water

MDPI

Article

A Conceptual Model of Groundwater Dynamics in the Catchment Area of the Zagorska Mrežnica Spring, the Karst Massif of Kapela Mountain

Renato Buljan [1,†], Krešimir Pavlić [2,*,†], Josip Terzić [1,†] and Dario Perković [2,†]

1 Croatian Geological Survey, Sachsova 2, HR-10000 Zagreb, Croatia; rbuljan@hgi-cgs.hr (R.B.); jterzic@hgi-cgs.hr (J.T.)
2 Faculty of Mining, Geology and Petroleum Engineering, University of Zagreb, Pierottijeva 6, 10000 Zagreb, Croatia; dperko@rgn.hr
* Correspondence: kpavlic@rgn.hr; Tel.: +385-1-553-5931
† These authors contributed equally to this work.

Received: 25 July 2019; Accepted: 16 September 2019; Published: 23 September 2019

check for updates

Abstract: The investigation area is located in the world-famous Dinaric karst. This study presents a conceptual model of groundwater dynamics and its interaction with surface waters, extending from the natural water retention of the Drežničko Polje to the spring zone on the far side of the Kapela Mountain range, including a description of the regional groundwater flow in the Zagorska Mrežnica spring zone. The aim of this research was to determine the possibility of an artificial enlargement of the natural retention of this karst field. Large amounts of water could be exploited in this way for the existing hydroelectric power plants of Gojak and Lešće on the Donja Dobra River. The prolonged retention of the water wave in the Drežničko Polje would extend its efficiency in regards to the production of electrical energy, and simultaneously achieve the mitigation of floods that frequently occur in the broader area of Ogulin. Photogeological analysis of the area was performed, together with geological and hydrogeological mapping, groundwater tracing, measurements of water flows in streams and springs, exploratory drilling and measurements of water levels in 26 piezometric boreholes in the Drežničko Polje. Available meteorological data from nearby weather stations (Jasenak, Drežnica and Modruš) were exploited, as well as hydrological data collected specifically for the modelling of runoff. Based on the results of the data processing, this study has determined: (1) the dynamics of the groundwater flow from the Drežničko Polje to the spring area of the Zagorska Mrežnica, (2) the dynamics of recharge and discharge of the natural retention of the Drežničko Polje; and (3) an improved interpretation of the Zagorska Mrežnica karst spring dynamics. The obtained results of groundwater flow dynamics indicate typical karst flow conditions in the Dinaric Karst, but also contain some specific features.

Keywords: Dinaric karst; hydrology; hydrogeology; groundwater tracing; water management; spring dynamics; cross correlation

---

1. Introduction

Research on Dinaric karst aquifers is usually limited to analyses of the geological setting through the study of water occurrences at the surface (springs, ponors, surface streams) and of preferential underground flow paths [1,2], but is rarely conducted using boreholes. The research area for the present study is located in the northern part of the Dinaric karst region, which is one of the world's locus typicus karst landscapes (Figure 1). The area is characterized by very deep karstification predefined by tectonics, as well as by extremely irregularly distributed dissolution of the carbonate rocks. The most important challenges at defining the direction of water flow in such a large catchment area are related to the delineation of catchments and subcatchments of the Dinaric karst aquifers [3–6]. In the water resource management in the Dinaric Karst, according to available quantities, hypsometric position and hydrogeological and morphological characteristics of the terrain, water is often collected in several reservoirs. Then, based on prognostic and runoff models, water is sought to be optimally utilized and, if possible, passed through several hydropower plants (HPP Peruća, HPP Orlovac, HPP Đale, HPP Kraljevac and HPP Zakučac on the Cetina River; Sabljaci and Bukovnik reservoirs for the needs of HPP Gojak and HPP Lešće on the Donja Dobra River). Around half of the Croatian territory is situated in the Dinaric karst belt, with 22 hydroelectric power plants (HPP) in the area and among them 14 large HPP with over 10 MW of available power.

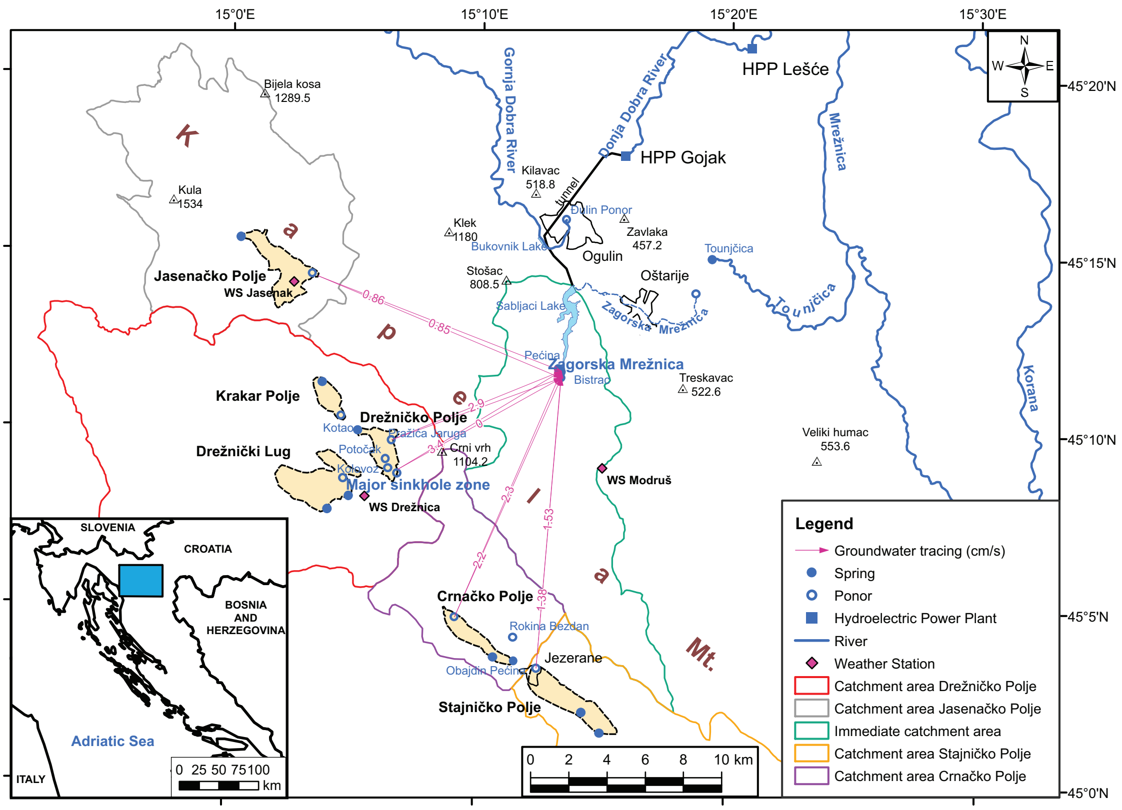

Figure 1. Location of the research area in Europe and in the local region, with the most important karst poljes, rivers, hydro-features and toponyms indicated.

The aim of the research was to increase the share of exploited water to generate more electricity in the power plants of Gojak and Lešće, which are located on the Donja Dobra River. The secondary aim was also to reduce the risk of floods in the area of Ogulin (Figure 1).

The Drežničko Polje is a typical karst polje (field), where a natural lake is formed periodically in the ponor (swallow-hole) zone in the southeastern part of the area. In accordance with established underground connections, water from these swallow holes drains to the Ogulinsko Polje through the Velika Kapela Mountain massif. The main spring in the Ogulinsko Polje is that of the Zagorska Mrežnica, which represents one of the focal points of this research. The maximum yield of this spring, together with nearby springs in the narrow zone of discharge, is 45 m^3/s. These include three major and several smaller springs along the southern edge of the artificial hydro-technical lake of Sabljaci. Permanent springs include the Zagorska Mrežnica (used for the public water supply of the city of Ogulin, with a flow rate of 200 l/s) and the Bistrac, while the Pećina spring is intermittent.

The distance between the swallow holes in the Drežničko Polje and the Zagorska Mrežnica spring is 10.4 km, and the difference in altitude amounts to 117 m (the swallow holes are at 436.4 m a.s.l.

and the spring is at 319.3 m a.s.l.). Immediately downstream of the spring zone the artificial lake of Sabljaci is located, the primary function of which is the production of electric power. The useful volume of the lake is 33×10^6 m^3, which is not sufficiently large to receive water from Zagorska Mrežnica spring during the rainy part of the hydrological year. As a result, a considerable portion of water overflows the dam (an annual average of 4.09 m^3/s with a maximum of over 80 m^3/s, whereas flows of over 40 m^3/s are a regular seasonal occurrence) and flows underground into the adjacent catchment of the Tounjčica and Dobra Rivers and does not pass through HPP Gojak and HPP Lešće turbines. An expansion of the volume of the Sabljaci reservoir is not possible due to the topographical features and the urbanization of the surrounding area.

