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Hydro-Energy Suitability of Rivers Regarding Their Hydrological and Hydrogeological Characteristics

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Abstract: The production of electric energy from rivers by using mini, as well as micro hydroelectric power plants, is a very promising solution, especially in rural and isolated areas. Numerous waterways in Croatia and their hydrological and hydrogeological diversity present an opportunity, but also a challenge, for the construction of hydroelectric power plants. Due to the complexity of the water courses' hydrology, as well as hydrogeological characteristics, it is very hard to determine an appropriate flow pattern (amount), which will be used as an input value for the sizing of hydroelectric power plants. Such analysis will be provided for real case studies in Croatia with special regard to present geological media—media with intergranular porosity (Bednja River), karst media (Gornja Dobra River), and flysch media (Mirna River). Considering different geological media increases the possibility of using the presented methodology on other locations in Croatia, as well in the world. It has been shown that the analyzed rivers definitely have potential for electric energy production, regarding the potential and kinetic river energy. The presented analysis is scientifically original, but also shows the procedure for the determination of the hydro-energy potential of the rivers, as well as for the sizing on the hydropower plants. Hydrology and hydrogeology analyses rounds out the usual hydro-energy analysis, which is in most cases based on basic statistical parameter analysis.

Keywords: water; energy; hydropower plant; river; flow

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1. Introduction

Energy consumption is rapidly growing from year to year and the public and decision makers have realized the importance of switching to clean and renewable energy sources. Renewable power is thriving, as innovations reduce costs and for the first time the promise of a clean energy future looks achievable. Nowadays, hydropower plants, including small-scale hydropower plants, produce a respectable part of the energy deemed as renewable. One cannot overlook both mini (from 100 to 500 kW) and micro (5 to 100 kW) hydropower plants which fit perfectly into the group of renewable energy sources. Unlike large-scale hydropower plants, mini and micro hydropower plants, if carefully planned and managed, tend to cause no environmental damage and can be considered perfectly safe for the environment. The small hydropower market (up to hydropower plants of a maximum power equal to 10 MW) was estimated to be USD 2.6 billion in 2019, and according to projections it will reach USD 3 billion by 2024 [1]. Although the technology used for the production of electric energy in hydropower plants is already well known and established, nevertheless there is always a need for technological improvements and the changes in the sizing methodology, especially in the operational work of mini and micro hydropower plants. In accordance with the worldwide call to "act locally-think globally", small-scale hydropower plants provide clean and available electric energy, especially in isolated and remote areas, where water streams are available.

Additionally, micro and mini hydropower plants are nature-friendly, cheaper in comparison to large hydro power plants, and can be installed at almost any water course.

Large hydropower plants can cause significant disturbances in fish migratory routes. This problem can be addressed by the construction of fish passages and fish-friendly turbine design. Fish passages are hydraulic structures that allow the upstream and downstream migration of fish when a dam impedes their migration. In order to overcome the limitations of fish passages, recent R&D efforts have focused on the development of fish-friendly turbines for relatively higher head hydro stations [2].

Small rivers and water coursers, with their changeable velocities and torrential characteristics, can pose a challenge when planning for an installation of mini or micro hydropower plants. The research of such issues has an important role in improvement of the efficiency of micro and mini hydropower plants. Appropriate understanding of all characteristics of the water courses, as well as a good anticipation of all possible situations and problems that may arise as a result of different climatic conditions in the system, are key prerequisites for successful design and high efficiency of small hydropower plants. Key input parameters for sizing of micro and mini hydropower plants (as an assumed size of the flows in analyzed rivers) will be provided with research and analysis of hydrological and hydrogeological properties of the rivers. One of the basic parameters for the estimation of hydropower potential of rivers is daily average flow. In light of that, thorough analysis of the time series of average daily flows of water course will be carried out, not just as a mentioned input parameter, but also for further elaboration of the project. Other key information for reliable analysis and sizing of the hydropower plant model is hydrogeological characterization of the medium underlying the riverbed.

The main purpose of the presented research is to provide insight into the potential for the production of electric energy from the torrential rivers. The potential energy and kinetic energy of the river will be analyzed not only from the usual energy aspect (calculation of the power), but also from the hydrology and hydrogeology aspects. Hydrology analysis shows when the smallest and/or biggest flows/velocity can be expected, while hydrogeology analysis gives insight about the losses of the water, which could occur when passing through different media.

2. Literature Review

There are many approaches for defining hydro-energy potential of the water courses, nevertheless the size and regime of the rivers, as well as insight into the potential and/or kinetic arrangement of the turbines are always considered as key factors. Santos et al. [2] used numerical modeling, i.e., computation fluid dynamics for the prediction of the flows and velocities in the Amazon River. Additionally, the authors used real measurements for validation. The research presented in [3] was based on the usage of GIS in the model which takes into the account variables that are decision-making criteria, all in the form of an open-source tool. The methodology for determining of the river energy potential presented in [3] has been employed by the SWAT (Soil and Water Assessment Tool) model, satellite data and GIS tools.

It is well-known fact that (in general) more complicated and longer time modeling and field measurement gives more reliable insight for the future projects of hydropower plants, regardless of their size. Field measurements require financial resources for the equipment and measurement procedures.

There are even simple methods for the hydro energy site analysis, like the procedure explained in [4], where analysis of the obtained values is made in the form of a comparison of the existing methods, with a quality description of the each one. In the same manner, the impact of climate change on electric energy production was provided in "Dynamics of Electricity Production against the Backdrop of Climate Change: A Case Study of Hydropower Plants in Poland" using a case study of Polish rivers. Analysis was based on the regression of the air temperature and precipitation during the time, with the statistical flow analysis, all with respect to the potential energy hydropower plants. Researchers in [5] described the three most common procedures for the prediction of the hydropower, which convert the discharge and height quantities into the hydropower amount. Additionally, they invented a fourth method (the Energy Tree Model), which is an improvement of the existing three methods, i.e., of their limitations. Their methodology is based on a decision tree, with the more completely and detailed inputs of not only the river subbasin areas and heights, but also all the tributaries.

