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Flood flows in the Odra River in 2010 – quantitative and qualitative assessment of ADCP data

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Abstract: During the 2010 flood in the Odra basin a measuring campaign was executed that produced a set of data on peak discharges. Flow measurements located near gauging stations were taken from a boat with an Acoustic Doppler Current Profiler (ADCP) equipped with a GPS. The paper presents a detailed analysis of the records, including referencing to ortophotomaps, to assess the quality of ADCP recording, local flow characteristics and finally to re-evaluate the total discharge values. Further, the flow is divided between the main channel and the floodplains, while the main channel in the case of the presence of groynes is additionally divided into a central zone between the groynes and zones of groynes. Partitioning of particular zones to the total discharge is calculated along with average and maximum local flow velocities. The study delivers data for the development of more reliable numerical modelling tools, which in turn may fulfil the measuring gaps in situ. It is shown that the modern field data acquisition GIS post processing, and numerical modelling support each other and improve the final overall result, bringing hydrologic products to a higher standard. The synergy of hydraulics and geoinformatics in hydrology is therefore highly recommendable.

Keywords: the Odra River, flood, hydrometric measurements, ADCP, discharge

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1. Introduction

Data on floods, in particular on extreme water levels and discharges, are the most relevant hydrologic river data. However, obtaining reliable data on extreme flows is a challenging business. Flow measurements under conditions of high waters are extremely difficult. In such situations hydrologists have to overcome high water velocities, highly turbulent flow fields, flowing debris, obstructive vegetation, trees and bushes, and restricted access to the river (over flooded areas), to eventually find a suitable cross-section for measurement. Time limits also play an important role. Performing successful and accurate measurements requires skill, experience, dedicated equipment, quick mobilisation and efficient organisation, as well as correct run-off and river flow monitoring. Therefore, comprehensively and reliably recorded flood events along extended river reaches are sparse and, therefore, of upmost value.

A recent remarkable event in the Odra river basin was the flood in May 2010 (IMGW-PIB 2011). During the flood the hydrometric service of the IMGW-PIB in Wrocław executed a campaign attempting to measure the peak discharges along the Odra River and its tributaries. The peak discharges for that event were around 2000 $m^3 \cdot s^{-1}$, which is close to the exceedance probability of 1% (IMGW-PIB 2013). New (in service) measuring devices exploiting the Acoustic Doppler effect were deployed. In fact, this technique was put to the test under extreme water flow conditions.

This paper has two major objectives: the first is to assess the quality of flow measurements realised with an ADCP, as it forms a new standard of measurement performance in hydrometric service. Hence, the raw data were analysed with the support of GIS to learn more about measuring with the ADCP. The second objective is the re-evaluation of discharge rates, along with a detailed analysis focussing on the local flow patterns and partitioning of the total flow over the cross-section parts of the channel, i.e. between the main channel and the floodplains. For this remarkable flooding event, knowledge of exact discharge values is important and helps to (re)assess the flood hazard and flood risk, and especially produces valuable data feeding the development and calibration of the numerical tools, i.e. 1D and 2D hydrodynamic models, as they are intensively exploited these days in the context of flood management policy. This is especially relevant, because the uncertainty of geometrical representation of a complex river channel, which applies to the Odra river with extended floodplains and regulation works, remains one of the major sources of error in such modelling (Verhoeven et al. 2004; Kuta et al. 2010). Further, out of all hydraulic parameters involved in the modelling process, roughness coefficients represent the key for a realistic numerical simulation of in-channel fluvial and floodplain flows, but remain especially difficult to be determined (DEFRA 2003; Wormleaton et al. 2005;

Yan, Tan 2008; Ballesteros et al. 2011; Banasiak 2012a). Uncertainty of a different nature may be reduced provided, as basic information, there is exact knowledge of flow rates.

2. Hydrometric data analysis

2.1. Measurement method

Discharge measurements were carried out with an ADCP Rio Grande 1200 instrument, a multi-beam type, operated from a boat (Fig. 1). The physics behind ADCP operation is the Doppler Effect: a sensor emits acoustic waves and receives their reflections from the bottom and from a in-water suspended particulate matter (Gordon 1996). The time lag and the intensity between the emitted and received pulses are translated into the distances and speed of suspended matter carried by water, hence, the speed of water itself. ADCP's offer remarkable advantages when compared to traditional measurement methods. They enable the recording of local and temporal flow velocity vectors with a high spatial resolution, up to several cm of the 'cell' size. The ADCP allows fast measurement of the flow over the whole channel cross-section within tens of seconds and the performing of more repetitions (runs) to increase measuring accuracy or to obtain a picture of the flow variation. Operation from a boat offers higher flexibility and more opportunity in the selection of measuring transects both in the main channel and over an extended floodplain. The ADCP may be further exploited to bottom echo sounding and tracking both the channel cross-sections, longitudinal profiles and even the bathymetry. The use of the ADCP is not free from drawbacks, as sensing near transducers is limited (due to immersion and ringing), measurements near boundaries are contaminated, and the measuring accuracy depends on the measuring speed (Muste 2014). The results in question will further show that the ADCP is sensitive to the presence of vegetation.

