ORIGINAL PAPER

EFFECT OF THE ACCURACY OF RIVERBED MEASUREMENTS USING ADCP ON THE WATER SURFACE LEVEL AT DISCHARGE $Q_{1\%}$

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ABSTRACT

In order to verify the impact of riverbed measurement using the Acoustic Doppler Current Profiler (ADCP) based on the Doppler effect on the accuracy of the structure of water surface level simulated in the numerical model, two series of field measurements were performed in the Skawa River, and another series in a hydraulic laboratory. The reference measurements of gravel riverbed were conducted using the classical method, by applying a measuring device. Precise measurement of riverbed elevations in the field was possible thanks to the use of a portable stable measuring station, which ensures stable probe movement during measuring. The obtained results were evaluated using the t-Student test, as well as the methods proposed by Ozga-Zielińska with Brzeziński, Moriasi, and Legates with McCabe. The analysis of the conformity between the results obtained using the ADCP methods and the reference measurements showed very good compatibility in the representation of riverbed elevations for the *RSR*, *NSE* and *PBIAS* evaluation statistics in the case of the laboratory series. The values obtained in both field series revealed an unsatisfactory representation of the riverbed elevations of the *RSR* and *NSE* evaluation statistics. Differences in the riverbed level have translated into differences in the water surface level. For the discharge of $Q_{1\%}$, the said differences do not exceed 0.066 m, which corresponds to the mean diameter d_m of bed material. Measurement of the riverbed configuration using the ADCP affects the water surface level and thus also the flood hazard zone. In mountainous areas, where the depth differences of the riverbeds and floodplains are significant, this impact is limited.

Keywords: ADCP current profiler, one-dimensional model, accuracy of riverbed configuration measurements, flood hazard areas

INTRODUCTION

As specified in the local spatial development plans, flood hazard areas constitute an important instrument in the decision-making by local authorities locate areas that are particularly threatened with flooding (Pijanowski, 2013). Numerical models allowing forecasting the water surface level during the passing of the flood wave are used in the determination of the flood hazard zone. In practice, the model is a compromise between the cost of obtain- ing a solution, and obtaining a sufficient number of parameters describing the object and the accuracy of the result (Szymkiewicz, 2000). The stages of developing a one-dimensional model include: implementation of river network, cross-sections and engineering structures; identification of land cover; setting of initial conditions; and finally, the calibration and verification of the model (Czajkowska and Osowska, 2014; Książek et al., 2010). In order to define the boundaries of flood zones, the water surface model, which is based on the water surface level in

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cross-sections, should be combined with the digital terrain model (DTM).

The accuracy of determining the water surface level consists of many factors, including: the quality of hydrological data, the type of numerical model, the accuracy of the DTM (Hejmanowska, 2005), the identification of land cover, or the accuracy of mapping the bottom of the water wetted channel (Sojka and Wróżyński, 2013). Measurements of the flow, of the distribution of water flow velocity, and of the bottom configuration with the use of hydro-acoustic devices employing the Doppler effect have been carried out for nearly 30 years (Wójcik and Wdowikowski, 2015). High-resolution bathymetric data of riverbed collected during measurements in combination with orthophotomaps constitute a powerful collection of data, offering the possibility of a detailed analysis of the riverbed. They are successfully used for spatial analysis of morphological changes to the riverbed forms occurring as a result of fluvial processes (Sziło and Bialik, 2016). The data obtained in this manner are also used in many other areas of research into riverbeds, such as: sediment transport, hydrodynamic modelling, fish habitat modelling, and morphology of riverbed forms (Muste et al., 2012).

The subject matter of the present work concerns the impact of the accuracy of measurements of the riverbed configuration on the structure of the water surface level in a one-dimensional numerical model, and it includes:

– the examination of the influence of the measurement of riverbed configuration using the Acoustic Doppler Current Profiler probe (ADCP) on the correctness of determining the elevations of the riverbed with a gravel composition,
– the analysis of the impact of the measurement of the riverbed configuration on the water surface level at $Q_{1\%}$ flow.

METHODOLOGY

Measurements of the riverbed topography were made using two methods: direct measurement by applying a measuring device to the riverbed surface (reference measurement), and indirect measurement with an ADCP probe, both on the real-life object in the field and in laboratory conditions, in the following order: field – laboratory – field. Laboratory measurements (in no flow conditions) were made in order to maintain the full traceability of the riverbed elevation measurement path in both methods.

FIELD MEASUREMENTS

Field measurements, which included the measurement of the riverbed configuration as well as grain size composition of sediments, were carried out on the Skawa River, a right-bank tributary of the Vistula River, 97.77 km long and the catchment area of 1177.70 km^2. During the two measurement series, fragments of the main channel of the Skawa River were subjected to testing: 1.36 m long, located at km 19 + 293, above the mouth of Choczenka River. The measurement series were performed on November 18, 2016 and December 14, 2017 with flows at the Wadowice gauging station of: $Q = 17.6$ m$^3 \cdot$ s^{-1} and $Q = 26.8$ m$^3 \cdot$ s^{-1}, respectively. Riverbed elevation values were determined using an AG-2 profilometer, and a profiling flow meter ADCP suitable for natural riverbeds. In addition, the granulometric composition of sediment was determined by taking a sample of the bedload.