Kinetic turbine analysis, provided in [6] was based on the calculation, but also a real measurement of the average velocity for the many locations in the world, with respect to the different types of turbines. Although the review was done in real conditions, a further hydrological and hydrogeological analysis will give a new aspect of the analysis. Another proof that kinetic hydro energy is a promising solution for a production of electric energy can be found in a high-quality review in [7]. Besides the presentation of the possibility and a data review for using of kinetic energy in Canadian rivers, the report shows sizing methodologies for kinetic turbines. Particularly, they are divided as "Estimation of Flow Duration Curves at Ungauged Basins", "Regional Estimation Methods", and "Determination of Homogeneous Regions".

Although all the presented methods provide thorough insight into hydropower potential and give detailed descriptions and nomenclature, it is a "first-hand" approach. It could be concluded that there is a need for broader projection and analysis. This is a motivation for the presentation of a new methodology for the analysis of a hydro-energy potential of the rivers, which will not entail complex modeling and/or calculation, or unreliable or simplified procedures which will give useless results.

3. Methodology

The presented procedure for defining the hydro-energy potential of the rivers consists of two parts. The first part is the rescaled adjusted partial sums (RAPS) method, while the second part is hydrogeological analysis of the analyzed location, in order to obtain the comprehensive view of the topic.

RAPS is a well-known method based on a visual determination of a subseries from original (given) series of data. By using the average value and standard deviations of the observed time series, RAPS values provide insight into the parts, where occurrence of the trends, data grouping, fluctuations, and similar appearances happen during the time:

$$RAPS_k = \sum_{t=1}^{k} \frac{Y_t - \overline{Y}}{S_y} \quad (1)$$

where Y_t is the value of the analyzed member (parameter) of the analyzed time series, $\overline{Y}$ is an average value of the analyzed time series, S_y is the standard deviation of the considered time series; n is a number of members of the analyzed time series, and k = 1, 2,..., [8]. The plot of the RAPS shows a reasonable visualization of the analyzed data trend, which cannot be seen in the usual time series plots [9]. Visual presentation of the $RAPS_k$ values points to the existence of regularities in the fluctuations of the analyzed parameters (Y_t) [10]. The process of determining a new subseries is based on the visual determination, i.e., looking for the highest "peak", or for the lowest "valley" on the RAPS diagram.

The RAPS method was mostly used for hydrological analysis of the river flow [6], but it also has a wide range of applications in all research areas. For example, in analysis of the precipitation [11], water temperatures [12], rising sea water levels [13], meteorological parameters for the purpose of irrigation [14] and clay excavation, as well as for wastewater quality analysis [10].

Regarding the size and flow of the river, as well as the selected type of installation where turbines use potential energy of the water, the power of the hydropower plant $P_{HP,P}$ can be calculated as [15]:

$$P_{HP,P} = \rho * g * Q_{HP} * \Delta H * \eta_{HP} \quad (2)$$

where ρ is water density (1000 kg/m^3), g is acceleration of the gravity (9.81 m/s^2), Q_{HP} is adopted flow rate (m^3/s), ΔH is the difference in hydraulic head within analyzed water course segment (m), while η_{HP} is the efficiency of the hydropower plant.

Additionally, the power of the hydropower plant $P_{HP,K}$, where turbines use kinetic energy of the water, can be calculated as [15]:

$$P_{HP,K} = \xi * \frac{\rho}{2} * v^3 * A_r \quad (3)$$

where ξ is the hydro powerplant efficiency, v is adopted velocity of the water moving, while A_r is the frontal (or swept) area of the device (m^2) [15].

Water depth will be calculated with respect of the lowest point of the river bottom. Due to sedimentation and erosion, the bottom of the riverbed changes over time, so it is difficult to accurately determine the depth, but at this level of research, obtained values meet the requirements of the calculations. Steps of the depths, i.e., partitions for the calculation of power of turbines will be 0.5, 1, and 2.5 m.

After the calculation/presentation of the hydrological and energy parameters, the last step is a detailed hydrogeological analysis in order to fulfill and round out the analysis of the hydro-energy potential of the analyzed locations.

4. Case Study

Three rivers located in different parts of Croatia were selected as the objects of analysis, due to the availability of the average daily flows with the longest possible time series, as well as for the possibility of field research, which are done or are still in progress. These are the Bednja, Gornja Dobra, and Mirna rivers (Figure 1) [16]. Hydrological (limnigraph) stations where time series of the average daily flow were taken are Ludbreg (Bednja), Turkovići (Gornja Dobra), and Motovun (Mirna).

Figure 1. Locations of the analyzed rivers and hydrological measuring stations.

Figure 2a–c show riverbed cross sections at the mentioned measuring stations. Insight into the analyzed locations are on photos in Appendix A.