2.2. Assessment of data quality and discharge calculation

The analysed measurement data are for 15 gauging stations on the Odra River, from Koźle to Połęcko. The ADCP-produced data include the flow velocity, water depth and plan tracking (coordinates) as an output of a GPS. The coordinates were utilised to visualise the exact location of the flow measuring points with respect to the local topographical and bathymetric situation, in a computer ArcGIS environment with ortophotomaps as the background. This significantly enhances the quality analysis and improves understanding of the flow velocity patterns (Banasiak 2012b). An example of measured trajectories (cross-sections) for the Opole-Groszowice station (500 m upstream of the gauge) is shown in Fig. 2. This visualisation also enables a control of the length/development of the measuring transect and its orthogonality to the main channel. Notably, the ADCP data processing software, called WinRiver, enables this problem to be tackled with the 'Distance made good' option, i.e. a projection of the record points on a straight line between two limiting points – the first and the last (Teledyne 2007). However, this procedure may not be sufficient to account for the actual measurement, whether for the whole section or for part of it. If a transect is not orthogonal to the main river channel, the flow area and flow rates need to be corrected.

Next, the recorded flow velocity data were analysed for each run in terms of completeness, relative proportion of the measured and unmeasured zones of the flow, local and averaged velocities, and, ultimately, the total discharge values (Q). For the Opole-Groszowice flow data, which are presented in Fig. 3, on the left floodplain and in the main channel a zone with no velocity registration can be noted – this is indicated by a blue arrow. In such a case the processing software routinely interpolates the depth-averaged velocity values from the neighbouring meaning-

Fig. 1. ADCP on boat during flood in 2010

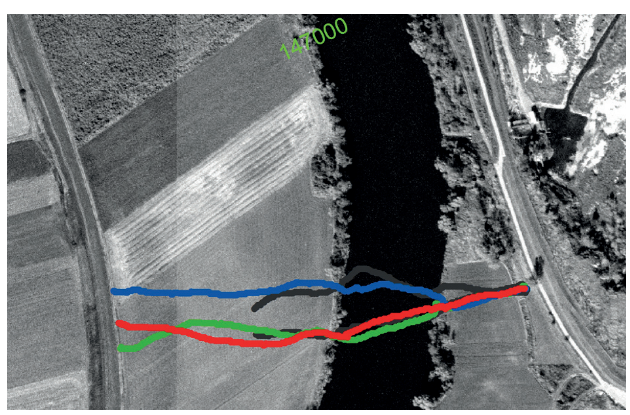

Fig. 2. Trajectories of the ADCP flow recording for the Opole Groszowice station, km 146,750; run Q_{000} – blue; run Q_{002} – red; run Q_{004} – green; grey – runs rejected)

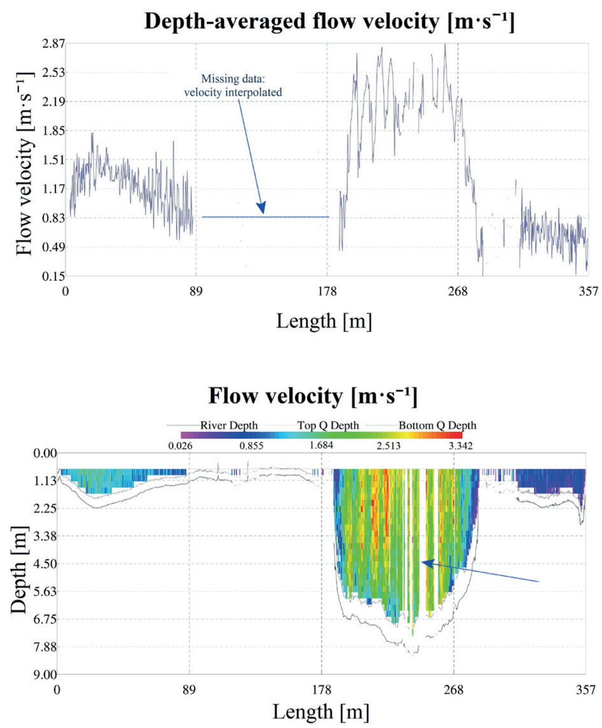

Fig. 3. Depth-averaged (top) and local flow velocities (down) in the cross-section Opole Groszowice (run Q_{004})

