ADCP DISCHARGE MEASUREMENTS ON THE RIVER DANUBE: POST-PROCESSING AND CORRECTION OF DATA

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Abstract

Accurate measurements and analyses of river discharges are one of the key tasks of hydrology. Nowadays, the traditional methods of discharge measurements are being supplemented or even replaced by novel approaches that utilize state-of-the-art technologies. One approach, which has recently become very popular in the hydrological practice both in Slovakia and abroad, is a method utilizing the Doppler effect of sound waves. In this study, a dataset of 185 discharge measurements on the River Danube was created using a RiverRay portable Acoustic Doppler Current Profiler (ADCP). All the measurements were taken on the River Danube at four different cross-sections in Slovakia. The measurements were processed using the manufacturer's WinRiver II software and further adjusted in Agila, which is a specialised third-party post-processing software aimed at correcting measurement errors from ADCP discharge measurements. Currently, some but not all countries lying in the Danube basin have included Agila post-processing in their methodologies. This causes problems and disputes between national water authorities when exchanging information about discharge measurements in the border regions. In order to respond to this problem, the main objective of this study was to compare the results of both original and corrected discharges, which were measured under a number of different circumstances, and to propose recommendations about the suitability of using Agila post-processing for discharge measurements of the River Danube.

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Key words

- Discharge measurements,
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- ADCP,
- Agila software,
- Data post-processing,
- Doppler effect.

1 INTRODUCTION

From the perspective of water managers and practitioners, measurements of river discharges have an irreplaceable role in solving a wide range of tasks in engineering hydrology and water management. Long-term monitoring of river discharges is important for evaluating its potential use in industry, agriculture, hydropower, water supply, and navigation. Moreover, this type of information is essential for civil en-

gineers who design various engineering structures (e.g., bridges, dams, flood protection), for ecologists who try to maintain rivers in a good ecological state, as well as for hydrologists who analyse the records to better understand runoff generation processes (Hlavčová et al., 2016; Jeneiová et al., 2016; Peksová Szolgayová et al., 2017). Nowadays, there is a wide range of tools and methods that can be used to measure river discharges. The right choice of methods and instruments used depends on a number of factors, such as the depth of the water, the flow

velocity, the geometry of the measurement profile, the presence of a bridge, the water quality, and the availability of human resources. As the dynamics of an open channel flow are a rather complex process, none of these methods is superior to the others. Each of them is associated with measurement errors, which result in measured discharges differing from the actual ones. The role of a hydrologist is to be aware of these errors and select the best method for the particular conditions.

Advancements in the field of information technologies and electronics have resulted in the development of new and sophisticated methods for river discharge measurements. Such methods are becoming more and more popular among hydrologists and water managers for their ease of use, quick and reliable measurements, and the visualisation and quality control tools available. Currently, the most common method for measuring discharges in larger rivers is a method utilizing the Doppler effect of sound waves. This method measures both the geometry and flow velocities within the measurement profile and uses them to calculate discharges from a continuity equation. The method uses an instrument called the Acoustic Doppler Current Profiler (ADCP); it contains piezoelectric transducers to transmit and receive sound signals scattered back from particles within a water column. As the velocity of sound waves in water is known, the ADCP measures the travelling time of sound waves to give an estimate of the distance they have travelled. The frequency shift of the echo is then proportional to the water velocity along the acoustic path. In order to measure water velocities in other directions, two or more transducers are used. The U.S. Geological Survey (USGS) has been using this type of instrument since 1985 (Simpson, 2001). In the 1990s, as new models of ADCPs were introduced, they became commonly used by other organisations throughout the world as well (Oberger et al., 2005). Apart from its use in measuring river discharges (Dinehart et al., 2005; Gordon, 1989; Guerrero et al., 2011; Jamieson et al., 2011; Muste et al., 2004; Nihei et al., 2008), the method has also been used for mapping flow velocity fields (Jacobson et al., 2004; Parsons et al., 2012; Polzin et al., 2002), geomorphic research (Dinehart et al., 2005; Kamnik et al., 2017; Kostaschuk et al., 2005; Woodward, 2007), measurement of bed-load discharges (Yorozuya et al., 2010), and bed-load velocities (Rennie et al., 2002).

This study deals with an analysis of a dataset of 185 discharge measurements that were recorded using an ADCP on the River

Danube in Slovakia. The original dataset that was processed with the manufacturer's WinRiver II software was also corrected for measurement errors using Agila software. As Agila is commonly used by several water authorities in the Danube basin, the main objective of this work was to assess the effect of Agila post-processing on the values of discharge measurements.

