GEOFIZIKA VOL. 40 2023

DOI: https://doi.org/10.15233/gfz.2023.40.1
Original scientific paper

The role of slope inclination, doline density and water budget analysis in delineation of complex karst catchment area of Slunjčica River (Croatia)

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Received 1 June 2022, in final form 15 November 2022

Due to the high vulnerability of the karst aquifer to the surface contaminants, a precisely defined catchment area has the highest priority. In this study, the influence of slope inclination, the doline density analysis, and the water budget analysis in the delineation process of a complex karst catchment area is discussed. To define hydrogeological role of lithological units, cross sections of slope inclination and doline density were combined with hydrogeological cross sections, while the degree of karstification was used to describe the permeability of rock units. The verification of karst catchment delineation area was performed with water budget analysis. The methodology used for the determination of hydrogeological behavior and delineation of a complex karst catchment area (Slunjčica River basin, Croatia) is shown with the flow diagram. It has been found that the highest doline density appears in the range from 0 to 1° of the slope inclinations, and that it decreases with a higher slope degree. Although the results of this study confirm that even with the relatively small number of input data it is possible to define the karst catchment area, it must be emphasized that the doline density analysis presents an indispensable tool in the research related to the definition of karst catchment areas.

Keywords: karst catchment, doline density, slope inclination, water budget analysis, Slunjčica River (Croatia)

1. Introduction

Research on complex karst areas is demanding, and very often an additional aggravating circumstance is the small number of input data, non-existent or weak monitoring data and the availability of only basic geological and topographic maps. Due to unique hydrogeological characteristics, the data requirements for the hydrogeological characterization of karst aquifers are more intensive and difficult to obtain than those for aquifers in most other types of hydrogeological settings (Teutsch and Sauter, 1991; Taylor and Greene, 2008; Guo et al., 2019; Torresan et al., 2020; Guo et al., 2021). Several authors have recognized the complex nature of flows resulting from the presence of karstic features (White, 2003; Bakalowicz, 2005; Lerch et al., 2005; Taylor and Greene, 2008; Vigna et al., 2010; El Alfy et al., 2019).

Taylor and Greene (2001) and Bakalowicz (2005) hold that the conventional study methods used in classical hydrogeology are invalid and unsuccessful in karst aquifers, because the results of the hydrogeological investigation at a local scale in these types of aquifers (respecting extreme heterogeneity and anisotropy of karst aquifers) very often cannot be extrapolated to the whole aquifer nor to distinct parts of it, as is often possible in non-karst aquifers. In such circumstances, it is necessary to find a straightforward way to achieve the goal, which is most often determining of the karst catchment area and identifying of the hydrogeological roles of its specific parts. The catchment divides of karst basins rarely coincide with topographic boundaries, which is the case in normal surface drainage basins. The main reason is the complex interconnected system of surface and underground fractures and karst conduits. The position of the catchment divide in the karst is defined in space, with a lithological and structural–tectonic relation, and in time, with a hydrological state and previously accumulated groundwater in the karst aquifer. Precise identification of the catchment area boundaries and its hydrogeological characteristics is an important issue for the effective management and protection of groundwater resources.

In complex karst terrains, a great emphasis must be placed on the identification of catchment boundaries, contributions of water from various recharge areas and the hydrogeological behavior of all parts of a catchment area. The acquisition of these data typically requires a multidisciplinary study approach that includes using more specialized investigation methods to estimate the recharge or contributing areas of karst springs (Ginsberg and Palmer, 2002). Recent research also showed that if hydrogeological context in karst area wants to be fully understood, it is necessary to control hydrological factors which affect its water budget (Gil-Márquez et al., 2021), while the identification of recharge areas of karst aquifers can enable sustainable management of groundwater resources (Iacurto et al., 2021). It was shown that inclusion of different tracers in monitoring can greatly reduce ambiguity of interpretation, but also that complete certainty in hydrogeology research of karst aquifers is still very hard to achieve (Stroj et al., 2020). Although numerous different approaches and methods of researching of karst hydrogeological systems have been developed, in many cases these methods are developed for a specific area and are not suitable in other areas for several reasons, from the lack of data required for a specific method to completely different relationships within the aquifer for which the applied method may not be applicable.

In a well-developed karst, solution dolines are the most specific surface morphotypes and their presence usually indicates soluble bedrock such as carbonates or evaporites. The gentle sloped surfaces of high karstic plateaus without active drainage also create suitable topographic conditions for the formation of dolines (Öztürk et al., 2015). Tectonic structure, especially joint intensity, and orientation, has a strong effect on doline development, density, orientation, and distribution on these plateaus (Öztürk et al., 2018). Dolines are readily identifiable areal features, and their locations are typically mapped for engineering and safety concerns and flooding hazards (Ford et al., 1997; Shofner et al., 2001; Angel et al., 2004). Doline density is variable and commonly used in models to assess aquifer vulnerability (Crawford and Veni, 1986; Ray et al., 1993; Doerfliger et al., 1999; Kochanov and Reese, 2003; Arthur et al., 2007; Biondić et al., 2021). It has been shown that high dolines density areas and strong fissuring corresponds to the areas with high and very high aquifer vulnerability (Moreno-Gómez et al., 2019).

In the wider research area different kind of hydrology and hydrogeology karst research has been done. Trend analysis of flows in the Kupa River showed almost equal amount of negative and positive trends in the period 1984–2013, with extremes during a wet period more pronounced than during arid periods (Pavlić et al., 2017). Furthermore, Selak et al. (2020) showed that very low and low water quality indices prevail for groundwater and surface water resources in Kupa River catchment. Cross-correlation and cross-spectral analysis of hydrographs in the northern part of the Dinaric karst of Croatia showed that the hydrogeological characteristics of karstic aquifer systems can present more controlling factor related to the runoff regime when compared to climate change influence (Pavlić and Parlov, 2019). Hydrogeology research of the catchment area of the Zagorska Mrežnica spring was focused to the definition of influence related to designing an injection curtain (Buljan et al., 2019), while in the southern part of Dinaric karst different kind of statistical analysis have been used to evaluate the functioning of Rumin springs (Denić-Jukić et al., 2020). In the northern part of Dinaric karst it has been shown that in the Nanoščica River and Ljubljanica River catchment lower summer discharge can be expected which indicates increase of karst river vulnerability and groundwater availability in near future (Sapač et al., 2019). Furthermore, in the southwestern part of Slovenia it was shown that the vegetation cover change, in addition to climate change, can have a significant impact on the spring hydrology, *i.e.* groundwater recharge, over a short and long time period (Kovačić et al., 2020).

Previous research in nearby river catchment basins was conducted with the aim of analyzing the hydrological regimes of the Mrežnica, Glina and Korana Rivers basins (Jurak, 1983). The catchments of these rivers and their sub-catchments were delineated, including the Slunjčica River catchment, which was estimated to be 347 km^2. Hydrogeological studies of Lička Jesenica springs were conducted for the purpose of establishing the regional water supply system and to determine the catchment area and sanitary protection zones of springs (Galović et al., 1998; Pavičić et al., 2007; Terzić et al., 2012). The Lička Jesenica River catchment is Slunjčica River's sub-catchment (Terzić et al., 2012). The nearby catchment area of Plitvice Lakes (UNESCO World Heritage) was delineated too (Meaški et al., 2014).

The focus of this study is to determine the relationship between slope inclination and doline density in order to determine the hydrogeological role of rock units and the delineation of the complex karst catchment area of the Slunjčica spring, which has not been studied separately before. The research area was selected for its importance and exceptional landscape value and has been protected since 1964. A subsequent evaluation established the importance of Slunjčica regarding biodiversity preservation so that it was included in the National Ecological Network and the proposal of EU NATURA 2000 ecological network. Since the water from the Slunjčica River is used for the public water supply, the analyzed catchment has been subjected to spatial analysis of doline bottoms regarding rock units and their density depending on the slope inclination at a local scale. With that approach, the Slunjčica River catchment area is closely delineated. Furthermore, hydrogeological cross sections with cross sections of slope inclination and doline density were made to emphasize areas with higher permeability. Water budget analysis is included as a verification tool for testing the accuracy of a defined karst catchment area. A well-defined karst catchment area serves as an important base for establishing quality sanitary protection zones of the karst springs and sustainable groundwater management.

2. Research area

The research area is shown in Fig. 1. The spring of Slunjčica River is at elevation of 244 m a.s.l., 6 km south of the City of Slunj. Slunjčica River flows northwards, and it pours into Korana River through branched waterfalls in Rastoke after 6 km of surface flow (the rivers Slunjčica and Korana belong to the large river basin of the Kupa River). The study area is mostly covered by woods, except in karst poljes, where lawns and cultivated surfaces prevail (CORINE land cover, 2021), and the climate is moderate continental with a warm summer (Šegota and Filipčić, 2003). From 1999 to 2019, the average annual air temperature was 10.7 °C, while the average annual rainfall was 1460 mm.

The geological settings of the study area were described by the following four Basic Geological Maps of the Republic of Croatia, produced at the scale 1:100 000: *Slunj* (Korolija et al., 1972), *Ogulin* (Velić and Sokač, 1980), *Otočac* (Velić et al., 1970) and *Bihać* (Polšak et al., 1967) and their associated interpreters. Since these maps were characterized by different chronostratigraphic units, the combined geology map of the study area is simplified with units that are divided into geologic series (epochs) (Fig. 2).