DIRECT MEASUREMENT OF THE RIVERBED CONFIGURATION

The AG-2 device was constructed at the Department of Water Engineering and Geotechnics of the University of Agriculture in Krakow for the purpose of measuring the roughness of the riverbed. The said device consists of a steel tripod equipped with two supports, between which 30 evenly spaced adjustable rods are placed (Florek and Strużyński, 1998). After setting the device to the bottom, levelling it, and releasing the blockage, the rods fall freely, reflecting the configuration of the riverbed. AG-2 profilometer was moved along the designated line, thus executing a series of "impressions". In the next step, a scaled photograph was taken (see: Fig. 1) from which it was possible to determine the length of individual rods, and then the elevations of the riverbed.
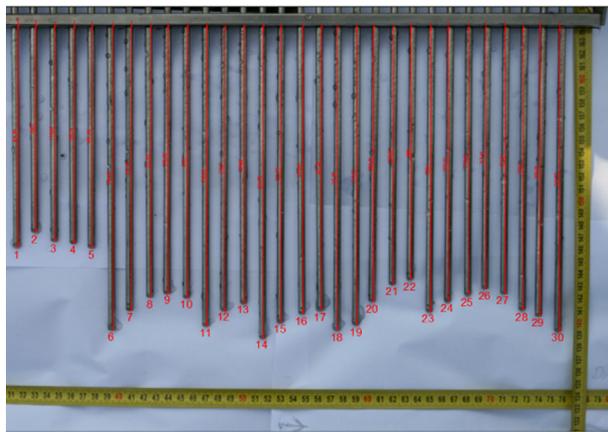
Fig. 1. Distribution of rods of the AG-2 profilometer, Skawa River at kilometre 19+293

INDIRECT MEASUREMENT OF THE RIVERBED CONFIGURATION

Subsequent measurements of the riverbed configuration were made by applying a profiling flow meter suitable for natural riverbeds, that is ADCP River-Surveyor M9. This hydro-acoustic device consists of a measuring head with transducers transmitting and receiving acoustic wave pulses (Laks et al., 2013). The velocity measurement is carried out using four beams with a frequency of 1 MHz, and it is based on the application of the Doppler effect, which consists in changing the frequency of the acoustic wave passing through the moving centre – in this case water – which is then sent and received by the source being in motion. The depth measurement is determined by a vertical beam with a frequency of 0.5 MHz. Bottom tracking function uses data from four angular beams in order to determine the depth of the water column, using the average depth from each beam. The measurement accuracy is 1%, while the depth measurement range is between 0.2 m and 80.0 m (Manual, 2014).
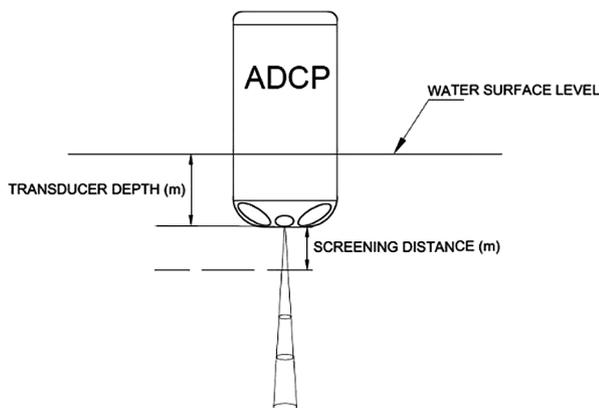
The measurements were carried out using a measuring trolley that was moving on a stable rail, set on two tripods (see: Fig. 2). Table 1 presents the parameters of the probe, and probe travel speeds for individual series: S1 field series, L2 laboratory measurements, and S3 field series. The transducer depth is the depth at which the transducer is immersed, measured from the water surface level to its head. The screening distance is the distance under the head, below which the reading of data begins (see: Fig. 3). This is used when it is necessary to avoid the influence of the turbulent zone on the measurement of the components of the flow velocity (Manual, 2014). The probe travel speed during the S1 series was $0.041 \div 0.082$ m · s^{-1} and $0.012 \div 0.080$ m · s^{-1} during the S3 series, the average water depth amounted to $H = 0.35$ m for S1 and $H = 0.54$ m for S3, whereas the water flow rate was 0.13–1.15 m · s^{-1} (average 0.52 m · s^{-1}) and $0.11-1.57$ m · s^{-1} (average 0.86 m · s^{-1}), respectively.