Several times a year the Drežničko Polje turns into a natural karst retention with an average annual total capacity of around 250×10^6 m^3 of water, representing around 7.6 times the volume of the Sabljaci reservoir. The maximum level of retention in the Drežničko Polje was 459.5 m a.s.l. (spring, 2013), with an acquired retention volume of 60.9×10^6 m^3 and a water column of around 20 m.

In order to increase the amount of exploited water for electricity production, efforts were made to investigate the feasibility of extending the controlled retention of flood water in the natural retention feature of the Drežničko Polje through a variety of hydrotechnical interventions on major swallow holes in the non-vegetation period (from 15 October to 15 April). This would reduce and slow down the underground flow of flood waters from the polje, whilst enhancing the regime of the Zagorska Mrežnica spring. The top of the water wave would be lower and the duration of relatively high levels of water in the Drežničko Polje would be extended. Such levelling out of the flow curve at the springs in the Ogulinsko Polje would enable better energy utilization, while seasonal flooding in the Ogulinsko Polje would be reduced.

For the purpose of this project modelling of the runoff from the Drežničko Polje toward the Zagorska Mrežnica spring was carried out using the Hydrologic Engineering Center-Reservoir System Simulation (HEC-ResSim) model. The emergence of extreme flows, the analysis of hydrological trends, definition of catchment area and the impact of an inter-basin water transfer on the river basins of Dinaric karst were the focus of studies by Bonacci and Andrić [7,8], Pavlić et al. [9], Pavlić and Jakobović [10], Pavlić and Parlov [11], Lončar et al. [12]. Precisely because of the expected extreme flows, this procedure is justified in order to reduce the flooding of the Ogulinsko Polje. In the Croatian karst, the correlation analysis of time series was performed in the works of Jukić and Denić-Jukić [13], Žganec [14], Jukić and Denić-Jukić [15], in the neighboring karst catchment by Terzić et al. [4] and in karst of Italy by Fiorillo and Doglioni [16].

The paper is based on the research conducted in 2013 and 2017, which are a continuation of research from 2005, 2004 and earlier. The results obtained are not published, but are documentation of Croatian Geological Institute, Faculty of Mining, Geology and Petroleum Engineering at University of Zagreb, Elektroprojekt-Zagreb and others. Due to all of the above, it is difficult to distinguish in the paper what is the result of recent research and what is previously conducted research.

2. Setting

2.1. Morphological and Climatic Characteristics

The research area is located in the northern part of the Lika region (Figure 1). The orientation of landforms generally follows the orientation of geological structures, along the so-called Dinaric strike (NW–SE). The area under consideration is built predominantly of limestone and represents a typical karst landscape with well-developed karst landforms (Figures 2 and 3). The area contains karst poljes, numerous shallow and deep sinkholes, swallow holes and caves, and many pronounced sharp-edged fractures and fault planes. Where dolomite and clastic rocks prevail, relief is slightly flattened and covered by thicker Quaternary sediments masking the structural-tectonic elements of the underlying rock mass. The basic hydrogeological feature of karst has led, due to the karstification of carbonate deposits, to a poorly developed surface hydrographic network limited to flow along the karst poljes, and a well-developed and branching underground hydrographic network as a result of fracturing and dissolutional processes. Karst aquifers are recharged by precipitation (rain and snow), which either infiltrates dispersedly into aquifers and flows toward the springs, or flows on the surface in the direction of the swallow holes and infiltrates in this way into karst aquifers. The effective infiltration is therefore relatively high and difficult to quantify.

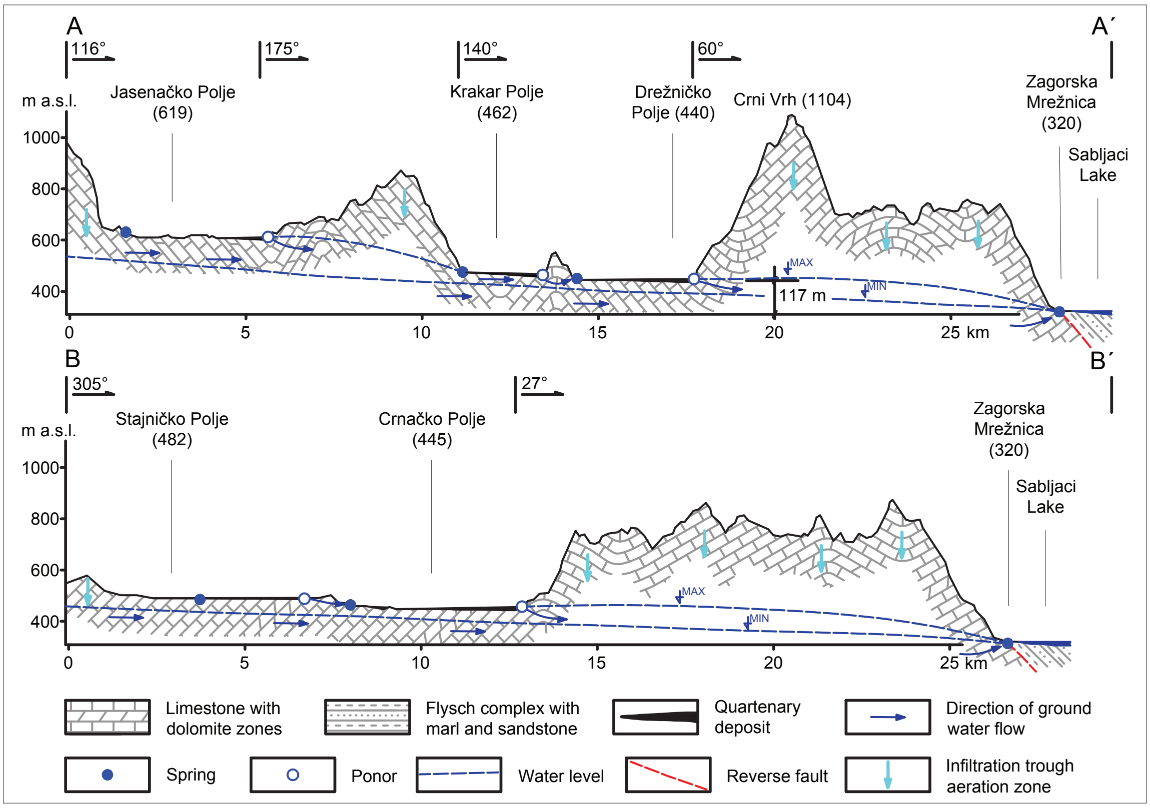

Figure 2. Cross-section profiles through the research area (locations shown in Figure 3) with schematized hydrogeological relations.

The wider area of the Ogulinsko Polje is characterized by a continental climate. Summers are dry and hot while winters are wet and cold. The air temperature is the highest in July and August, and the lowest in January. The average annual air temperature varies between 8–12 °C, while the average annual rainfall ranges from 1300–1600 mm. The Kapela Mountain range is characterized by a mountain climate, which is distinguished from a continental climate by lower air temperatures and by a snow regime with longer-lasting and more plentiful snowfalls. The highest peak in the mountain range is Kula (at 1534 m a.s.l.), followed by Crni Vrh, directly east of Drežničko Polje (at 1,104 m a.s.l.). In the Kapela Mountain range, the average annual rainfall varies from 1800–2200 mm and the average annual temperature is between 6–10 °C. According to Köppens climate classification, this area belongs to climate denoted as *Cfb* (maritime temperate climate) [17–19].

