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Hydrogeological Evaluation of Water Retaining Properties of the Kosinj Reservoir (Lika, Croatia)

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Key words: Karst hydrogeology, Karstification, Water retaining, Hydrogeological zoning, Kosinj reservoir, Lika, Croatia.

Abstract

Construction of the Kosinj reservoir was planned in a karst terrain on the lower part of the river Lika. Preceding studies of this area did not completely define the water constraining elements of the terrain, and therefore the more reliable Kruščica reservoir was built. Further studies were undertaken in order to evaluate in detail the terrain of the anticipated location of the dam impoundment at Kosinj. Due to the lithological homogeneity of the karst terrain, the studies focused on tectonics and geomorphology, with emphasis on karstification. Terrain zoning was made on the basis of hydrogeological favourability for water retaining in the reservoir.

The Velebit hydrogeological barrier influences the general water runoff in the hinterland, as well as the depth and the direction of advancement of recent karstification processes. In the hinterland of the Velebit barrier the karstification is shallow, increases in depth towards the sea, and is characterized by the zoned distribution of springs, estavelles and ponors. This concept played a major role in later hydrogeological studies of the proposed reservoir.

1. INTRODUCTION

The completion of the Kruščica reservoir with a volume of 134 x 10^6 m^3 on the Lika river did not satisfy the needs for reservoir space, because the achieved volume is only 15% of the average annual recharge of the Lika river (Q_{mean} = 27.9 m^3s^{-1}). Together the headwaters of the Gacka and Lika rivers are utilized by the hydroelectric plant HE Senj but, due to the shortage of water storage space, a portion of the high waters is discharged into ponors, which in turn causes flooding of the polje. In order to utilize larger volumes of water and to eliminate flooding, studies which would enable the construction of the Kosinj reservoir with a volume of 433 million m^3 were continued in 1972. The upper course of the Bakovac tributary lies in an estavelle zone and, therefore, this valley will be separated by a dam from the lake.

The waters from the Bakovac tributary are to be discharged into the Lika river through a tunnel downstream from the lake and utilized in the HE Senj.

During exploratory drilling, the rim of the future reservoir, at the side of the Lipovo polje, and the boundary area by the Gacka river were investigated. The majority of the drilled holes contain equipment which has produced water level data for over 30 years. Recently drilled observation boreholes were also used for monitoring groundwater level variations. Groundwater flow tracing tests were performed (from the eastern side of the lake and in the Bakovac valley) which enabled the expansion of flow data obtained in previous studies (from areas surrounding Pazarište and Studenci). Detailed geophysical studies were performed in areas where injection barriers were planned and the narrow locations where damming was to be performed.

To perform these rather complex studies, a large volume of varied data, from both published papers and professional studies was required. The fundamental published papers were the result of studies done during the construction of the Kruščica artificial lake. BAHUN (1962) described in detail the lithological composition of the rocks, with emphasis on the Jelar beds. The same author (BAHUN, 1973), related the karst processes and fluvial erosion in the Lika river area and gives an account of karstification phases. On the basis of data from the region surrounding the artificial Kruščica lake, PAVLIN (1970) delineated a ponor zone, an estavelle zone and a spring zone. PAVIČIĆ (1984) also included a large part of this area when dealing with the Velebit groundwater divide. BAHUN & FRITZ (1975) studied the hydrogeological features of the Jelar beds, while FRITZ & PAVIČIĆ (1975) and PAVIČIĆ & FRITZ (1976) outlined in detail Cretaceous beds and the Jelar beds, determined numerous faults in the area and described the hydrogeological relationships in the lower course of the Lika river. PRELOGOVIĆ (1989) described the Neotectonic movements in the area of northern Velebit and a part of Lika and provided new insight to the structural and tectonic relationships. The data on the

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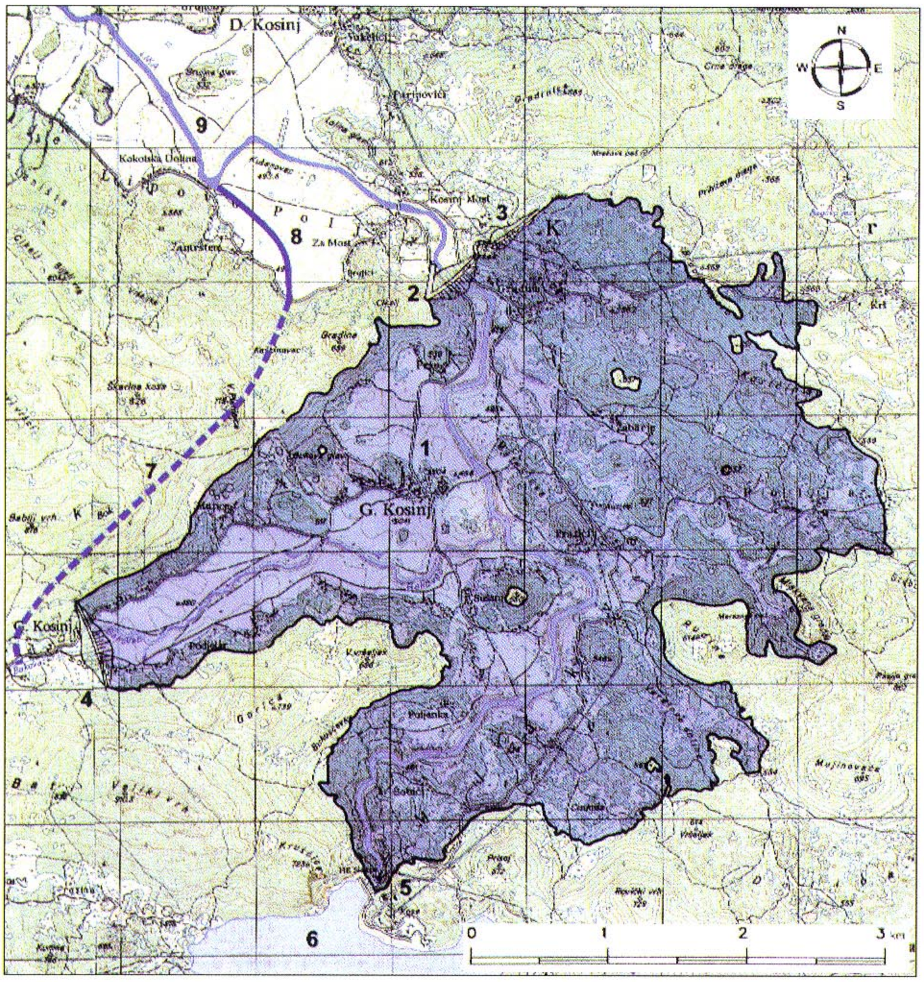

