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Determining the Hydrokinetic Potentials of the Transversal Section of the Watercourse Via the ADCP Method and Dimensioning of Hydrokinetic Power Plant

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Preliminary note

The kinetic energy of river current is weakly researched for the possibility of production of electrical energy. Thus presentation of a model of optimizing the results of measuring the partial speeds of the transversal section of the watercourse is made, based on which the hydrokinetic potential of the transversal section of the River Drava near Donji Miholjac is determined. This location is favorable because here the most modern method of measuring the partial speeds of the watercourse with the help of the ADCP (Acoustic Doppler Current Profiler) device is used. In this paper the data obtained are statistically processed and a graphical interpolation is done, with the help of the obtained data, by which the local maximum values of partial speeds of the transversal section of the watercourse are determined, which then represent the most favorable micro-locations for floating small hydro power plants, facilities which bear a resemblance to traditional water mills which use the hydrokinetic potential of river currents. Aside from the energy value, floating hydro power plants are suggested because of their historical and tourist significance whereby they add to the development of the economy in the area of appropriate micro-locations.

Određivanje hidrokinetičkog potencijala poprečnog presjeka vodotoka ADCP metodom i dimenzioniranje hidrokinetičke elektrane

Prethodno priopćenje

Kinetička energija riječnih struja je slabo istražena za mogućnost proizvodnje električne energije. Stoga se prikazuje model optimizacije rezultata mjerenja parcijalnih brzina poprečnog presjeka vodotoka na temelju čega se određuje hidrokinetički potencijal poprečnog presjeka rijeke Drave kod Donjeg Miholjca. Ova lokacija je pogodna zbog toga jer se tu vrše mjerenja parcijalnih brzina vodotoka najsuvremenijom metodom pomoću ADCP (Acoustic Doppler Current Profiler) uređaja. U ovom radu se dobiveni podaci statistički obrađuju te se vrši grafička interpolacija dobivenih podataka čime se određuju lokalni maksimumi parcijalnih brzina poprečnog presjeka vodotoka koji predstavljaju najpovoljnije mikrolokacije za ploveće hidroelektrane, objekte slične tradicionalnim riječnim mlinovima na vodi, koji koriste hidrokinetički potencijal riječnih struja. Osim energetske namjene, ploveće hidroelektrane se predlažu i zbog njihove povijesno-turističke važnosti što također doprinosi razvoju gospodarstva u području pogodnih mikrolokacija.

Keywords
ADCP method
Hydrokinetic energy
Partial speed
Floating hydro power plants
The river Drava

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1. Introduction

In modern literature concerning hydroenergetics, the term hydrokinetic energy and hydrokinetic potential is connected mostly to kinetic energy of the ocean currents [1]. According to that there are many ways of using this kind of energy [2]. On the other hand, the energy of river currents, or hydrokinetic energy of river watercourses is not mentioned in a non-conventional way. So the purpose of this paper is to draw attention of the expert and scientific community to the possibility of using the hydrokinetic energy of rivers for the production of electrical energy which, today, remains unused. All this may become increasingly significant in times when the future of energy becomes more and more uncertain, despite various energy strategies on a global and national level [3, 4]. The illustrated example [4], a document passed in the final trimester of the year 2008, in which the energy policy of the Republic of Croatia is given for the following 10 years, and after 3 months since the document has been brought into effect, the Republic of Croatia has already entered a serious energy crisis due to gas import problems.