2 MATERIALS AND METHODS

The Danube River, which is the second longest European river after the Volga, plays an important role in its economy and biodiversity. Its 2,850 km-long channel passes through 10 countries and a large number of different geological and topographical areas that significantly influence its water regime. In general, the Danube's water regime is mainly characterised by the large variability of flows between February and June. During this period higher flows occur as a result of either the rapid melting of snow accumulated in the lowlands or as a combination of heavy rain and snow melting in the upper parts of the basin. As a result, the highest mean monthly discharges can be observed during this spring period. Nevertheless, most extreme floods occur during the summer as a result of intensive rainstorm activities over a larger area of the basin. The lowest mean monthly flows are observed in November and the first winter months as the precipitation which falls in the upper parts of the basin is accumulated in the form of snow.

Selecting an appropriate discharge measurement profile is one of the most important preconditions for accurate and unbiased measurements. In this study, a 172 km-long reach of the River Danube was selected for the analysis. Within this reach, the Slovak Hydrometeorological Institute (SHMI) operates 18 water stage gauging stations. Out of these, direct measurements of river discharges are regularly conducted in the following four stations: Bratislava-Devín (1-4-20-01-001-01), Medved'ov (1-4-20-01-011-02), Komárno (1-4-20-01-016-03), and Štúrovo (1-4-20-02-016-01). The values of the mean annual and 100-year discharges estimated for this river reach exceed 2,000 m³/s and 10,000 m³/s respectively. The river reach selected and the position of the four gauging stations are shown in Figure 1.

Fig. 1 The selected reach of the River Danube at the border between Slovakia and Hungary together with the position of the four discharge measurement profiles

Fig. 2 RiverRay ADCP from Teledyne RD Instruments was used to measure river discharges in the River Danube

2.1 Instruments and methods

The discharge measurements were carried out using Teledyne RD Instrument's RiverRay ADCP (Teledyne RD Instruments, 2015). The instrument enables measuring water velocities up to 5 m.s^{-1} with a measurement error of only $\pm 1\%$. It was particularly designed to measure discharges in rivers with high depths of water or velocities. The instrument is made of three floats arranged in a trimaran-like configuration ($120 \times 80 \times 18 \text{ cm}$) as seen in Figure 2. The middle float is the housing for the transducer assembly, batteries and other electronics. The transducer assembly comprises four 600 kHz transducers that are configured at a 30° beam angle. An additional fifth transducer enables the direct measurement of the water depth under the ADCP (0.4 to 60 m). The instrument is also equipped with a temperature sensor that enables measuring water temperatures in a range between 5 to 45°C . As the ADCP is not self-propelled, it has to be either towed from one bank of the river to another or mounted on a boat.

In this study, the measurements were carried out by pulling the ADCP from bridges from one bank of the river to another. Each time four independent measurements were taken to increase the reliability of the estimated discharges. The discharge observed was then calculated as the arithmetic mean of all four measurements. Apart from the discharge measurements, this type of instrument also enables the collection of additional information, such as the length of the profile,

its cross-sectional area, the instant velocity of the ADCP, its tilt in all three axes, and a detailed field of the flow velocities. As the ADCP permits wireless communication with end devices over a Bluetooth protocol, the measurements were displayed and inspected in real time on a tablet using the manufacturer's WinRiver II software.

The main sources of errors are associated with the measurements of flow velocities, which are influenced by water turbidity and the amount of sediments transported. Another source of measurement errors is linked with measurements in rivers with a large amount of bed load sediments, where the estimation of the current position of the ADCP is biased due to the so-called "moving bed". In such a case, it is often more convenient to use an ADCP equipped with a GPS localisation module (Mueller et al., 2009).

2.2 Data collection

The dataset of the 185 discharge measurements that are the subject of the analysis comes from four different river profiles. The measurements were conducted between 2010 and 2016 using an ADCP. The raw measurements of the flow velocities and the geometry of the river's cross-section were further processed with the WinRiver II software to produce a dataset of river discharges and other important characteristics. The basic information about the measurements conducted is listed in Table 1.

Tab. 1 Information about the discharge measurements conducted on a River Danube reach in Slovakia

Hydrological number	Station name	River km [rkm]	Profile width [m]	Period of measurements	Number of measurements
1-4-20-01-001-01	Bratislava-Devín	1871.4	300.5	18.06.2010 – 15.07.2016	48
1-4-20-01-011-02	Medveďov	1806.3	305.5	16.04.2010 – 15.07.2016	48
1-4-20-01-016-03	Komárno	1767.8	370.0	15.04.2010 – 09.11.2016	43
1-4-20-02-016-01	Štúrovo	1718.6	438.5	14.04.2010 – 10.11.2016	46