The oldest rock unit belongs to the Permian age (P), represented by shales and sandstones as well as super positioned Lower Triassic (T_1) deposits that are

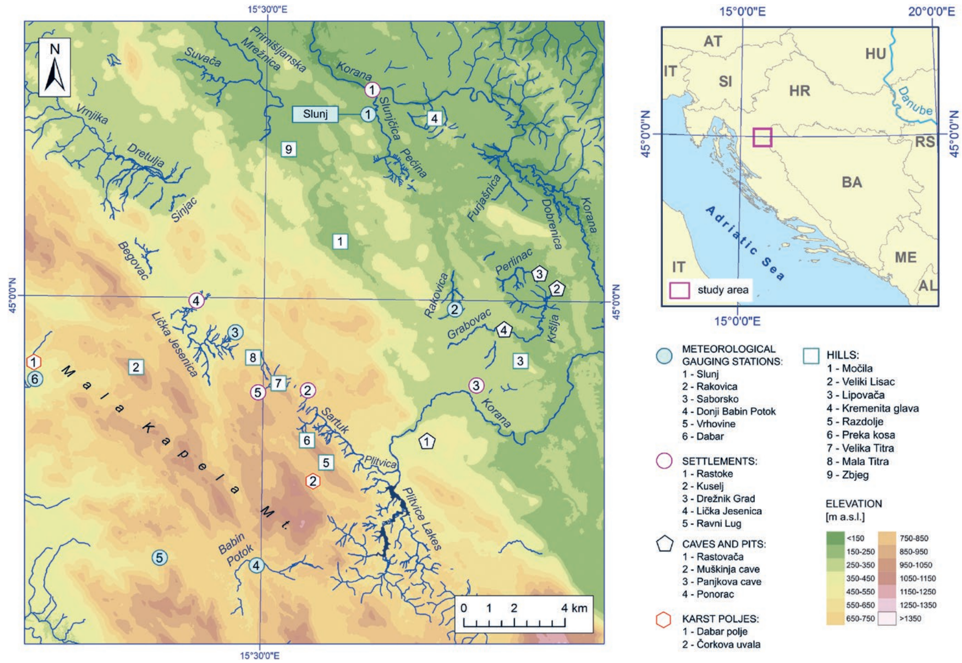

Figure 1. Location of the study area (names of toponyms and oronyms in map legend are listed as they appear in text).

also described as clastic rocks but with lenses of dolomite in the upper part. Middle Triassic (T_2) and Upper Triassic (T_3) units consist of fine-grained early diagenetic dolomite. Considering the different evolution of Jurassic and Lower Cretaceous deposits in some parts of study area, rock units are divided in two groups.

Those in the first group are deposits where dolomites prevail in the bottom part of Lower Jurassic (J_1), while the upper part consists of fine layered limestone. Limestone continues to the Middle Jurassic (J_2), while thick layered dolomite and limestone alternates vertically and horizontally in the Upper Jurassic (J_3). The Lower Cretaceous (K_1) unit is represented by limestone and dolomite, with an abundance of dolomite in the most upper part. The transition zone from the Lower to Upper Cretaceous ($K_{1,2}$) is found on the Močila hill with the presence of dolomite and unlayered dolomitic breccia.

Those in the second group are Jurassic deposits (J_1, J_2, J_3) represented by dolomite and Lower Cretaceous (K_1) deposits made of limestone. Massive limestone of the Upper Cretaceous (K_2) is present in a large part of the study area.

NE of the Korana River is a continuous zone of Cretaceous-Paleocene (K,Pc) clastic rocks, flysch. The Middle Miocene (M_2) erosion residue of fine-grained

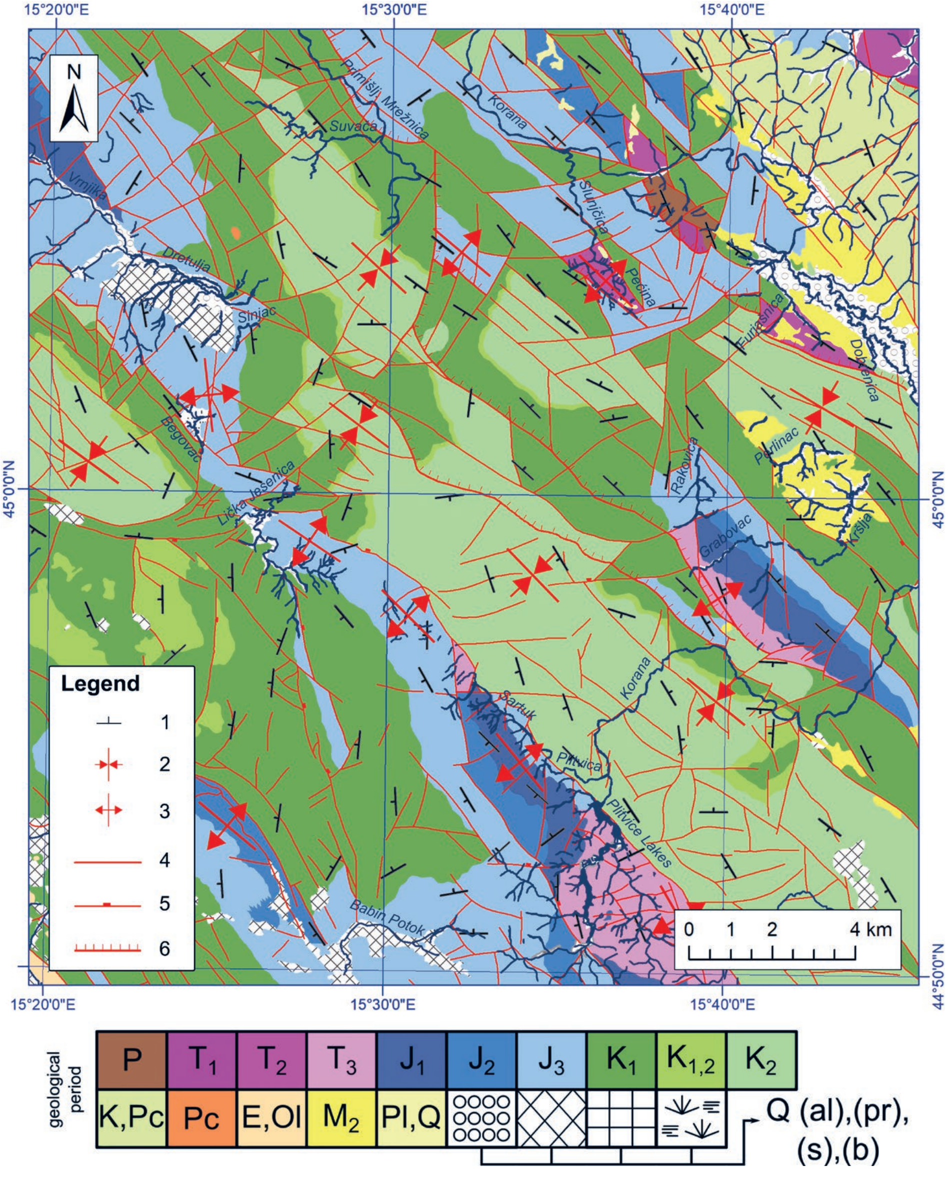

Figure 2. Geological map of the study area (1 – strike and dip of beds, 2 – syncline, 3 – anticline, 4 – fault without type, 5 – normal fault, 6 – reverse fault), compiled after (Polšak et al., 1967; Velić et al., 1970; Korolija et al., 1972; Velić and Sokač, 1980).

gravels, sands with tufitic clay and marls, are found in the Kršlja area. They are transgressive to all the older units. Near Slunjčica spring and Pećina stream, there are small areas of Pliocene-Quaternary (Pl, Q) sands and gravels. Quaternary deposits are divided into proluvium (Q[pr]), tufa (Q[s]), swamp (Q[b]) and alluvium (Q[al]).

The whole area is folded and disarranged with vertical faults where the main structures have a characteristic northwest–southeast direction (the so-called Dinaric direction). Compressional tectonics with the presence of normal faulting caused the existence of several structural units in the area.

3. Materials and methods

The input data for the water budget analysis were provided by Croatian Meteorological and Hydrological Service (DHMZ) for a period of 20 hydrological years (1999/2000–2018/2019). The data that were used for hydrological modeling of karst catchment include the daily amount of precipitation measured on rain and climatological gauge stations, average daily temperatures, and average daily discharge on the karst river. The three rain gauge stations are positioned within the catchment and three are outside the catchment divide. Besides that, rain gauge stations were positioned both below and above the mean karst catchment elevation. A brief description of the precipitation data from rain gauging stations (Rakovica, Saborsko, Donji Babin Potok, Vrhovine and Dabar) and climatological gauge station Slunj is given in Tab. 1. Vrhovine, Donji Babin Potok and Dabar are new rain gauge stations that subsequently started operating and there are no data for the entire period of 20 hydrological years.

The process of determining hydrogeological behavior and delineation of the complex karst catchment area of Slunjčica spring is shown in Fig. 3 with a flow diagram. It is a visual guide that has its start point with input data (lithology and tectonics, doline positions, slope inclination) and major end point in the protection of a karst catchment. Blue rectangles are associated with the main aims of this study. Separate steps of the flow diagram conducted during this research are described in next subchapters. All the implemented steps are the basis for the last step related to management and protection of the karst catchment.

Table 1. Brief description of data from rain/climatological gauging stations.

Rain / climatological gauging station	Elevation (m a.s.l.)	Number of full annual data (1999/2000–2018/2019)	Average annual precipitation, P_{av} (mm)	Range (average) of annual days with precipitation (day)
Slunj	254	20	1287	96–159 (130)
Rakovica	394	20	1368	97–163 (130)
Saborsko	551	20	1684	78–188 (146)
Donji Babin Potok	757	14	1299	109–180 (146)
Vrhovine	730	19	1243	81–162 (120)
Dabar	648	5	1416	94–163 (126)