Fig. 1 Kosinj reservoir layout. Legend: 1) Kosinj reservoir; 2) Kosinj dam and HPP; 3) Sedlo dam; 4) Bakovac dam; 5) Sklope dam and HPP; 6) Kruščica reservoir; 7) Bakovac - Lika tunnel; 8) Bakovac - Lika channel; 9) Selište compensation basin.

origin of structures and faults and Neotectonics enabled better interpretation of the hydrogeological relationships and groundwater flow. PAVIČIĆ (1995) in his PhD thesis described the hydrogeological conditions for the construction of water reservoirs in the karst of the Velebit hinterland, where he also studied the area around Kosinj, and this was used as the basis for the present paper.

2. HYDROGEOLOGICAL RELATIONSHIPS IN THE KOSINJ RESERVOIR AREA

2.1. HYDROGEOLOGICAL PROPERTIES OF ROCKS

On the hydrogeological map presented in Fig. 2 the main lithostratigraphic members outlined are grouped by their hydrogeological properties. In the studied recharge area Triassic, Jurassic, Cretaceous and Lower Palaeogene carbonate rocks dominate.

The rocks are divided into five groups according to their permeability. The limestones in alternation with dolomites and limestone breccia (T_2^2, J, K_1) are very permeable rocks. Partly impermeable are the Jelar beds ($Pg_{2,3}$), while the dolomites (T_3) are partly permeable. The shales and sandstone (T_1, T_3^1) and tuff and tuffite are impermeable. The Quaternary deposits are mainly represented by colluvial beds, deposited in the poljes, and their relics can be found on elevated surfaces of the terrain. These clay-silty deposits can be very thick and impermeable in some areas, allowing surface water flow in the polje where the groundwater level is below the water bed (e.g. Lipovo polje).

2.2. TECTONIC BASIS OF HYDROGEOLOGICAL CONDITIONS

Almost all of the area studied belongs to the Dinaricum megastructural unit (HERAK, 1986, 1991). The geodynamics of the studied area is characterized by structures resulting from folding and faulting which occurred after deposition of the Eocene flysch deposits. These movements defined the existing structures, which are outlined by regional faults which are often accompanied by the Jelar beds (BAHUN, 1974, 1984; HERAK & BAHUN, 1980). These tectonic structures were formed during the Upper Oligocene and Miocene, principally by tangential movements (BAHUN, 1974; PRELOGOVIĆ, 1989). The final phase of these movements occurred in the Upper Pliocene and the Quaternary when transcurrent faults were active and were particularly intensive in the Velebit region. The Neotectonic movements have influenced recent karstification