Fig. 2. Measuring station in the main channel, the Skawa River at kilometre 19 + 293, $Q = 17.6$ m^3 · s^{-1}, Series 1

Table 1. ADCP probe parameters during field measurements

Series	Number of the measurement	Probe speed [ms⁻¹]	Transducer depth [m]	Screening distance [m]
	S1-1	0.041	0.01	0.01
	S1-2	0.054	0.01	0.01
	S1-3	0.082	0.01	0.01
S1	S1-4	0.050	0.05	0.05
	S1-5	0.061	0.05	0.05
	S1-6	0.082	0.05	0.05
	S3-1	0.068	0.05	0.05
	S3-2	0.080	0.05	0.05
	S3-3	0.039	0.05	0.05
	S3-4	0.050	0.05	0.05
S3	S3-5	0.014	0.05	0.05
	S3-6	0.012	0.05	0.05
	S3-7	0.072	0.05	0.05
	S3-8	0.052	0.05	0.05
	S3-9	0.014	0.05	0.05

Fig. 3. Scheme of the parameters defining the operation of the ADCP probe

Source: Manual, 2014

ANALYSIS OF THE GRANULOMETRIC COMPOSITION OF THE SEDIMENT

The bottom sediment measurement was carried out using the traditional method, by mechanical sample sieving at the site where the riverbed configuration measurements were taken. The material sampled from the bottom of the watercourse, in the quantity of ca. 80 ± 0.1 kg, was sieved successively through sieves with diameters of 2, 4, 6 and 8 cm. The maximum grain diameter was measured at $d_{max} = 0.170$ m, and the mean diameter of $d_m = 0.066$ m was determined.

LABORATORY MEASUREMENTS

Laboratory tests were carried out in a hydraulic flume, containing within the section with a length of 2.16 m there were, in succession: a flat bottom and sediment with a diameter in the range of 0.06––0.001 m. As a reference method, constituting the reference level (baseline) for the measurements of the bottom of ADCP, a pin was chosen, placed on the measuring trolley. The measured using the pin was conducted along the axis of the hydraulic channel with a spacing of 0.015 m. The probing of the riverbed was carried out at the water depth of the channel amounting to $H = 0.41$ m and $H = 0.49$ m (see: Table 2).

Table 2. ADCP probe parameters during laboratory measurements

Series	Number of the measurement	Probe speed [m · s⁻¹]	Transducer depth [m]	Screening distance [m]	Water depth [m]
	L2-1	0.047	0.03	0.00	0.41
	L2-4	0.127	0.03	0.05	0.41
	L2-5	0.077	0.03	0.05	0.49
	L2-6	0.098	0.03	0.05	0.49
L2	L2-7	0.068	0.03	0.00	0.49
	L2-8	0.108	0.03	0.00	0.49
	L2-9	0.053	0.03	0.00	0.49
	L2-10	0.057	0.03	0.05	0.49

NUMERICAL MODELLING

Determination of the conditions of catastrophic water flow was made using the one-dimensional MIKE 11 model (2009), which is based on the system of conservation of mass and the conservation of momentum for-

mulas of de Saint-Venant, describing the slow-changing unsteady flow in the open channel (Szymkiewicz, 2003). The accuracy of the water surface level reproduced in the model is the result of the iterative calculation of 10^{-4} flow and the area of 10^{-3}, which are then converted to the water surface level (Książek et al., 2010).

EVALUATION OF THE MEASUREMENT OF BOTTOM ELEVATIONS

By applying Student's t-test for independent samples, the mean values of the bottom elevations for individual measurements with an ADCP probe were compared with the corresponding reference measurement. The value of Student's t-statistic calculated in the Statistica program (version 13) was compared with the corresponding critical value, in order to check whether it indicates a statistically significant correlation. At the assumed significance level of $\alpha = 0.05$, the H_0 hypothesis was verified, assuming that the mean values of the riverbed elevations are equal for both of the compared methods $\mu_w = \mu_m$, against the alternative hypothesis H_A stating that $\mu_w \neq \mu_m$. If $t < t_{kr}$ then null hypothesis has been assumed. Where $t > t_{kr}$ then the H_0 hypothesis was rejected in favour of the alternative hypothesis.

The assessment of the accuracy of the measurements made of the riverbed configuration was based on the calibration methods used to assess the quality of the models. The qualitative classification of the model according to Ozga-Zielińska and Brzeziński (1997) has been assumed, and the statistics for model assessment based on the recommendations of Legates and McCabe (1999) were applied.

The formula for the R correlation according to Ozga-Zielińska and Brzeziński assumes the following structure:

$$R = \frac{N \sum_{i=1}^{N} X_{o(1)} \cdot X_{c(1)} - \sum_{i=1}^{N} X_{o(1)} \cdot \sum_{i=1}^{N} X_{c(i)}}{\left\langle \left[N \sum_{i=1}^{N} X_{o(i)}^2 - \left(\sum_{i=1}^{N} X_{o(1)} \right)^2 \right] \left[N \sum_{i=1}^{N} X_{c(i)}^2 - \left(\sum_{i=1}^{N} X_{c(1)} \right)^2 \right] \right\rangle^{1/2}} \tag{1}$$

where:
$X = h$ in the case of the correlation between riverbed levels (h_o, h_c – baseline value and the riverbed level being compared),

with the formula for a special correlation coefficient:

$$R_s = \left[\frac{2 \sum_{i=1}^{N} X_{o(i)} \cdot X_{c(i)} - \sum_{i=1}^{N} X_{c(i)}^2}{\sum_{i=1}^{N} X_{o(i)}^2} \right]^{1/2} \tag{2}$$

whereas the total mean squared error is calculated from the following formula:

$$MSE = \frac{\left[\sum_{i=1}^{N} \left(X_{o(i)} - X_{c(i)} \right)^2 \right]^{1/2}}{\sum_{i=1}^{N} X_{o(i)}} \cdot 100\% \tag{3}$$