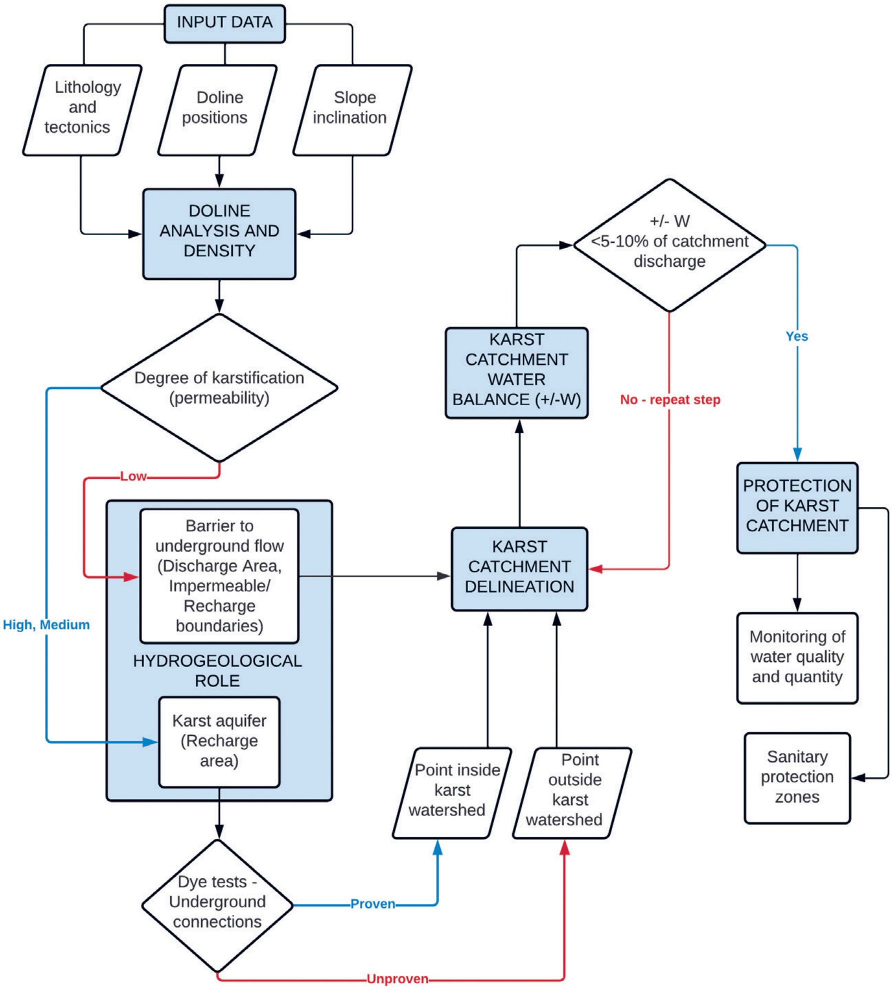

Figure 3. Procedure of delineation of karst catchment area.

3.1. Doline analysis and density

Geomorphological forms, which can be determined on the surface, are the first indicator of the degree of karstification of carbonate rocks. Within the meso-morphological features the most frequent are dolines (Mihljević, 1994), which can also be used for determining the character and direction of tectonic features. Dolines are depressions in karst areas that enable a concentrated and direct path for surface water to drain into the karst aquifer, if the surface is not covered with a thick layer of soil (Gams, 2000; Ford and Williams, 2007). Dolines (and other karst phenomenon) define karst areas, while their distribution is defined by lithological, structural, tectonic, and climatologic characteristics (Faivre, 1992), slope inclination and dimensions of dolines (Pahernik, 2012). With doline analysis and doline density maps, it is possible to recognize groundwater recharge areas. Furthermore, it has been shown that all exposed karstifiable evaporite and carbonate rocks can be mapped as potentially permeable material (Goldscheider et al., 2020), but also that degree of karstification is closely related to the permeability (Torresan et al., 2020).

The positions of doline bottoms were determined using topographic imagery. A topographic map was provided by Croatian Geodesic Administration scaled to 1:25,000. After mapping doline bottoms, doline bottoms were intersected with rock units defined by a combined geological base map. Subsequently, the rock units were subdivided with respect to differences in the number of dolines per square kilometer for further analysis. Analysis included an intersection of doline bottoms with the degree of slope inclination. The most significant relation between morphometric characteristics of terrain and doline density in Dinaric karst is established with slope inclination and vertical relief dissection (Faivre, 1992 – North Velebit and Senjsko Bilo Mtn.; Telbisz, 2010 - Montenegro, Sinjajevina Mts.; Pahernik, 2012 - Croatian karst). The U.S. Geological Survey 30-meter digital elevation model (DEM) was used to determine the terrain slope inclination.

In Croatia, in previous research, doline density was classified according to the (Faivre and Pahernik, 2007; Pahernik, 2012) where four and six categories were identified. However, within this research much more detail classification of doline density was done, and 11 categories have been defined. To compute the doline density, the kernel method was used, which focuses on nearest neighbor analysis in a continuous set of data represented in raster form (Mitchell, 1999). The raster grid enables relative permeability differences in parts of the individual rock units to be recognized, and their hydrogeological role to be better understood. To calculate the doline density, the circle area of 1 km^2 was used, which fits to a radius of 564 meters (Pahernik, 2012).

3.2. Hydrogeological role of rock units and underground connections

The following two types of rock porosity define the study area: karst-fissure and intergranular porosity. Carbonate rocks, limestone, and dolomite, have karst-fissure porosity, while clastic rocks and alluvium deposits have intergranular porosity. Rocks with karst-fissure porosity are divided into three groups (rocks with high, medium, and low permeability; similar to Lukač Reberski et al., 2009) which was defined by hydrogeological characteristics of lithostratigraphic members. In this study, the degree of karstification was used as an additional tool. In the end, the relation between the permeability of rocks, tectonics, spatial and hypsometric positions of lithological bodies, morphology, amount, and position of rainfall described the hydrogeological role of rock units, which was identified as: true barriers, relative barriers, and aquifers (Bahun, 1989).

True barriers form discharge areas cause an interruption to and prevention of deeper groundwater circulation as well as surface runoff. Relative barriers do not entirely interrupt the groundwater flow, but depending on geological settings, regulate or redirect the flow (transverse flow or flow beneath a relative barrier). The formation of relative barriers formation can be conditioned by tectonics, lithological characteristics (dolomite and limestone alteration) and hydrological settings (seasonal variation of groundwater levels). True and relative barriers of underground flow can represent karst catchment impermeable and recharge boundaries, depending on their stratigraphic position and tectonics. Aquifers form recharge areas which are characterized by both point and diffuse recharge, and high effective infiltration.

Owing to the complexity of karst catchments, the incorporation of dye tests is important to define the karst catchment divide. Data shown in Tab. 2 (and Fig. 8) were collected and interpreted based on previous dye tests (Herak, 1956; Bahun, 1968; Jurak, 1983; Marušić and Ćuruvija, 1991; Garašić, 1997; Ivičić, 1999; Ivičić et al., 2003; Pavičić et al., 2007; Trpčić and Pletikosić, 2010; Mlinarić, 2012; Biondić and Meaški, 2016).

Table 2. Underground connections proven with dye test in the study area from 1949 till 2007 (proven connections visible as numbers in squares in Fig. 8).*

Injection point	Injection point elevation (m a.s.l.)	* Proven connection to		Spring elevation (m a.s.l.)	Distance from injection point (km)	Apparent velocity (cm/s)	Literature
Dabar polje stream sink	518	1	Dretulja	375	13.80	2.10	Jurak, 1983
		2	Sinjac spring	367	13.71	2.50	
Dretulja stream sink	365	3	Primišljanska Mrežnica	254	5.50	unknown	Bahun, 1968; Jurak, 1983
		4	Suvača springs	295	4.37	unknown	
Lička Jesenica stream sink	465	5	Slunjčica spring	244	13.67	2.06	Jurak, 1983; Trpčić and Pletikosić, 2010
Crno jezero (Čorkova Uvala)	825	6	Plitvica spring	609	2.39	1.44	Pavičić et al., 2007
Rakovica stream sink (Švica)	326	7	Slunjčica spring	244	8.53	0.60	Ivičić et al., 2003
Belac stream sink	777	8	Sartuk left spring	718	1.15	0.14	Marušić and Ćuruvija, 1991
		9	Mlinište spring	725	0.97	unknown	

Table 2. Continued.

Injection point	Injection point elevation (m a.s.l.)	* Proven connection to		Spring elevation (m a.s.l.)	Distance from injection point (km)	Apparent velocity (cm/s)	Literature
Rastovača doline	545	10	Klokot (Una basin) spring	230	16.92	1.14	Biondić and Meaški, 2016
piezometer in Drežnik Grad	390	11	Klokot	230	18.14	1.13	Mlinarić, 2012; Biondić and Meaški, 2016
		12	Gavranića spring	292	6.47	0.31	
		13	Baračevac spring	297	6.22	0.25	
Muškinja cave (Kršlja stream sink)	285	14	Crno vrelo	255	2.48	unknown	Garašić, 1997
		15	Zečevac	255	3.44	unknown	
		16	Bijelci springs	256	4.06	unknown	
Panjkova cave (Perlinac stream sink)	285	17	Crno vrelo	255	3.32	unknown	Garašić, 1997
		18	Zečevac	255	3.46	unknown	
		19	Bijelci springs	256	3.46	unknown	

Results of dye tests prove underground connections between stream sinks (boreholes, dolines) and spring zones. Karst catchments often share their catchment divide with an adjacent karst catchment. Therefore, information on unproven underground connections is helpful for setting the catchment divide between them. Complex karst catchments have sub-catchments and tributaries. It is important to know about proven/disproven underground connections related to their spring zones. Using dye tests, two underground connections with Slunjčica River spring were proven, with stream sinks of Lička Jesenica River and Rakovica stream.

Lička Jesenica springs (Malo and Veliko Vrelo) were part of a dye test with an injection point in Dabar polje (Pavičić et al., 2007), well in Kuselj (Ivičić, 1999) and Crno jezero (Pavičić et al., 2007) without confirmed underground connections. Additionally, there is no information from a dye test of Lička Jesenica stream sink and Primišljanska Mrežnica spring as a sampling point (adjacent spring of Slunjčica River spring).

Slunjčica River spring was part of dye test from piezometer in Kuselj (Ivičić, 1999) without a proven connection. There is no information about Slunjčica's spring as the sample point from dye tests from Dretulja stream sink, Begovac estavelle, the sinking zone of Korana River. Dye tests in Rastovača doline and piezometer in Drežnik Grad proved a connection between Una catchment (Klokot spring) and downstream part of Korana River which indicates that there is a low possibility for draining groundwater towards Slunjčica River.

Pećina spring (Slunjčica's right tributary) was part of sampling for Rakovica stream sink (Švica), and that connection was not proven (Ivičić et al., 2003).

3.3. Karst catchment delineation

Combined data (lithology, tectonics, permeability of rocks defined by degree of karstification, hydrogeological behavior of the study area and proven/disproven underground connection using dye tests) allowed the creation of a hydrogeological map of the studied area, including the karst catchment divide (presented in Fig. 8).