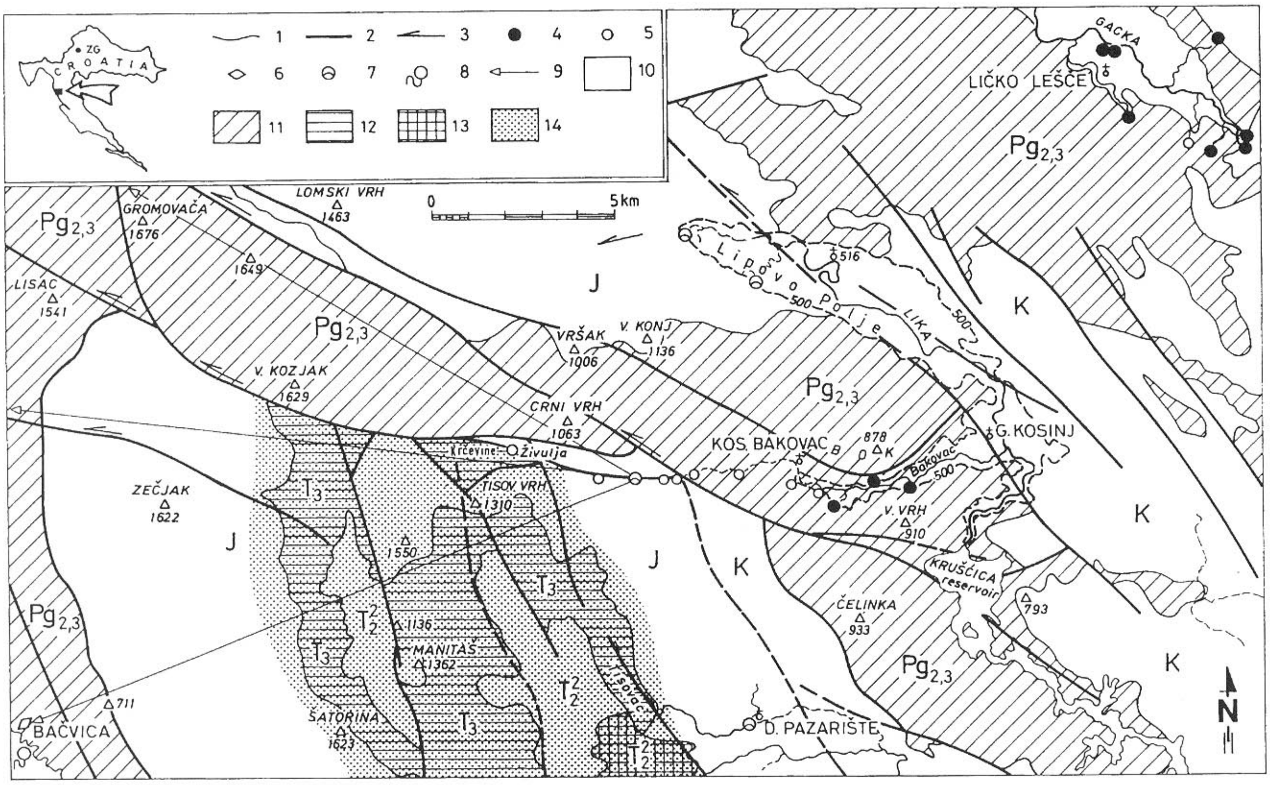

Fig. 2 General hydrogeological map. Legend: 1) geological boundary; 2) fault; 3) assumed direction of groundwater discharge; 4) permanent karst spring; 5) intermittent karst spring; 6) intermittent coastal spring; 7) swallow hole (ponor); 8) submarine spring (vrulja); 9) defined underground connection between a ponor and a spring; 10) permeable zone; 11) Velebit hydrogeological barrier; 12) partly impermeable rocks; 13) partly permeable rocks; 14) impermeable rocks.

and recent water flow patterns. Although the prevailing geological structures in the studied area are governed by deep tangential and reverse tectonics, the hydrogeological conditions can be interpreted mainly from surface outlines of the structures. Alternatively, the water dynamics of the studied area is confined to relatively shallow parts of the terrain, well above the contact between megastructural units, so the deep tangential tectonics has no influence on water emergence and flow.

On the basis of the geology of the studied area and the basic tectonics involved, distinctive areas, structural units and faults that influence the hydrogeology of the terrain are presented in Fig. 3.

The Velebit mountain range forms the south-western limb of an extensive regional fold (BAHUN, 1974) thrusted during the first phase, and later disintegrated by radial Neotectonics. In the core of the anticline, along the fault on the edge of Ličko polje, to the west from the water accumulations Kruščica and Kosinj, outcrops of Palaeozoic and Lower Triassic, and to a lesser degree Middle Triassic impermeable clastic rocks occur. The position of these impermeable rocks in the Velebit massif, the uplift of which began after the Miocene and concluded in the Upper Pliocene and the Quaternary (PRELOGOVIĆ, 1989), influenced the hydrogeological conditions in the hinterland, especially as reflected in the direction of karstification and the groundwater level in the area of recharge surrounding the water reservoirs.

The occurrence of Neogene marls in a deep sinkhole (borehole K-4-2, Fig. 4) confirms the existence of very young fault tectonics. The thickening marl and morphology of the terrain indicate a throw along the fault plane of over 100 m.

The faults, together with the structural and lithological features of the rocks, are the most important elements that influence the karstification process and groundwater flow in karst terrains, as first stressed by HERAK (1957). More recent studies (FRITZ, 1972, 1991, 1992; FRITZ & PAVIČIĆ, 1986; BAHUN & FRITZ, 1987) suggest that the principal influence is that of recent karstification, which is associated with the youngest Neotectonic faults. During map elaboration, the data from studies of the northern Velebit and parts of Lika (PRELOGOVIĆ, 1989) was used.

As a consequence of regional tangential stress, compression faults occur within smaller or larger areas. These are usually manifested as hinge, transcurrent and reverse faults. Tension faults, that occur as fissures parallel with the principal stress direction, have the least pronounced strike displacement, and they are confined to smaller areas, usually within tectonic blocks. They are important for local groundwater flow conditions.

The transcurrent faults are of primary importance in groundwater flow, since the rocks in which they occur are compressed, and thus can act as a barrier to groundwater flow perpendicular to the fault plane. The groundwater flow is directed parallel to the fault plane, and