Moriasi et al. (2007) use the following statistics to assess the quality of models: *RSR*, *NSE* and percentage error (*PBIAS* – percent bias). The observations standard deviation ratio *RSR* is calculated as the ratio of *RMSE* to the standard deviation of the observed data. The *RSR* standardizes the *RMSE*, and it combines the error rate and additional information recommended by Legates and McCabe (1999). A lower *RSR* value indicates a lower *RMSE* level and a better model fit.

$$RSR = \frac{RMSE}{\left[\sqrt{\sum_{i=1}^{n} \left(Y_i^{obs} - Y^{mean} \right)^2} \right]} \tag{4}$$

$$RMSE = \sqrt{N^{-1} \sum_{i=1}^{N} \left(O_i - P_i \right)^2} \tag{5}$$

The Nash-Sutcliffe efficiency ratio is calculated from the following equation:

$$NSE = 1 - \frac{\sum_{i=1}^{N} \left(O_i - P_i \right)^2}{\sum_{i=1}^{N} \left(O_i - \bar{O} \right)^2} \tag{6}$$

Table 3. Evaluation of compatibility measures of the numerical model

Evaluation criterion	Compatibility measure. code				
	excellent	very good	good	fair	unsatisfactory
	1	2	3	4	5
Correlation coefficient R [–]	> 0.95	(0.95) ÷ 0.80	(0.80) ÷ 0.70	(0.70) ÷ 0.60	≤ 0.60
Special correlation coefficient Rs [–]	> 0.95	(0.95) ÷ 0.80	(0.80) ÷ 0.70	(0.70) ÷ 0.60	≤ 0.60
Mean square error MSE [%]	< 3	(3) ÷ 6	(6) ÷ 10	(10) ÷ 25	≥ 25
Observations standard deviation ratio RSR [–]	–	(0.00) ÷ (0.50)	0.50 ÷ (0.60)	0.60 ÷ (0.70)	> 0.70
Nash-Sutcliffe efficiency NSE (E) [–]	–	0.75 ÷ (1.00)	0.65 ÷ (0.75)	0.50 ÷ (0.65)	≤ 0.50
Percent bias $PBIAS$ [%]	–	< ±10	(±10) ÷ ±15	(±15) ÷ ±25	≥ ±25
Index of agreement d [–]	1.00				
Mean absolute error MAE [–]	0.00				

PBIAS is used to check whether the average trend of predicted data is greater or lower than the observed values. *PBIAS* is the deviation from the average of the data under evaluation, expressed as a percentage. The optimum percentage error is 0.0.

$$PBIAS = \frac{\left[\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right) \cdot (100)\right]}{\sum_{i=1}^{n}\left(Y_i^{obs}\right)} \quad (7)$$

The statistics for the model assessment, based on the recommendations by Legates and McCabe (1999), include commonly accepted absolute and total indices such as: coincident index of agreement d, Nash-Sutcliffe model efficiency coefficient, root mean square error *RMSE*, and total average mean absolute error *MAE*. The model is evaluated using the coincident index, where Oi is the baseline data, Pi is the compared data, whereas is the average from the measured data (Tena et al., 2013):

$$d = 1 - \frac{\sum_{i=1}^{N}(O_i - P_i)^2}{\sum_{i=1}^{N}\left(\left|P_i - \bar{O}\right| + \left|O_i - \bar{O}\right|\right)^2} \quad (8)$$

$$MAE = N^{-1}\sum_{i=1}^{N}\left|O_i - P_i\right| \quad (9)$$

Coefficients of d and NSE are widely used as dimensionless indicators of good fit of the model, as developed by Willmott (1981) and Nash and Sutcliffe (1970) respectively. In the first case, the parameter values are in the range from 0 to 1, while in the second case, the values oscillate from minus infinity to 1, and in both cases the forecasts improve and perfectly match up to 1. The next two statistics are absolute errors of good fit indicators, and they describe the absolute differences between the observed and the predicted values (Legates and McCabe, 1999). Forecasts are considered "excellent" when both the *RMSE* and the *MAE* equal 0. However, when the *RMSE* and the *MAE* are less than half of the standard deviation (*SD*) of the measured data, the forecasts can be considered poor (Tena et al., 2013).

RESEARCH RESULTS

The analysis using the statistics for the assessment of the measurement of the model's compliance has been applied to the elevations of the riverbed using the direct measurement as the reference, that is the AG-2 profilometer in the case of field measurements, and the pin in in the case of laboratory measurements. Table 4 presents the values of the Student's t-test with critical values t_{kr}, the indicators of the model fit according to Ozga-Zielińska and Brzeziński, classification according to Moriasi et al. (2007), and classification by Legates and McCabe. The best-fitting measurements were then used to determine height differences compared to the baseline reference.

