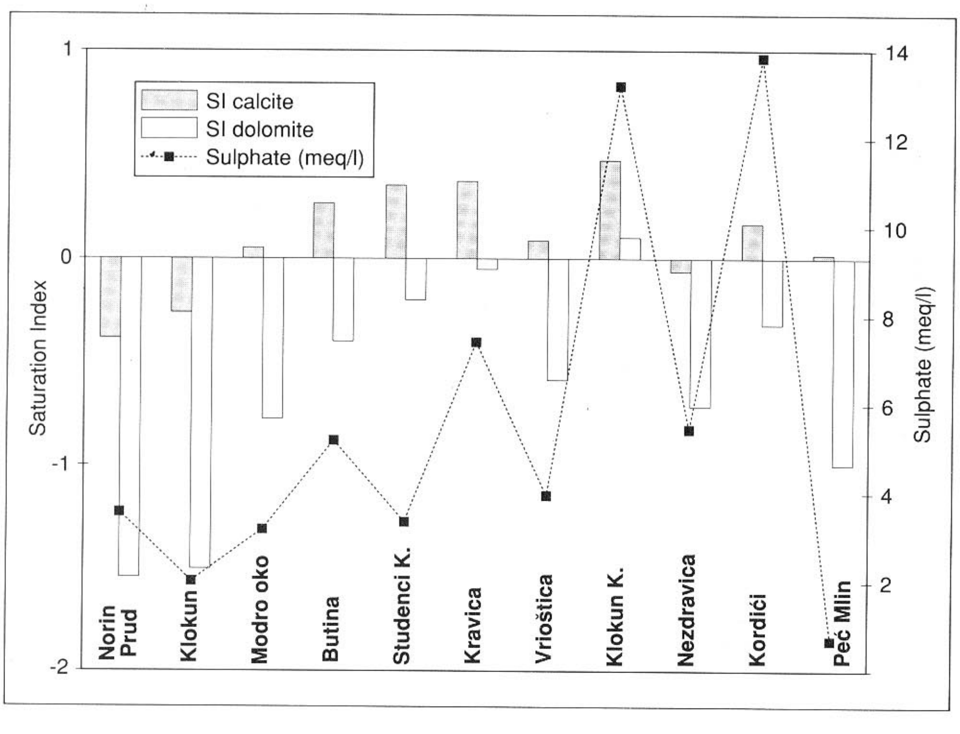

Fig. 6 The relation of spring water saturation state and sulphate concentration.