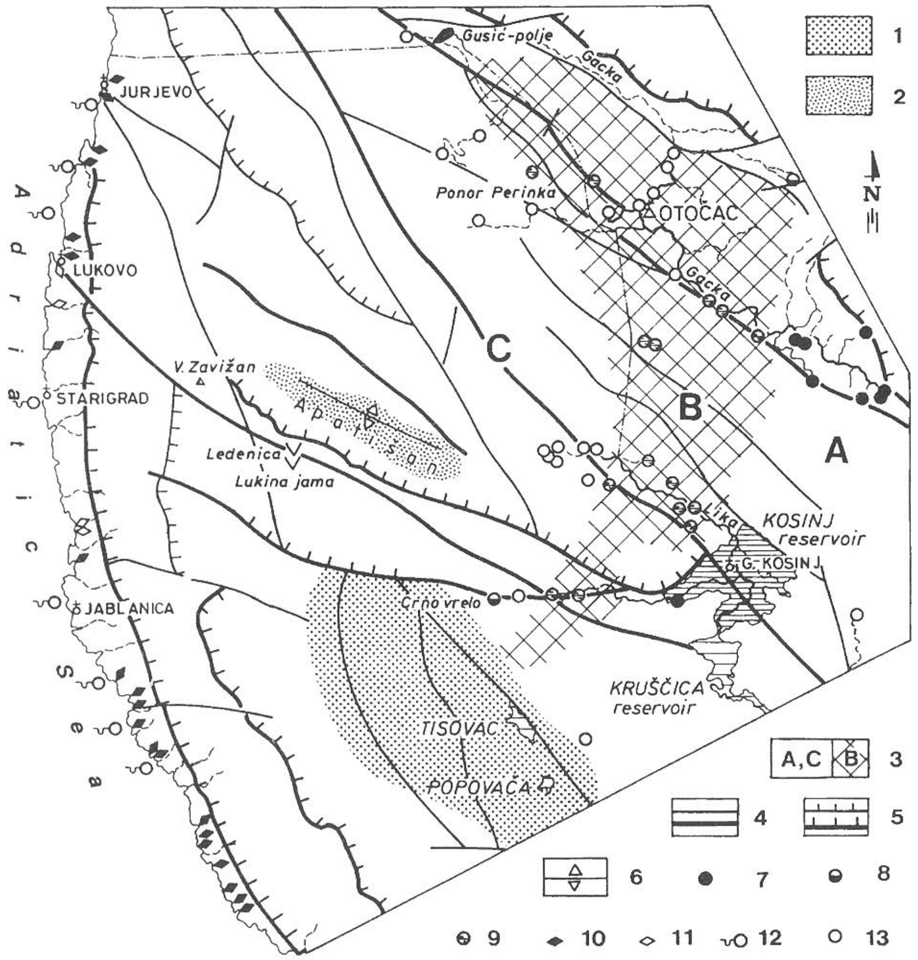

Fig. 3 Map showing the tectonic structure and hydrogeological function of the terrain. Legend: 1) Velebit hydrogeological barrier; 2) Apatišan relative barrier; 3) hydrogeological zones: A - spring zone, B - estavelle zone, C - ponor zone; 4) normal fault; 5) reverse fault; 6) anticline axis; 7) permanent karst spring; 8) intermittent karst spring; 9) estavelle; 10) permanent coastal spring; 11) intermittent coastal spring; 12) submarine spring; 13 swallow hole (ponor).

natural retention can occur on the upstream side of the fault. This group of faults is represented by the Vratnik - Senjsko Bilo - Perušić fault on the eastern margin of the Senjsko Bilo - Krasno structural unit, and the Lika fault, west of the studied water reservoir locations. These faults are characterized by groundwater flow parallel to the fault plane, while groundwater flow perpendicular to the fault plane is of a lower degree, particularly in recently active fault zones. The Neotectonic active faults in the area of northern Velebit are vertical to very steep with a WNW-ESE strike.

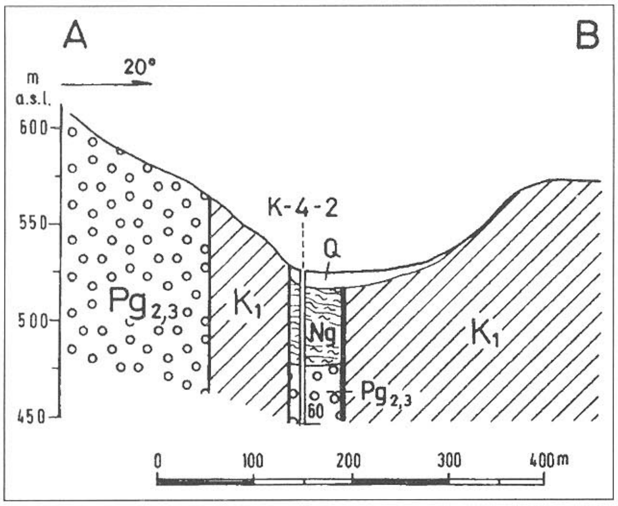

Fig. 4 Cross-section through the borehole K-4-2, showing the position of the Neogene marls.

2.3 HYDROGEOLOGICAL FUNCTIONS OF THE TERRAIN

The hydrogeological functions of the studied terrain were determined on the basis of the hydrogeological features of rocks, tectonics, and the spatial distribution and relative positions of geological bodies and their morphology. In the studied area the following hydrogeological functions of different parts of the terrain were determined: full barriers, partial barriers and permeable areas.

2.3.1 Hydrogeological barriers

Barriers can be classified according to the degree that they obstruct water flow as full or partial (relative) barriers.

In the studied area the principal hydrogeological feature is the Velebit full barrier which extends from the Bakovac valley to the Štikadsko polje (Fig. 3). The strike of this barrier is confined within the Velebit structural unit. The existence of this barrier is determined by impermeable Palaeozoic and Lower Triassic deposits the elevation of which is much higher than the