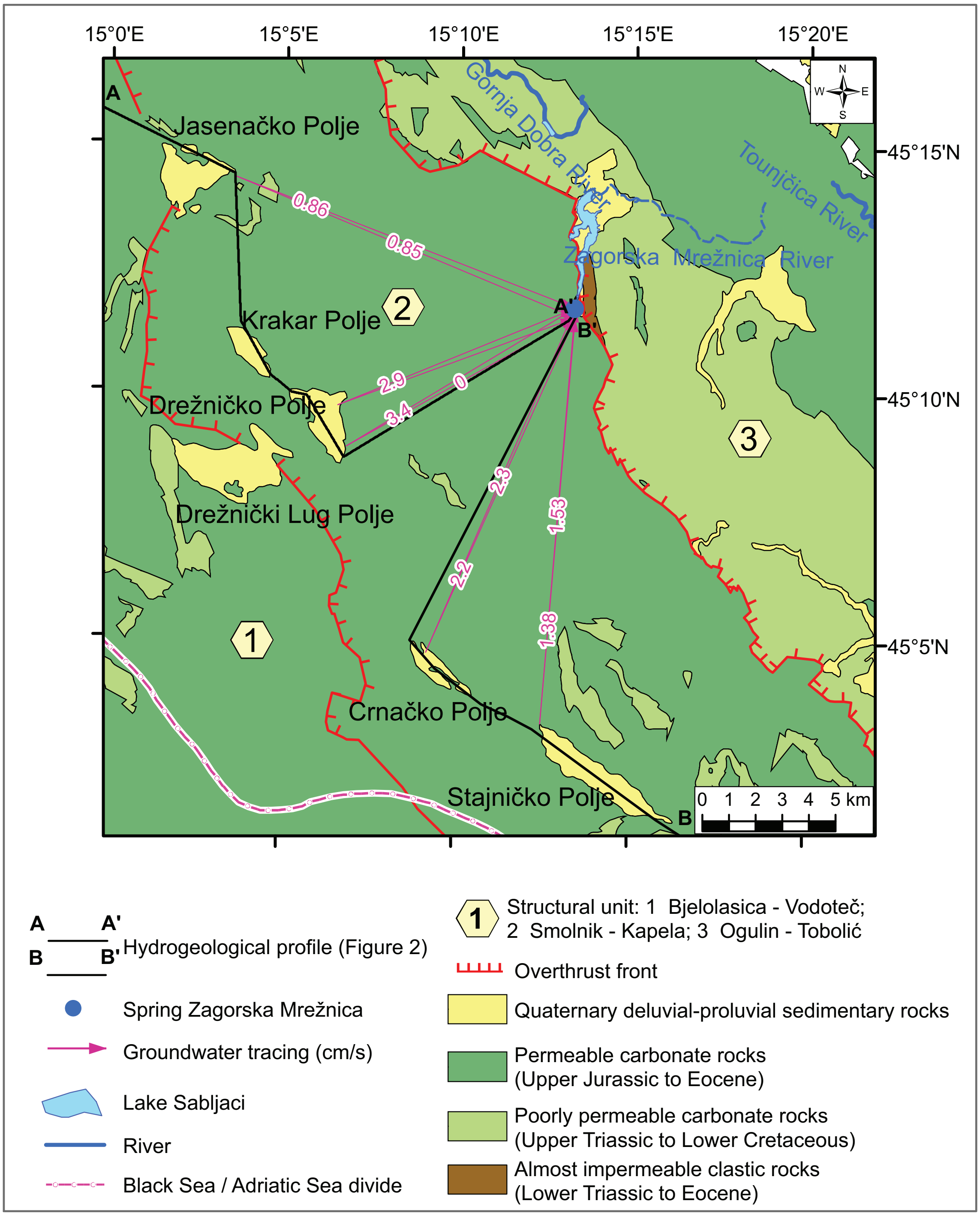

Figure 3. Schematized hydrogeological sketch-map.

2.2. Geological Setting and Tectonics

For the tectonic and lithological description of the study area, data were obtained from the Basic Geological Map (Ogulin sheet) [20], as well as the performed hydrogeological and structural studies required for the construction project and the drainage model of Drežničko Polje. The geological and tectonic setting of the Croatian Dinaric karst is described in numerous publications. However, the evolution of the region is still a matter of scientific debate and the focus of ongoing fundamental research [21–26].

The area under consideration represents part of the lithospheric crust of the Adriatic or Apulian microplate. From the Triassic to the Early Cenozoic, this area was characterized by carbonate platform sedimentation. Following sedimentation, the main deformation of the Dinaric carbonate platform took place between the Paleogene and Miocene [27–29]. Tectonic activity over geological time resulted in intense folding of the carbonate platform rocks, which evolved into reverse faulting and thrusting of the rock mass and the destruction of primary anticlinal and synclinal structures through the formation of large thrusts, due to compression of the area. In this way, the separate structural units in the area were created. During the Late Miocene and Pliocene, these units were further disintegrated due to a change in stress orientation from the NE–SW when the Dinaridic structures were created, to a N–S orientation, and by the formation of diagonal conjugated shear and transverse faults further broken into smaller structures. These building blocks and sub-blocks were further exposed to uplift or subsidence and/or rotations in space, due to permanent stress that continues to the present time and is evidenced by numerous earthquakes. The modern geomorphology of the region was formed in the Neogene, predominantly along steep fault zones trending mainly in the NW–SE direction [30,31].

For the analysis of the structural-tectonic setting, the most important events were tangential movements (sub-horizontal displacements due to lateral stress) and the emergence of reverse and thrust faulting, near-surface relationships between the structural units. A secondary consideration is the pronounced transverse and diagonal fragmentation of the units. The tectonic unit of the Smolnik-Kapela (2) (Figure 3) is located in the central portion of the research area. This tectonic unit is separated from adjacent units by dominantly reverse faults and is crucial in the formation of the catchment of the Zagorska Mrežnica spring. This unit is in thrust-faulted contact with the neighboring terrains. It was uplifted to the altitude of the boundary with the SW tectonic unit Bjelolasica-Vodotoč (1) along the fault zones intersecting the Jasenačko Polje and the Drežnički Lug. The basic structural-tectonic feature of this unit is the form of a degraded synclinorium dominated by two large synclines that are separated by an anticline. The southwestern syncline is important for hydrogeological relations in the area as it strikes in the direction of the Zagorska Mrežnica spring. Transverse faults in a NE–SW orientation and diagonal faults in a NW–SE orientation are especially pronounced in this area and are important for the groundwater streams. The described tectonic movements are also important for the genesis of the karst poljes. The NE rim of the central tectonic unit is obducted by another tectonic unit Ogulin-Tobolić (3) characterized by the same tectonic style, striking along the spring zone of the Zagorska Mrežnica. To the north, the karst plane of the Ogulinsko Polje was formed. Underlying this part of the terrain is an anticline with clastic and carbonate rocks of Triassic age in the core of the structure while the flanks are composed of dolomite rocks, providing a structure with special hydrogeological importance. Significant hydrogeological features that may be observed include divides, karst poljes and the spring zone of the Zagorska Mrežnica, which are all associated with the boundary terrains occupied by separated structural-tectonic units and their lithological composition.

2.3. Hydrogeological Relationships

The karst aquifers of the Zagorska Mrežnica and Tounjčica springs are composed of limestone and dolomitic rocks of Jurassic and Early Cretaceous age. Transgressive sequences consist of clastic rocks (shales and Upper Triassic and Upper Triassic dolomite (hauptdolomite), along with various overlying Quaternary sediments). Based on lithological composition, the degree of deformation observed on the surface, and the research work presented in this paper, the basement sedimentary rocks of this area can be classified into three basic hydrogeological groups [32] (Table 1; Figure 3):

Table 1. Hydrogeological classification of rock mass.

Water Permeability	Lithology	Stratigraphic Range	Porosity Type	Porosity %	Permeability (m/s)
Permeable rocks	limestone and limestone with dolomite intercalations	from the Upper Jurassic to Eocene	joint and dissolution	1–50	10^{-4}–10^{-6}
Poorly permeable rocks	dolomite, dolomitized limestone, platy limestone	from the Upper Triassic to Lower Cretaceous	joint and dissolution	35–55	10^{-6}–10^{-8}
Almost impermeable sedimentary rocks	flysch complex composed of marl and sandstone, siltite, shale	from the Lower Triassic to Eocene	intergranular	1–50	$<10^{-8}$

Numerous authors deal with similar values for different karst terrains all over the world [2,33–35], with clear statement that these values in such terrains can only be used as rough estimation, an order of magnitude.

The hydrogeological functions of rock masses in the investigated terrain, as well as the boundary conditions of the groundwater flow, are determined based on the lithological and tectonic features of the area [36]. In the hydrogeological sense, the complex of high-permeability limestones, which contain lower-permeability dolomite intercalations, is distinguished from the complex of generally impermeable thick dolomitic and clastic fine-grained rocks functioning as a hydrogeological barrier. The role of Quaternary deposits depends on their thickness and the hydrogeological features of the underlying rock mass. In the karst poljes, these deposits constitute barriers and allow surface water flow to occur. The high-permeability limestones represent the largest part of the catchment area of the Zagorska Mrežnica spring. These are thick-bedded, intensely karstified limestones of Jurassic and Lower Cretaceous age. The hydrogeological characteristics, along with the generally mildly-folded geological and tectonic structures of these units have resulted in the formation of concentrated preferential groundwater flow paths allowing the formation and evolution of springs, swallow holes, karst poljes and other karst forms. Altered dolomite zones amid high-permeability limestones are also significant for local routing of the groundwater flows. The pronounced dolomite sequences in the research area (especially in the environments covered with fine-grained clastic deposits) represent hydrogeological barriers for water flows from the carbonate hinterland. As the barrier is approached, groundwater levels increase and surface flows appear. Due to the reverse tectonic contact where the impermeable structural unit was tectonically uplifted with respect to the water-permeable unit, the abundant karst springs of the Zagorska Mrežnica and its surface flow were formed along strike. The Sabljaci Accumulation Lake was built on the lower-permeability rocks.