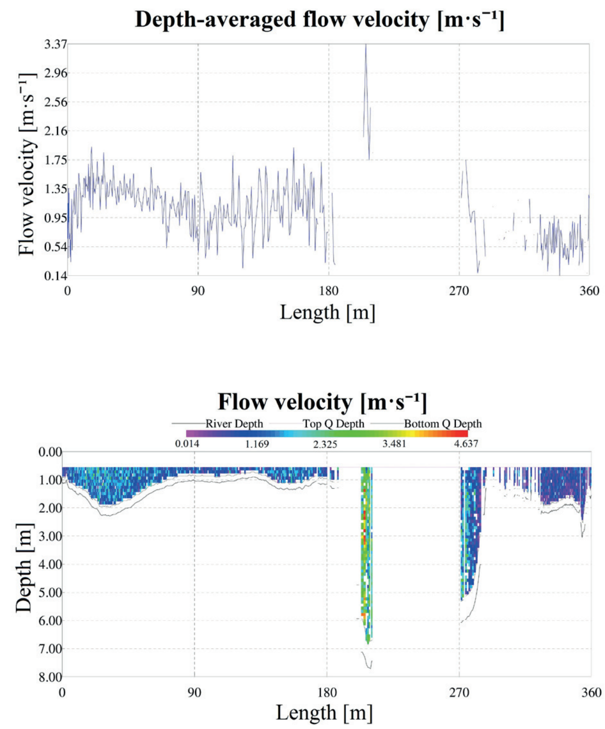

Fig. 4. Depth-averaged (top) and local flow velocities (down) in the cross-section Opole Groszowice (run Q_{000})

ful verticals. Obviously, this lack of data is detrimental to the measurement accuracy, especially when the unregistered zone is relatively significant. Therefore such data sets have been excluded from the analysis either completely, or in part, i.e. for a specific channel part. The reasons for such discontinuity of recording could be twofold: the massive transport of bed and suspended load inhibiting the detection of the channel bottom and/or the rough surface of the stream making the boat carrying the ADCP unstable. For the floodplain the presence of vegetation is believed to be responsible for the lack of records. The part of the flow unmeasured near the water surface and the channel bottom is also relatively large, so the velocities have been extrapolated toward the surface and the bottom from limited data, see Fig. 3. However, in the other run the flow record over the flood-plain was more successful, although it completely failed in the main channel, as shown in Fig. 4. Therefore, the discharge was calculated for each section, thus for the main channel and the floodplains separately for accepted runs as collated in Table 1. Further, the total discharge is a sum of the discharges in the subsections; not as an average of the discharges in each run as is standard procedure.

Table 2 contains a summary of the analysis for the all the hydrometric data available. The present results form an errata to the previously published values in the flood monograph (IMGW-PIB 2011). For example, for the described Opole Groszowice section the present discharge is 1520 $m^3 \cdot s^{-1}$, against the previous 1477 $m^3 \cdot s^{-1}$.

2.3. Peak discharges

The flow measurement in Opole-Groszowice was executed for the water stage at the gauge $H = 713$ cm, while the maximum stage observed during the flood was H_{max} = 799 cm (Table 2). The assessment of the corresponding peak discharge was made with use of a numerical 1D and 2D models. With the present measured data used as

Table 1. Discharge determination, Opole Groszowice

Run	Left floodplain (1)	Bank channel (2)	Right floodplain (3)	Total discharge (1+2+3)
	$[m^3 \cdot s^{-1}]$	$[m^3 \cdot s^{-1}]$	$[m^3 \cdot s^{-1}]$	$[m^3 \cdot s^{-1}]$
Q_{000}	445.4	x	80.3	x
Q_{002}	x	1036.6	96.70	x
Q_{004}	313.8	1062.0	97.8	1527.1
average for sections	379.6	1049.3	91.60	**1520**

Table 2. Discharge data on the July 2010 flood

			Hydrometric measurements				Gauges observation		
Gauge station	River kilometre	Gauge zero	Date of measurement	H	Q	Q (IMGW 2011)	Date of observation	H_{max}	$H_{max,abs.}$ (1997)
		[m Kr]		[cm]	[$m^3 \cdot s^{-1}$]	[$m^3 \cdot s^{-1}$]		[cm]	[cm]
Koźle	97.2	162.5	18.05, 10:40	658	1023	958	19.05	805	947
Krapkowice	124.7	155.51	19.05, 14:00	755	1723	1536	20.05, 08:00	826	1032
Opole-Groszowice	147.4	147.12	19.05, 17:00	713	1520	1477	20.05, 20:00	799	–
Ujście Nysy	180.6	135.54	20.05, 12:00	698	1869[1)]	1510	21.05, 02:00	724	768
Brzeg	199.1	129.2	20.05, 15:00	680	1530	1476	21.05, 14:00-16:00	728	730
Oława	216.5	121.98	20.05, 19:20	746	1080	1022	21.05	765	766
Czernica	230.7	114.52	22.05, 09:00	650[2)]	2174	2038	22.05, 14:20	658[2)]	724
Brzeg Dolny	284.7	97.73	23.05, 10:00	957	1960	1970	23.05, 10:30	959	1070
Malczyce	304.8	93.03	23.05, 12:00	796	2025	1959	23.05, 17:40, 20:30	805	892
Ścinawa	331.9	86.73	24.05, 13:00	664	2006	1987	224.05	664	732
Głogów	392.9	68.57	25.05, 15:30	682	1865	1871	25.05, 08:00-14:00	686	712
Nowa Sól	429.8	58.82	25.05, 17:20	646	1615[3)]	1683	26.05, 09:00	654	681
Cigacice	471.3	47.4	26.05, 14:30	645	1771	1670	26.05, 23:20	649	682
Nietków	491.5	42.11	27.05, 09:30	638	1785	1786	27.05	639	667
Połęcko	530.3	32.62	27.05, 12:30	549	1788	1771	27.05	557	595