For a better understanding of underground processes in a karst catchment, hydrogeological cross sections were made (presented in Figs. 9 to 11). They may help us to understand the underground flow of water, depth of karst aquifer and approximate catchment divides with nearby karst catchments. Hydrogeological cross sections were compared with cross sections of slope inclination and cross sections of doline density. A combination of hydrogeological cross sections and cross sections of slope inclination and doline density can explain the cause of the higher/lower permeability of lithological units (hydrogeological role). Besides that, with those cross sections, the dependence of doline density on slope inclination can be tested. Vertical exaggeration is 10 times larger in scale to better represent directions of underground water flow, which would be difficult to show without vertical exaggeration. Maps are made using ArcGIS 10.1 software. The coordinate reference system of all maps in this study is WGS 1984. Hydrogeological cross-sections were drawn in Inkscape, and parts of hydrogeological profiles (slope inclination and doline density) were drawn in Surfer 13.

3.4. Karst catchment water budget

Water budget analysis was used for the verification of karst catchment delineation determined by the previously described procedure. A water balance calculation can provide an order of magnitude estimation of reserves and storage changes (Ford and Williams, 2007).

Water budget (ΔW) is defined by the following equation:

$$\pm\Delta W = I - O = \frac{\left(P_{av} - E_T\right)A}{T} - (Q_{av} + Q_{ex}), \tag{1}$$

where ΔW is the annual water budget (m^3/s), I – the annual inflow in karst catchment (m^3/s), O – annual outflow from defined karst catchment (m^3/s), P_{av} – average annual precipitation on defined karst catchment (m), E_T – real annual evapotranspiration (m), A – defined karst catchment area (m^2), T – time, year (s), Q_{av} – average annual discharge from karst catchment (m^3/s) and Q_{ex} – average annual amount of extracted water (m^3/s).

The Thiessen method (Thiessen, 1911) was used to determine the average annual precipitation. The Thiessen method defines influence polygons (areas) for every rain gauge station in the catchment. Polygon, which belongs to an individual rain gauge station, is bounded by bisectors of lengths that connect nearby stations. For n rain gauge stations, average annual precipitation (P_{av}) on catchment with area (A) is as follows:

$$P_{av} = \frac{P_1A_1 + P_2A_2 + \ldots + P_nA_n}{A_1 + A_2 + \ldots + A_n}, \tag{2}$$

where P_i is the annual precipitation (mm), and A_i is the influence area of *i-th* rain gauge station (km^2). If precipitation data were not available for a certain rain gauge station, for a whole hydrological year, that rain gauge station was excluded from the calculation and new Thiessen's polygons were established.

Turc's formula (Turc, 1954) was used to calculate the average annual real evapotranspiration as follows:

$$E_T = \frac{P}{\sqrt{0.9 + \frac{P^2}{\left(300 + 25T_p + 0.05T_p^3\right)^2}}}, \tag{3}$$

where P is the average annual precipitation in the catchment area (mm), T_p is the corrected average annual temperature (°C) which is corrected if average monthly temperature is available, while it is calculated using the following:

$$T_P = \frac{\Sigma(P_iT_i)}{\Sigma P_i}, \tag{4}$$

where P_i is the average monthly precipitation in the catchment (mm) and T_i is the average monthly temperature in the catchment [°C].

Turc's formula is often used to calculate runoff deficit (evapotranspiration) in Dinaric karst because of the limited amount of hydrometeorological data (Bonacci and Magdalenić, 1993; Bonacci, 1999; Bonacci et al., 2006) and for preliminary results to determine the catchment area size before more detailed hydrogeological investigations.

Errors in calculating the water budget are considered and an error of ± 10% is a reasonable result (Ford and Williams, 2007). To verify the quality of a delineated karst catchment, an error in water budget analysis that is lower than ± 5–10% of the average discharge from the delineated karst catchment (considering the period of data set) is defined as a fulfilled condition for good determination of karst catchment divide. If an error in water budget analysis is higher than ± 5–10%, delineation of karst catchment should be repeated.

4. Results and discussion

4.1. Doline analysis and density

The maximum values of doline density were measured in the middle sinking zone of Korana River (135 to 166 dolines per km^2 – Number 1, Fig. 4), and in the fault where T_3 dolomite and K_1 limestone come into contact, NE of Plitvice Lakes where Korana River forms (158 dolines per km^2 – Number 2, Fig. 4). Doline densities above 100 dolines per km^2 are developed in: the fault contact between T_3 dolomite and K_1 limestone where the Rakovica and Grabovac streams forms (160 dolines per km^2 – Number 3, Fig. 4), between Kršlja stream and Korana River in K_1 limestone (149 dolines per km^2 – Number 4, Fig. 4). Toward the NW, where J_3 dolomite and K_1 limestone come into contact in the Lička Jesenica sinking zone (139 dolines per km^2 – Number 5, Fig. 4). Going N, where J_3 limestone and dolomite with K_1 limestone come into contact before forming Primišljanska Mrežnica River spring (132 dolines per km^2 – Number 6, Fig. 4). Furthermore, in the area between Rakovica stream and Slunjčica spring (109 dolines per km^2 – Number 7, Fig. 4) at the contact of K_1 limestone and J_3 limestone and dolomite, and the larger area in K_1 in the sinking zone of Korana River (113 dolines per km^2 – Number 8, Fig. 4).

Less than 1 doline per km^2 is determined in the J_2 and J_3 dolomite in the SW study area (Letter A, Fig. 4); toward the NE, at K_1 limestone with a higher degree of slope inclination (Letter B, Fig. 4), and at $K_{1,2}$ dolomite and dolomitic breccia on Veliki Lisac hill (Letter C, Figure 4); and toward the east, at J_3 dolomite from Lička Jesenica to Kuselj (Letter D, Fig. 4) and at dolomite (J_2, J_3, T_3) on Plitvice Lakes territory (Letter E, Fig. 4). Additionally, the following areas show a low doline density: J_3 dolomite and Q alluvium of Dretulja River (Letter F Fig. 4), swamp sediments of Begovac estavelle (Letter G, Fig. 4), J_2 dolomite where Slunjčica River and the Pećina stream forms (Letter H, Fig. 4), J_3 and T_3 where the Rakovica stream forms (Letter I, Fig. 4), J_3 dolomite on Lipovača hill (Letter J, Fig. 4), M_2 clastic rocks where the Kršlja stream flows (Letter K, Figure 4), Korana River alluvium (Letter L, Fig. 4) and Permian clastic rocks on Kremenita Glava hill (Letter M, Fig. 4).

In general, the maximum values of doline density are related to fault zones, while the minimum values are predominantly in less permeable rocks and in the areas of higher degree of slope inclination.

Limestone, dolomite, and clastic rock deposits occupy 64.75%, 26.31% and 8.94% of the study area, correspondingly. Lower and Upper Cretaceous limestone deposits spatially predominate in the study area. Figure 5 shows the numbers

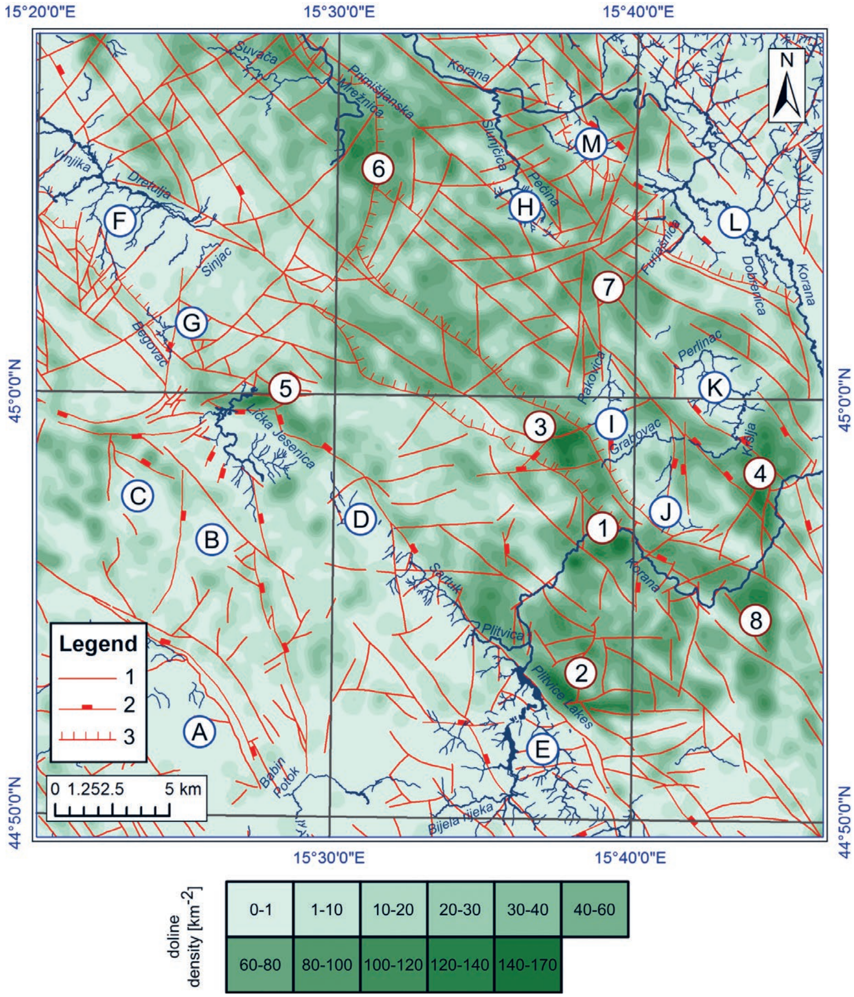

Figure 4. Doline density map (Legend: 1 - fault without type, 2 - normal fault, 3 - reverse fault).

of doline bottoms per each geological period, the average doline densities per each geologic period and the number of dolines (in %) per geological units compared to the total number of dolines in the study area. Lower and Upper Cretaceous limestone deposits also have the largest number of dolines at their surface (80.12%). On the surfaces of limestone deposits (J_2, K_1, K_2), dolomite deposits (T_2, T_3, J_2, J_3, K_1, $K_{1,2}$), combined limestone and dolomite deposits (J_1, J_3) and clastic rocks deposits (P, T_1, K, Pc, Pc, M_2, Pl, Q, Q) of 80.86%, 7.42%, 10.93% and 0.79% dolines are developed, correspondingly. The average karst density of dolines in the study area is 21.26 dolines per square kilometer. However, the