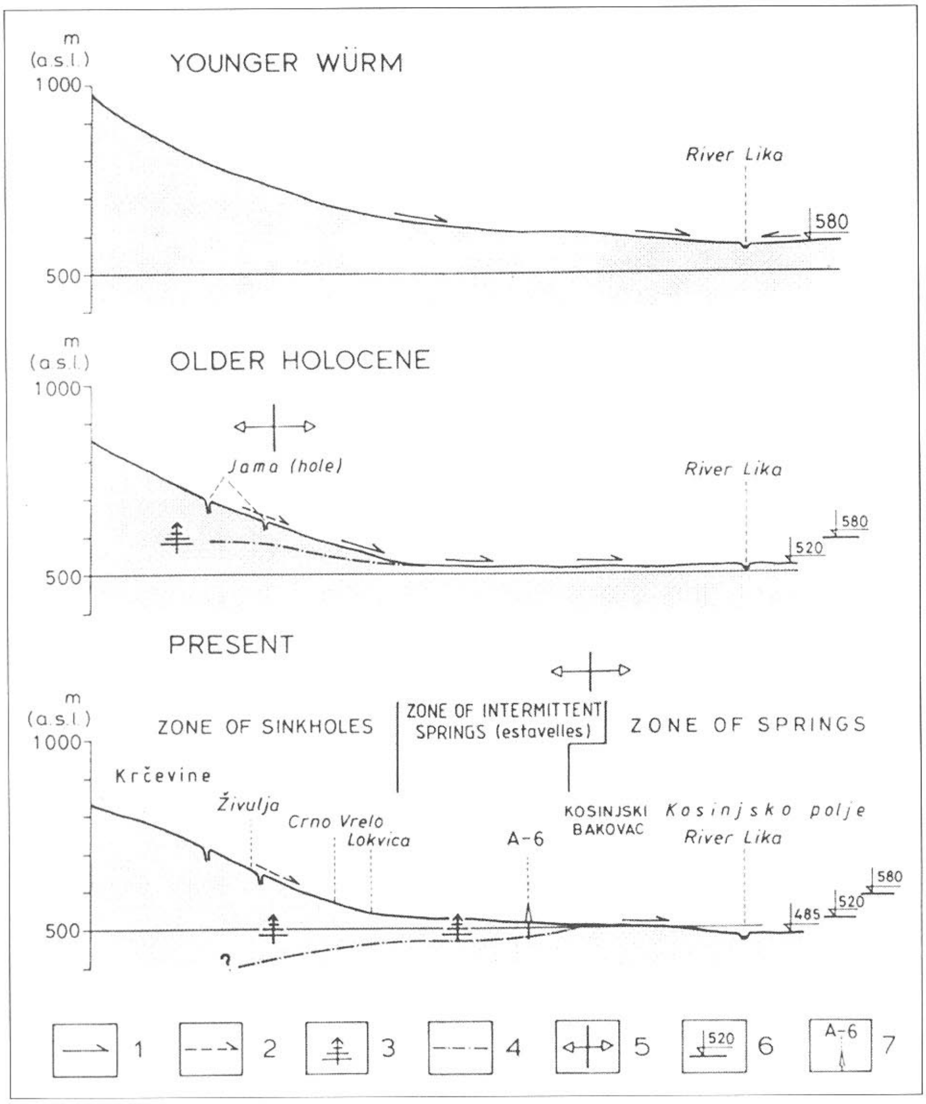

Fig. 5 Development of the Bakovac valley and water drainage. Legend: 1) permanent surface discharge into the Lika river; 2) intermittent surface discharge into the Lika river; 3) groundwater discharge; 4) groundwater level; 5) zonal water divide; 6) remains of a terrace; 7) observation borehole.

groundwater level in the Ličko polje. The impermeable Middle Triassic pyroclastic rocks also supplement the hydrogeological barrier in the area to west from Pazarište. This part of the Velebit structure is an impermeable barrier which cannot be penetrated either by surface or groundwater from the hinterland. It forces the waters to flow either in an eastward and south-eastward direction or northward and north-eastward.

The function of the Velebit barrier as a full barrier is not diminished by the occurrence of permeable Middle Triassic deposits, because the loss of water is confined within the permeable rocks, and the occurrence of deep karst forms, such as jamas (karst shafts), is only local.

The Upper Triassic clastic rocks and dolomites present in areas where no tectonic disruption occurred, act as hanging barriers within a full barrier.

Another partial barrier is the Apatišan anticline situated within the Senjsko Bilo structural unit, where the Liassic deposits in the core of the anticline reduce the floor and alter the direction of groundwater flow, which results in relatively high groundwater levels in the Lipovo polje and the occurrence of intermittent springs and flooding.

2.3.2 Permeable areas

The permeable areas mainly consist of highly permeable carbonate deposits. Due to tectonic activity, these rocks have been fractured and suffered later karstication. Due to the positive hydrogeological function of the Velebit massif, particularly in the hinterland of the Velebit barrier the karstification in the Lika region occurs at relatively shallow depths.

In the permeable terrain, an area with minimal groundwater levels above the surface water flow of the rivers Lika and Gacka (these are also the local erosion base levels - Area A in Fig. 3), was delimited from the parts of the terrain where the groundwater levels are lower than the surface river beds, so that the water from these areas drains to the coastal springs and submarine springs through the underground (Area C, Fig. 3).

In the carbonate terrains (limestones and limestone breccia) with the minimal groundwater levels above the water level of the rivers (Area 5, Fig. 6), the river water flow is permanent. Waters from adjacent terrains drain towards the rivers, both underground and on the surface, in the same direction during the periods of both high