[1)] measured 4 km upstream of the Nysa Kłodzka mouth
[2)] related to the gauge station in Trestno (km 242,1)
[3)] does not include an uncontrolled flow through the dam break upstream

a reference, the maximum discharge was estimated to a value of 2100 $m^3 \cdot s^{-1}$. This value is significantly larger than the previously released value of 1850 $m^3 \cdot s^{-1}$ (IMGW-PIB 2011), which was derived from the rating curve for the gauge (this was vague, or even speculative, for high levels because of the lack of measuring data). This is not the only case of amendment: especially for the locations of Koźle and Krapkowice, the peak discharges are significantly higher. For the Krapkowice station the specific topographical configuration is important, along with earlier poor hydrometric/hydraulic documentation of extreme flows. The gauging cross-section is influenced by the elevation of a street (crossing the right floodplain) being flooded above a certain water level, and thus yielding additional significant flow. The reevaluation of the measured data from 1536 $m^3 \cdot s^{-1}$ to 1723 $m^3 \cdot s^{-1}$ and the extrapolation of the discharge against the maximum water level lead to the conclusion that for this section the maximum discharge reached a value of ca. 2150 $m^3 \cdot s^{-1}$.

Another location upstream, the Koźle station, also requires comment. This station is located in the city of Koźle and the historically collected hydrometric data refer to the gauging cross-section between levees. However, during the floods the city on the left side of the river was flooded and an uncontrolled flow bypassed the gauge section. A 2D hydrodynamic model, as shown in Fig. 5, was employed to reproduce the flooding and water levels in 2010. The result was that some 350-400 $m^3 \cdot s^{-1}$ were, at maximum, conveyed through the city's left bank. Therefore, the total peak discharge for this location is estimated in the range of 2000-2200 $m^3 \cdot s^{-1}$. More calibration effort is needed to determine more exact values.

The next comment relates to the station located in the city of Oława. The city is protected against extreme floods by means of the Lipki-Oława polder, with inflow structures of the polder located upstream of the city, so only a part of the total discharge is directed to the city. The discharge of 1780 $m^3 \cdot s^{-1}$ (IMGW-PIB 2011) previously envisaged for the city, is incorrect – both the measurement data analysis and numerical modelling indicates that the maximum discharge for the gauge station in the city of Oława could reach 1150 $m^3 \cdot s^{-1}$; with the rest of the total 2100 $m^3 \cdot s^{-1}$ taken by the polder that freely releases waters downstream of the city, near the Czernica cross-section. Additionally, the analysis of assisting numerical modelling proved that the Oława gauge station remains under the backwater effect during high flows.

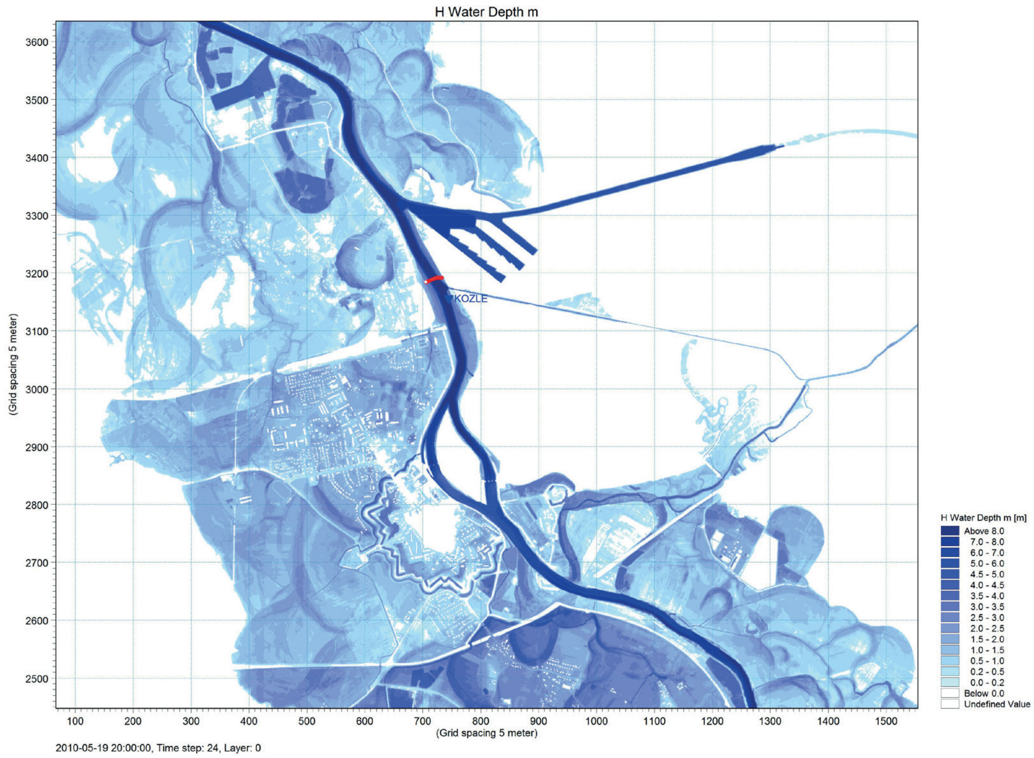

Fig. 5. A 2D simulation of the 2010 flood near the Koźle gauging station (ADCP record marked in red 200 m downstream of the gauge)

During the May 2010 flood of the Upper and Middle Odra river, from the station Koźle to Brzeg Dolny, and also further downstream through Wrocław, Brzeg Dolny, Ścinawa to Głogów station, the peak discharges generally varied in the range between 2000 and 2200 $m^3 \cdot s^{-1}$, with local variations caused by inputs from tributaries and by the retention of the river valley.