This paper shows the process of determining the hydrokinetic potential of the transversal section of the river watercourse based on the knowledge of hydrological data. Knowing the hydrological data of the

Symbols/Oznake

f_D - Doppler frequency, s^{-1}
- Dopplerova frekvencija

f_S - sound frequency from a stable source (receiver), s^{-1}
- frekvencija zvuka iz stabilnog izvora (prijemnika)

v - relative speed of movement between the sound source and the receiver, m/s
- relativna brzina kretanja između čvrstog izvora i prijemnika

c - sound speed, ms^{-1}
- brzina zvuka

θ - angle between vectors of the relative speed of the boat and the direction of the wave trajectory, rad
- kut između relativne brzine broda i smjera trajektorije vala

A_{TS} - area of the transversal section of the watercourse, m^2
- površina popr. presjeka vodotoka

Q_i - measurements of the flow with the accompanying speeds v_i, $m^3 \cdot s^{-1}$
- mjerenja protoka s pripadajućim brzinama v_i

n - number of measurements
- broj mjerenja

P - power of the water wheel, W
- snaga vodenog kotača

A_P - area of the paddles of water wheel, m^2
- površina lopatica vodenog točka

attributes of some watercourse constitutes one of the key foundations of water-management and hydro-energetic basis and plans [5]. The amount of water and exploitative decline determine the potential for the use of energy of the water's position. Precipitation and soil (configuration and composition) determine both of these measurements. It is necessary to know the probable duration of a certain water flow, or the curve of the duration of the flow and the exploitative decline for a concrete location [6,7]. On the other hand, in order to plan the use of hydrokinetic energy of the current of river, the most important issue is in knowing the partial speeds of the transversal section of the watercourse, and the curve of the duration of the water flow. Using the energy current the of river or the hydrokinetic energy of rivers in the past has been quite intensive, mostly for powering the water mills, saw mills or other similar production plants. Such a form of energy is seldom used today.

Considering the increasing signs of the future energy crisis [3], it is necessary to consider all the possibilities which might contribute to an increase of the energy balance, which means we should not reject the possibility of using the hydrokinetic energy current the of river to gain electrical energy. Therefore, this paper explores the hydrological characteristics of the River Drava which determine its hydrokinetic potential for the production of electrical energy in a fashion similar to the water mills, meaning that the turbine uses a waterwheel with a downward flow.

The entire plant is placed on a pontoon in order to achieve the effect of a small scale floating hydro power plant. Figure 1 shows a copy of a part of the design for a floating hydro power plant from the year 1920, which has never been built due to more popular and simpler diesel aggregates.

Aside from the electro-energy purpose, the advantage of such a facility is also in its touristic value, because of its similarity to the traditional water mills. One should also not neglect the possibility of using these plants to water agricultural spaces adjacent to the river bed, but also for the prevention of erosion of river banks which poses a great problem in water management.

The measuring of the flow in Croatia is done by the State Weather Bureau [8] along with a company called *Hrvatske vode* [9]. The measuring of the water flow on watercourses in non-stationary flow conditions has always posed a great challenge for hydrologists. Today, such problems are best solved with the help of the ADCP device (Acoustic Doppler Current Profiler) which opens whole new possibilities in flow measuring on open watercourses [10]. ADCP is a device which, with the use of emitted acoustic signals, on the principle of the Doppler effect [11], determines the flow section (profile) of the observed watercourse as well as the speed profiles across that flow section, based on which the flow of the watercourse is determined [12]. This system is still under development, yet it is already far more efficient and precise than measuring the flow with the moving boat method, which is still in use.

2. The application of the ADCP method for calculating the hydrokinetic potential

With the standard method of statistical data gathering and processing the curve of the duration of the flow of the River Drava near Donji Miholjac is determined. This is done based on the results of the 18-year-long flow measuring obtained from the State Weather Bureau. Then we show the model of optimizing the most favorable micro-locations for the use of hydrokinetic energy via the ADCP method. We use the method of graphical interpolation of the obtained data, and the transformation of various types of graphical charts. This determines