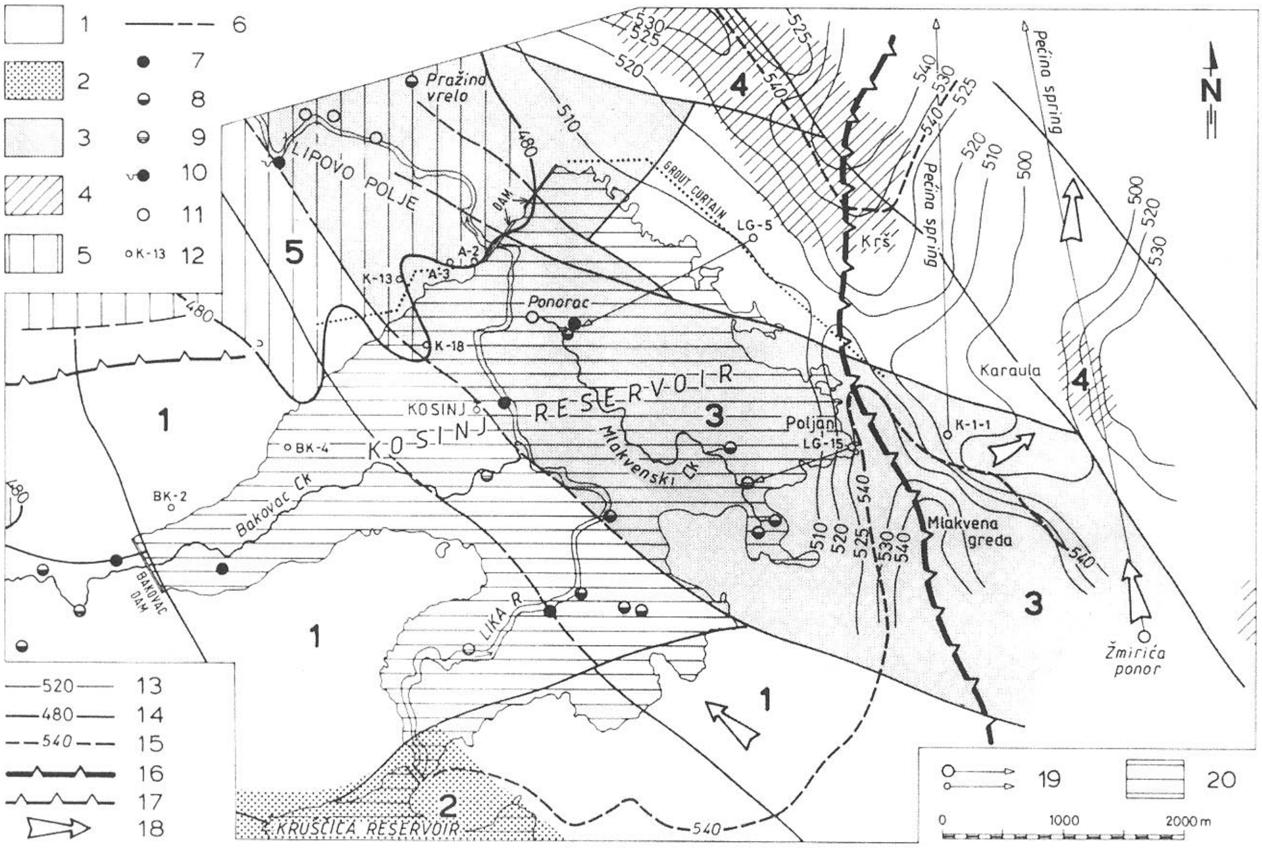

Fig. 6 Hydrogeological zoning of permeable areas. Legend: 1) groundwater above the Lika river stage; 2) Jelar deposits impermeable as a unit; 3) relatively uplifted tectonic block; 4) terrain under a higher influence of clay deposits; 5) low groundwater under Lika river; 6) fault; 7) major karst spring, permanent; 8) major karst spring, intermittent; 9) permanent karst spring, discharge less than 1 l/s; 10) estavelle; 11) swallow hole (ponor); 12) observation exploratory borehole; 13) water table contour line (mainly low water); 14) assumed boundary of the area without vertical leakage; 15) boundary of the area where groundwater is above 540 m a.s.l. during the rainy season; 16) water divide between the Lika and Gacka rivers; 17) local water divide; 18) groundwater flow direction; 19) determined underground hydraulic connection (between a ponor and a spring); 20) Kosinj reservoir.

and low flow. Along these river valleys permanent and intermittent springs exist, but estavelles and ponors are absent. The water divide in this region is shown in Fig. 6. The water divide between the Lika and Gacka rivers is confirmed by the existence of numerous springs along the eastern bank of the Lika river and by the groundwater levels in the boreholes.

The permeable zone, that is drained towards the sea, incorporates the area of estavelles from the Bakovac valley, through the Lipovo polje to the Gacka river (Area B in Fig. 3). The main features of this area are the existence of ponors and estavelles, and rarely some intermittent springs of low discharge rate. The Gacka and Lika rivers in this part of the terrain have their levels above groundwater levels for almost all of the year and are considered as "hanging" surface-water streams.

Lower groundwater levels in this area are a consequence of cessation of the function of the Velebit and Apatišan barriers, and progradation of recent karstification from the coast towards the hinterland.

The estavelle zone in the downstream direction passes into the ponor area. During all hydrological conditions, the groundwater level in the ponor area is considerably lower than the stream that is sinking.

More detailed zoning of the karst terrain, and particularly the permeable areas at the edge of the Velebit barrier was performed during investigations for the Kosinj water reservoir project.

2.4. KARSTIFICATION

Since the Kosinj reservoir recharge area is in a relatively lithologically homogeneous karst terrain, an important element for the evaluation of reservoir water constraining capacity and reservoir feasibility, are the processes of tectonism and karstification. The geological conditions in the studied terrain indicate, that before the Neotectonic uplift which preceded the forming of the current landscape, several emersion events occurred in the Dinarides. The first favourable conditions for karstification occurred in the Dinaride area after flysch deposition, when, during the Pyrenean orogeny, large masses of carbonate rocks were exposed to exogenous processes. During this orogenic event, the clastic-carbonate Jelar beds were formed in the Lika region. The molasse characteristics of these sediments indicate that the flattening and erasing of the elevated landscape was contemporaneous with their formation (BAHUN, 1990).

The Neotectonic movements which commenced in the Miocene and were intensified toward the end of Pliocene and the beginning of Pleistocene played a major role in the reshaping of the landscape and the development of karstification. Velebit was then uplifted together with other mountain ranges, while depressions developed as isolated karst plateaux and poljes. In some depressions, deposition of Plio-Quaternary sediments occurred, the remnants of which are found in several recent depressions and karst poljes. The Neotectonic movements changed not only the shape of the landscape but also influenced the change of groundwater drainage through previously formed channels and cavities. The links between the subsurface channels were cut, and some water-bearing cavities were separated from the newly formed groundwater dynamics. The principal drainage direction from the Velebit hinterland towards the Adriatic basin was preserved, but the local erosion base levels changed. Together with the uplift of Velebit the impermeable Palaeozoic and Lower Triassic deposits were also raised closer to the surface, resulting in their action as a hydrogeological barrier to the south of the Bakovac fault from the time of uplift until the present. To the north of the Bakovac fault, the impermeable rocks lie deeper beneath the surface, enabling deeper karstification and groundwater drainage from the Velebit karst hinterland towards the Adriatic sea.

The depth of karstification in the Lika region, (manifested in the existance and depth of speleological phenomena), the groundwater level conditions, the occurrence of ponors, estavelles, intermittent and permanent springs and their zoned distribution, are the consequences of the positive role of the Velebit hydrogeological barrier. The karstification process generally progresses from the sea towards the hinterland. In the near hinterland of the Velebit barrier, the current erosion base levels are the Lika river and the section of Gacka river that is upstream from the zone of permanent springs. The depth of recent karstification is approximately the same as the depth of the river beds, towards which groundwater drainage occurs. Only small local variations can occur as a consequence of the most recent movements of tectonic blocks. Karstification deeper than the level of the river bed in the area under the influence of the Velebit barrier is linked to an earlier phase of karstification. This was determined in the area of the Kruščica reservoir, where at a depth of 250 m below the level of the river bed, caverns filled with quartz sand were encountered during exploration drilling. These findings indicate that these deep caverns were once a part of the groundwater dynamics. The subsurface cavities and channels, developed in earlier phases of karstification, locally can be "inherited" into the complex underground systems. However, for the interpretation of current hydrogeological conditions, the landscape and karstification are a consequence of exodynamic processes that were active in the Pleistocene and Holocene, and where the erosion base levels are rivers (Lika and Gacka) or the sea. To evaluate water retention potential of a reservoir in karst terrains, it is of prime importance that the study of landscape development and karstification is performed (FRITZ, 1992). Recent studies performed in the Dinaric karst terrains indicate that the present landscape is very young. The majority of river valleys and lake depressions were created during the Lower Pleistocene and Holocene.