Table 4. Assessment of the accuracy of the measurements of the riverbed elevations

Number of the measurement	t-Student test		According to Ozga – Zielińska and Brzeziński, (1997)			According to Moriasi et al., (2007)			According to Legates and McCabe, (1999)		
	t	t_{kr} ($\alpha = 0.05$)	R (h)	R_s (h)	CBK (h)	RSR	NSE	PBIAS	d	RMSE	MAE
S1-1	12.455	1.973	0.70	1.00	0.00	1.79	−2.20	−0.02	0.99	0.06	0.05
S1-2	13.197	1.973	0.77	1.00	0.00	1.81	−2.29	−0.02	0.99	0.06	0.06
S1-3	11.376	1.973	0.74	1.00	0.00	1.81	−2.29	−0.02	0.99	0.06	0.05
S1-4*	7.332	1.973	0.78	1.00	0.00	1.22	−0.49	−0.01	0.98	0.04	0.03
S1-5	8.462	1.973	0.80	1.00	0.00	1.34	−0.81	−0.02	0.99	0.04	0.04
S1-6	117.177	1.973	0.00	1.00	0.00	12.39	−152.56	−0.16	0.99	0.41	0.40
S3-1	12.848	1.978	0.25	1.00	0.00	2.18	−3.76	−0.01	0.98	0.04	0.04
S3-2	12.463	1.978	0.30	1.00	0.00	2.12	−3.48	−0.01	0.98	0.04	0.04
S3-3*	11.550	1.978	0.19	1.00	0.00	2.09	−3.39	−0.01	0.98	0.04	0.03
S3-4	13.247	1.978	0.01	1.00	0.00	2.80	−6.81	−0.02	0.98	0.05	0.05
S3-5	14.283	1.978	−0.07	1.00	0.00	2.79	−6.77	−0.02	0.98	0.05	0.05
S3-6	12.725	1.978	0.08	1.00	0.00	2.49	−5.19	−0.02	0.98	0.05	0.04
S3-7	13.739	1.978	0.06	1.00	0.00	2.21	−3.89	−0.01	0.98	0.04	0.04
S3-8	12.428	1.978	0.02	1.00	0.00	2.44	−4.96	−0.02	0.98	0.05	0.04
S3-9	13.920	1.978	0.09	1.00	0.00	2.76	−6.59	−0.02	0.98	0.05	0.05
L2-1	−1.565	1.968	0.94	0.99	0.01	0.40	0.84	7.65	0.97	1.42	−0.66
L2-4	−2.531	1.968	0.91	0.98	0.02	0.53	0.72	12.76	0.98	1.88	−1.09
L2-5	0.101	1.968	0.94	0.99	0.01	0.37	0.86	−0.51	−5.14	1.31	0.04
L2-6	−0.136	1.968	0.93	0.99	0.01	0.39	0.85	0.70	−2.76	1.39	−0.06
L2-7	−0.333	1.968	0.93	0.99	0.01	0.40	0.84	1.71	0.34	1.44	−0.15
L2-8	−0.299	1.968	0.94	0.99	0.01	0.37	0.86	1.50	0.27	1.32	−0.13
L2-9	0.280	1.968	0.95	0.99	0.01	0.33	0.89	−1.39	0.31	1.19	0.12
L2-10*	1.031	1.968	0.94	0.99	0.01	0.35	0.88	−4.95	0.94	1.25	0.42

* used for further analysis

On the basis of Student's t-test, it was found that the mean values of the compared elevations of the riverbed at the assumed significance level of α = 0.05 significantly differ from each other in all field measurements from the series S1 and S3 ($t > t_{kr}$) (see: Table 4.). In the case of the laboratory series, none of the obtained values of statistics t exceeded the critical values of the weights *tkr*. It was found that at the significance level of α = 0.05, mean values of the riverbed elevations in the laboratory conditions were equal for both compared methods.

The values obtained in both field measurement series revealed an unsatisfactory mapping of the riverbed elevations of the *RSR* and *NSE* indices, and a very good fir of the *PBIAS* index for all measurements carried out under field conditions. In the case of the S1 measurement series, the best fit was found for the S1-4 measurement, belonging to the group of measurements made

with the smallest probe travel speed. In the S3 series, which best reflects the elevations of the riverbed, the best-fit measurement is recorded for the average running speed of the trolley with the probe – measurement No. S3-3.

In the case of laboratory measurements, the analysis of ADCP measurement compliance with the baseline measurement indicates a very good representation of the riverbed elevations of the *RSR, NSE* and *PBIAS* indices for the all measurements in the laboratory series. All the measurements analysed therein also achieved a very good value of the correlation coefficient $R(h)$, and excellent values of the correlation coefficient Rs (h) and the total mean square error. The riverbed elevations were best fitted to the measurement of L2-10 belonging to the group of readings with the slowest passage of the trolley with the probe (see: Table 4).

RIVERBED ELEVATIONS

Figures 4–6 show longitudinal profiles of the riverbed, made with the ADCP probe, against the background of the results from the reference method for the best-fitting measurements from the series S1, S3 and L2. In the case of both field measurement series (see: Fig. 4 and 5), differences in the riverbed elevation values from ADCP measurements and from surveying measurements are similar to each other, and they amount to 0.04 m (0.06 m for all trials), whereas the minimum and maximum differences remain within the range between 0.01 m and 0.08 m.