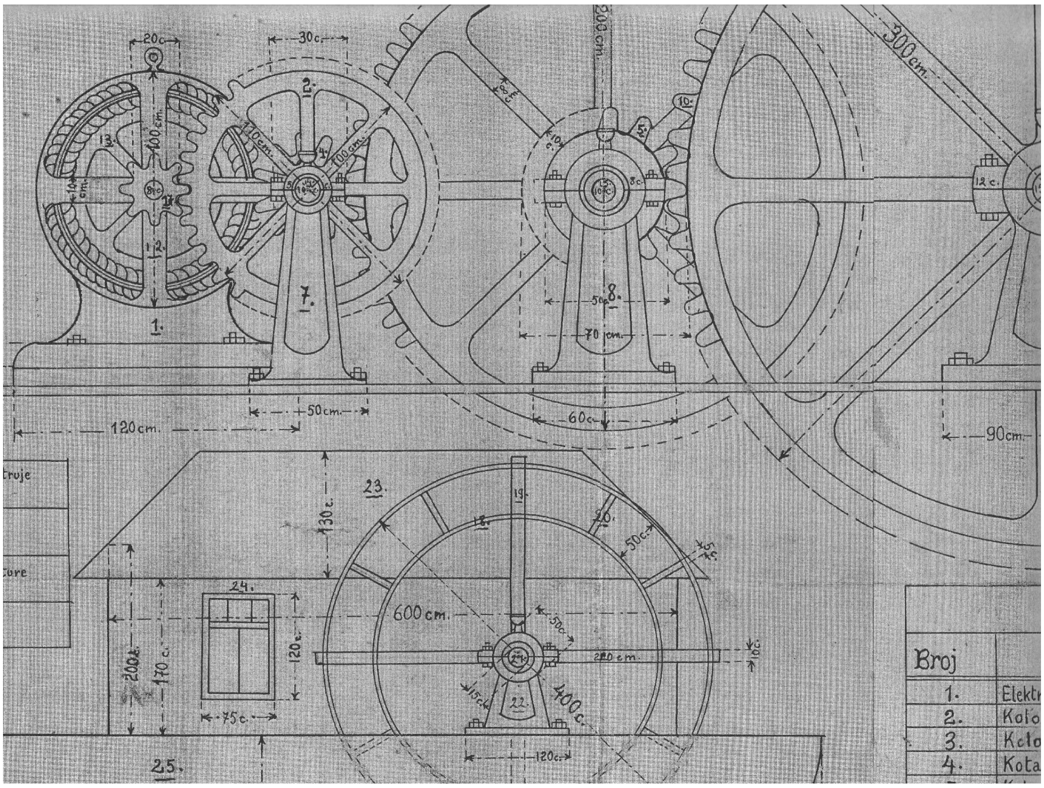

Figure 1. Part of the design for a floating hydro power plant from the year 1920, courtesy of Janči Đuro from Đurđevac

Slika 1. Dio nacrta ploveće hidroelektrane iz 1920. godine, ustupio Janči Đuro iz Đurđevca

the local maximums of partial speeds which represent the most suitable locations for using the hydrokinetic potential.

In order to determine the hydrokinetic potential we use the mean values of the speed and the flow, from which, by algebra methods the overall hydrokinetic potential of one transversal section is calculated.

While determining the speed of the water flow with the ADCP we use sound waves in the ultrasound area. The usual frequencies are larger than 30 kHz, and we mostly use devices based on the 300 kHz, 600 kHz or 1200 kHz frequencies. Measuring the flow speed with the help of the ADCP is based on the physical principle of the apparent frequency change, as explained by Christian Johann Doppler [10,11]. The apparent frequency change of the determined sound source appears when the source moves relatively according to some observer. When measuring the water flow speed, the ADCP emits an acoustic impulse into the water pillar, through its receiver. The receiver simultaneously records the returning echo of the signal which reflects off the particles suspended in water which are always present in a larger or smaller number. The reflected signal is first analyzed and compared with the emitted signal by applying the auto-correlation functions and algorithms. The reflected signal must have a form similar to the originally emitted one. After that, the Doppler shift is calculated, from which the speed of the watercourse current is determined, through the expression:

$$f_D = 2 f_S \frac{v}{c} \cos\theta. \qquad (1)$$

The ADCP is attached to the boat so that it is immersed in the water and pointed toward the bottom of the watercourse. In the device's case four acoustic receivers, angled approximately 25° in relation to the device's vertical axis, are most commonly placed. Each receiver generates its own independent ultrasonic beam and determines the speed of the watercourse independently. In this manner the device completely covers the space beneath it. In the illustrated example the ADCP device has been placed at a 50 cm depth, below the surface of the river current.