The analysis of landscape development and karstification processes is performed through the study of river valleys. The analysis involves not only the relationship between the valleys and the elevated surroundings in a karst environment, but also utilizes the data on hydrological characteristics, the occurrence of springs and ponors and the water-level fluctuations in the terrain through which the river flows. The most abundant data, that can be used for analysis of landscape development and karstification, is available for the areas of the Ličko-Gračac plateau, the Lika river and the Bakovac valley, while correlation is possible with the southern part of Velebit in the area surrounding the cave area Cerovačke pećine. In the Lipovo polje, the Lika river bed partly cuts through Quaternary sediments. After this incision, new terraces were not formed. The left ridge of the valley, upstream from the hydroelectric plant Sklope, consists of Plio-Quaternary marls, overlain by Pleistocene colluvial clays, which were deposited both in the Kosinjsko and Lipovo polje. Along the river banks, intermittent and permanent springs occur, with no noticeable water loss, and the groundwater levels are higher in the banks than in the river bed.

The stream in the Bakovac valley, (the northern tributary of Lika river), cuts through Triassic and Jurassic deposits in its upper course, and in its middle and lower course through the Jelar beds. In the valley, deposition of Pleistocene and Holocene sediments of various genetic types took place. In the higher part of the valley, remnants of loose moraine material and solid bedded fluvioglacial conglomerates can be found. On the valley slopes and the valley floor colluvial clays were deposited.

On the basis of relatively small patches of Quaternary deposits preserved in the higher part of the Bakovac valley and Velebit, it can be concluded that valley incision occurred in two phases. The incision of a relatively shallow valley occurred before the deposition of fluvioglacial conglomerates which are preserved in the area of Krčevine at 720-780 m a.s.l. In the highest part of the valley on the slopes of Velebit, moraine material is preserved. The downstream part of the valley was at that period either deeper, or was lowered along a younger diagonal fault in the area downstream from the Živulje spring. In this part of the valley, fluvioglacial conglomerates are situated at an elevation of 580 m a.s.l. During deposition of colluvial clays in the broader area of the Lika plateau, the Bakovac valley was considerably shallower than today.

The association of Bakovac valley development with the evolution of the Lika plateau and the canyon incision of the Lika river, is the consequence of the function of the Velebit hydrogeological barrier (Fig. 3). The Bakovac valley is situated at the edge of influence of the Velebit full barrier, i.e. on the boundary towards northern Velebit and Senjsko Bilo. In this region, the karstification is much deeper and the waters drain towards the sea. The progression of deep karstification develops from the sea towards the mainland in the Lika region through the Bakovac valley, and on through to the lower course of the Lika river, and then into the Lipovo polje and the periphery of Kosinjsko polje. The progression of the karstification process is manifested in changes of stream flow paterns, the occurrence of intermittent springs, the presence of estavelles and ponors, and an increase of depth to groundwater.

The advance of the karstification process from the sea to the hinterland has affected the Bakovac valley in its higher and middle parts. As a result, part of the water drains beneath the valley floor through its northern side directly into the sea. During heavy rainfall, when water flows in the stream bed through the middle part of the Bakovac valley, the groundwater level there is below the valley floor. From the activity of this ponor, it can be concluded that the groundwater level there is always below the stream bed, which was confirmed with measurements performed in the observation borehole A-8.

The spelaeological phenomena situated along the middle and lower course of the Lika river, and the region between the Lika and Gacka rivers occur at shalow depths (BOŽIČEVIĆ, 1965, 1969) which corresponds to the relatively high erosional base level encountered there. This is a result of the function of the Velebit full barrier. The development of the karstification process can also be viewed in terms of sufficient sinking of the paleoplateau on the southeastern part of the Velebit barrier, in the cave area Cerovačke pećine along the southern edge of the Gračačko polje (MALEZ, 1965).

3. GENERAL CONDITIONS FOR THE CONSTRUCTION OF THE KOSINJ RESERVOIR

The construction of the Kosinj reservoir is planned for part of the lower course of the Lika river. The dam is to be built some 800 m upstream from the bridge (Kosinjski most), in fact downstream from the existing reservoir Kruščica.

In order to determine the hydrogeological conditions that would allow the feasibility of reservoir construction, the area downstream from the reservoir "Kruščica" in the valley of Lika river was also studied, as well as the broader area of reservoir recharge towards the Bakovac valley, Lipovo polje and the boundary zone towards the Gacka river. Detailed hydrogeological mapping was performed on a scale of 1:5,000 of the local area and the margins of the reservoir. A better understanding of tectonic conditions of both the immediate and broader regions of reservoir recharge was enhanced by Neotectonic studies of the same area (PRELOGOVIĆ, 1989).

Extensive exploration drilling was performed, accompanied by permeability measurements, geophysical tests, and water tracing tests. The groundwater level monitoring was conducted for many years, in over 50 observation boreholes in the recharge area of the future reservoir. In the groundwater-level studies, data were used from observation and other exploration boreholes made during the elaboration of the Kruščica reservoir.

The Kosinj reservoir area mainly consists of permeable Cretaceous carbonate rocks and the Jelar beds, so it is a hydrogeologically homogeneous terrain. Therefore, the hydrogeological conditions and water retaining characteristics are explained by zoning of the broader region surrounding the reservoir, according to the hydrogeological functions of the terrain (Fig. 3).