Groundwater connections within the catchments were identified through tracing experiments under different hydrological conditions, conducted from the Jasenačko, Drežničko, Crnačko and Stajničko karst poljes (Figure 3). The tracer appeared only in the spring of the Zagorska Mrežnica. During the underground flow from the karst fields SW of the Velika Kapela Mountain, the streams therefore probably join within the karst aquifer before being discharged. Preferential flow paths near the spring zone have a limited maximal capacity of around 45 m^3/s. This results in a decreasing velocity of the underground flows and increasing groundwater levels in the aquifer, the consequence of which is flooding of the karst poljes.

The catchment area of the Zagorska Mrežnica extends to around 650 km^2, and topographically consists of a direct and a peripheral sub-catchment. The direct catchment with a surface area of 112 km^2 extends over the NE slopes of the Velika Kapela Mountain and over a small part of the Ogulinsko Polje. The peripheral part of the catchment area comprises the SW slopes of the Velika Kapela Mountain, together with the Jasenačko, Krakarsko, Drežnički lug, Drežničko, Crnačko and Stajničko karst poljes (Figure 1). The Zagorska Mrežnica spring and other springs north of the Velika Kapela Mountain all share this part of the catchment area, depending on the hydrological conditions. Each of the above-mentioned poljes has its own local watershed in the topographic sense, which is connected to one of the two sub-catchments by the well-developed karst channels. The NW sub-catchment is linked to a series of karst poljes, from the Jasenačko and Krakarsko, via Drežnički Lug to the Drežničko Polje, and further to the Zagorska Mrežnica spring. The SE sub-catchment is also linked to a series of karst poljes, from the Stajničko Polje via Jezerane, to the Crnačko Polje and further in the direction of the Zagorska Mrežnica spring (Figure 2). The whole catchment area of the Zagorska Mrežnica belongs to the Black Sea (Danube) catchment, and represents a boundary area to the catchment of the Adriatic Sea. Given the "cascade" hypsometric position, the karst hydrogeological characteristics, the fact that all fields of the peripheral watershed in the annual rainy season are repeatedly partly or completely flooded, and acknowledging the established underground water connections, the Drežničko Polje represents the last step of the surface flow, as the lowest situated natural retention south of the Velika Kapela Mountain. This polje is a compensating pool that "levels" the water inflow from the gravitating karst poljes towards the Zagorska Mrežnica spring (Figure 2). The permeability (i.e., capacity) of underground waterways (i.e., the karst channels and the flow through the rock mass) from other karst poljes dominantly determines the regime during high water levels in the Drežničko Polje. The surface flow from the Stajničko Polje (SE sub-catchment) in the low and medium water level regimes takes place to the greatest extent along the diagonal faults in which the well-known cave complex of Rokina Bezdana developed. Occasionally, on a short-term basis (over a few days to two weeks) in the high groundwater level regime in the Velika Kapela Mountain, water flows around the abundant spring of the Obajdin Pećina ($Q > 10$ m^3/s), flooding the Crnačko polje and continuing through the swallow hole towards the spring of the Zagorska Mrežnica. The flooding of the Crnačko and Drežničko Poljes often overlaps over time as they are situated at similar altitudes. However, because of the partially common underground flows towards the spring of the Zagorska Mrežnica, their simultaneous underground discharge is limited. This is indicated by the opposite gradient in the Velika Kapela Mountain massif during high groundwater levels, when the ponors of the Drežničko Polje act as springs (under the lake), which was corroborated by the tracing experiment conducted in this research. During the dry part of the year, the hydraulic system of the wider catchment of the Zagorska Mrežnica functions as three separate hydrogeological systems of the karst poljes: (1) the Jasenačko Polje to the NW, (2) the Drežnički Lug, Krakarsko and Drežničko Poljes in the central area, and (3) the Crnačko and Stajničko Poljes to the SE. At that time, the springs in these poljes have minimal yields, barely sufficient for the needs of the local population as groundwater flows through the rock mass deep below the poljes.

Drežničko Polje, in which an anthropogenic hydro-technical intervention is designed (Figure 4), is a typical karst polje formed as a result of tectonics and karstification of the carbonate rock mass, with springs and swallow holes. It lies topographically between 440–445 m a.s.l., is 3.5 km long and 1.5 km wide, and the total flow takes place underground. The field regularly floods several times a year due to the limited capacity of the swallow holes (estavelles). The natural accumulation in the Drežničko Polje is the result of its position in the wider karst region, the hydraulic connection with the neighboring poljes and the natural gravitational water flow towards the core of the syncline in Velika Kapela Mountain massif.

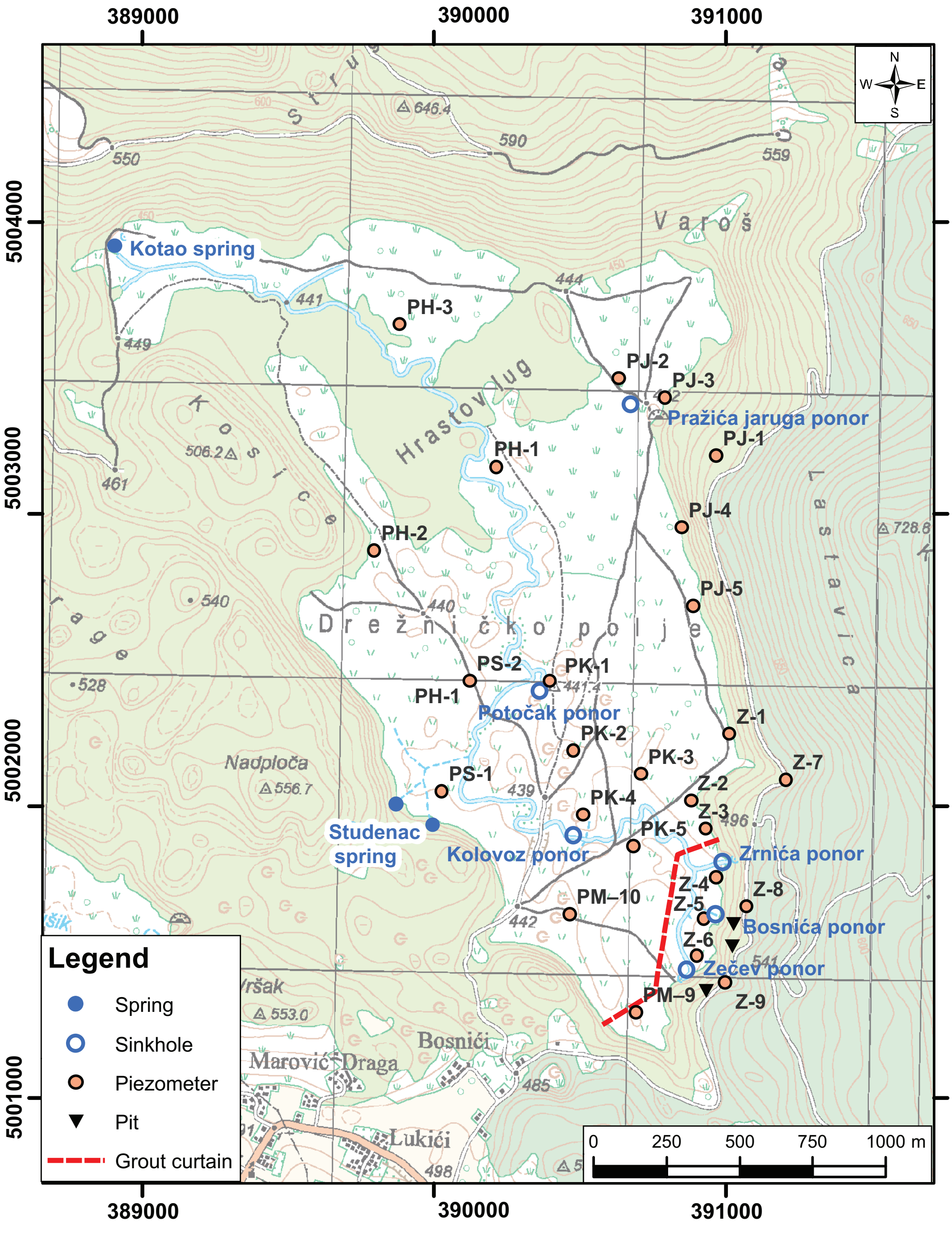

Figure 4. Location of the Drežničko karst polje with with existing hydrogeological objects, piezometers and a designed grout curtain.