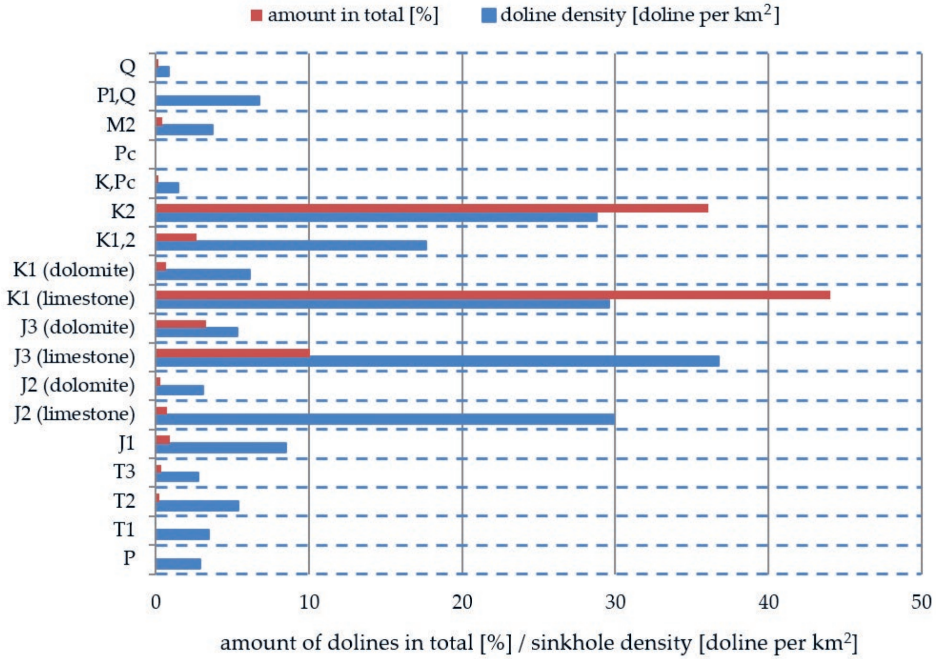

Figure 5. Number of dolines per geological periods.

average doline density in the limestone areas is higher (28.75 to 36.72 dolines per square kilometer), and in dolomite areas, it is lower (2.75 to 17.63 dolines per square kilometers). A higher doline density in dolomite is found in K_1 dolomite, which is in contact with the highly karstified K_1 limestone in the Lička Jesenica area. Besides them, dolomite and dolomitic breccias ($K_{1,2}$), which are, in the most cases, inserted in K_1 and K_2 limestone, show a higher doline density (17.63 dolines per km^2) because of the limestone surroundings and small thickness of the rock unit. The lowest number of dolines per km^2 (0 to 6.76) is detected in clastic rocks deposits that lay on top of the carbonate deposits.

From the results of this study, the limestone, and dolomite rocks in the study area contrast in doline density. With that reason in mind, slope inclination analysis was performed separately for the limestone and dolomite areas (Fig. 6). The results of this analysis indicate that inclined terrains (5–12°) are mostly developed in carbonates. The greatest numbers of dolines in carbonates are in low inclined terrains (2–5°). Dolines in limestone develop with up to 26 to 27° of slope, and in dolomite with up to 20 to 21°.

The highest doline density appears at a 0 to 1° slope both in limestone and dolomite and declines with a higher degree of slope. Values higher than the

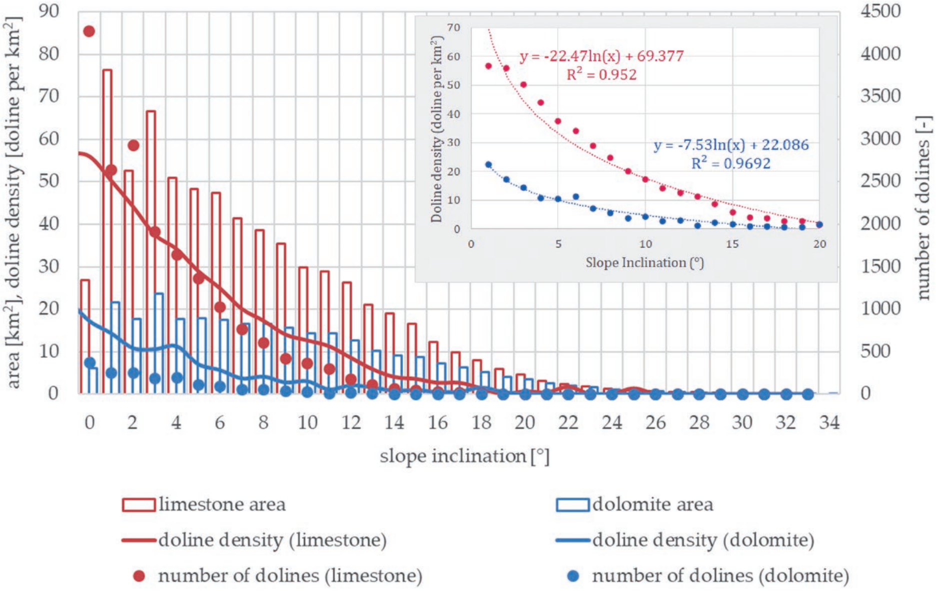

Figure 6. Doline density vs. slope inclination and carbonate rock type.

average density in limestone in the study area (29.84 dolines per km^2) show up until a 5–6° slope, and the doline density above 10 per km^2 is determined above a 13–14° slope. Values higher than the average density in dolomite in the study area (7.02 dolines per km^2) show up until 6–7°. The similar results have been observed in the Dinaric karst of Slovenia (Gams, 2000).

4.2. Hydrogeological role of rock units

In the study area three categories of permeability related to karst-fissure porosity have been identified. Limestone (K_1, K_2) has a high permeability (58.42% of the study area), while limestone with dolomite (J_1, J_2, J_3) have medium permeability (5.81% of the study area). Both types of rock have a high degree of karstification and are strongly fractured. Dolomite (T_2, T_3, J_1, J_2, J_3, K_1, $K_{1,2}$) has a low karst-fissure porosity, with a low degree of karstification (26.31% of the study area). Quaternary alluvium deposits and spatially limited Pliocene–Quaternary deposits have a variable intergranular porosity owing to the alteration of sand/ gravel and clay. Cretaceous–Paleocene flysch deposits and Quaternary swamp sediments have a low intergranular porosity. Permian, Lower Triassic and Middle Miocene clastic deposits have an impermeable intergranular porosity.

Figure 7 shows the defined hydrogeological roles of the rock units in the study area. Recharge areas do not have surface streams and they lack springs but, on the other hand, they are rich in karst morphology forms. The exception is the lower recharge area, where surface streams flow on impermeable Permian and Lower Triassic clastic deposits. Those deposits are at a higher elevation than the adjacent carbonate rocks; therefore, the surface streams flowing on them, under gravitational force, sink into the karst underground. They do not act as a

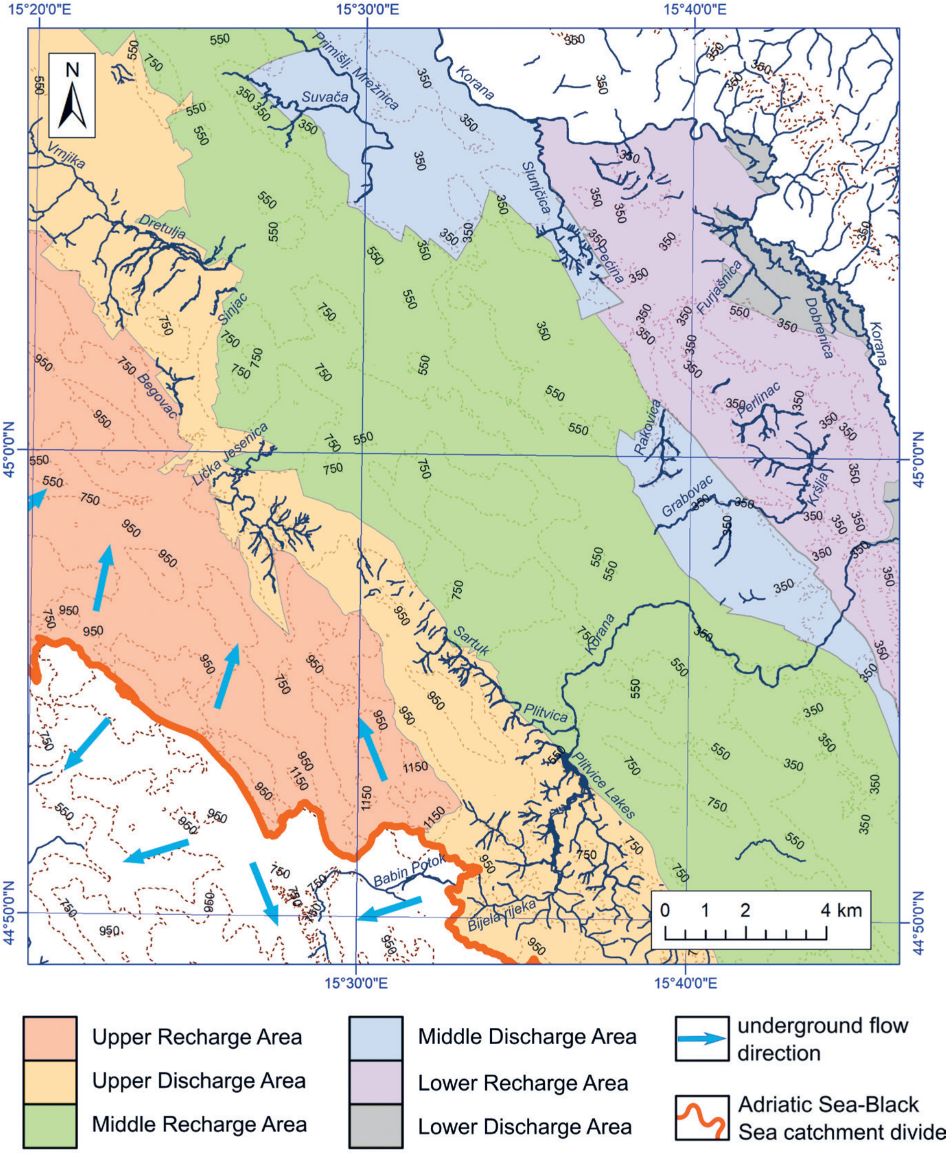

Figure 7. Hydrogeological role of different parts of the study area (modified according to Bahun, 1968).

true barrier to underground flow, which is evident with a lack of springs. Besides them, surface streams are present on Middle Miocene clastic rocks, which act as a thin impermeable layer on a limestone rock basis. Due to those facts, their hydrogeological role presents a relative barrier to underground flow.