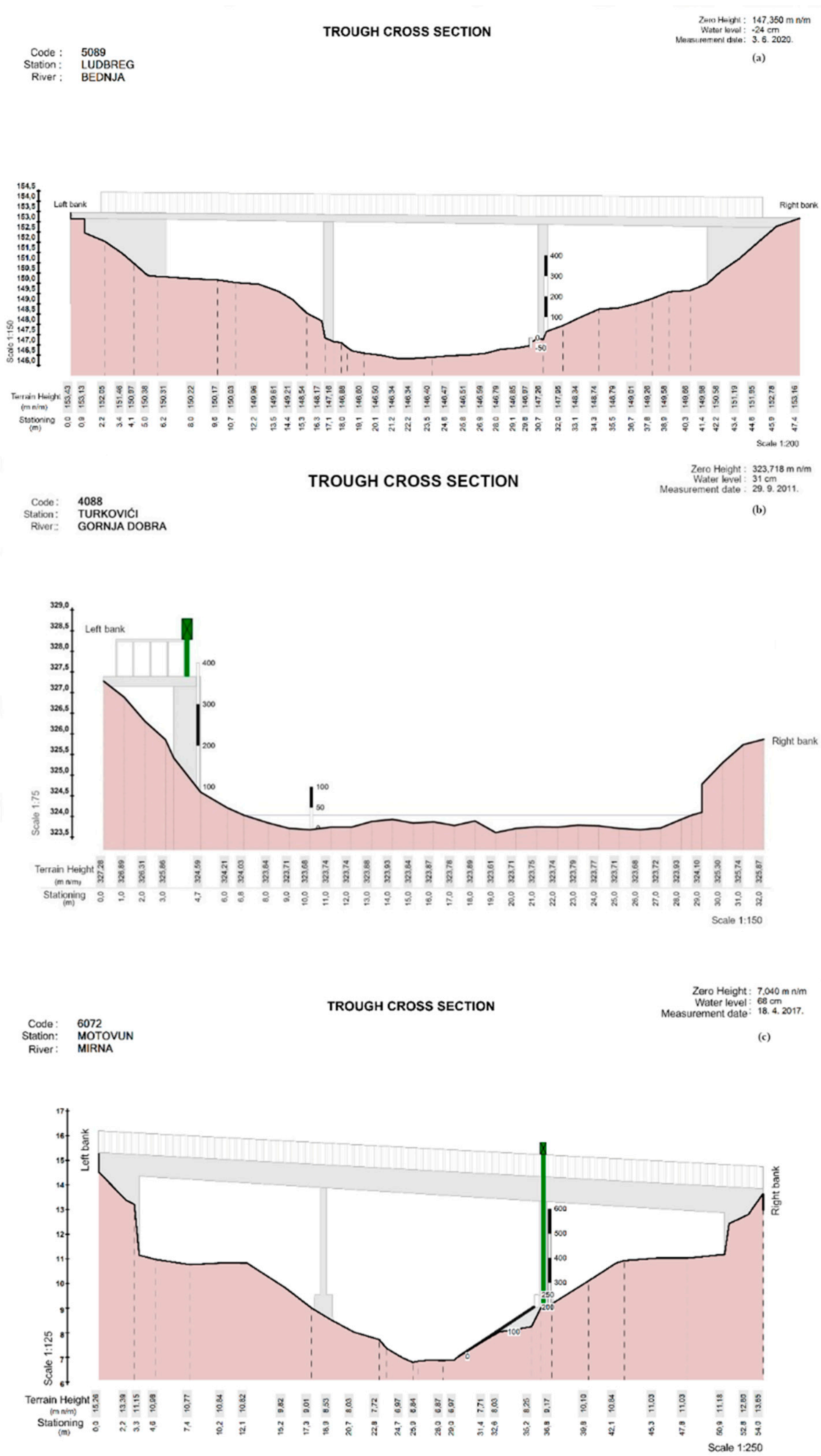

Figure 2. Riverbed cross section at the measuring station Ludbreg, Bednja River (**a**), measuring station Turkovići, Gornja Dobra River (**b**), and measuring station Motovun, Mirna River (**c**).

5. Results

Figures 3–5 show hydrograms and RAPS diagrams for the flows measured at the measuring stations on the rivers Bednja, Gornja Dobra, and Mirna for the analyzed period of 20 years, from 1999 to 2018 [17].

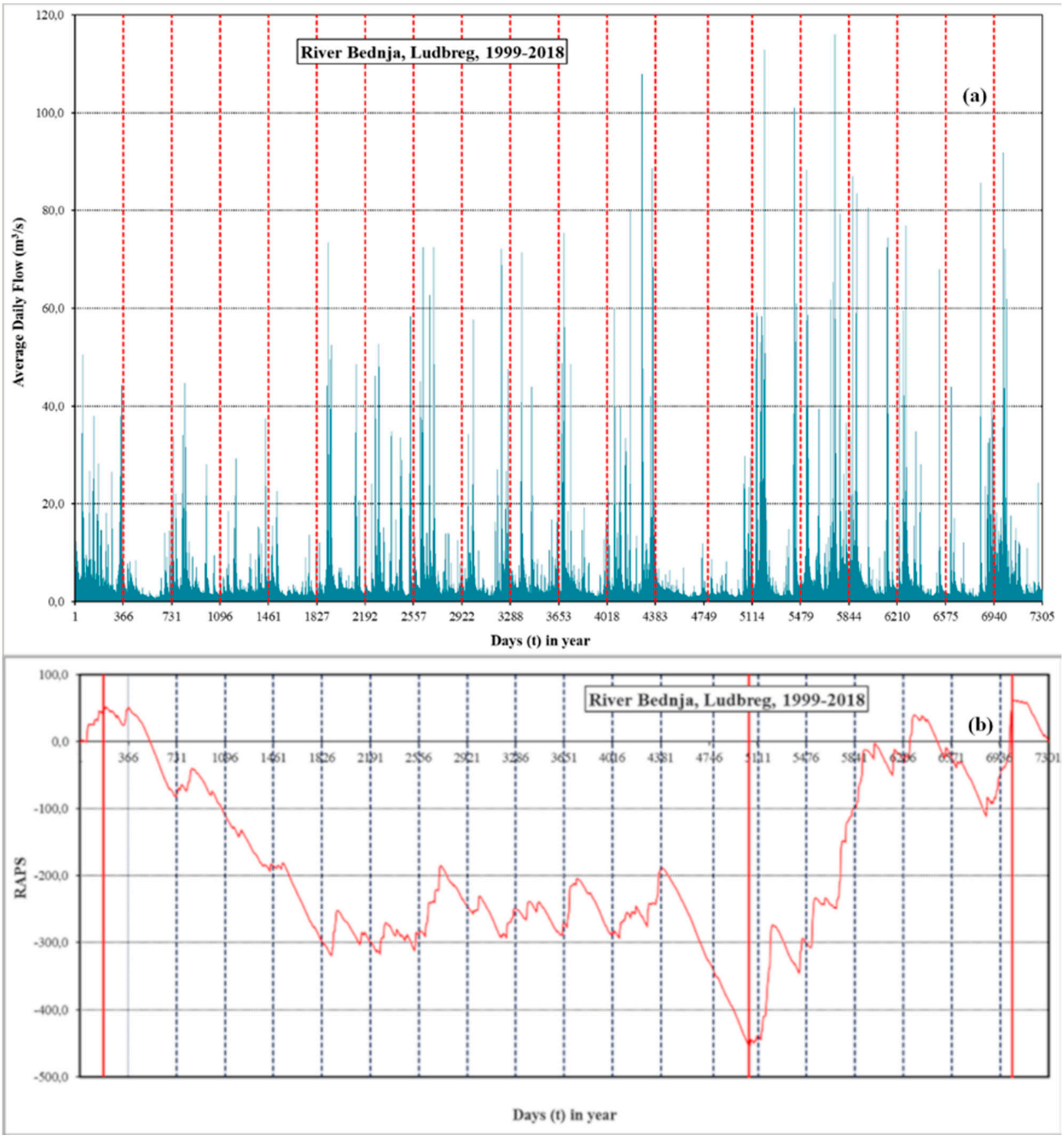

Figure 3. Average daily flows (**a**) and RAPS diagram (**b**) for the Bednja River during the period 1999–2018.