For comperison Table 2 also includes absolute maximums ($H_{max,abs.}$) observed at the gauges during the catastrophic of 1997 flood. Notably, for some cross-sections the water levels in 2010 were close to that of 1997.

2.4. Flow partitioning in river cross-section

The partitioning of the total discharge over the cross--section zones is relevant information, for instance in the course of calibration of hydraulic models, as it helps in improved estimates of the roughness in the main channel and the floodplains separately, and ultimately gives better predictions of the conveyance and water surface elevations. In our example, for Opole-Groszowice, 1049 $m^3 \cdot s^{-1}$ was conveyed in the main channel, and the remaining 471 $m^3 \cdot s^{-1}$ on the floodplains (69% and 31% of the total discharge respectively). The partitioning of flow changes with discharge is site specific. Another example, and valuable information, has been obtained for the Brzeg station, which is hydraulically complex but strategic in terms of decision-making during the floods for Wrocław city. The measurement transects for the flood in 2010 are located upstream of the gauge in the main channel and the right floodplain as illustrated in Fig. 6. The measuring of flow over the intensively grown vegetation in an extended floodplain is typically highly problematic, however in this case a route along a road crossing the valley was found and successfully used for measurement (although not 100% of the flow was captured). Here the main channel and extended floodplain conveyed, as recorded, 878 $m^3 \cdot s^{-1}$ and 603 $m^3 \cdot s^{-1}$ respectively. It is reasonable to expect the floodplain contribution to be higher at peak discharge.

The Odra River is regulated by groynes through hundreds of kilometres of its course. These structures, perpendicular to the main flow direction, narrow the channel width to some 50-60 m at the bottom to ensure the chan-

Fig. 6. Main channel and floodplain measurement transects (red) in Brzeg

nel's morphologic stability and favourable conditions for navigation. These structures, however, have an impact on flood flow conditions. Although the influence of groynes on flow patterns have been the subject of many studies, this was mostly in terms of the morphological stability of channels, and there has been relatively little research in terms of flood conveyance (DEFRA 2003). Valuable information in this respect may also be derived from the analysed measurements.

Fig. 7 presents a location near the Połęcko station, indicating the measuring transect in respect of the regulation works. Next, Fig. 8 presents the corresponding flow velocities. One may clearly note reduced flow velocities in the zones of the groyne field.

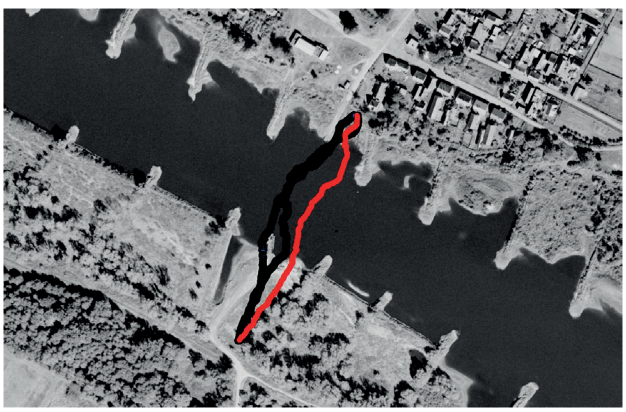

Fig. 7. Measurement transect near Połęcko gauge, km 530+550

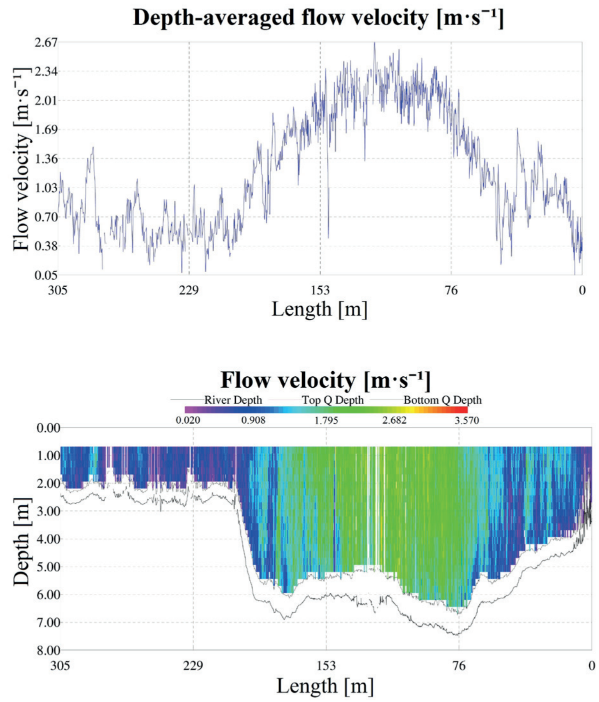

Fig. 8. Flow velocity distributions for the Połęcko cross-section ($Q = 1788\ m^3 \cdot s^{-1}$)