3. The hydrokinetic potential of the River Drava near Donji Miholjac

The State Weather Bureau, with its headquarters in Zagreb, has provided, as of September 2008, the data for average monthly and yearly minimums, means and maximums for the period between 1990 and 2007, from the measuring station Donji Miholjac. From these data we have extracted information about the average values of the minimums, means and maximums of each month from this period (Table 1).

We have also obtained the data regarding the measuring of profile or partial speeds of the transversal section of the watercourse via the ADCP method for the measuring station Donji Miholjac. The data have been obtained in a graphical and numerical form by being directly read from the computer of the State Weather Bureau. The example of the graphical chart for the middle water level is as shown in Figure 2, with the accompanying data shown in Table 2.

3.1. The curve of the duration of the flow

By transforming the tabulation of the average monthly flow values of the mean flow in a way that the data are aligned according to size from highest to lowest, we got a curve of the duration of the flow for the period between 1990 and 2007 (Figure 3).

From the flow duration curve for the eighteen-year period, we have observed that the flow is variable which is to be expected due to highly changeable climate. The most significant data for calculating the hydrokinetic potential is that the flow exists throughout the year, and that the smallest values of the middle flow are larger than 300 m^3/s.

3.2. The model of optimizing the locations of run of river hydro power plants by using the ADCP method

In order to determine the most suitable micro-locations for using the hydrokinetic energy it is necessary to determine the local maximums of partial speeds. So the data obtained by the ADCP method (Table 2) have been transformed into a graphical chart of the dependency of speed to the distance from the right riverbank (Figure 4).

Table 1. The mean monthly values of the flow for the period between 1990 and 2007

Tablica 1. Srednje mjesečne vrijednosti protoka za period 1990. – 2007.

Month / Mjesec	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.
Minimum / Minimum, m^3/s	274	249	276	342	430	431	393	316	309	307	330	296
Mean / Prosjek, m^3/s	378	327	393	502	613	612	590	479	470	530	549	469
Maksimum / Maksimum, m^3/s	557	462	631	742	805	865	898	728	764	885	939	767

Table 2. Partial speeds of the transversal section of the watercourse for three various water levels, measured at a 50 cm depth

Tablica 2. Parcijalne brzine poprečnog presjeka vodotoka za 3 različita vodostaja, mjereno na dubini 50 cm

Distance from the right bank / Udaljenost od desne obale, m	Speed / Brzina, m/s		
	Low flow / Mali protok (*LQ*)	Middle flow / Srednji protok (*MQ*)	High flow / Veliki protok (*HQ*)
5	0,438	0,726	0,898
15	0,727	0,834	1,092
25	0,630	0,829	1,148
35	0,687	0,920	0,976
45	0,787	0,858	1,115
55	0,763	0,891	0,888
65	0,691	0,914	1,066
75	0,759	0,965	0,789
85	0,642	0,868	1,083
95	0,617	0,952	0,954
115	0,687	0,486	1,164
125	0,726	1,029	1,199
135	0,752	0,866	1,131
145	0,659	1,041	1,073
155	0,726	0,840	1,085
165	0,644	0,656	0,873
Accompanying data / Popratni podaci			
Flow / Protok m^3/s	260	480	650
Water level / Vodostaj cm	-66	52	134
Date / Datum	2008-02-07	2007-10-11	2008-06-05