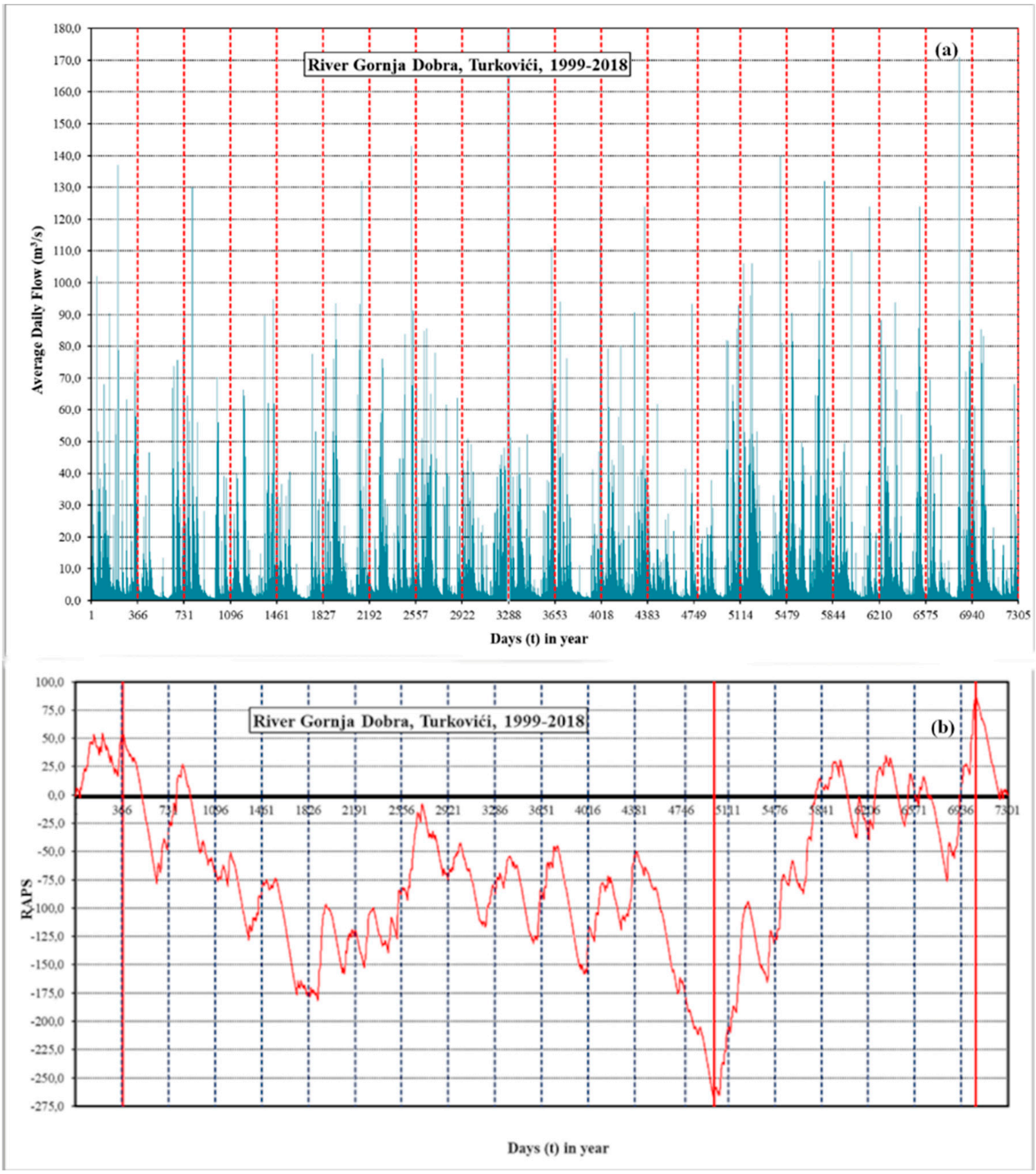

Figure 4. Average daily flows (**a**) and RAPS diagram (**b**) for the Gornja Dobra River during the period 1999–2018.