Much better than the aforementioned fit is presented by the values of bottom elevations obtained during laboratory measurements (L2 series, see: Fig. 6), where the mean difference in height between the analysed methods is 0.009 m, with the minimum difference of 0.005 m, and the maximum difference of 0.046 m.
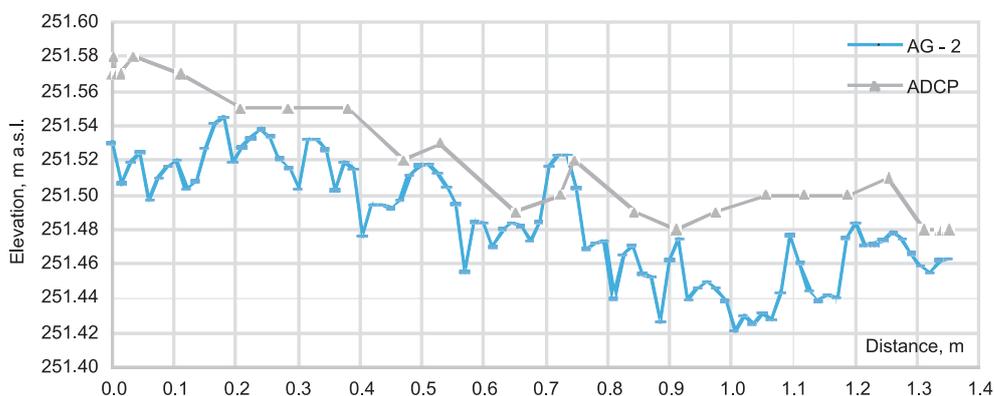

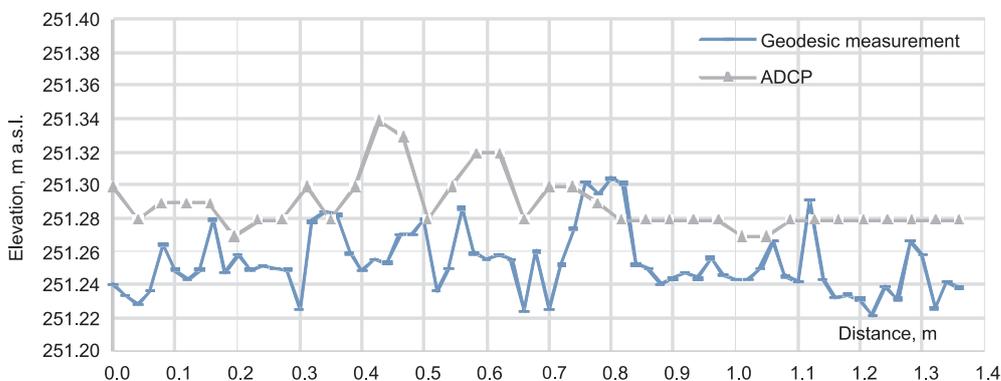**Fig. 4.** Longitudinal riverbed profile, section of the Skawa River, sample S1-4

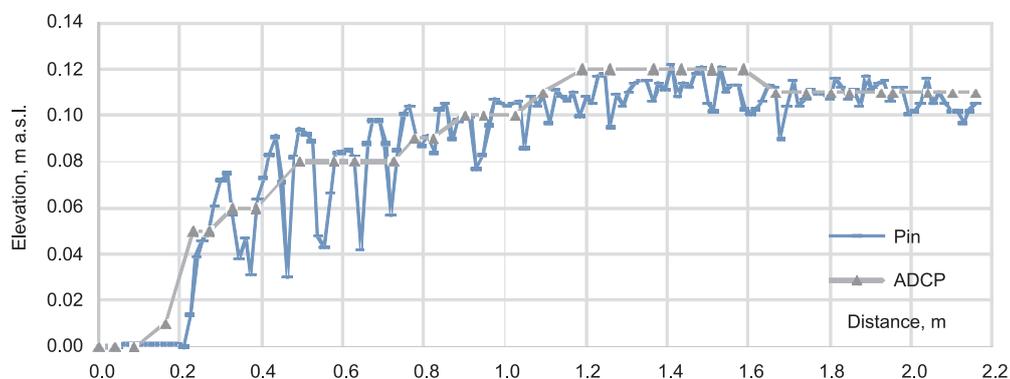**Fig. 5.** Longitudinal riverbed profile, section of the Skawa River, sample S3-3

Fig. 6. Longitudinal profile, section of the Skawa River, sample L2-10

WATER SURFACE LEVEL IN FLOOD CONDITIONS

On the section of the Skawa River at kilometre $18 + 620 \div 21+046$, calculations of the water surface level for the flow with the probability of $Q_{1\%}$ occurrence were performed. A 2426-metres long section was selected from the numerical model, made for the purpose of analysing the development of investment programme of flood protection in the Skawa River catchment. The average distance between the cross-sections was 485 m, and the maximum distance was 575 m. At the flow of $Q_{1\%} = 346.86$ m$^3 \cdot$ s^{-1}, the average value of the fill in the selected section is $hmean = 2.91$ m (with $h_{max} = 3.44$ m). In cross-sections, modifications to the W0 baseline Variant "0" were introduced, assuming the most unfavourable conditions of the riverbed configuration through raising their elevations by +0.06 m in the W_{up} variant, and lowering it by −0.06 m in the W_{down} variant. The value of 0.06 m corresponds to the average difference in height between the riverbed level determined by means of surveying measurements, and the level of the riverbed averaged from all *ADCP* measurements made during the field measurement series. Table 5 shows the results of modelling the water surface level in cross-sections, with respect to the W0 version.