The groundwater flow from the poljes is predisposed by the fault zones. It is concentrated through the Kolovoz and Potočak ponors, in the central part of the field along the riverbed of the intermittent Jaruga stream, through the Pražića Jaruga Ponor and through the main ponor zone represented by the Zrnića, Bosnića and Zečev ponors. Along the rims of the Drežničko Polje, the surface rocks consist of limestone and occasionally dolomites, in the Upper Jurassic-Lower Cretaceous stratigraphic range (a monoclinic geological structure). The thickness of poorly permeable Quaternary silty-clayey deposits in the polje is the largest in the SE area (generally 5–10 m, and up to 20 m), and is lower in the SW area (1–3 m). Quaternary fine-grained deposits were formed by erosion and deposition of weathered material from the surrounding slopes in the lowland areas of the relief (proluvial-deluvial sediments). Their bedrock is predominantly built of the limestone rock mass with some dolomite and carbonate tectonic breccias.

The Drežničko Polje (440–445 m a.s.l., with a direct catchment area of over 225 km^2) is hydraulically connected by the numerous karst channels to the hypsometrically more elevated Drežnički Lug (465 m a.s.l.), Krakarsko Polje (462 m a.s.l.) and Jasenačko Polje (610 m a.s.l.) (Figures 1–3). In the NW part of the area, there is a permanent spring named Kotao, which is connected to the streams in the Krakarsko Polje, with a maximum discharge estimated at over 10 m^3/s. In the SW part of the area, there is a minor spring known as Studenac that periodically dries up. There are also around thirty minor karst springs in the polje. Between the Kotao Spring and the main ponor zone, the intermittent Jaruga stream meanders across the entire field, while a portion of its water gradually sinks underground through the two major ponors (Potočak and Kolovoz) and numerous minor ponors. Southwards (downstream) of the Kolovoz ponor, water flows only when the aquifer is completely saturated and ponors (estavelles) in the middle of the field cannot accept the water surplus and periodic lake fill. Along the E and SE part of the polje, numerous suffosions were recorded together with around sixty major and minor ponors.

3. Methods

3.1. Geological and Hydrogeological Mapping

The flows of the three main Zagorska Mrežnica springs were measured systematically, as well as the open surface flows in the upper levels of the Zagorska Mrežnica catchment in the Drežnički Lug, Krakarsko, Crnačko and Stajničko Poljes, and water levels in the Jaruga watercourse of the Drežničko Polje (staff gauge). For modelling the runoff of the Drežnčko Polje, the stage-discharge curves of all hydrological stations, as well as the stage-discharge curves of the ponor zones were used in the Drežnički Lug, Krakarsko, Drežničko, Crnačko and Stajničko poljes. The model result, in the form of a runoff through the ponor zone of the Drežničko Polje, was used in the cross-correlation analysis with the measured discharge at the Zagorska Mrežnica spring.

All the measured values, and thus the values obtained from the runoff model, represent the mean daily values. The runoff model was conducted in the period from 2000 to 2013, in the form of hydrological years from 1 October to 30 September. The discharge in the ponor zone of the Drežničko polje was compared with the discharge at the Zagorska Mrežnica spring using the cross correlation analysis. The same methodology was also used to compare the discharge in the ponor zone of the Drežničko Polje and the discharge of the Zagorska Mrežnica spring with precipitation data. As the runoff during the hydrological year can be broken into two significantly different hydrological regimes, the cross correlation analysis was carried out for the warmer (vegetative) part of the year from 1 April to 30 September, and the colder (non-vegetative) part of the year from 1 October to 31 March.

The water levels were measured in 22 deep piezometric boreholes in the poljes and four in the eastern carbonate hinterland. Measurements of the groundwater level and temperature in the Drežničko Polje were carried out by automatic Mini Diver produced by Schlumberger Water Services. The measuring range of the embedded limnigraph is 100 m and is set to the frequency of measurements per hour. In addition to the Mini Diver, two wells were equipped with Baro Diver type devices for measuring atmospheric pressure and for a more accurate calculation of results. The precipitation gauge data were taken from the Croatian Meteorological and Hydrological Service (DHMZ) for three nearby weather stations: Jasenak, Drežnica and Modruš (Figure 1).

3.2. Underground Water Flow Tracings

Dye tracings were carried out during earlier investigations on a number of locations in various hydrological conditions, in the Jasenačko, Drežničko, Crnačko and Stajničko Poljes. The underground connections of ponors and springs as well as apparent groundwater flow rates were determined in this way. All previous tracings were taken into account, together with the tracing experiment performed for the present study. In all cases, Na-fluorescein was applied as a fluorescent tracer. The samples were analyzed in the Croatian Geological Survey using a Perkin Elmer 3000 digital spectrofluorometer with a detection limit of 0.002 µg/l.

3.3. Borehole Drilling and Piezometric Data

Seven new exploratory boreholes were drilled during the exploration works during 2013. During this study and former research campaigns, 26 piezometric boreholes were drilled in the Drežničko polje and its vicinity. All of them were equipped with dataloggers measuring groundwater levels, temperature and electroconductivity. All new boreholes were drilled by coring and the geological, hydrogeological and engineering-geology characteristics of cores were studied. The deepest boreholes are in the side of the Drežničko polje: Z-6 (160 m), Z-7 (120 m), Z-8 (120 m), Z-9 (120 m). The boreholes in the Drežničko polje are 60 to 80 m deep. There are no deep exploration boreholes outside the Drezničko polje because the Velika Kapela mountain rises in the direction of the Zagorska Mrežnica spring from 440 m a.s.l. to 1104 m a.s.l. and gradually descends to 320 m a.s.l.

3.4. Auto-Correlation and Cross-Correlation

In this paper is given just a basic review of auto-correlation and cross-correlation. More complete methodology is described in [37]. By means of the autocovariance cov_{xx}, it is possible to describe the variance of the signal $x(t)$ with N data points over the lag time k.

$$cov_{xx}(k) = \frac{1}{N-k-1}\sum_{i=1}^{N-k}(x_i - \bar{x})(x_{i+k} - \bar{x}) \tag{1}$$

Since the covariance depends on the amplitude of the signal $x(t)$, the autocorrelation function is obtained by normalizing the covariance by the variance σ^2 of the signal $x(t)$. The autocorrelation involves correlating the signal with itself as a function of time lag k.

$$corr_{xx}(k) = \frac{cov_{xx}(k)}{cov_{xx}(0)} = \frac{cov_{xx}(k)}{\sigma_x^2} \tag{2}$$

Cross-spectral analysis correlates a two time series in a frequency domain. The measure of variance between the signals $x(t)$ and $y(t)$ over time lag k is the cross-covariance. An unbiased estimator of the cross-covariance of two signals with N data points over the time lag k is

$$cov_{xy}(k) = \frac{1}{N-k-1}\sum_{i=1}^{N-k}(x_i - \bar{x})(y_{i+k} - \bar{y}) \tag{3}$$

The cross-covariance depends on the amplitude of both signals $x(t)$ and $y(t)$. By normalizing the covariance by the standard deviations of the signals $x(t)$ and $y(t)$, the cross-correlation function is obtained.

$$corr_{xy}(k) = \frac{cov_{xy}(k)}{cov_{xy}(0)} = \frac{cov_{xy}(k)}{\sigma_x \sigma_y} \tag{4}$$

4. Results and Discussion

Underground flow tracings are one of the key sources of data for the definition of catchment borders in karst areas. Tracings in the Jasenačko Polje during medium water levels demonstrated the existence of a groundwater connection between springs of the Zagorska Mrežnica and the spring in the Krakarsko Polje. Repeated tracings in the Jasenačko Polje during low groundwater levels showed a direct connection only with the Zagorska Mrežnica spring. Tracing experiments from other karst poljes showed a direct connection only with the Zagorska Mrežnica spring (Table 2).

Table 2. Underground waterflow tracing results in Zagorska Mrežnica basin.

Tracing Location	Date (dd/mm/yy)	Tracer Detection Location	Emergence of Tracer (hours)	Apparent Flow Rate (cm/s)
Jasenačko polje	1972	Zagorska Mrežnica, Bistrac, Krakar polje	-	-
Crnačko polje	12/4/1985	Zagorska Mrežnica, Bistrac	160–173	2.16–2.3
Drežničko polje	13/5/1985	Zagorska Mrežnica, Bistrac	88	2.9–2.96
Jasenačko polje	27/11/1986	Zagorska Mrežnica, Bistrac	448–457	0.85–0.86
Stajničko polje	22/4/1988	Zagorska Mrežnica, Bistrac	320	1.21–1.36
Stajničko polje	8/12/2000	Zagorska Mrežnica, Bistrac	248–308	1.38–1.53
Drežničko polje	21/11/2013	-	-	-

A new tracing was carried out for the present study from the Bosnića Ponor in the Drežničko Polje (Figure 4) during the period of high water levels. The tracer was prepared using fire hoses and was directly poured into the ponor, although that particular portion of the polje was flooded. In so doing, the intention was to show how the ponors in this area function under these conditions. As the tracer was not recorded in either of the springs on the opposite part of the Velika Kapela Mountain, and it was greatly deluted in the vicinity of the insertion site (lake above ponor), it was determined that during high groundwater levels the gradients were created from the Velika Kapela Mountain toward the Drežničko Polje while the ponors, then situated at the lake bottom, functioned as springs. In this way, the occurrence of estavelles was demonstrated and proven.