When analysing such flow data, the river cross-section was divided into the channel zone between the groynes, the zone of groynes (left and right), and floodplains, as depicted in Fig. 9. The flow parameters (flow velocity, flow area, discharge, water surface width) are determined for all zones separately and the bank channel discharge (Q_B) is the sum of discharge in the central zone (Q_C), left groyne zone (Q_L) and right groyne zone (Q_R).

As a result, first, the discharge in the bank channel with respect to the total discharge (including floodplain flow) is obtained as presented in Fig. 10. The main channel contribution is cross-section specific, however it clearly diminishes with the discharge, so that out of 2000 $m^3 \cdot s^{-1}$ and 603 $m^3 \cdot s^{-1}$ respectively. It is reasonable to expect for the total discharge, ca. 50-80% takes place in the main channel.

Further, for the river with groynes, the discharge by percentage conveyed in the main channel between the groynes is even smaller, which is shown in Fig. 11. Its contribution drops to only 35% of the total discharge at a rate of 2000 $m^3 \cdot s^{-1}$. The knowledge of this contribution is important for better understanding and estimating the main channel roughness with sediment motion and its potential influence on the water level predictions. It also delivers a clue on the discharge part affected by the groynes, as has been studied in more detail elsewhere (Banasiak et. al. 2014).