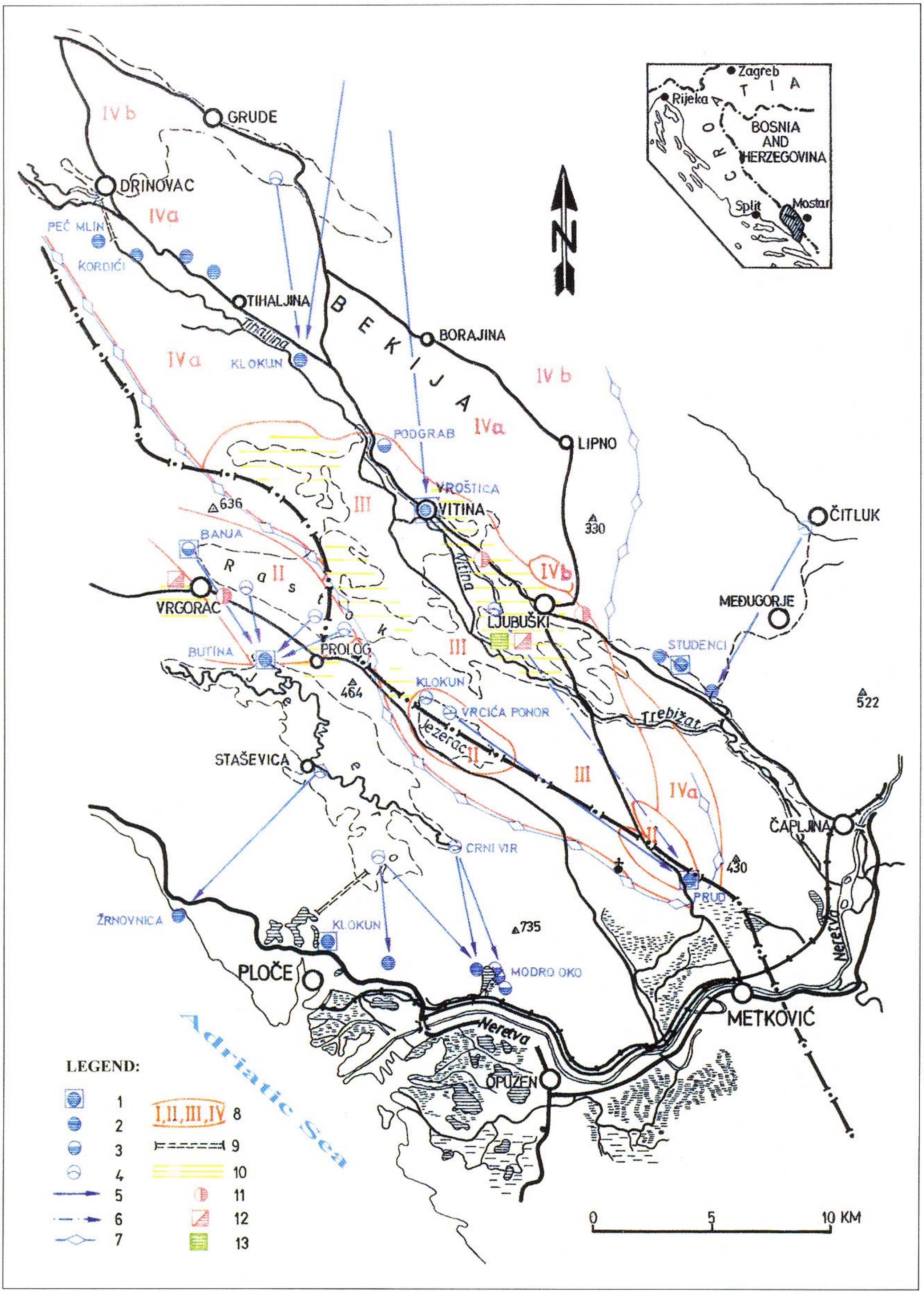

Fig. 7 Map of the sanitary protection zones. Legend: 1) water supply pumping site ; 2) permanent karst spring; 3) intermittent karst spring; 4) swallow hole; 5) groundwater flow, proven; 6) groundwater flow - supposed; 7) subsurface water divide zone; 8) sanitary protection boundary; 9) drainage tunnel; 10) inhabited area; 11) oil-service station; 12) municipal waste disposal; 13) industry with effluent of inorganic waste.

an outlet into the Norinska river, after appropriate treatment of the sewage. Also it is necessary to mitigate "wild" solid waste landfills in Norin village and take measures to prevent deposition of waste that could threaten the water, in the vicinity of the fence.

According to the protection criteria, the second (II) zone covers the hinterland of the spring in the direction of groundwater flow, and the terrain surrounding ponors for a radius not less than 20 m. Since only one tracing was performed with assumed velocity higher than 5 cm/s, the second zone extends for 5 km along the main groundwater flow direction. This zone is also extended in the northwestern direction where we presume that the second major groundwater flow direction is situated. The expansion of the second sanitary protection zone covers the area of Jezerac polje with the Virine ponor, located in its central part, and the ponors and suffosions located on its edge.

The hinterland of Norin spring consists of Upper Cretaceous and Palaeogene carbonate rocks. Detailed geological mapping was performed over a rather restricted area, with the aim to determine faults, caves and ponors (swallow holes) through which tracing could be performed, in order to determine the flow directions towards the spring, and the groundwater flow velocity. Numerous faults with different hydrogeological significance were determined. The most pronounced are the reverse faults of Dinaric strike, and the transcurrent fault mentioned before which acts as a recipient for the groundwater. Also of importance are the NW-SE cross faults which act as secondary recipients, along which groundwater is drained into the major groundwater course which flows from Jezerce and Ljubuški (Humac, Vitaljina) through Bijača and Zvirić to the Norin spring.

The karst poljes Rastok, Jezerac and Ljubuško polje are covered with thin Quaternary clay deposits allowing the formation of ponors, zones with ponors and suffosions (even in the middle of the poljes), where the thickness of the cover is less than 10 m (Virina in Jezerce polje). During high water the poljes are flooded and the water is drained through the ponors and suffosions of limited capacity.

The part of the drainage basin in which groundwater flow with relative velocities above 1 cm/s predominates is classified as the third (III) protection zone. These are the terrains from which it takes ten days for the water to reach the spring. In the Norin spring drainage basin this is the area between the second (II) zone and zone IVa. On the map presented in Figs. 2 and 7 this is the area of Pozla gora, Nova sela, Stubica and Jasenjan (the edge of zone II), the more distant areas of Humin, Vašarović, Ljubuško polje and Rastok polje, and the whole area covered by the town of Ljubuški to Vitina and Podgrab. This zone also covers the middle course of the Trebižat river from Klobuk to the Kravica waterfall. The values of groundwater flow velocities from Ljubuško polje have not been determined, but geological-hydrogeological features in this part of the drainage basin indicate that this area should be classified as zone III protection. The groundwater levels vary from 0-50 m so velocities of groundwater flow above 1 cm/s are also expected. The terrain covered by zone III contains a series of ponors and ponor zones, suffosions and estavelles, which confirms the necessity to classify this area as zone III. The most distant terrains are located over 20 km away from the spring while the closest are 3-5 km distant.

The principal criterion that defines the fourth sanitary protection zone is that the groundwater flow takes more than 50 days with velocities below 1 cm/s. This zone is divided into two subzones IVa and IVb.

The IVa protection zone presented in Fig. 7 covers the area of the immediate spring drainage basins of north-northeast bank of the "river with three names" (Tihaljina, Mlada, Trebižat) and distant karst terrain with numerous developed karst phenomena. This area extends from the southeast towards the northwest (from Jasenjan, through Lipno, Grljević, Brojana, and Klobuk to the Tihaljina spring). The boundary between zone IVa and the zone IVb is arbitrary and not defined rigorously.