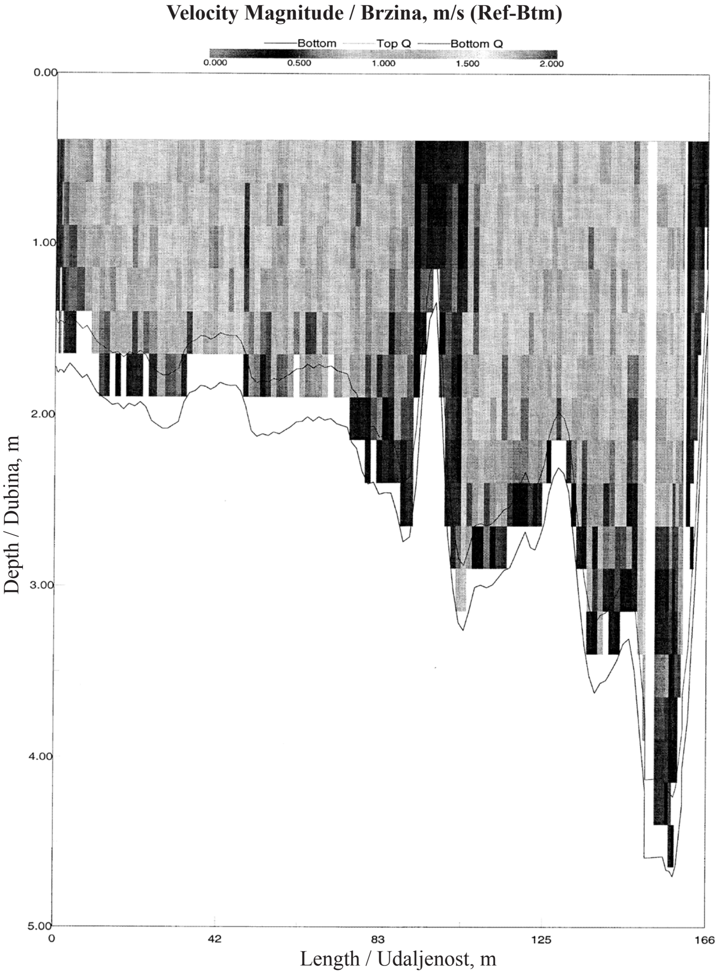

Figure 2. The dependency of the partial speeds of the transversal section of the watercourse to the depth and distance from the right riverbank for the middle water level

Slika 2. Ovisnost parcijalnih brzina poprečnog presjeka vodotoka o dubini i udaljenosti od desne obale za srednji vodostaj

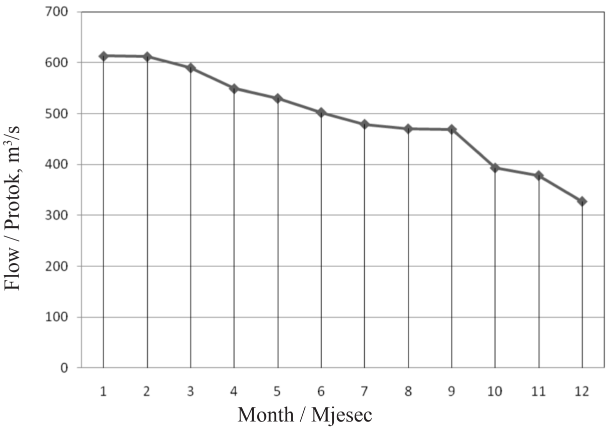

Figure 3. The curve of the flow duration of the River Drava for the period between 1990 and 2007, measuring station Donji Miholjac

Slika 3. Krivulja trajanja protoka Drave za razdoblje 1990. – 2007., mjerna stanica Donji Miholjac

Figure 4. The dependency of the partial speeds of the transversal section of the River Drava watercourse to the distance from the riverbank for three various water levels, measuring station Donji Miholjac

Slika 4. Ovisnost parcijalnih brzina poprečnog presjeka vodotoka Drave o udaljenosti od obale za tri različita vodostaja, mjerna stanica Donji Miholjac

In order to use the hydrokinetic energy in a traditional manner, as the old water mills did, or as floating hydro power plants, we require data about the locations with maximum speeds. Such places could be determined with the help of Figure 4 so that the local maximums are read off the middle flow chart (*MQ*). According to that, the most suitable locations for floating hydro power plants are located at 125 m and 145 m from the right river bank.