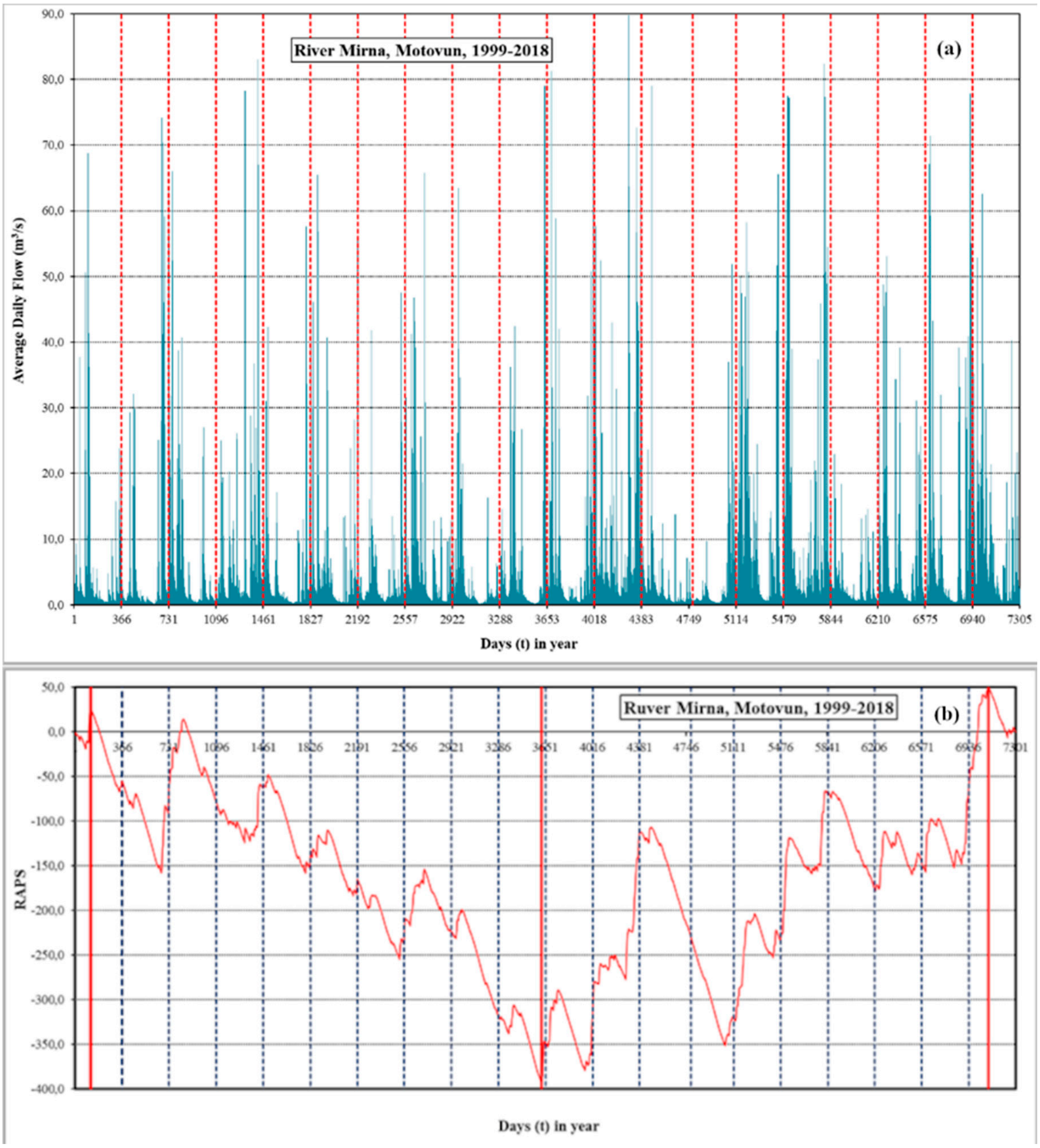

Figure 5. Average daily flows (**a**) and RAPS diagram (**b**) for the Mirna River during the period 1999–2018.

Table 1 shows average values, standard deviations, minimum and maximum values of the average daily flow of the analyzed rivers during the observed period of 20 years.

Table 1. Statistical parameters of the average daily flows for the Bednja, Gornja Dobra, and Mirna rivers during 20-year observation period.

River	Average (m^3/s)	Standard deviation (m^3/s)	Minimum (m^3/s)	Maximum (m^3/s)
Bednja	6.171	9.980	0.431	116.000
Gornja Dobra	11.727	15.414	0.627	171.000
Mirna	5.559	9.909	0.061	89.800

Gornja Dobra has the biggest average flow, but also the biggest standard deviation, which is characteristic of the flow in a karst area. The purpose of the analysis is not primarily the hydrogeology analysis. So, it should be enough to mention that karst relief consists of depressions, sinkholes, as well as the other structures. This is manifested in a certain amount of water which is lost, but also with springs in/from the main karst river flow.

The Bednja River shows torrential characteristics, as well as the Gornja Dobra River and Mirna. This is defined by frequent changes of smallest and the biggest values.

A common attribute of the Bednja and Mirna Rivers are drought periods from the years 2011 and 2012 (time periods from 4500 until 5000 days). Such observation was not perceived for the Gornja Dobra, which can be explained by the karst characteristics of the media.

Hydropower Potential for the Bednja, Gornja Dobra, and Mirna Rivers

Power of the turbines which use potential energy of water is calculated by using Equation (1). In this calculation, the value of the water depth is a function of a bulkhead of particular height H. Adopted potential turbine efficiency is equal to 80%, while for the kinetic turbine it is 30% with regards to [18,19] and experienced recommendations. Between the lowest and the highest water depth, calculation steps are 1.0 m in order to obtain better insight into the changes of the turbine powers with the increasing height of the bulkhead H. Input river flows were selected with accordance to the analysis of the hydrograms and water-level values, obtained from the Croatian Meteorological and Hydrological Service (CMHS) By using Equation (2), the potential power of the turbines which use potential energy are calculated, as shown in Table 2.

Table 2. Insight into the potential power of the turbines with respect of the potential hydro energy for the Bednja River.

H (m)	Q (m^3/s)	$P_{HP,P}$ (W)
0.50	4.45	17,461.80
1.50	28.65	337,267.80
2.50	64.42	1,263,920.40

On the same manner, and by using Equation (3), the velocity and potential power of the turbine which uses kinetic power of water are calculated, as shown in Table 3.

Table 3. Insight into the potential power of the turbines with respect of the kinetic hydro energy for the Bednja River.

H (m)	A_r (m^2)	v (m/s)	$P_{HP,K}$ (W)
0.50	3.75	1.19	947.90
1.50	24.10	1.19	6091.85
2.50	43.00	1.50	21,768.75

In the same manner as was done for the Bednja River, identical analysis was provided for the Gornja Dobra River (Tables 4 and 5) and Mirna (Tables 6 and 7).

Table 4. Insight into the potential power of the turbines with respect of the potential hydro energy for the Gornja Dobra River.

H (m).	Q (m^3/s)	$P_{HP,P}$ (W)
0.50	4.46	17,508.89
1.50	50.34	592,602.48
2.50	124.30	2,438,766.00

Table 5. Insight into the potential power of the turbines with respect of the kinetic hydro energy for the Gornja Dobra River.

H (m)	A_r (m^2)	v (m/s)	$P_{HP,K}$ (W)
0.50	5.66	0.79	418.59
1.50	19.66	2.56	49,476.01
2.50	50.66	2.45	111,751.84

Table 6. Insight into the potential power of the turbines with respect of the potential hydro energy for the Mirna River.

H (m)	Q (m^3/s)	$P_{HP,P}$ (W)
0.50	3.25	12,764,77
1.50	29.24	344,213,28
2.50	60.24	1,181,908,80

Table 7. Insight into the potential power of the turbines with respect of the kinetic hydro energy for the Mirna River.

H (m)	A_r (m^2)	v (m/s)	$P_{HP,K}$ (W)
0.50	2.50	1.30	823.88
1.50	14.50	2.01	17,662,31
2.50	45.00	1.34	16,241,20

6. Hydrogeological Characteristics of the Analyzed Locations

Each of the rivers flows through different geological features, i.e., hydrogeological media, which definitely has an impact on the hydrological characteristics of the observed rivers. The Bednja flows through intergranular media, Gornja Dobra through karst, while Mirna flows through flysch (marl) media. This consequently has an impact on the hydro-energy potential of the rivers.