The Slunjčica River catchment belongs to the Black Sea catchment, therefore, catchments that belong to the Adriatic Sea catchment are excluded in the description (Babin Potok stream catchment, Gacka River catchment).

The Upper Recharge Area encompasses the southwest part of the study area, which is built of the highly permeable Lower and Upper Cretaceous limestone. Due to contact with the Lower Cretaceous and/or Upper Jurassic dolomite, which is less permeable than the limestone from the Upper Recharge Area, a partial, occasional, and local slow-down of groundwater flow occurs, where the contact with a true hydrogeologic barrier forms permanent karst springs. This area belongs to the Upper Discharge Area. The prevalence of dolomite deposits (from Upper Triassic to Upper Jurassic) and an anticline form, condition them as a true hydrogeologic barrier (Bahun, 1989). Due to the contact between Upper Jurassic dolomite and Lower/Upper Cretaceous limestone, karst rivers from the Upper Discharge Area sink into limestone, at elevations from 360 to 490 m a.s.l.

The Middle Recharge Area spreads NE from the Upper Discharge Area and recharges the Slunjčica, Primišljanska Mrežnica, Rakovica and Grabovac springs, including the upstream part of Korana River. The Middle Recharge Area is characterized by a syncline setting with a low permeable dolomite floor that restricts the deep circulation of groundwater, while fractured and karstified limestone predisposes groundwater movement horizontally (Meaški et al., 2014). The Middle Recharge Area is interspersed by dolomite and dolomitic breccia ($K_{1,2}$) with the regulation and redirection of groundwater flow acting as relative barriers. In the SE part, Korana River is sinking into Upper Cretaceous limestone; therefore, the riverbed can dry up during the summer 1.5 km downstream of source, and 10 km from the source, the riverbed is fully without water for more than 4 months (Biondić et al., 2010; Biondić and Meaški, 2016). The Middle Discharge Area is defined with true barriers formed of (NE towards SW) Upper Jurassic dolomite and limestone (J_3), Middle Triassic dolomite (T_2) and Upper Triassic dolomite (T_3). In that area, the Primišljanska Mrežnica spring forms its groundwater level as well as spring of the Slunjčica River and Rakovica and Grabovac springs at elevation between 240 and 260 m a.s.l.

The Lower Recharge Area is spread downstream from the Slunjčica, Rakovica and Grabovac springs. The north part consists of impermeable Permian and Lower Triassic clastic rocks. From hill tops surficial flow under gravitation force flows into the medium permeable Upper Jurassic dolomite and limestone. Going to the SE, this recharge area consists mainly of a high permeable Lower and Upper Cretaceous limestone with transgressive deposits of impermeable Middle Miocene clastic rocks and Quaternary alluvium of temporary streams on top of them. The Lower Discharge Area begins in contact with the true hydrogeological barrier and in reverse contact with low permeable Middle Triassic dolomite, impermeable Middle Miocene clastic rocks and Quaternary alluvium deposits of Korana River.

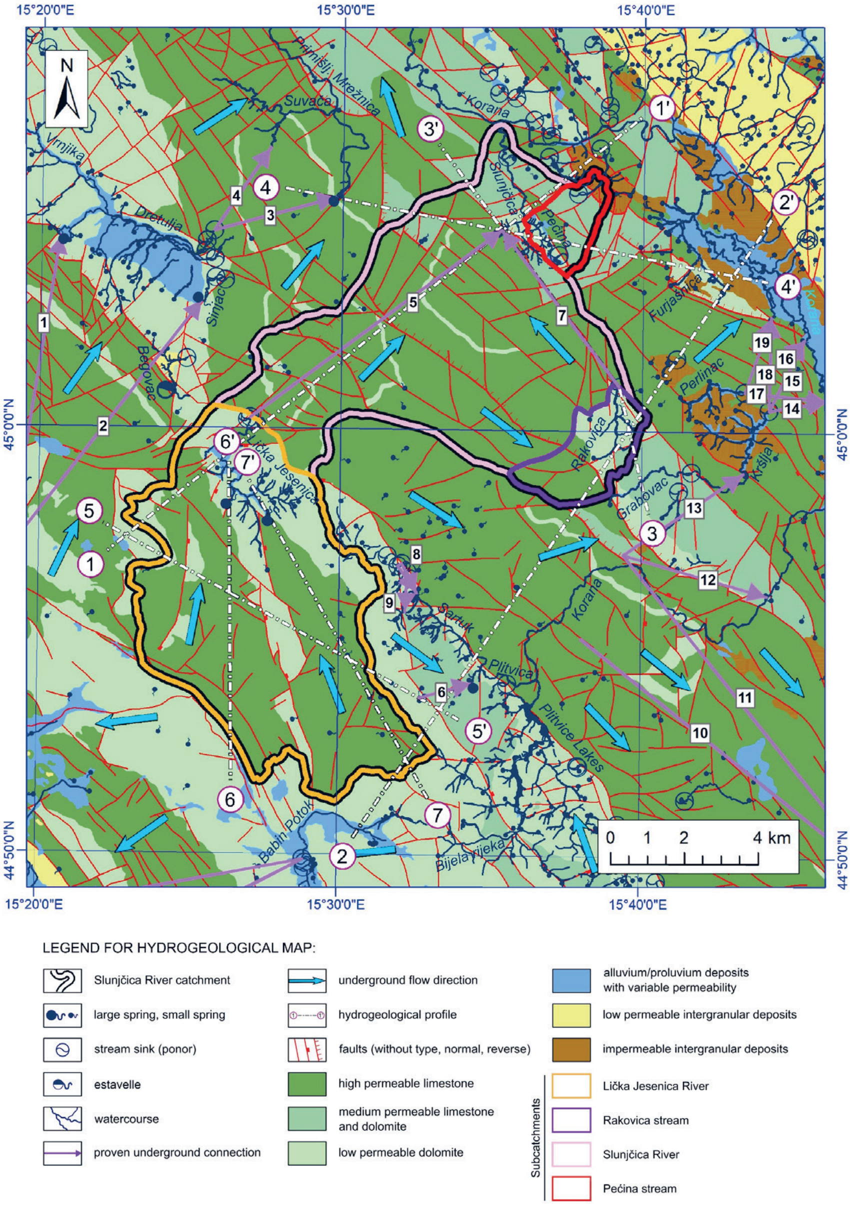

Figure 8. Hydrogeological map of the study area.

4.3. Slunjčica River catchment area

The Slunjčica River catchment area was delineated, and it covers an area of 282.74 km^2 (Fig. 8). Hydrogeological cross sections are shown at Figs. 9 to 11. The Slunjčica River catchment area was divided into the following sub-catchments conditioned by the hydrogeological role of rock units and proven under-

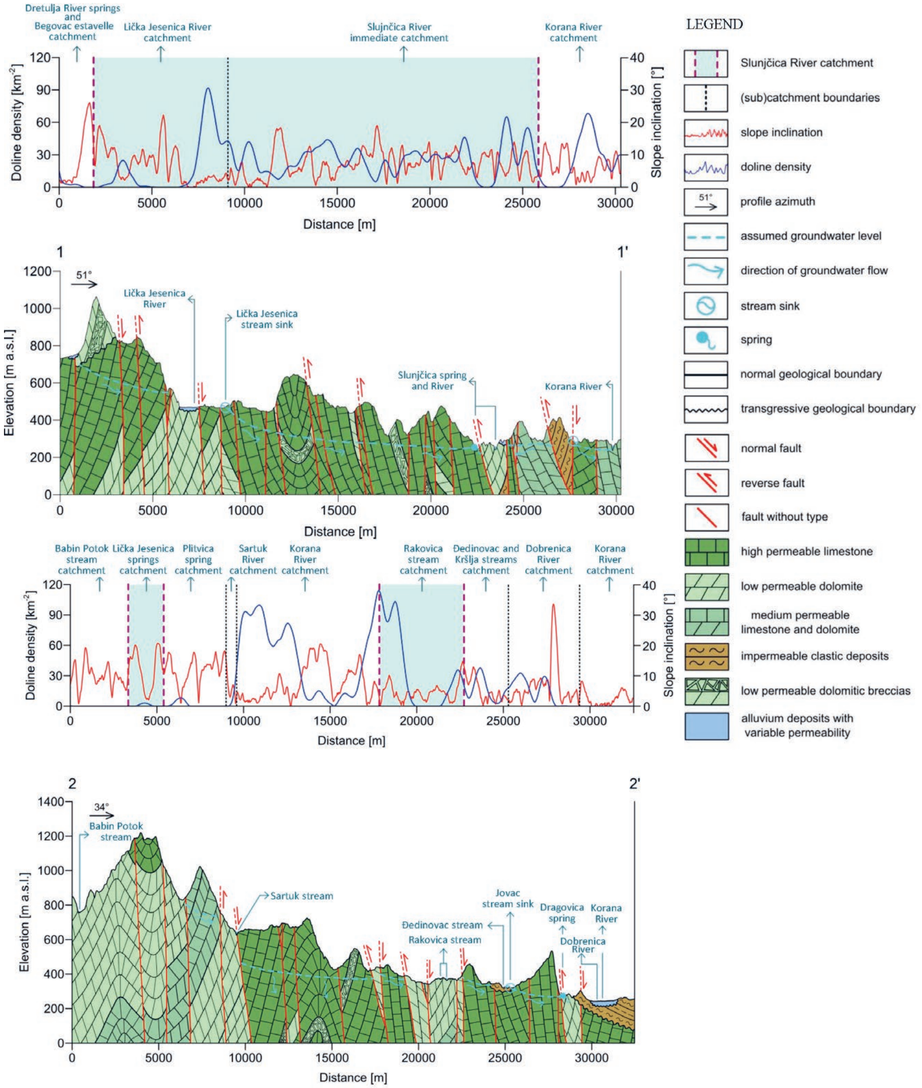

Figure 9. Comparison of hydrogeological cross section and cross section of slope inclination and doline density (profiles 1-1' and 2-2').

ground connections: the sub-catchment of Lička Jesenica River, the sub-catchment of Slunjčica spring, the sub-catchment of Rakovica stream and the sub-catchment of Pećina stream.