By considering all tracing data, it may be concluded that the apparent groundwater flow rates vary from 0.86 cm/s to 2.9 m/s during medium groundwater levels. During high groundwater levels, groundwater from the catchment flows (drains) only from the mountain massif of the Velika Kapela Mountain in the spring zone (the direct catchment) while the poljes from the other side of the Velika Kapela Mountain, together with the related karst aquifer, are entirely saturated with water. Natural retentions appear in the karst poljes, forming lakes. Due to the lowering of the groundwater levels, these lakes and the surrounding rock mass begin to drain until all the lakes are drained off. Groundwater levels then drop considerably below the poljes and groundwater flows toward springs in the Ogulinsko Polje.

Results of conducted borehole investigations in the Drežničko polje determined the thickness of the Quaternary sediments, the fracturing and karstification of the rock mass beneath them, and the position of major caverns in the carbonate bedrock of the karst polje, as well as the definition of the direction of groundwater flows. Morphological anomalies in the relief in the form of an elongated succession of sinkholes, meanders or abrupt divergences of the bed of the Jaruga stream (Figure 4) indicate the presence of minor faults in the polje, as well as branches of determined marginal faults and faults with different strikes. From the results of borehole drilling, the dimensions of vertical cross-sections of the conduits clearly vary from 0.2–3.0 m and the majority of these are located in the depth interval between 435 and 399 m a.s.l. (5–41 m below the polje surface).

The water regime of the Drežničko Polje during the hydrological year has two states. In the non-vegetative (colder) period, from 1 October to 31 March, the polje is regularly flooded. In the vegetative (warmer) period, from 1 April to 30 September, the polje is regularly dry, with rare, short-term flooding.

According to the results of the runoff model at the hydrological station in the Drežničko Polje on the Jaruga watercourse, the flows in the Drežničko Polje in the non-vegetative period reach 90 m^3/s, with the water level in the field at around 459.5 m a.s.l.

In Figure 5, cross correlation functions between the flows in the ponor zone of the Drežničko Polje and the Zagorska Mrežnica spring (CCF DM) are shown, as well as between precipitation data and the flow in the ponor zone of the Drežničko Polje, and precipitation data and the flow in the Zagorska Mrežnica spring (CCF RM) for the winter and summer parts of the hydrological year.

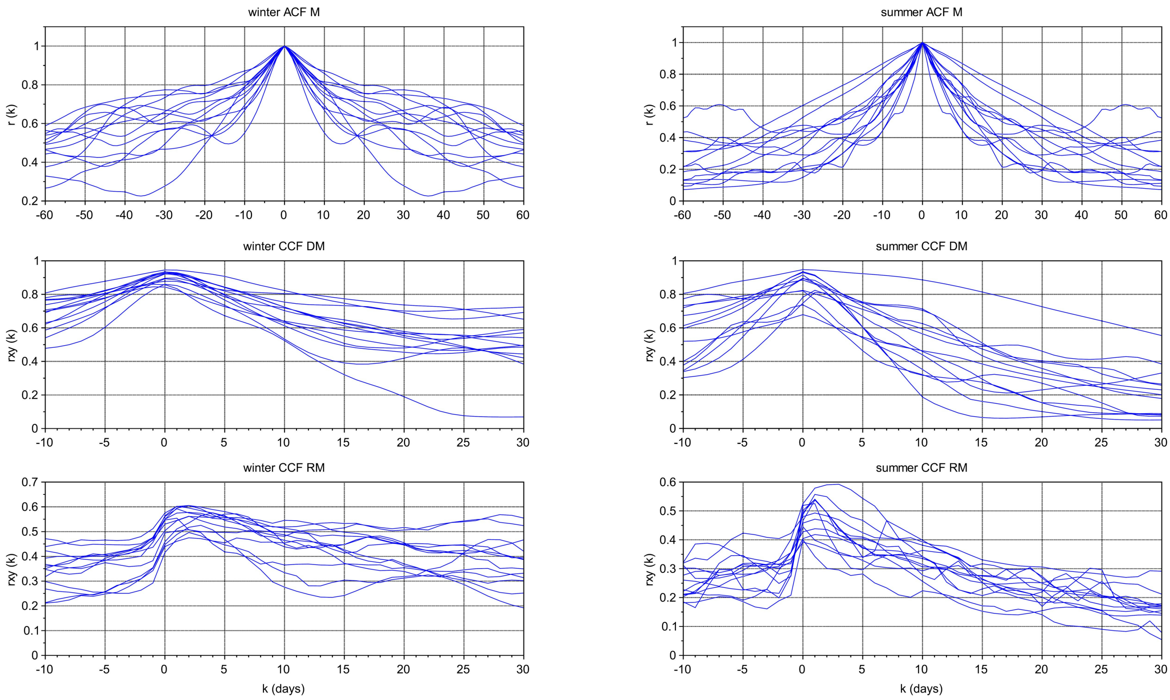

Figure 5. Autocorrelation functions for the Zagorska Mrežnica spring (ACF M), cross correlation functions between the swallow zone of the Drežničko polje and the Zagorska Mrežnica spring (CCF DM), and cross correlation functions between rainfall data and the Zagorska Mrežnica spring (CCF RM) for the winter and summer parts of the hydrological year (over the period 2000–2013).

The autocorrelation functions of the Zagorska Mrežnica spring (ACF M) show that the signal is autocorrelated with itself for the winter and summer periods. The winter ACF M shows no memory loss, whereas the summer ACF M shows memory loss after a lag time of 26 days, where the value of the ACF falls below 0.2, according to Mangin [38]. This result is consistent with the fact that the karst aquifer is constantly saturated with groundwater during the winter part of the year, and that it is not uniformly saturated with water during the summer part of the year. A lag time of 26 days, after which the memory effect is lost, indicates the existence of underground caverns that have a retention effect on the flow of water during the summer part of the year. During low groundwater levels, the main water table (the phreatic zone) significantly lowers, amounting to a decrease of tens of meters in the Velika Kapela Mountain massif (Figure 2). In the vadose zone, this probably results in many "hanging" aquifers (limited aquifers above the water table, or caverns filled with water that drains slowly through fractures within the rock mass) that slowly infiltrate towards the phreatic zone.

Cross correlation functions between flows in the ponor zone of the Drežničko Polje and the Zagorska Mrežnica spring discharge for the summer part of the year have a steeper decrease with lag time, as the flows through the ponors are abrupt. A maximum CCF value of around $r_{xy}(k) = 0.94$ is generally obtained for a lag time of one day. For the winter part of the year, CCF do not show as steep a decrease with lag time, because flows through the ponor zone are more permanent. A maximum CCF value of around $r_{xy}(k) = 0.85$ is generally observed for a lag time of two days. The CCF DM reveals one common property in that the CCF never reaches a zero value during the winter and summer parts of the year, which is explainable by noting the fact that the Zagorska Mrežnica spring never dried up. This observation, in conjunction with the results of dye tracer experiments during high groundwater levels (which demonstrated that these ponors are estavelles and act as sub-lake springs in that period), suggests that this is mainly the result of the limited conductivity of the karst conduits near the main springs, which causes a significant groundwater level rise in the entire Velika Kapela Mountain massif.

Cross correlation functions between the rainfall data and the Zagorska Mrežnica spring (CCF RM) show a maximum correlation coefficient for lag times of around two days for the winter part of the year, and from 2–4 days for the summer part of the year.

In accordance with the great number of mapped ponors, suffosion depressions and sink holes in the Drežničko Polje, as well as with results of exploratory drilling, the rock substrate of the polje may be qualified as strongly karstified. In addition, from the dynamics of flooding and dry periods, the karstification may be estimated to decrease considerably with depth. An abrupt increase of the gradient is related to the polje margins with the main swallow holes.