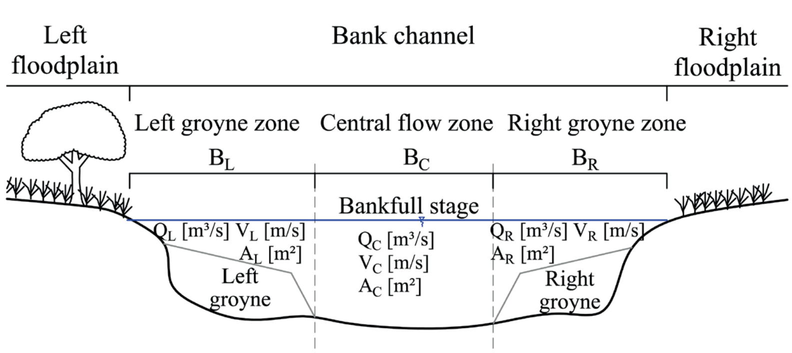

Fig. 9. Scheme for flow analysis in groyne regulated river

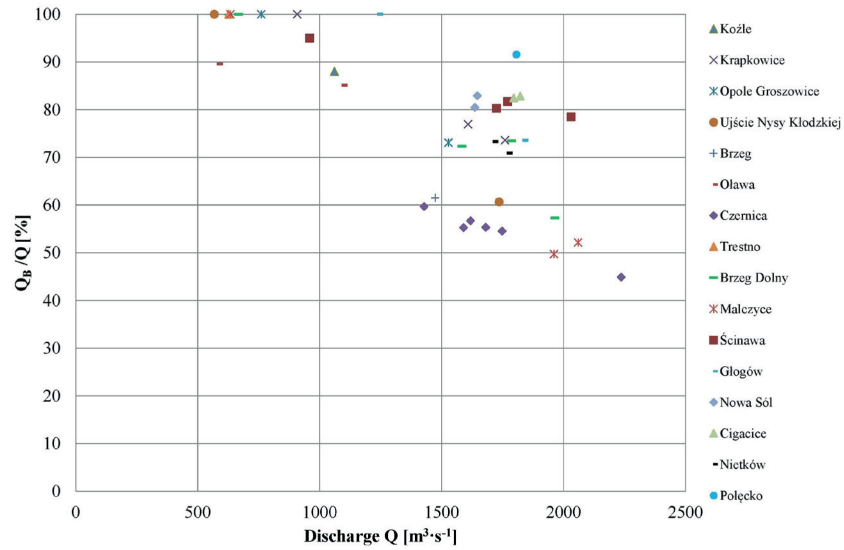

Fig. 10. Main channel flow contribution in a function of the total flow

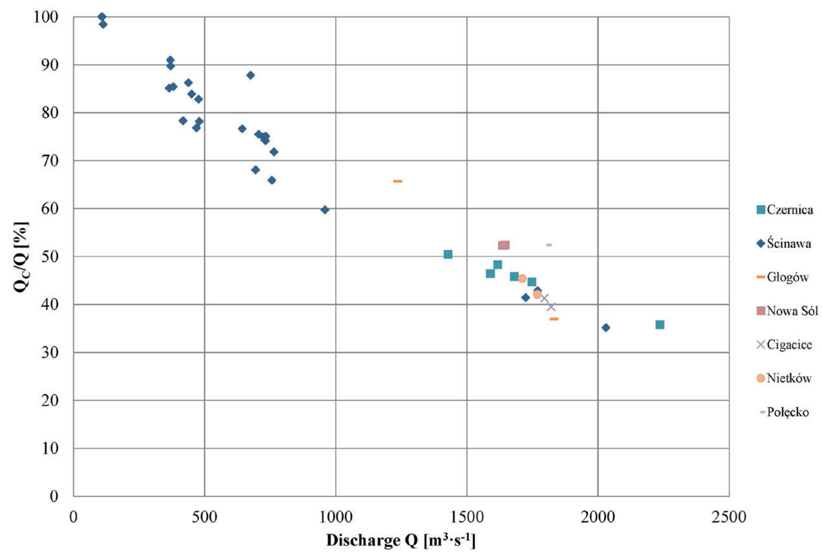

Fig. 11. Flow in the channel zone between groynes as a function of the total flow

2.5. Flow velocity

Obviously, the flow velocity is a basic hydraulic parameter for open channel flows. It is indicative regarding the effect of the stream on the boundaries and sediment transport, and also as a design parameter for engineering works. Typically, the mean flow velocity (over the cross-section) is calculated, e.g. with the Manning formula, and then used. However, this parameter can poorly reflect the actual flow conditions in a river, as it can be strongly affected, next to the energy slope variation, by the cross-section shape and flow separation, if not by hydraulic structures.

First, in Fig. 12 the average flow velocity against average flow depth (calculated as h = A/B, where A – cross section area, B – water surface width width) for the main channel part (possibly for the part between the groynes) is presented. Fig. 13 presents the flow velocity averaged over the bank channel and the section between the groynes (where applicable), then maximum depth-averaged velocity over a 5 m wide section, and finally the maximum flow velocity recorded in a section. The figure reflects the magnitude and variability of the flow velocity depending on the spatial scale. A local depth averaged velocity is often twice as large as the cross-section average. Local maximums reached about 4 $m \cdot s^{-1}$. Notably, Fig. 13 is made for discharges, which are different from section to section, so a comparison of vector values between the sections is therefore not straightforward.

2.6. Estimates on the influence of vegetation

The effect of vegetation on the flow and conveyance of river channels is a vital issue and has long been studied both in the laboratory and, to a lesser extent, in the field.