Based on the values of the M-day and N-year discharges estimated for the four river profiles selected from the long-term observations by SHMI, the measured discharges were categorized according to the following three distinctive classes: a) small, b) medium, and c) large. The first class of small discharges comprised observations, the value of which were smaller than or equal to the long-term value of the 355-day discharge Q_{355} ($Q \leq 1,050 \text{ m}^3/\text{s}$). Only 11 out of the 185 observations, most of which were observed during the first winter months, fell into this class. In the case of the large discharges, the threshold above which all the observations fell into this class was defined by the value of a 1-year discharge Q_1 ($Q \geq 4,300 \text{ m}^3/\text{s}$). This class consisted of 32 observations, most of which occurred in the summer as a response to intensive rainstorm events in the upper parts of the basin. As expected, most of the observations were assigned to the second class of medium discharges with as much as 142 observations. This class, the interval of which could be formally defined as $1,050 \text{ m}^3/\text{s} < Q < 4,300 \text{ m}^3/\text{s}$, comprised all the observations that did not fall into the first or third classes.

2.3 Post-processing the data and error correction

Discharge measurements using ADCP are very often influenced by different sources of errors, which aggravate their reliability and informative value. Measurement errors can be either random or systematic. The biggest uncertainties are associated with flow velocity measurements, the accuracy of which also depends on the volume of sediments suspended in the water. In case the amount of sediments in the water is very small, the acoustic waves of the ADCP's transducers cannot create a sufficient number of reflections to reliably estimate flow velocities along the whole depth of a water column. On the other hand, high concentrations of suspended sediments, e.g., during floods, can prevent the acoustic waves from reaching the river bed and thus even further aggravate the already problematic measurements during periods of high flows.

Fig. 3 An example of the measurement paths when measuring discharges from a boat (Adler et al., 2012)

In order to correct the above measurement errors, a number of methods have been developed worldwide. One of them is the Agila software solution, which was developed by the German Federal Institute of Hydrology (BfG) to correct the discharges measured by ADCP instruments. This method was developed in response to the German technical standard, which strictly requires all discharge measurements to be conducted on a river profile perpendicular to the direction of the flow (Adler et al., 2012). The methods used in Agila are based on van Rinsum's empirical method for estimating discharges. As the ADCP is always either pulled from a bridge or mounted on a boat, it is not possible to follow the exact same path that would be perpendicular to the direction of the flow. Because of this, the length

and cross-sectional area of the profile recorded are not constant among the individual measurements (see Figure 3). Agila tackles this problem by projecting arbitrary measurement paths into a reference profile that is perpendicular to the direction of the flow. This means that as long as the measurements are carried out around the reference profile and the depths and flow velocities within both river banks are not significantly different from each other, the discharges calculated are independent of the measurement path selected. In addition, Agila also accounts for slight changes in the river discharges during the time of the measurement.

Even though preliminary tests of applying Agila to the methods used by Europe's water authorities have already been undertaken (Adler et al., 2008), further analyses and comparisons with the national's reference methods should be conducted.

In hydrological practice in Slovakia, the maximum acceptable deviation between the discharges estimated by different methods is 5% (Danáčová, 2012). Measurements with larger deviations are considered to be inaccurate and erroneous. Danáčová (2012) has already shown that on the River Danube, the discharges estimated by the ADCP method (using the WinRiver II processing) comply with those estimated by a reference method that utilizes mechanical current meters. In order to properly analyse the difference between the measured (Q_{WinRiver}) and corrected (Q_{Agila}) discharges, their deviations were divided into a number of classes (see Table 2). In addition, these classes were further aggregated into three main acceptance groups according to the degree of the deviations between these two methods. The acceptance groups were the following: a) negligible (green colour), b) acceptable (orange), and c) unacceptable (red).

Tab. 2 Deviation classes between the measured (Q_{WinRiver}) and corrected (Q_{Agila}) discharges

Deviation class	Threshold [%]	Acceptance group
xxl	< - 5.5	Unacceptable - wrong ADCP settings or instrument error (red)
-5	- 5.5 to - 4.5	Acceptable - possible error in ADCP settings (orange)
-4	- 4.5 to - 3.5	
-3	- 3.5 to - 2.5	
-2	- 2.5 to - 1.5	Negligible - the measurements are reliable (green)
-1	- 1.5 to - 0.5	
0	- 0.5 to 0.5	
1	0.5 to 1.5	
2	1.5 to 2.5	
3	2.5 to 3.5	Acceptable - possible error in ADCP settings (orange)
4	3.5 to 4.5	
5	4.5 to 5.5	
xxl	> 5.5	Unacceptable - wrong ADCP settings or instrument error (red)