For each chosen location we can determine the average speed of the river current according to the following expression:

$$v = \frac{\sum_{i=1}^{n} v_i}{n}. \tag{2}$$

For example, for a location located at a distance of 145 m off the right bank, by using the formulae (2) and Table 2, we get the result $v = 0{,}88$ m/s.

The power of the water wheel which uses the hydrokinetic energy (Figure 1) is identical to the expression for the power of the wind-turbine in kW [13, 14]:

$$P = \eta \frac{1}{2} v^3 A. \tag{3}$$

According to (3) the theoretical power of the micro-location at 145 m from the right bank for the floating hydro power plants is determined. The area of the paddles A according to Figure 1 is 4 m x 0,5 m, or 2 m^2. By including the previously obtained speed $v = 0{,}88$ m/s we get the power of 0,68 kW. The technically usable power depends on the usefulness factor η. For the traditional type of the water wheel with vertical paddles, the usefulness is approximately 25 %, while for the tangentially placed paddles [15] it is approximately 60 %.

According to this, the technically useable power of the micro-location at 145 m from the right bank in Donji Miholjac is 0,17 kW for the traditional type of the water wheel, and 0,4 kW for the water wheel with tangentially placed paddles. These are very small power, so in order to have a more efficient work one must find locations with greater speeds which do exist upstream. Experience dictates that this could be found in places where water mills used to exist, especially in the vicinity of Đurđevac where a plan for the construction of a floating hydro power plant has been made, as is shown in Figure 1. That hydro power plant has been designed for a watercourse speed of 2 m/s. For such a micro-location the technically useable power would be 1,36 kW for a water wheel with vertical paddles, or 3,2 kW for a tangentially placed paddle type. The advantage of the ADCP method is that suitable micro-locations could be very easily and quickly determined. In a single crossing, or measuring we could have practically usable data.

While analyzing the graphical chart it is necessary to mention that the measuring done by the ADCP method, begins and ends at the 5-meter distance from the water bank, due to the water boat's length, although data obtained from the distance nearer the bank have no significant meaning because the water near the bank has very small speeds. It is also significant, for further investigation, that the measured speeds relate to 50 cm depth from the water surface.

3.3. The hydrokinetic potential of the transversal section of the watercourse

The overall hydrokinetic potential of the transversal section of the watercourse could be calculated based on the formulae for power (3), so that the usefulness η is omitted. Considering that the middle speed is obtained according to (2), and its value is 0,88 m/s, it is necessary to calculate the area of the transversal section of the watercourse, which we can get by inserting the flow and speed data into the expression:

$$A = \frac{\dfrac{\sum_{i=1}^{n} Q_i}{n}}{\dfrac{\sum_{i=1}^{n} v_i}{n}}. \tag{4}$$

By using the data from Table 1 and the expression (4) we get that A = 529 m2. By applying this information and the formulae (3) we have obtained the overall power of the water currents on the transversal section of the Drava watercourse near Donji Miholjac, which is 180 kW, or the overall energy on a yearly level, which is 1576 GWh. The technical potential is approximately 3 times smaller than the overall, which would mean that the technically exploitable strength is 60 kW and the yearly level of energy is 525 MWh. We must take into consideration that the area obtained is not the area of the overall transversal section of the Drava watercourse near Donji Miholjac, because the measuring with the ADCP method is not done on distances smaller than 5 m from the water bank. Thus, there are no data about the speeds for distances less than 5 m from the water bank. In spite of this fact, the obtained data for the area of the transversal section of the watercourse could be considered relevant for analysis, because the speeds near the bank are very small or equal to zero, thus making the flow rather small. According to these facts, the hydrokinetic energy on these sections of great watercourses is negligible. Discrepancies from the calculated area could occur due to the speed data measured at the depth of 50 cm below water surface.