The maximum difference in water surface level in the case of the W_{up} version was +0.066 m, the minimum difference was +0.055, and the average water surface level in cross sections varied by a height of +0.062 m. For the W_{down} variant, the maximum water level elevation difference was −0.062 m, and the minimum was −0.045 m (with the average of –0.555 m).

Table 5. Differences in water surface level at discharge of $Q_{1\%}$, Skawa River at kilometre $18 + 620 \div 21 + 046$

Chainage	$W0-W_{up}$ Δzww [m]	$W0-W_{down}$ Δzww [m]
18+620	+0.061	−0.045
19+136	+0.066	−0.054
19+711	+0.064	−0.058
20+191	+0.065	−0.058
20+737	+0.055	−0.054
21+046	+0.061	−0.062

DISCUSSION

Assessment of the accuracy of measuring flow rates, water velocity, and water depth in open channels with the use of ADCP was performed among others by Lee et al. (2005), Oberg et al. (2007), and Justin et al. (2015). These studies included, among others, various cases of probe settings, and methods of carrying out the measurement (Jongkook et al., 2016; Kim et al., 2015). In the present work, the results of the measurements of the riverbed configuration were analysed using the ADCP probe, and carried out in the main channel of the Skawa River. The elevations obtained with the ADCP probe show a similar way of mapping of the riverbed configuration in relation to the reference measurements. In both series of field measurements, overestimated values of the riverbed elevations were obtained. The average differences in riverbed levels are 0.04 m for the best-fitting measurements, and

0.06 m for all measurement series. Despite the methodology used in the laboratory measurements being analogous to that applied in the field measurements (only the AG-2 profilometer was replaced by a laboratory pin), much higher compliance of the riverbed elevations was found in the first case. In the case of riverbed profiles determined in the laboratory channel, the average difference in elevations of the bottom was 0.009 m. The difference in field and laboratory measurements is 0.031 meters, that is, it equals the value by which the riverbed elevations obtained from field measurements are overestimated in relation to laboratory measurement results.

The differences between the results of survey measurements and those obtained by means of acoustic techniques can reach up to 20%, but usually they do not exceed 10% of the depth (Wójcik and Wdowikowski, 2015). During field measurements on the Skawa River, the average water depth was 0.35 m (S1) and 0.54 m (S3), hence the depth underestimation for the series made using the ADCP probe could be between 0.035 and 0.070 m for S1, and between 0.054 and 0.108 m for S3. For laboratory measurements (L2) where the water depth was 0.41 m and 0.49 m, this underestimation could take the values from 0.041 to 0.082 m, and from 0.049 to 0.098 m, respectively.

Kim et al (2015) evaluated the accuracy of depth, velocity and water flow measurements using ADCP, by applying the "moving boat" method and a fixed measuring point. The authors recommend choosing the ADCP depth measurement function depending on the irregularity of the riverbed, the volume of vegetation, and bottom material. Based on depth measurements performed using the ADCP in a straight open channel, they found that bottom tracking (BT) based on four angle beams is more efficient than the vertical beam (VB) function, both for the moving boat method and a permanent measuring position. This method is particularly useful in the case of riverbeds with dense vegetation. In the case of water depth measurement (0.530–0.815 m) using the BT bottom tracking function, the average measurement error was 6.1%, and the maximum error was 12.4% at mobile measurement. At stationary measurement, the mean depth measurement error was 1.8% and the maximum error was 6.4%. Using the VB (vertical beam) function in order to measure the depth, the average measurement error

was 9.5% (maximum 16.0%) (Kim et al., 2015). For water depth during field and laboratory measurements in the range of 0.35 ÷ 0.54 m, underestimation of the water depth did not exceed 11.4% on average in the best-fit measuring series, and 15% in all measuring series (maximum 22.9% for water depth close to the minimum measuring range).

According to Wójcik and Wdowikowski (2015), the main factors that can disturb the bottom profiling by the ADCP probe include the type of bottom substrate, the nature of the flow, and the failure to observe the established measurement procedure. The influence of the turbulence zone below the probe in the case of laboratory measurements can be completely omitted due to the lack of flow in the laboratory flume. This discrepancy can be influenced by individual factors resulting from the specific conditions in which the measurements were carried out, as well as a whole group of factors that can include: incorrectly selected temperature and water salinity, probe travel speed, lateral displacement of measurement points relative to the designated measurement section, sinking of the measuring device in the bottom material. Temperature and salinity of water affect the measurement result due to the properties of sound waves moving in media of different density. As the water density increases, the speed of propagation of acoustic waves increases, thus the device overestimate the actual value of the water depth when exceeding the values of temperature or salinity in relation to the observed ones, and it undervalues those when when they are given as too low.

The accuracy of the mapping of the bottom elevations translates into the water surface level in numerical models. Based mainly on the $Q_{1\%}$ flow, analyses related to flood protection are carried out, that is, the determination of flood risk zones (Nachlik et al., 2000), analyses of investment programs (Grela et al., 2015), or flood risk management plans (Tiukało et al., 2015).