The IVb protection zone contains poorly karstified carbonate areas with prevailing dolomite and limestone-dolomite rocks, and covers areas distant to the immediate Tihaljina river drainage basin. The areas that comply to this criterion are terrain of Imotski polje and the drainage basins of the north-northeast banks of the rivers Tihaljina, Mlada and Trebižat. However, these areas will be protected more rigorously since they represent the immediate drainage basins for municipalities in southwestern Herzegovina, where protection zones have not been defined.

The pollution threat by microbiological organisms and products of faecal disintegration is a reality, but dealt with successfully by chlorination. A much greater threat is the pollution of water by pesticides, heavy metals, mineral oils and fertilizers from which there is no effective protection.

Since the water from the Norin spring is not significantly polluted, it is still possible to undertake measures to prevent potential future pollution. Considering the fact that the drainage basins are in most part situated in the Republic of Bosnia and Herzegovina cooperation will be necessary between the water management institutions of Split and Mostar.

The towns of Vrgorac and Ljubuški have only a minor impact on the pollution of Norin spring waters since only a small quantity of water is drained directly towards the spring. Treated waste waters from the sewers and the industrial waste waters from the factory "Famos" in Ljubuški, which have functional water treatment plants, do not significantly influence the rate of pollution. This is due to the fact that only a small fraction of these waters is drained through suffosions and ponors along the Trebižat river, from the bridge at Humac to the Kravica waterfall.

Most parts of the catchment basin are poorly populated and without industry and large farms, so the present groundwater quality can be easily maintained. However, since the groundwater levels are very shallow (from 0 to 50 m deep), the possibility of unconstrained pollution through swallow-holes (caves), ponors and ponor zones is present and therefore caution and protection measures should be practiced. In the immediate hinterland of Norinska draga and Rotna valley the most likely pollution threats are the traffic accidents that can occur on the road from Norin to Ljubuški. The most dangerous point source of pollution is the mineral oil disposal facility which is situated some 300 m upstream from the spring and should be removed as soon as possible. The spring is protected from pollution by a collection channel for surface and subsurface waters.

A potential source of pesticide and fertilizer pollution is the Jezerac polje from which the groundwater emerges at the spring in two days. Since agricultural activity is low in the polje at present no real pollution threat exists, but if this activity will be intensified in the future it could pose a threat. A more realistic pollution threat are waters that sink in the Ljubuško polje which is characterized by intensive agricultural production. Since no confirmation of a subsurface connection with the spring exists, it is necessary to perform tracing from the ponor situated in the middle of the polje (Markovica), on the western side of Humac to solve the existing predicament. This tracing would also solve the impact problem of the series of ponors and suffosions that are located from Vašarović to the Kravica waterfall. Since the suburban areas of Ljubuški are under intensive development, but without an accompanying sewage infrastructure and waste water treatment facility it is necessary to monitor the water quality of the Trebižat river and the Norin spring.

The sanitary-chemical and bacteriological analysis give insight into the present water quality state, and since these are not permanent characteristics of the water it is necessary to monitor the water quality under different hydrological conditions. This is the only reliable parameter that can influence the decision making for further interventions in the catchment basin.

7. CONCLUSIONS

The catchment basin forms part of the Dinaric karst terrain and has all of its morphological, hydrographical and hydrogeological features. The terrain is composed of a thick Cretaceous and Palaeogene carbonate rock complex. Clastic rocks of Eocene, Oligocene and Quaternary age are present in a subordinate extent. The studied area is also part of the Svitava-Ljubuški tectonic unit which is overthursted by the Stolac-Čitluk high karst tectonic unit.

The middle course of the "hanging" Trebižat river, together with Rastok polje, Jezerce polje and the karst plateaux Vašarović and Humin are the principal recipients for groundwater which are discharged at the Norinska river spring. The terrain is karstified, and the infiltration of water is either direct, or through ponors and ponor zones.

The protection of pumping plant waters has been determined according to regulations, and the restrictions were enforced in order to maintain the present water quality. The aim of protection measures is to control all existing and potential pollution sources and if possible their exclusion.

The delineated protection zones should be protected according to legislation, and the areas of influence should be further studied, to allow better definition of the catchment area and therefore, its protection. The undefined parts of the catchment basin are to be protected by the general regulation acts. Local waste disposal landfills and "wild" landfills should be reduced as much as possible.

The areas in which numerous swallow holes (caves) are located should be marked with warning signs that prohibit waste disposal and the disposal of livestock corpses. Active ponors which require protection in the vicinity of Humac and the village of Kutac (Markovića ponor) should be traced because this is the most important parameter for extension or reduction of the II and III protection zones.

It is necessary to control potential pollution sources and to perform sanitary procedures as soon as possible. In order to perform this cooperation between the water supply management of Herzegovina (Mostar) and Dalmatia (Split) is necessary. Therefore it is necessary to analyze and control the waste waters from Vrgorac, Grude and especially Ljubuški.

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