3.4. The projection of the hydrokinetic potential of the transversal section of the watercourse for various water-current speeds

The partial speeds of the transversal sections of the Drava watercourse vary according to the water level or water flow. The research which has been previously described has indicated that there are significant differences in partial speeds on various distances from the water bank for the same transversal section of the watercourse. It is also known that middle flow speeds vary according to the measuring site (on an average, they are larger if measured closer to the water spring then those closer to the estuary). So it is necessary to make a projection of the hydrokinetic potential for locations with various speeds, particularly for locations with greater speeds which are more suitable for the use of hydrokinetic energy. The projection is made for speeds greater than the measured middle speeds for 30 %, 50 %, 80 % and 100 % (Table 3). The power is determined according to the formulae (3), with omitting the data for effect level.

According to the potential projections, it is visible that the hydrokinetic potential of the transversal section of the watercourse rises significantly for relatively small speed increases. For example, for 50 % greater speed, the power of the river courses is 3,38 times larger than the original value, and if the speed is doubled, the power is eight times bigger. So it is necessary to find locations with greater speeds for a more efficient use of the hydrokinetic potential, for which the ADCP method is highly suitable, as has been shown in this paper.

4. Conclusion

The technically usable strength of the water currents on the transversal section of the Drava watercourse in Donji Miholjac is approximately 60 kW. This is not a large strength when compared to the usual strength of smaller hydroelectric power plants, ranging from 500 kW – 5 MW in our country, or up to 10 MW in the European Union. Even so, these are not data which can be overlooked considering the predictions of an increasing energy crisis. Exploiting this energy could contribute to fulfillment of the obligations for increasing energy production from renewable sources. We must consider that this is the strength from only one transversal section, meaning that exploitation of the hydrokinetic energy could be done on a series of such sections. Aside from that, it is logical that there are transversal sections of smaller areas, which means that speeds would need to be greater in order for the flow to remain the same. The existence of such places has been confirmed in practicie, because water mills were built only on certain locations.

The ADCP method for measuring partial speeds of the watercourse is suitable for determining the micro-locations for floating hydroelectric power plants, because after statistical analysis of obtained data and their graphical display, the local maximums of partial speeds of the transversal section of the watercourse could be very precisely determined, and the most suitable micro-locations for floating hydroelectric power plants could be found. According to the projection of the hydrokinetic potential for locations with greater speeds it is visible that the power of the transversal section of the watercourse rises significantly for relatively small speed increases, because the power is proportional to the third speed exponent. This should be taken into consideration when determining potential micro-locations suitable for exploitation of the hydrokinetic potential.

The future investigations should focus on determination of the suitable technical solution which would take into consideration the actual efficiency when producing the electrical energy using optimal and adequate power generator.

Table 3. The projection of the hydrokinetic potential of the transversal section of the watercourse for areas with greater speeds than the speed measured in Donji Miholjac

Tablica 3. Projekcija hidrokinetičkog potencijala poprečnog presjeka vodotoka za područja s većim brzinama od brzine izmjerene u Donjem Miholjcu

	Measured speed and potential / Izmjerena brzina i pripadajući potencijal	Speeds increased by the specified percentages and the related potential / Uvećane brzine za navedene postotke i pripadajući potencijal			
		30 %	50 %	80 %	100 %
Speed / Brzina, m/s	0,88	1,14	1,32	1,58	1,76
Overall potential / Ukupni potencijal, kW	180	392	608	1043	1442
Technical potential / Tehnički iskoristiv potencijal, kW	60	131	203	348	481

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