The Lička Jesenica River sub-catchment (Cross sections 1-1’, 2-2’, 5-5’, 6-6’ and 7-7’, Figs. 9 and 10) is in the SW part of the Slunjčica River catchment area and belongs to the Upper recharge area of groundwater. The S and SW part of the catchment is the Black Sea and Adriatic Sea basins’ catchment divide. It stretches on the normal fault where high permeable (K_1) limestone and low permeable (J_2, J_3, K_1) dolomite (impermeable boundary) come into contact. Low permeable dolomite deposits have a layer dip toward the SW and the terrain elevation declines toward the SW; therefore, the temporary watercourses that form flow toward the SW (Cross section 2-2’ and 6-6’, Figs. 9 and 10). On the south part of the Black Sea–Adriatic Sea basins’ catchment divide, the elevation declines on low permeable dolomite (J_3, K_1) toward the S; therefore, temporary watercourses flow downstream to the Babin Potok stream (Adriatic Sea catchment) and SE, which belongs to the Bijela rijeka catchment (Black Sea catchment). On the E part of the sub-catchment, the catchment divide stretches between high permeable (K_1) limestone and low permeable (J_3) dolomite. The catchment divide is hydrogeological; elevation in low permeable dolomite declines toward the E into a ravine (NW–SE direction) where, with a dye test injection in Crno jezero, an underground connection with Plitvica spring but not Lička Jesenica’s springs was proven (Pavičić et al., 2007). NE from the ravine, the terrain rises (Razdolje, Preka kosa hills) and separates this territory from the Sartuk and Plitvica River catchment (Cross section 2-2’ Fig. 9). Toward the NE, on Velika Titra hill territory, the catchment divide is topographic (it separates the Lička Jesenica sub-catchment from springs on Kuselj since an underground connection with Veliko Vrelo (Lička Jesenica spring nor with Slunjčica spring) was not proven, since the terrain is on a low permeable base made of dolomite (J_3) of the Upper Discharge Area. The topographic catchment divide goes into the territory of Mala Titra, which divides temporary watercourses flowing towards the SW (Ravni Lug) in high permeable (K_1) limestone (Lička Jesenica sub-catchment) and temporary watercourses flowing towards the NE into high permeable (K_2) limestone (SE from Saborsko). On the W part of the Lička Jesenica sub-catchment, the catchment divide goes toward the N on dolomitic breccias ($K_{1,2}$) and is mainly topographic (Cross sections 1-1’ and 5-5’, Figs. 9 and 10). The catchment divide represents a recharge boundary between the catchments of Lička Jesenica, Begovace estavelle and Dretulja River. The Lička Jesenica sub-catchment divide enters deposits of high permeable (K_1) limestone and stretches northwards, entering low permeable (J_3) dolomite. The Lička Jesenica sub-catchment is mainly recharged by catchments of Malo Vrelo spring (Cross section 6-6’, Fig. 10) and Veliko Vrelo spring (Cross section 7-7’, Fig. 10; Galović et al., 1998).

The Slunjčica River sub-catchment begins after the sinking of Lička Jesenica River and the groundwater flows NE toward Slunjčica spring (Middle re-

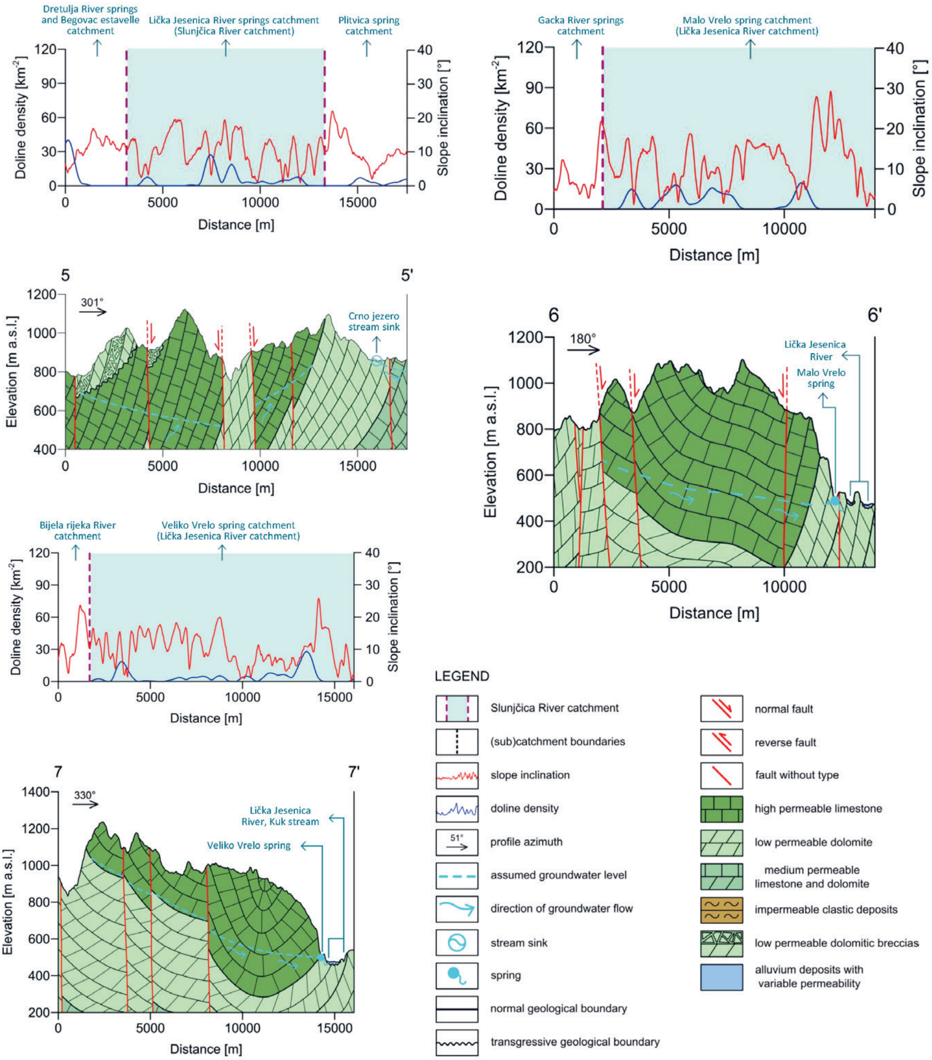

Figure 10. Comparison of hydrogeological cross section and cross section of slope inclination and doline density (profiles 5-5', 6-6' and 7-7').

charge area), which was proven with dye tests of the Lička Jesenica stream sink (Cross section 1-1', Fig. 9). The NW part of the catchment divide in the Middle Recharge Area divides the Primišljanska Mrežnica River spring catchment and the Slunjčica River spring catchment. In this area, there are no significant hydrogeological barriers and structurally, it is a syncline shape. For that reason, parts of the catchment divide stretch where low permeable dolomite (a relative barrier to groundwater movement), and dolomitic breccias ($K_{1,2}$) and high perme-

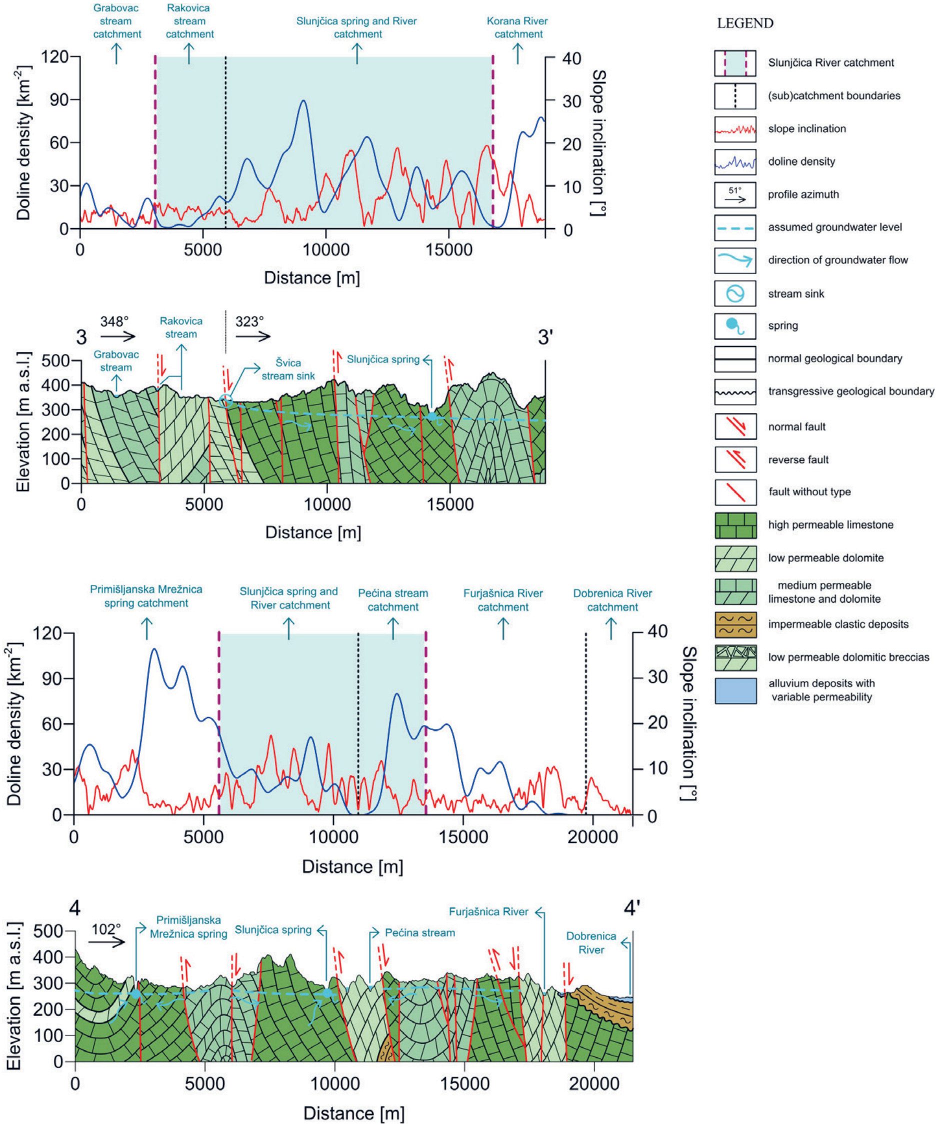

Figure 11. Comparison of hydrogeological cross section and cross section of slope inclination and doline density (profiles 3-3' and 4-4').

able (K_1, K_2) limestone come into contact. The catchment divide stretches to a reverse fault contact in the Zbjeg territory where medium permeable (J_3) dolomite and limestone emerge in an anticline form (Cross section 4-4', Fig. 11). The catchment divide stretches toward the NE on high and medium permeable (K_1, J_3) limestone without significant hydrogeological barriers.