The Velebit hydrogeological barrier prevented deeper karstification of the transition region, which is reflected by high groundwater levels and the drainage of water towards the Lika river. Outside the area of barrier influence, ponors and estavelles exist, and the streams are intermittent or "hang" above the deeper groundwater levels. Under these conditions, in order to perform the studies, to evaluate the permeability of the broader area, and to plan the necessary intervening procedures, detailed hydrogeological zoning of the terrain recharging the reservoir (Fig. 6) was performed. The following four zones with unique hydrogeological features were outlined:

The area with permeable surface conditions and groundwater above the water level of the Lika river (1) covers a large part of the Kosinj reservoir bottom surface. All the waters in this zone flow towards the Lika river. Along the stream bed of the Lika river and its tributaries Bakovac and Mlakvenski potok, several permanent and intermittent springs exist. In this part of the terrain, only one ponor exists which drains the waters from the Mlakvenski potok. The tracing tests, performed in the borehole LG-5 on the northern bank of the reservoir, indirectly proved that the water of Mlakvenski potok drains through Ponorac into the Lika river. In the terrain within this zone, all the waters either drain towards the Lika or Gacka rivers.

The impermeable Jelar beds (2) are situated in the southwestern part of the terrain on which the Kruščica reservoir lies. The Jelar beds in this part of the terrain contain breccia with clayey marl cement and lenses of marl. The water retaining characteristics of the Kruščica reservoir is attributed to the favourable hydrogeological features of these deposits.

The zone of the uplifted tectonic block and the terrain under the larger influence of the now eroded Neogene clay deposits (3) - on the map showing hydrogeological provinces, this area is situated in the middle part, and the eastern margin of the Kosinj reservoir. This is also the water divide between the Lika and Gacka rivers. The existence of this water divide is the consequence of the uplifted tectonic block Mlakvena greda - Poljan, where recent karstification is fairly shallow. The occurrence of Neogene marl deposits in fossil depressions, found in boreholes K-4-2 and K-9, has a certain impermeable role in this terrain.

The boreholes revealed fissures and cavities containing compressed clay, a feature also indicated by the geophysical exploration performed along the route of the planned grout curtain. Spelaeological phenomena in this zone occur at relatively shallow depth and are above the Kosinj reservoir backwater level.

The groundwater level measurements performed in the drill hole over a longer period showed that the groundwater levels along the water divide towards the Gacka river do not fall bellow 520 m a.s.l. (Fig. 6). The precise position of the water divide was determined by tracing of water drainage from the drill holes.

The area in which the low waters are below the Lika river stream flow, and the erosion base level is the Adriatic sea (4) occupies the terrain north and northwest from the Kosinj reservoir. Downstream from the Kosinj dam is the Lipovo polje and its recharge zone. In the upstream part of the Lipovo polje on its eastern and western slopes a string of intermittent springs and estavelles exist. Ponors are located in the downstream part of the polje and, through them, water from the Lika river drains to the see. The estavelle zone during the dry season "passes" from the upstream part of the Lipovo polje into the area of the Kosinj reservoir. The groundwater level decline below the level of the Lika river stream bed was observed on the western bank between the Lipovo polje and Kosinjsko polje, where the 480 m water-table contour enters the area of the reservoir. Near the borehole BK-4, the boundary between the spring zone and the estavelle zone is close to the reservoir. The groundwater level decline in this reservoir bank was also observed in the borehole BK-2. In the Bakovac valley this boundary is upstream from the position of the dam.

Hydrogeological zoning (Fig. 6) is the basis for the understanding of hydrogeological conditions and the evaluation of the water retaining properties of the Kosinj reservoir; it also allowed the separation of impermeable areas from the permeable ones, the definition of locations for the construction of dams and the identification of banks which have to be made impermeable by grouting.

Further studies (drilling exploration, geophysical exploration, detailed study of Neogene marls in depressions on the East reservoir bank) should more precisely determine the conditions that will enable the construction of the reservoir, i.e. produce the data necessary for the construction of the grout curtain.

4. CONCLUSION

The necessary studies performed for the construction of a sufficiently impermeable reservoir in a karst terrain, for a big hydroelectric plant, are presented through the results obtained in the case of the Kosinj reservoir. The reservoir is situated in terrain composed of permeable limestone and limestone breccia (Cretaceous and Jelar deposits). The karst terrain in the hinterland of the Velebit barrier is divided into a **spring zone**, an **estavelle zone** and a **ponor zone**. Because the location of the Kosinj reservoir is almost completely situated within the spring zone, a basis for further studies exists, although this location was previously rejected.

The homogeneous karst terrain, largely composed of massive Jelar deposits with relatively undefined relationships with the Cretaceous deposits, required a specific approach, so the studies were focused on the structural and tectonic setting, the landscape development and the karstification processes.

In order to evaluate the permeability of the broader area and to plan the necessary intervening procedures, detailed hydrogeological zoning in the area of reservoir influence was performed and several zones with similar hydrogeological features were outlined.

From the exploration boreholes it was possible to obtain the data about groundwater levels, the character and depth of karstification. By groundwater tracing, the flow directions and the positions of groundwater divides were defined.

The Bakovac valley development is associated with the incision of the Lika river into the Lika plateau as a continuous process of the recent karstification. This karstification incorporates the spelaeological phenomena situated along the Kruščica dam and in the region between the Lika and Gacka rivers. The performed studies confirmed the existence of karstification beneath the Lika riverbed (the river is incised into a previously karstified terrain). Nevertheless, this does not diminish the hydrogeological importance of the Lika river as a recent erosional base level, because the older subsurface systems and groundwater flows were interrupted by Neotectonics, or because the drainage channels are clogged with clay material.

The results of the studies confirmed that the recent karstification, with which the present water dynamics is associated, is relatively shallow in the Kosinj reservoir area. Therefore, it is possible to achieve an impermeable reservoir with the aid of additional construction work.

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