6.1. Bednja River

The Bednja River emerges at the foot of Maceljska Hill and flows 106 km before its confluence with the Drava River near the settlement of Mali Bukovec (Figure 6). The Bednja River basin covers approximately 596 km^2 and can be divided into two main parts: larger upland (70%) and smaller lowland (30%). In the upland part whose surface area is roughly 480 km^2, there are 48 torrential basins with around 250 km of waterways. As the river flows from west to east, its basin is also elongated in that direction. The river turns more strongly near the Presečno settlement, where it changes course in a north–south direction, and after bypassing the eastern part of the Varaždin-Toplica mountain, it continues to flow in an east–west direction. The maximum width of the river basin is 29 km and is characteristic of the source part, while the basin is narrowest at the mouth and is only 4 km. This form of the basin contrasts with the "normal" appearance of the river basin where the basin is widest in the part near the mouth. This funnel-type basin causes low water permeability at its narrowest part, which creates hydrotechnical problems primarily for the outflow of high waters. The drainage basin is also asymmetrical; the right side is bigger (331 km^2) in comparison to the left side of the basin (265 km^2). A lower coefficient of asymmetry shows the natural affinity of the simultaneous inflow of high waters into the Bednja River which can cause floods. The Bednja has a very dense network of smaller tributary streams and rivers. Due to the small slope of the watercourse, water velocity is slow. The riverbed meanders and frequently floods the nearby fields [20]. Due to the specific shape and relief of the Bednja River Basin, floods in the upper parts of the watercourse are typical torrential floods that occur on streams that flow from the slopes of Ivanščica, Ravna gora, and Kalnik. In the middle and lower part of the basin, floods occur after a large amount of rain and/or melting of snow [21].

Figure 6. Spatial presentation of hydrological and meteorological stations in the Bednja Basin (from [21]).

Three relief parts can be distinguished—alluvial plains, tertiary foothills and Palaeozoic highlands [20,22]. The oldest sediments in the Bednja catchment are located in the deeper parts of the sedimentation basin and in the mountains surrounding the Bednja River valley. They are middle Triassic clayey schists, sandstones, dolomites, cherts, and tuffs. Miocene sediments are dominated by yellow quartz sands with intercalation of sands, conglomerates, sandy marls, and marly clays. The youngest deposits are Holocene alluvial sediments consisting of fine gravel, sand, mud, and clay. The main component of alluvial beds is poorly sorted sandy-clayey mud. The aquifers of small thickness and laterally and vertically heterogeneous composition have formed in the alluvial sediments of Bednja. They are characterized by intergranular porosity and low permeability [23]. The whole area is intersected with numerous faults. The main fault zone, known as the Mt. Ivanščica, reverse to strike-slip faults, runs alongside the valley of the Bednja River and also stretches along Mt. Ivanščica [24].

The Bednja River has a Peripannonian pluvial-nival regime with two highs and two lows during the year [25]. The first maximum occurs during March or April, and the second during December. Two lows occur during August and February. More extreme flow values occur from November to April.

6.2. Gornja Dobra River

The Dobra River Basin is located in a transitional area connecting the Dinaric and Pannonian areas. Regionally speaking, the area is a part of a large nappe structure associated with the tangential tectonic movements of Middle Eocene Pyrenean orogenetic phase. Younger, mainly block tectonics affect the predominantly Dinaric northwest–southeast trending structures [26]. Geological characteristics of the area also influence hydrological and hydrogeological characteristics of the river and the flow of the Dobra River can be divided into three parts [27]. The Upper Dobra begins as surface runoff at foothills of the Velika Kapela Mountain, near Skrad, in the area comprised of Palaeozoic clastites and it retains such characteristics as Vrbovsko (Figure 7). In the area of Vrbovsko the Upper Dobra accepts water from a couple of karst springs formed on the contact of permeable and impermeable deposits. After Vrbovsko, the river flows over the Jurassic limestones and dolomites of the Ogulin-Oštarije karst platform. During its flow through the dolomites, water losses are minimal. The Upper Dobra flows above ground 51.2 km but when it reaches limestones, sinkholes start to occur, the biggest being Đula's abyss in the city of Ogulin. Đula's abyss is the beginning of the Đula–Medvedica cave system, the longest cave system in Croatia. The middle part of the river flow is an underground river which flows through the system of caves and conduits with a total length of 16.39 km. Dobra re-emerges as a strong permanent karstic spring near village Gojak and flows 52.1 km until it joins the Kupa River. The flow of the Lower Dobra mostly depends on the operation of the hydroelectric power plant Gojak. During the first 18 km of the Lower Dobra, water losses are high, and in the last 33 km the Lower Dobra River is a perennial watercourse. Both Upper and Lower Dobra lose parts of their water through their riverbed into the karstic underground, but the karstic aquifer also feeds the river depending on the hydrogeological situation and underground water level. The Upper parts of the Upper Dobra have characteristics of the mountain torrential watercourse, and the lowermost parts of the Lower Dobra exhibit characteristics of the lowland watercourse [27–29].