The maximum capacity of the main swallow hole zone, measured during the surface flow in the Jaruga stream with free sinking into the swallow holes, amounts to around 22 m^3/s. The total maximum recharge of water into the Drežničko polje during the rainy period and/or in the snow melting season, is estimated to be 90 m^3/s according to the model. In the period of high inflows (i.e., the increasing portion of the discharge curve) the spring capacity exceeds the capacities of ponors. The karstified underground rock mass is filled first, and following this the polje is flooded and turns into a lake which can contain up to 60.9×10^6 m^3 of water. According to the hydrological analysis, the biggest floods in the field occur from the middle of October to the end of February, and minor floods occur during the spring months of April and May. Floods usually last from a few days to around twenty days, with an increase of water in the field to a maximum of 20 m (459.5 m a.s.l., April and May of 2013). During the greater part of the year when the field is not flooded, the carbonate underground rock mass is more or less totally saturated by groundwater. From the observations of the groundwater levels in the 26 piezometers (Figure 4), and from the water level measurements of the Jaruga stream, the flooding of the polje begins after the filling of the "underground karst retention". When the water level of the Jaruga stream rises from 436.4 m a.s.l. (the bed of the stream) towards 440 m a.s.l. (as the SE lower part of the polje begins to flood), the karst underground rock mass is abruptly saturated, which is why the surface and groundwater levels align. The entire field is flooded at the level of 445 m a.s.l. The measured water levels indicate that surface flow occurs relatively quickly in the swallow holes of the Potočak and Kolovoz. In accordance with the analysis of the corresponding levels of the flood waters and their descending trend, as well as groundwater levels in the piezometers, it was determined that after the discharge of the surface part of the retention, the discharge of the underground retention begins first in the area of the main ponor zone, and then gradually occurs from the southern part towards the northern part of the polje. The natural retention of the Drežničko Polje functions as a single unit in its underground and surface portions, in a hydraulic sense. This is shown by the overlapping of the water levels of the Jaruga stream above the elevation of 440 m a.s.l. and the levels in all piezometers, regardless of either ascending or descending trends of the flow curve. The greatest difference between the maximum and minimum groundwater levels is found in the zone ahead of the main ponors on the SE margin of the Drežničko Polje. This amounts to 37.72 m and the lowest difference is found along the eastern edge of the middle area of the polje, and amounts to 9.2 m. Regardless of the difference in the water levels, the level curves of all piezometers show very similar frequencies and trends, meaning that the rock mass forms a single unit in a hydraulic sense, while the changes of groundwater levels have a broader regional character (Figure 6).

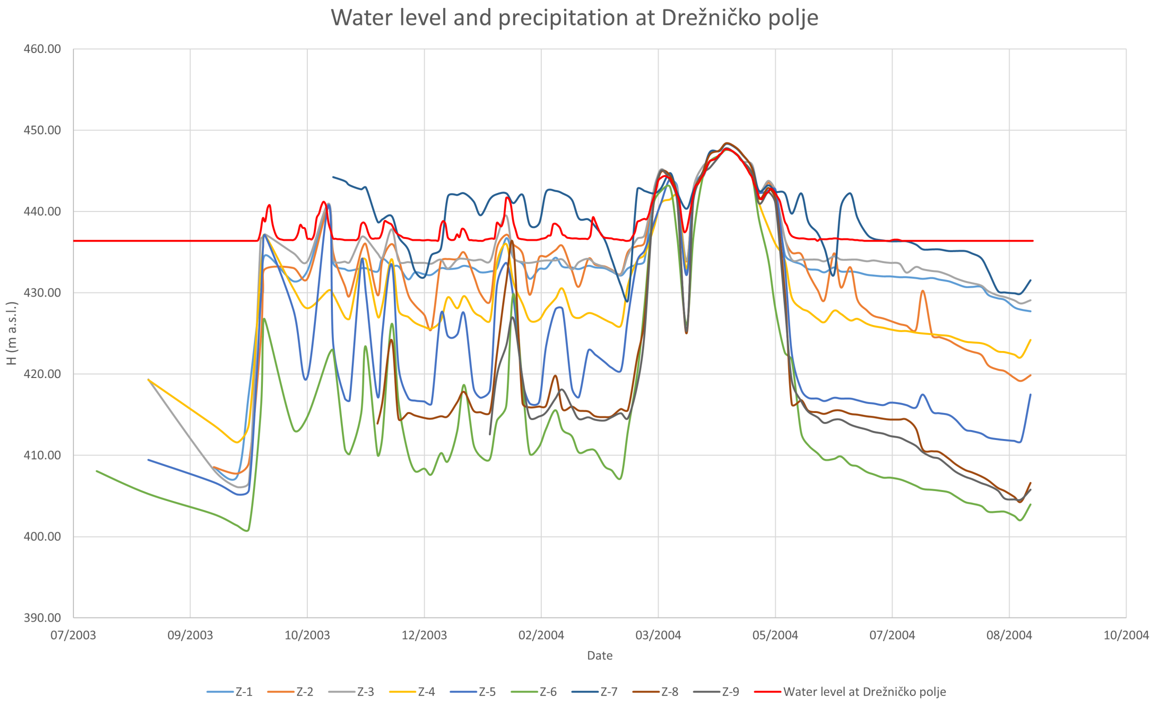

Figure 6. The level curves of all piezometers show very similar frequencies and trends, regardless of the difference in the water levels.

Conduits in the karst underground rock mass are interconnected and their orientations and distribution are in line to a great extent with registered fault zones. The greater portion of the caverns and fractured zones in the rock mass are located in the depth interval between 435 m a.s.l. and 399 m a.s.l. Based on the analysis of the water levels in piezometers (Z-4, Z-5, Z-6 in the field and Z-8, Z-9 on the eastern carbonate boundary), as well as on structural-tectonic investigations, the main zone of discharge from the Drežničko Polje was located in the SE margin where the main zone of ponors were formed. Based on the low water levels in piezometers (i.e., the levels in summer 2003 and summer 2004) the lowest position may be concluded to have decreased to an altitude of 399 m a.s.l. at those times.

5. Conclusions

The combined data from geological mapping, exploratory drilling and hydrogeological monitoring presented in this study have significantly improved the hydrogeological map of the Drežničko Polje, especially the ponor zone. Tracing experiments in the ponor zone during very high groundwater levels have demonstrated that in such hydrological conditions the ponors act as springs at the bottom of the lake, and are therefore estavelles. Further tracings should therefore be performed during lower groundwater levels, when surface water inflows into the ponors (i.e., medium groundwater levels in the middle of the recession period), and during low groundwater levels using artificial washing of dye into the ponor. The connection of other karst poljes from the SW side of the Velika Kapela Mountain with the Drežničko Polje or directly with springs on the other side of the mountain must be investigated in much more detail and in different hydrological conditions, using different tracers simultaneously.

Hydrological analyses of stage-discharge curves led to the division of the year into two main parts, corresponding approximately to two halves of the year. Auto-correlations gave significantly different results for these two periods, which was explained by the very large groundwater level changes in the karst massif of the Velika Kapela Mountain and the fact that in heterogeneous karst aquifers such as this one, many small limited aquifers and pockets of water remain in the vadose zone when the water table drops rapidly. A similar result was obtained with cross-correlations, which showed that the two periods were also clearly separated and results pointed to limitations of the karst conduits, which cannot conduct such a large quantity of water during high groundwater levels, both on the Zagorska Mrežnica spring side and near the ponors (estavelles) in the Drežničko Polje. The rock mass conductivity is naturally much lower and contributes less in a karstified environment such as this one than karst voids, caverns, ponors, dissolution conduits, or, commonly, preferential flow paths. Similar rain events during high groundwater levels would have a completely different influence than during low groundwater levels. Due to this heterogeneity, standard hydro(geo)logical modelling cannot provide plausible results and numerous different methods should be applied to minimize ambiguity.

From groundwater level monitoring in and near the Drežničko Polje, it was concluded that natural accumulations, such as a lake in the polje, and the groundwater beneath and around it, represent a completely interdependent and connected system. The intensity of the groundwater discharge from the Drežničko Polje at the beginning of water recession could be significantly reduced by placing an injection (i.e., a grout curtain) in front of the main zone of the swallow holes, to the west of piezometers Z-4, Z-5 and Z-6, to a depth of 390 m a.s.l., ending at the southern and eastern margins of the field. The results of this research program, which included all the former findings on the area, have illuminated the very complex karst system of the Velika Kapela Mountain and its surroundings. The main purpose of this work, which focused on the possibility and feasibility of a grout curtain that would partially separate the ponor zone from the rest of the Drežničko karst Polje underground, was thus achieved. Designing such an injection curtain with mobile closers above the three largest ponors in the Main ponor zone and the surface sanation of suffosions of the terrain between the grout curtain and the Main ponor zone in the field would: (1) prolong a relatively high groundwater wave which would increase electrical power production in the Gojak and Lešće HPP; (2) enhance the discharge curve shape on the Zagorska Mrežnica water supply spring (which is comparatively less important as only a small proportion of the discharge is used); and (3) cause a slight decrease in the highest part of the discharge curve, which could have an effect in decreasing the maximal floods in Ogulin and its surroundings.

Author Contributions: R.B. provided conceptualization, investigation, methodology, project administration, supervision, validation and written original draft. K.P. provided data curation, formal analysis, methodology, data interpretation, data visualization and written original draft. J.T. provided conceptualization, investigation, supervision, validation and written original draft. D.P. provided data curation, methodology, data visualization and written original draft.

Funding: This research received no external funding.

Acknowledgments: The authors express their gratitude to the offices of the Croatian Electric Power Company, Elektroprojekt-Zagreb, the Croatian Geological Institute, the Geoekspert project and the Faculty of Mining and the Geological Faculty of the University of Zagreb, for their co-operation for this work. We especially thank the many colleagues who participated in field or office work, as well as the co-authors of unpublished technical reports used in drafting this paper.