In the water flow calculations, resistance to motion is assumed, as expressed in the coefficient of roughness in the main channel and on flood terraces (Ballesteros et al. 2011, Mrokowska et al., 2015). Coefficient of roughness combines different types of friction and resistance to motion into one parameter, resulting from the roughness of the river channel material, the degree of irregularity of the cross-section, and its vari-

ability along the length, the obstacles occurring in the riverbed, vegetation, and channel layout within the plan (degree of meandering). The composition of the granulometric grain size composition along the length of the river changes in places where the slope changes, and where there are significant inflows coming in, which is reflected in the method of sampling of the sediment. Ratomski (2012) recommends taking samples at distances not exceeding 1 km, whereas Surian (quoted in Kondolf, Piégay, 2009) performed measurements approximately every 3–3.5 km. The coefficient of roughness therefore includes local changes in the granulometric composition of the grain size composition. In addition, numerical models of rivers undergo the calibration and verification procedure (Książek et al., 2010). Modifications to the model of the Skawa River section, whose length exceeded 2.4 km, concerned changes in the configuration of the riverbed in the main channel without modification of the coefficient of roughness. Implemented and included in the model of the river section was the value of the error in measuring the elevations of the bottom, averaged from all measuring series, that is 0.06 m as the most unfavourable one.

CONCLUSIONS

To summarize the results of the research, the following conclusions are drawn:

- The analysis of the degree of compliance between the ADCP measurements and the reference measurement showed very good mapping of the riverbed elevations for the laboratory series. The values obtained in both field series revealed an unsatisfactory mapping of the riverbed elevations. In both series of field measurements, overestimated riverbed elevations were obtained, and thus underestimated water depth values were shown;
- The differences in the level of the riverbed in the field measurements were on average 0.06 m (15 trials), the maximum ones were 0.08 m, and corresponded to the grain size expressed in effective diameter $d_m = 0.066$ m. At water depth up to 0.54 metres, underestimation of the water depth did not exceed 15%;
- The ADCP probe travel speed influences the shape of the riverbed profiled by the device, due to the number of the generated measuring points. The average fast or slow measurement reflects the actual level of the riverbed to a greater extent, which was demonstrated by assessing the consistency of the riverbed elevations, which in all measurement series showed much lower consistency of the riverbed elevations for fast probe travel. In the case of hydroacoustic devices operating on the basis of the Doppler effect, the velocity of approx. 4-6 cm · s^{-1} proved best;

- On the modelled section of the Skawa River, the differences in the water surface level in particular cross-sections for flow of $Q_{1\%}$ do not exceed +0.066 m, which corresponds to the effective diameter of the sediment d_m. It can therefore be concluded that the measurement of the main channel riverbed configuration via the ADCP method influences the extent of the flood hazard zone. However, in mountainous areas where the depths of the riverbed and floodplain terrace are significant, this impact is limited. One should beware of errors resulting from the use of inadequate equipment. For this purpose, the measurement methods should be appropriately selected for different research objects and one should strictly adhere to the assumed measurement procedure.

ACKNOWLEDGEMENTS

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WPŁYW DOKŁADNOŚCI POMIARU KONFIGURACJI DNA CIEKU SONDĄ ADCP NA UKŁAD ZWIERCIADŁA WODY PRZY PRZEPŁYWIE $Q_{1\%}$

ABSTRAKT

Aby sprawdzić wpływ pomiaru rzędnych dna na dokładność wyznaczanego w modelu numerycznym układu zwierciadła wody wykorzystano sondę Acoustic Doppler Current Profiler (ADCP), działającą na zasadzie efektu Dopplera i przeprowadzono dwie serie pomiarów terenowych w korycie rzeki Skawy oraz jedną w warunkach laboratoryjnych. Pomiar referencyjny dna o podłożu żwirowym wykonano metodą klasyczną poprzez przyłożenie urządzenia pomiarowego. Precyzyjny pomiar rzędnych dna w terenie był możliwy dzięki zastosowaniu przenośnego stanowiska pomiarowego, zapewniającego stabilny ruch sondy. Uzyskane wyniki poddano ocenie za pośrednictwem testu t – Studenta, metod zaproponowanych przez Ozgę-Zielińską i Brzezińskiego, Moriasi oraz Legates i McCabe. Analiza miar zgodności pomiarów ADCP z pomiarem referencyjnym wykazała bardzo dobre odwzorowanie rzędnych dna dla wskaźników RSR, NSE i PBIAS dla serii laboratoryjnej. Wartości uzyskane w obydwu seriach terenowych ujawniły niezadowalające odwzorowanie rzędnych dna wskaźników RSR i NSE. Różnice poziomu dna w korycie rzeki przełożyły się na różnice układu zwierciadła wody, które dla przepływu $Q_{1\%}$ nie przekraczają 0,066 m, co koresponduje ze średnicą miarodajną rumowiska d_m. Pomiar konfiguracji dna koryta głównego z wykorzystaniem sondy ADCP wpływa na układ zwierciadła wody, a tym samym strefę zagrożenia powodziowego. Na terenach górskich, gdzie deniwelacje koryt i taras zalewowych są znaczące, wpływ ten jest ograniczony.

Słowa kluczowe: sonda ADCP, model jednowymiarowy, dokładność pomiarów konfiguracji dna, strefy zagrożenia powodziowego