Similar to a case in the NW part of the Slunjčica spring sub-catchment divide, the SE part of the catchment divide stretches on a boundary between low permeable dolomite and dolomitic breccia ($K_{1,2}$) and high permeable (K_1) limestone. The catchment divide gently turns toward the SE to reverse fault (strike NW-SE) where, at its SE part, it causes contact between medium permeable (J_3) limestone and dolomite with high permeable (K_1) limestone. The catchment divide goes E, following the fault contact, where the hanging wall with high permeable (K_1) limestone is lowered against low permeable (J_3) dolomite and high permeable (K_1) limestone (middle part of Cross section 2-2', Fig. 9).

On Rakovica territory, the catchment divide comes into reverse fault contact with a foot wall made of high permeable (K_1) limestone and a hanging wall is made of low permeable (T_3) dolomite that form a true hydrogeological barrier to groundwater and enter the Middle Discharge Area. The sub-catchment of Rakovica stream includes territory of low permeable (J_3) dolomite; therefore, the catchment divide turns topographically toward the NE. This part of the catchment divides the sub-catchment of Rakovica from the catchment of the Grabovac stream (Cross sections 2-2' and 3-3', Figs. 9 and 11).

Due to the Rakovica stream sinking into very high permeable (K_1) limestone (Cross section 3-3', Fig. 11), the catchment divide turns gently toward the NW to a true hydrogeological barrier and Middle Discharge Area, which is made of the low permeable (T_2) dolomite and, beneath it, are impermeable (T_1, P) clastic rocks. On that barrier Slunjčica spring discharges groundwater and here ends the sub-catchment of Slunjčica spring (Cross sections 1-1', 3-3' and 4-4', Figs. 9 and 11). A kilometer downstream of the Slunjčica spring, the Pećina stream pours into Slunjčica River.

Moving to the NE, Slunjčica River catchment divide crosses the Lower Recharge Area on medium permeable (J_3) limestone without significant hydrogeological barriers. From Kremenita Glava (SE part of the hill), made of impermeable (P) clastic rocks, watercourses are flowing gravitationally toward the SW and sink into medium permeable (J_3) limestone and dolomite (finishing part of Cross section 1-1', Fig. 9) and possible emerges up as Pećina stream springs come in contact with low permeable (T_2) dolomite (true barrier). In the NW and NE part of Kremenita Glava hill, a surficial flow is gravitationally flowing into high permeable (K_1) limestone toward the Korana River catchment.

4.4. Water balance of Slunjčica River catchment

The results of the water budget analysis are shown in Tab. 3. It should be mentioned that the surface watercourse downstream for the Slunjčica River spring is extracted for water supply with a capacity of Q_{ex} = 50 l/s (Trpčić and Pletikosić, 2010). Slunjčica River catchment's water budget analysis shows annual variability ranging from –2.440 m^3/s to 2.814 m^3/s (the most abundant hydrological year in precipitation – 2013/2014), which further proves that karst

Table 3. Annual water budget analysis on Slunjčica River karst catchment.

Hydrological year	T_p (°C)	E_T (mm)	P_{av} (mm)	$I = P_{av} - E_T$ (m)	$I = P_{av} - E_T$ (m^3/s)	$Q_{av} + Q_{ex}$ (m^3/s)	$\pm\Delta W$ (m^3/s)
1999/2000	8.91	501.9	1088.16	0.586	5.242	7.06	–1.818
2000/2001	10.963	592.3	1484.68	0.892	8.001	7.677	0.324
2001/2002	11.041	599.0	1558.46	0.959	8.602	8.605	–0.003
2002/2003	9.92	538.8	1188.34	0.650	5.824	8.264	–2.440
2003/2004	10.134	567.5	1547.05	0.980	8.758	8.379	0.379
2004/2005	11.513	617.6	1592.80	0.975	8.744	10.082	–1.338
2005/2006	10.646	588.9	1636.99	1.048	9.397	11.61	–2.213
2006/2007	12.821	588.7	954.50	0.366	3.280	4.204	–0.924
2007/2008	9.972	555.2	1404.47	0.849	7.594	8.612	–1.018
2008/2009	9.549	543.8	1443.27	0.899	8.065	7.522	0.543
2009/2010	9.038	535.9	1661.97	1.126	10.096	8.824	1.272
2010/2011	11.724	605.7	1312.97	0.707	6.341	6.723	–0.382
2011/2012	11.087	540.0	935.44	0.395	3.536	4.639	–1.103
2012/2013	8.735	530.7	1841.9	1.311	11.756	9.925	1.831
2013/2014	11.704	640.7	1993.84	1.353	12.132	9.318	2.814
2014/2015	11.096	608.9	1736.12	1.127	10.106	10.77	–0.664
2015/2016	11.704	628.0	1660.65	1.033	9.233	8.561	0.672
2016/2017	10.659	548.4	1073.29	0.525	4.706	5.296	–0.590
2017/2018	10.078	577.7	1908.76	1.331	11.934	10.003	1.931
2018/2019	11.907	607.3	1265.99	0.659	5.905	6.145	–0.240
							$\pm\Delta W_{av} = -0.148$

catchment boundaries are not fixed in space and time. The average annual water budget (for 20 hydrological years) is $\Delta W_{av} = -0.148$ m^3/s. The average discharge (Q_{av}) from Slunjčica River in the study period is 8.11 m^3/s and the result of water budget analysis fulfills the condition of $<|5\%|$ of the average discharge from karst catchment, in this case it is 1.82%. Negative results in water budget analysis represent that the discharge from the karst catchment is greater than the inflow values, consequently the Slunjčica River catchment area should be enlarged. Considering that result is within the allowable deviation, the catchment area was not increased. A wide range of annual water budget indicate that the boundary of the Slunjčica River catchment area is a time-variant hydrological boundary dependent on the fluctuations in groundwater levels.

5. Conclusions

The aim of this study was to confirm the importance of slope inclination and doline density in determining the hydrogeological role of the karst rock units. On top of that, even in very complex karst systems, it is possible to carry out a delineation of the catchment areas without extensive field geological, hydrological, and hydrogeological investigations.

A total of 22,304 dolines were mapped and analyzed based on existing maps. The average density of the dolines was determined to be 21.26 doline per square kilometer, with a maximum of 166 in the Middle sinking zone of the Korana River. Dolines in limestone develop with up to 26 to 27° of slope, and in dolomite with up to 20 to 21°. The highest doline density appears in the range from 0 to 1° of the slope inclinations, both in limestone and dolomite, and it decreases with a higher slope degree.

According to the lithology and degree of karstification, rocks with karst-fissure porosity are divided into three groups with high, medium, or low permeability. After defining the permeability of the rock units, a hydrogeological role was assigned to every part of the study area. The recharge and discharge areas, i.e., zones that act as aquifers, true or relative barriers, were defined. Based on these data, the Slunjčica catchment area was delineated, and it covers an area of 282.74 km^2. In addition, several hydrogeological cross sections were constructed and compared with doline density values and slope inclination. This analysis enabled the determination of the sub-catchment areas within the Slunjčica catchment area.

Finally, a water budget analysis was performed for a period of 20 hydrological years. The average annual water budget is $\Delta W = -0.148$ m^3/s and the requirement of $< |5\%|$ of an average discharge from a karst catchment is fulfilled (1.82% in this case). This result confirms that even with a relatively small number of input data, it is possible to obtain quality solutions. The importance of the role of a doline density analysis has been shown as an indispensable tool in the research of karst areas.

Funding – This research received no external funding.

Conflicts of Interest – The authors declare no conflict of interest.

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SAŽETAK

Uloga nagiba padina, gustoće vrtača i analize vodne bilance u izdvajanju kompleksnog slivnog područja rijeke Slunjčice (Hrvatska)

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Radi vrlo visoke prirodne ranjivosti krških vodonosnika, izrazito je važno precizno određivanje slivne površine. U okviru ovog istraživanja razmatran je utjecaj nagiba terena, gustoće vrtača i vodne bilance u procesu razdvajanja složenih krških slivnih područja. Za definiranje hidrogeološke uloge pojedinih litoloških jedinica korištena je kombinacija hidrogeoloških profila s podacima o gustoći vrtača i nagibu terena, dok je za opis propusnosti pojedinih stijenskih jedinica korišten stupanj okšenosti. Za verifikaciju i provjeru izdvojenih slivnih područja korištena je vodna bilanca. Metodologija korištena za utvrđivanje hidrogeološke uloge pojedinog područja i određivanje slivnog područja (rijeka Slunjčica, Hrvatska) prikazana je dijagramom toka. Utvrđeno je da se najveće vrijednosti gustoće vrtača pojavljuju u dijelovima terena s nagibom padina od 0 to 1°, te se smanjuju s povećanjem nagiba padina. Iako rezultati istraživanja potvrđuju da je čak i s malim brojem ulaznih podataka moguće odrediti slivno područje u kršu, potrebno je dodatno naglasiti da analiza gustoće vrtača predstavlja nezamjenjiv alat prilikom istraživanja vezanih za određivanje slivnih područja u kršu.

Ključne riječi: krško slivno područje, gustoća vrtača, nagib padina, analiza vodne bilance, rijeka Slunjčica (Hrvatska)

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