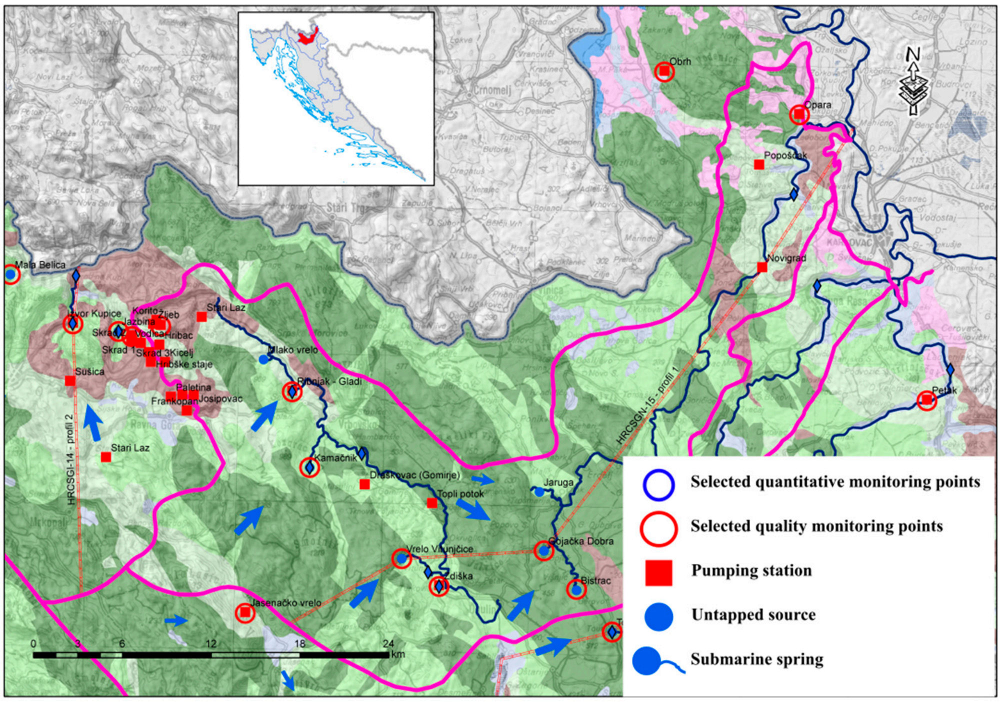

Figure 7. Spatial presentation of hydrological and hydrogeological relations in the Dobra River catchment [30].

6.3. Mirna River

The Mirna River is formed by the confluence of rivers Rečina and the Draga some 2.3 km upstream from Buzet and makes the longest surface watercourse in Istria with a total length of 53 km. The size of the Mirna River immediate hydrological catchment is about 380 km^2 and it is situated in the central and western part of the Istrian peninsula which is, structurally speaking, part of the External Dinarides [31]. According to the authors of [32], they were dominated by limestone deposition on the Adriatic Carbonate Platform from the Lower Jurassic to the Eocene. This part of the Istrian peninsula is called "gray Istria" due to widely spread layers of the gray-colored Eocene flysch and Quaternary sediments. Flysch layers are consisted mainly of marls in alternation with sandstones, bedded limestones and conglomerates. These layers have a reduced permeability which causes a formation of a network of surface water courses [33]. Quaternary sediments can be found in the Mirna River valley as in the valleys of the tributary rivers and streams. Carbonate sediments in the Mirna drainage area are Cretaceous and Eocene limestones (Figure 8). The Mirna River is a very significant river in the area since its water balance accounts for 30% of the total water balance of the Istrian Peninsula. Karstic springs of Gradole, Bulaž, and Sv. Ivan also contributes to the Mirna water balance making the Mirna River's hydrogeological catchment much bigger, up to 583.5 km^2 [33–36]. Downstream from the city of Buzet, Mirna forms a 5 km long canyon in carbonate rocks. After the canyon Mirna valley becomes a floodplain which is widest near the Sv. Stjepan thermal spa. Mirna enters the Adriatic Sea near Novigrad.

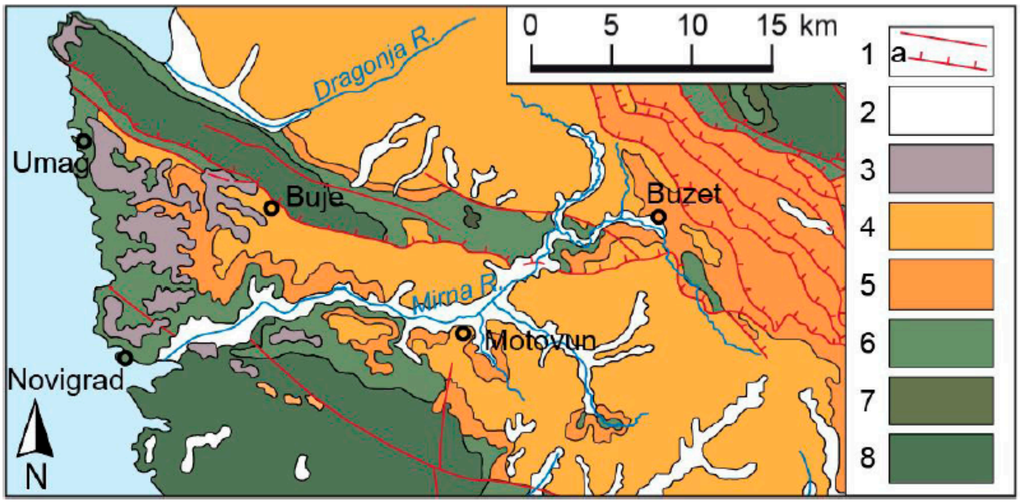

Figure 8. A geological map of Istria (1. Fault, 1a. Thrust, 2. Quaternary deposits (mainly Holocene), 3. Terra rossa deposits (Holocene), 4. Flysch deposits (Eocene), 5. Liburnia deposits, Foraminiferal limestone, and transitional deposits (Paleocene, Eocene), 6. Rudist limestone (Cretaceous), 7. Dolomite and breccia (Cretaceous), 8 Limestone and dolomite (Cretaceous), 9. Limestone and dolomite (Jurassic)) (taken from [31]).

7. Discussion

The general conclusion is that all three rivers have torrential characteristics, which could be seen from the hydrograms. Pronounced peaks are one of the indicators mentioned. Precipitation causes a very fast rising of the hydrograms after at least one day after the precipitation ends, and very short lag of the alighting. Additionally, during summer periods, i.e., the middle of each observed year, in most of the cases it could be concluded that flows are the smallest in comparison to the entire year. Additionally, the years with smallest flows, 2011 and 2012, are common for all analyzed rivers.

Analysis of the RAPS diagram for the Bednja River establishes four subperiods (Figure 3b). The first one is from the middle of 1999, the second from the middle of 1999 until the end of 2012, the third from the end of 2012 until the beginning of 2018, and the last one from the beginning of 2018 and extending further (fourth subseries). The second subperiod divides the period of the conditionally speaking "low flows", compared with the third subperiods' "high flow" years.