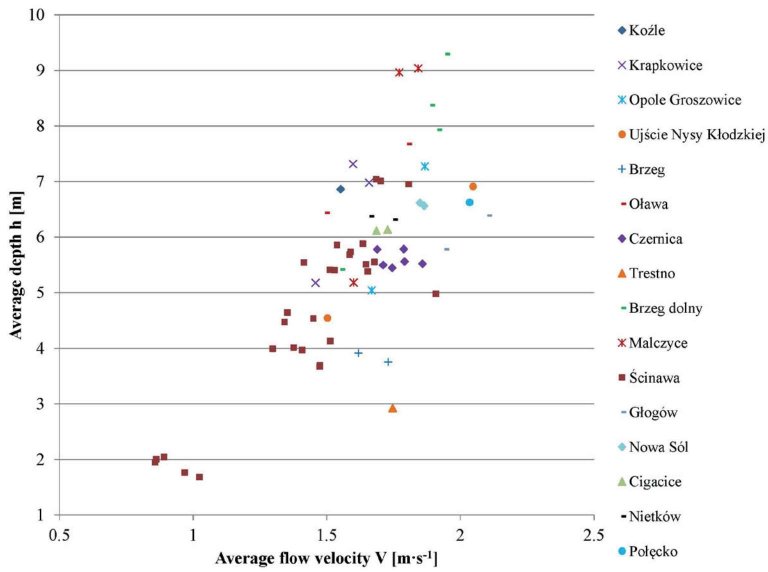

Fig. 12. Bank channel average flow velocity for the Odra River

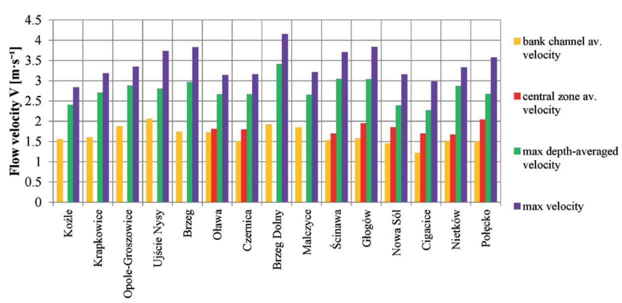

Fig. 13. Bank full average flow velocity for the Odra River

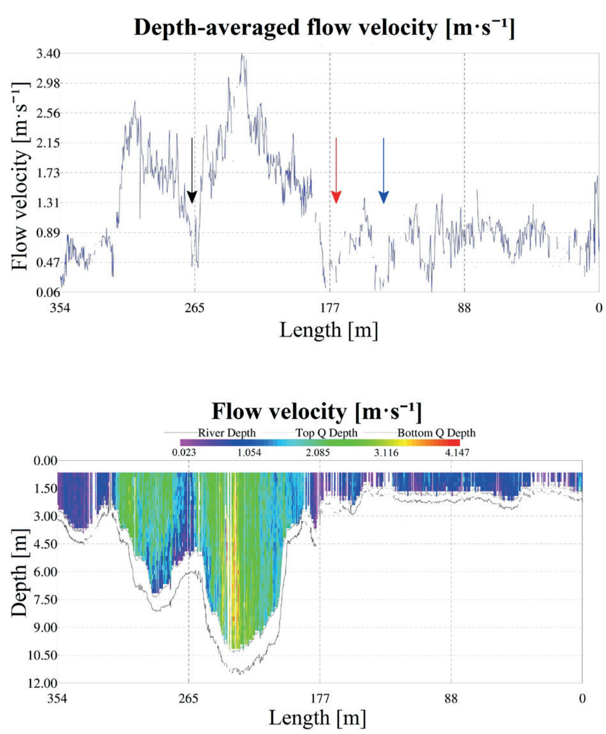

Fig. 14. Local (top) and depth-averaged flow velocity distribution in the Brzeg Dolny cross-section – arrows indicate the local flow velocity reduction due to vegetation growth (*cf.* the next figure)

The uncontrolled growth of vegetation on floodplains, possibly combined with sedimentation, may create a direct hazard of flooding (Bartnik 2011). Direct measurements of velocities under the influence of vegetation over extended floodplains under flood conditions were practically impossible, and were limited to the bridge cross-sections only. The ADCP instruments operated from a shallow draft boat offer also new possibilities here. The data for the 2010 flood provide many examples. One is shown here regarding the records near the Brzeg Dolny gauging station. In Figs. 14 and 15 both the local and depth-averaged flow velocities are depicted, along with the trajectory of the recording in respect to the vegetation covering the banks and the floodplain. Local reductions of the flow velocity can be noted – they are caused by the presence of dense vegetation and trees. Such a reduction of depth-averaged velocity (for a comparable depth) translates to a several-fold local roughness factor increase. Hence, this data again may be used for the hydraulic model calibration and for estimates of the efficiency of the removal of vegetation from the floodplains as a measure of flood hazard control.

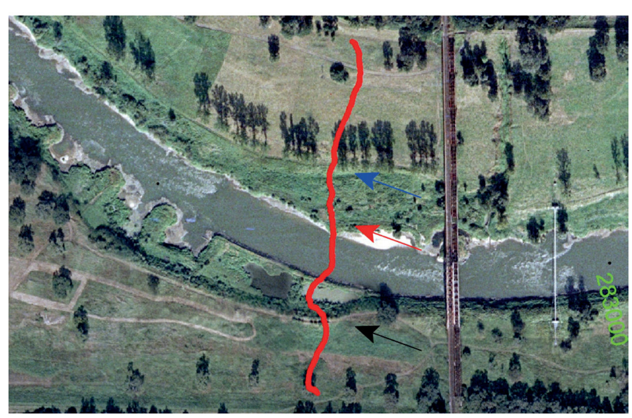

Fig. 15. Velocity record transect for Brzeg Dolny

3. Conclusions

Measurements of flow with an ADCP offer new opportunities for field data collection. However, measurement execution is often not a simple task, and the data collected are not free from faults, and need careful revision and possible correction. This is especially true for the data obtained during extreme flow conditions, where the control of the measurement is most difficult with a fast flowing stream. From the measurement campaign of 2010, a lot has been learned regarding the equipment performance and execution of effective flow measurements. The limitations are better known, and the advantages will be further exploited. The new equipment currently available is believed to cope better with some of the problems encountered and discussed. Regardless of this, the post-processing of the raw data, supported by GIS visualizations, enhances the understanding and final quality of results.

An important outcome of the present analysis is that the previously estimated flow rates and peak discharge values for the 2010 flood published previously were underestimated, especially on the section of the Upper Odra River between Koźle and Ujście Nysy. Generally, from the Koźle to Brzeg Dolny stations, and further to the Głogów station, the peak discharges varied in the range between 2000 and 2200 $m^3 \cdot s^{-1}$, with local variations caused by inputs from the tributaries and the retention of the river valley. This discharges marked the flood as the second largest during the last one hundred years (after the catastrophic flood of 1997).

In addition, better knowledge has been obtained as to the main channel and floodplain flow distribution and the contribution to the overall flow rate at given cross-sections. For the flow of 2000 $m^3 \cdot s^{-1}$, the flow in the main channel may be as low as 50%. For the river regulated by groynes, the regulation zone conveys 35-40% of the total flow. These findings provide a relevant context for numerical modelling purposes and the understanding of individual hydraulic factors that play a role, thus giving the opportunity for further analysis of roughness factors and the influence of vegetation. The breakdown of the flow velocity data according to the local scales also adds to this. The ADCP data can be used for a detailed calibration of 2D models via measured velocity vectors. In return, well calibrated models may fulfil the measuring gaps in situ.

The final conclusion is that the modern field data acquisition, GIS post processing, and numerical modelling, support each other and improve the final overall result, bringing hydrology products to a higher standard than they would do separately. The synergy of hydraulics and geoinformatics in hydrology is therefore highly recommendable.

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