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

References

1. Bakalowicz, M. Karst groundwater: A challenge for new resources. *Hydrogeol. J.* **2005**, *13*, 148–160. [CrossRef]
2. Ford, D.; Williams, P.W. *Karst Hydrogeology and Geomorphology*; John Wiley & Sons, Inc.: West Sussex, UK, 2007; p. 562.
3. Bonacci, O.; Jukić, D.; Ljubenkov, I. Definition of catchment area in karst: Case of the rivers Krčić and Krka, Croatia. *Hydrol. Sci. J.* **2006**, *51*, 682–699. [CrossRef]
4. Terzić, J.; Stroj, A.; Frangen, T. Hydrogeological investigation of karst system properties by common use of diverse methods: A case study of Lička Jesenica springs in Dinaric karst of Croatia. *Hydrol. Process.* **2012**, *26*, 3302–3311. [CrossRef]
5. Terzić, J.; Marković, T.; Lukač Reberski, J. Hydrogeological properties of a complex Dinaric karst catchment: Miljacka Spring case study. *Environ. Earth Sci.* **2014**, *72*, 1129–1142. [CrossRef]

6. Lukač Reberski, J.; Kapelj, S.; Terzić, J. An estimation of groundwater type and origin of the complex karst catchment using hydrological and hydrogeochemical parameters: A case study of the Gacka river springs. *Geol. Croat.* **2009**, *62*, 157–178. [CrossRef]
7. Bonacci, O.; Andrić, I. Karst Rivers Hydrology: Case of the Lika and Gacka (Croatia). *Acta Carsologica* **2008**, *37*. [CrossRef]
8. Bonacci, O.; Andrić, I. Impact of an inter-basin water transfer and reservoir operation on a karst open streamflow hydrological regime: An example from the Dinaric karst (Croatia). *Hydrol. Process.* **2010**, *24*, 3852–3863. [CrossRef]
9. Pavlić, K.; Kovač, Z.; Jurlina, T. Trend analysis of mean and high flows in response to climate warming - Evidence from karstic catchments in Croatia. *Geofizika* **2017**, *34*, 157–174. [CrossRef]
10. Pavlić, K.; Jakobović, D. High flows from Gornja Dobra basin. *Rud.-Geološko Zb.* **2018**, *33*, 45–52. [CrossRef]
11. Pavlić, K.; Parlov, J. Cross-Correlation and Cross-Spectral Analysis of the Hydrographs in the Northern Part of the Dinaric Karst of Croatia. *Geosciences* **2019**, *9*, 86. [CrossRef]
12. Lončar, G.; Šreng, Ž.; Bekić, D.; Kunštek, D. Hydraulic-Hydrology Analysis of the Turbulent Seepage Flow within Karst Aquifer of the Golubinka Spring Catchment. *Geofluids* **2018**, *2018*, 6424702. [CrossRef]
13. Jukić, D.; Denić-Jukić, V. Partial spectral analysis of hydrological time series. *J. Hydrol.* **2011**, *400*, 223–233. [CrossRef]
14. Žganec, K. The effects of water diversion and climate change on hydrological alteration and temperature regime of karst rivers in central Croatia. *Environ. Monit. Assess.* **2012**, *184*, 5705–5723. [CrossRef] [PubMed]
15. Jukić, D.; Denić-Jukić, V. Investigating relationships between rainfall and karst-spring discharge by higher-order partial correlation functions. *J. Hydrol.* **2015**, *530*, 24–36. [CrossRef]
16. Fiorillo, F.; Doglioni, A. The relation between karst spring discharge and rainfall by cross-correlation analysis (Campania, southern Italy). *Hydrogeol. J.* **2010**, *18*, 1881–1895. [CrossRef]
17. Gajić-Čapka, M.; Perčec Tadić, M.; Patarčić, M. A digital annual precipitation map of Croatia | Digitalna godišnja oborinska karta Hrvatske. *Croat. Meteorol. J.* **2003**, *38*, 21–33.
18. Zaninović, K.; Srnec, L.; Perčec Tadić, M. A digital annual temperature map of Croatia. *Croat. Meteorol. J.* **2004**, *39*, 51–58.
19. Zaninović, K.; Gajić-Čapka, M.; Perčec Tadić, M.; Vučetić, M.; Milković, J.; Bajić, A.; Cindrić, K.; Cvitan, L.; Katušin, Z.; Kaučić, D.; et al. *Klimatski Atlas Hrvatske—Climate atlas of Croatia: 1961–1990: 1971–2000*; Croatian Meteorological and Hydrological Service: Zagreb, Croatia, 2008; p. 200.
20. Velić, I.; Sokač, B. *Basic Geological Map of the Rrepublic of Croatia 1:100.000*; Croatian Geological Survey: Zagreb, Croatia, 1982.
21. Vlahović, I.; Tišljar, J.; Velić, I.; Matičec, D. Evolution of the Adriatic Carbonate Platform: Palaeogeography, main events and depositional dynamics. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **2005**, *220*, 333–360. [CrossRef]
22. Velić, I. Stratigraphy and Palaeobiogeography of Mesozoic Benthic Foraminifera—Part 1. *Geol. Croat.* **2007**, *60*, 1–60.
23. Velić, I. Stratigraphy and Palaeobiogeography of Mesozoic Benthic Foraminifera—Part 2. *Geol. Croat.* **2007**, *60*, 61–86.
24. Velić, I. Stratigraphy and Palaeobiogeography of Mesozoic Benthic Foraminifera—Part 3. *Geol. Croat.* **2007**, *60*, 87–113.
25. Šumanovac, F.; Weisser, M. Evaluation of resistivity and seismic methods for hydrogeological mapping in karst terrains. *J. Appl. Geophys.* **2001**, *47*, 13–28. [CrossRef]
26. Šumanovac, F.; Markušić, S.; Engelsfeld, T.; Jurković, K.; Orešković, J. Shallow and deep lithosphere slabs beneath the Dinarides from teleseismic tomography as the result of the Adriatic lithosphere downwelling. *Tectonophysics* **2017**, *712–713*, 523–541. [CrossRef]
27. Tari, V. Evolution of the northern and western Dinarides: A tectonostratigraphic approach. *Eur. Geosci. Union: Stephan Mueller Spec. Publ. Ser.* **2002**, *1*, 223–236. [CrossRef]
28. Schmid, S.M.; Bernoulli, D.; Fügenschuh, B.; Matenco, L.; Schefer, S.; Schuster, R.; Tischler, M.; Ustaszewski, K. The Alpine-Carpathian-Dinaridic orogenic system: Correlation and evolution of tectonic units. *Swiss J. Geosci.* **2008**, *101*, 139–183. [CrossRef]
29. Korbar, T. Orogenic evolution of the External Dinarides in the NE Adriatic region: A model constrained by tectonostratigraphy of Upper Cretaceous to Paleogene carbonates. *Earth-Sci. Rev.* **2009**, *96*, 296–312. [CrossRef]

30. Prelogović, E.; Kuk, V.; Buljan, R. The structural fabric and seizmotectonic activity of northern Velebit: Some new observations. *Rud.-Geološko Zb.* **1998**, *10*, 39–42.
31. Prelogović, E.; Pribičević, B.; Ivković, Ž.; Dragičević, I.; Buljan, R.; Tomljenović, B. Recent structural fabric of the Dinarides and tectonically active zones important for petroleum-geological exploration in Croatia. *Nafta* **2004**, *55*, 155–161.
32. Terzić, J. Hydrogeology of Adriatic Karst Islands. Ph.D. Thesis, University of Zagreb, Zagreb, Croatia, 2006.
33. Freeze, R.A.; Cherry, J.A. *Groundwater*; Prentice-Hall: Upper Saddle River, NJ, USA, 1979; p. 604.
34. Motyka, J. A conceptual model of hydraulic networks in carbonate rocks, illustrated by examples from Poland. *Hydrogeol. J.* **1998**, *6*, 469–482. [CrossRef]
35. White, W.B. Karst hydrology: Recent developments and open questions. *Eng. Geol.* **2002**, *65*, 85–105. [CrossRef]
36. Bahun, S. Geološka osnova hidrogeoloških odnosa krškog područja između Slunja i Vrbovskog (Geological basis of the hydrogeological relations in the karst area between Slunj and Vrbovsko). *Geološki Vjesn.* **1968**, *21*, 19–82.
37. Trauth, M.H. *MATLAB® Recipes for Earth Sciences*; Springer: Berlin/Heidelberg, Germany, 2015.
38. Mangin, A. Pour une meilleure connaissance des systèmes hydrologiques à partir des analyses corrélatoire et spectrale. *J. Hydrol.* **1984**, *67*, 25–43.