3 RESULTS AND DISCUSSION

In order to justify the use of Agila software to correct discharge measurements using ADCP, a dataset of 185 measurements from a River Danube reach in Slovakia was analysed. The dataset was used to create two distinctive discharge estimates. The first estimates were

calculated using the ADCP manufacturer's WinRiver II software and designated as $Q_{WinRiver}$. The second estimates were calculated using Agila software, which corrected the values and projected them into the reference profile. The discharges estimated by this method are designated as Q_{Agila} . In the first step, the discharge estimates were ordered chronologically by the date of the measurement and used to calculate the differences between $Q_{WinRiver}$ and Q_{Agila} (Figure 4). Figure 4 shows that most of these differences are negative, which means that in general, the corrected discharges are larger than the measured ones. This is also confirmed in Figure 5, which shows both the percentage of the measurements, the value of which was increased and decreased

by the Agila post-processing (when compared to $Q_{WinRiver}$), and the relationship between $Q_{WinRiver}$ and Q_{Agila} . Moreover, the highest differences between $Q_{WinRiver}$ and Q_{Agila} (Figure 4 left) corresponded to the high flow periods that had no effect on the $Q_{WinRiver} / Q_{Agila}$ ratio (Figure 4 right). The results clearly demonstrate that this relationship is linear and follows the $f(y) = y$ line (slope parameter of the linear trend $\theta_1 = 1.004$) with a coefficient of determination of $R^2 = 0.999$.

In the analysis, the differences between $Q_{WinRiver}$ and Q_{Agila} were divided into a number of classes according to Table 2. A histogram of these differences (see Figure 6) shows that most of them fell into class 0 ($\Delta = \pm 0.5\%$). Moreover, as much as 96% of the differ-

Fig. 4 Left: Differences between the uncorrected and corrected discharge measurements ($Q_{WinRiver} - Q_{Agila}$). Right: Ratio between the uncorrected and corrected discharges $Q_{WinRiver} / Q_{Agila}$. The x-axis represents an index of chronologically ordered measurements

Fig. 5 Left: Percentage of discharges that were either increased or decreased (when compared to $Q_{WinRiver}$) as a result of the Agila post-processing. Right: Relationship between $Q_{WinRiver}$ and Q_{Agila} with the coefficient of determination

Fig. 6 Left: Histogram of the deviation classes between $Q_{WinRiver}$ and Q_{Agila} . Right: Percentage of the measurements falling into one of the three acceptance groups

es were considered negligible, and none of them were unacceptable (see Figure 6). This is a very important finding as the hydrological practice in Slovakia requires that two distinct methodologies produce discharge estimates with a maximum deviation of $\pm 5\%$. This requirement was met in each of the 185 measurements.

The maximum deviation between $Q_{WinRiver}$ and Q_{Agila} observed in the dataset was 4.06%, which corresponded to an absolute difference of 169.6 m³/s. This situation occurred during a flood event, which is more prone to measurement errors. In addition, the mean deviation calculated from the whole dataset was only 0.95%, which corresponded to an absolute difference of 26.8 m³/s on average.

4 CONCLUSION

Nowadays, the traditional methods of river discharge measurements are slowly being replaced by more sophisticated methods that utilize state-of-the-art instruments. In particular, methods based on the Doppler effect of sound waves are coming to the forefront. This transition from the traditional methods to more sophisticated ones often results in a number of different methods and instruments being used by the individual water authorities of large river basins. This inconsistency in the methods used (especially in an international context) causes disputes between water authorities when comparing river discharge measurements in border regions.

This study has assessed the impact of a discharge measurement correction technique on the values of ADCP discharge measurements taken in Slovakia. This technique was implemented using Agila software and is employed in some but not all countries in the Danube basin. The dataset comprised 185 discharge measurements from four measurement profiles on the River Danube in Slovakia. The analysis

of the original and corrected discharges showed that none of the discharges corrected by Agila deviated from the corresponding original discharges by more than 5%. Moreover, as much as 96% of the deviations between the original and corrected discharges were negligible with a deviation threshold of $\pm 2.5\%$.

Adler et al. (2008) summarized results of 42 ADCP discharge measurements on the River Rhine that were carried out by the representatives of European countries. The measurements were also corrected by Agila and in half of the cases showed only negligible differences (up to $\pm 2\%$) between the corrected and uncorrected measurements.

The results of this study showed that even though Agila corrected the original measurements, they could be considered minor. Thereby, making them more or less equally reliable over a whole range of discharges. This implies that even though a unique methodology for discharge measurements and post-processing in the Danube basin would simplify sharing data between national water authorities, it is not a prerequisite.

In order to properly assess the benefits of Agila corrections on minimizing measurement errors, a similar analysis should be carried out on other watercourses in Slovakia and abroad. In addition, simultaneous discharge measurements using both ADCP with Agila corrections and a mechanical current meter should be conducted under different flow conditions.

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