Analysis of the RAPS diagram for the Gornja Dobra River asserts four subperiods (Figure 4b). The first one is until the end of 1999, the second from the end of 1999 until the end of 2012, the third from the end of 2012 until the beginning of 2018, and the last one from the beginning of 2018 and extending further. RAPS diagrams for Gornja Dobra and Bednja also show four subseries, the same as Bednja, but there is no complete overlapping. The joint parts are the beginning of the subdivision during 1999 and 2018. This has implications within the regional climate change. Other subdivisions are not so easy to explain. Such could be a consequence of regulation work on the rivers, or maybe local climate changes, which are particular for the analyzed area(s).

For Mirna River, analysis of the RAPS also asserts four subperiods (Figure 5b). The first one is from the beginning of 1999, the second from the beginning of 1999 until the end of 2008, the third from the end of 2008 until the beginning of 2018, and the last one from the beginning of 2018 and extending further.

Table 1 shows that the Gornja Dobra River has the biggest deviation of the average daily flow, compared with the Bednja and Mirna Rivers. It can be explained by the characteristics of the riverbed. Gornja Dobra emerges near Skrad, in the area comprised of Paleozoic celestites. After that, the river flows over the Jurassic limestones and dolomites of the Ogulin-Oštarije karst platform. During its flow through the dolomites, flow losses are small due to the lack of caverns and sinkholes which are characteristic features of the limestones [28]. Dolomites are mostly impermeable, and, in the karst, they represent a barrier to the passage of water.

From the hydrotechnical aspect, it can be seen that, a bigger height of the bulkhead gives bigger power to the turbine. However, due to installation of a barrier, any increase in water level could cause a downstream slowdown. Such slowdowns can be negligible but can also cause overflow. A possible combination for increasing the power of turbines is the placement of turbines and bulkheads in a series, at a certain distance from each other.

From Tables 2, 4 and 6, it can be seen that the calculated power for the usage of potential hydro energy is relatively similar for all three observed locations. Such is explained by the fact that bulk provides accumulation of the water, where different geometrical properties do not come to the fore. Regarding the kinetic potential of the hydro energy, rivers which are in intergranular media (Bednja) have smaller average velocities, compared with the rivers in karst (Gornja Dobra) and flysch media (Mirna).

Globally, it can be concluded that in karst and flysch media number of the deposits in the rivers is smaller, compared to the deposits in the rivers in intergranular media. In other words, deposited particles in the Bednja River can have negative effects on river velocity.

8. Conclusions

The presented original methodology for the analysis of hydropower plant potential of torrential rivers was applied on a real case study of the three rivers in Croatia, each with different hydrological and hydrogeological properties. All analyzed rivers have potential for the building of small hydropower plants. Due to the low velocities, calculated powers are small compared to turbines which use the potential energy of the water. It must be emphasized that not all the cross-section areas of the river can be used for operational work of the kinetic turbines, but for this conceptual elaboration such insight is satisfactory.

In a similar way to turbines that use potential energy of the water, an increase of the power of turbines can be achieved by placing the turbines and bulkheads in a series and in parallel, at a certain distance from each other. Since there is no deceleration of water, the kinetic turbines have advantage over turbines that use the potential energy of water. Additionally, the environmental impact of the kinetic turbines is negligible, because there is no need for building the bulk construction, as well as for the large foundations, compared with the turbines which use potential energy. A demerit of the kinetic turbines is that the speed of the watercourse must be as high as possible.

Regarding hydro-energy potential, such analysis indicates that in case of occurrence of the subseries within original time series of the flow, attention should be focused on these parts of the analyzed time periods. Specifically, in analyzed cases, periods from 2018 are interesting because there are present irregularities, which affect average daily flow series. Calculation of the flow required for sizing of the hydropower plants should be focused on those values in such subseries. This surely depends on the duration of the available time series (10, 20, or longer), because RAPS calculation will not show the same division of the given time series. That is the object of a further analysis, which will not be presented in this paper due to the purpose and length of the paper.

Detailed analysis, i.e., an extension of the research in the first step will include analysis of the other measuring stations on the analyzed rivers and establishing of the functional connections between flows measured on several measuring stations. Next steps are field measurement and prospecting of potential locations where installation of the hydropower plants is possible, and where data does not exist, collecting data with regards to the hydrogeological properties.

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Appendix A

Figure A1. View at the location of the measuring station Ludbreg on the Bednja River.

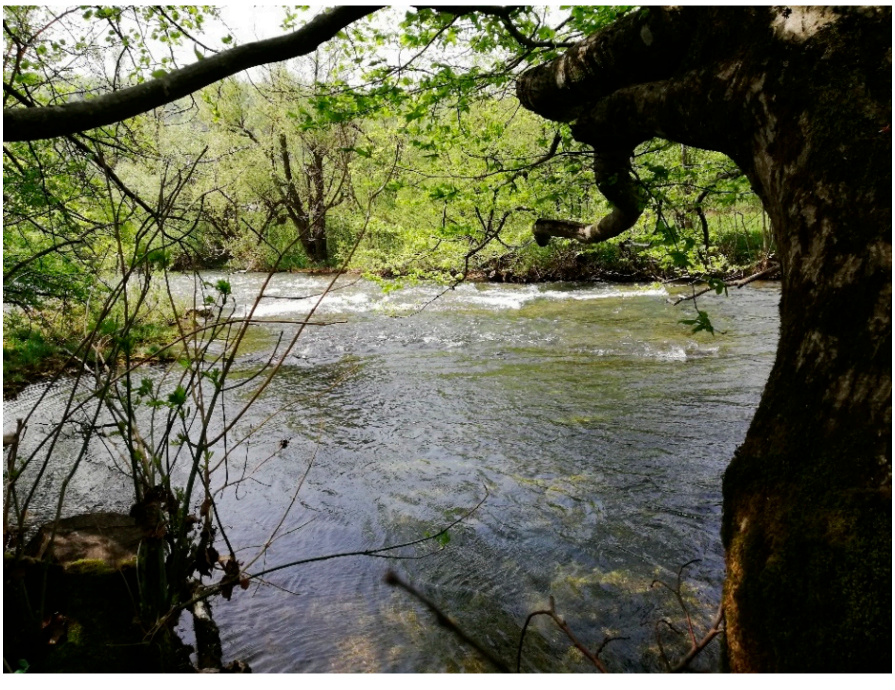

Figure A2. View of the location of the measuring station Turkovići on the Gornja Dobra River.

Figure A3. View at the location of the measuring station Motovun on the Mirna River.

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