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BANKFULL VALUES IN GAUGE STATION CROSS SECTIONS OF THE RABA RIVER – POLISH CARPATHIANS

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Abstract. This paper presents comparison of differents methods of bankfull discharge calculation. The methods used were: Gauckler-Manning [Chow 1959], Williams [1978], Wolman and Leopold [Leopold et al. 1964], Hey and Thorne [Thorne et al. 1997]. Calculations were carried out for the Raba river. The results shows that there is not one method which is better than the other, results are differing depending on what is took into account.

Key words: bankfull, discharge, calculation.

INTRODUCTION

Water is a vital element for human kind. So, since centuries, man has settled near to water areas: seas, lakes, and what is interesting us, rivers. During his evolution, he has built many infrastructures, which run with or against the power of water. And for centuries, man has suffered the tantrums of it, in particular its floods [Navratil et al. 2006].

That is why, in a first time, he tried to control water and to enslave it. He built dams, dykes, he reworked many of its embankments and stream beds always without

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trying to understand it. In a result, wave were always higher, floods were stronger and damages worst.

However, in the late 19th century, some scientists begun to be interested in understanding the behaviour of a river. Then was discovered a link between floods and an important characteristic of the river stream: bankfull discharge [Radecki-Pawlik 2002].

Firstly, bankfull discharge was just seen as a volume of water, running down the bed of the river. That is what french Philippe Gauckler presented in 1867 and Robert Manning improved then in 1890, the whole theory known as the Gauckler-Manning formula [Radecki-Pawlik 2002, 2011, Radecki-Pawlik et al. 2015; see also Chow 1959].

An other view of bankfull discharge is that it corresponds to the water level when water starts to flow in the active floodplain, meaning that river has overpassed the banks and flows out of its bed. Markley Gordon Wolman, Luna Leopold and John Miller [Leopold et al. 1964] described it in their book *Fluvial Processes in Geomorphology*, published in 1964. Later, Hey and Thorne [Thorne et al. 1997], in 1986, will introduce the sediment discharge concept on the bankfull discharge calculation.

Nowadays with the new European Frame Directive, which decrees, among many other orders, to all the european countries that they should make an inventory of all their rivers and their properties before the fourth year of application of the law, bankfull discharge concept has become an important index of a river.

Furthermore, it is now seen as a better mean to determine how to design the water's infrastructures, to be more efficient, but also to be less expensive. It is also a good way to predict the river's behaviour, which is really important to know when there are sensible constructions on its way, such as bridges, houses.

This study tries to present some methods of bankfull calculation applied on a polish river, the Raba. That is why we will detail the four used methods: Gauckler-Manning [Radecki-Pawlik 2011], Williams [1978], Wolman and Leopold [Leopold et al. 1964], and finally Hey and Thorne [Thorne et al. 1997], before discussing their results and trying to determine advantages and drawbacks of each.

CATCHMENT AREA DESCRIPTION

Our study was lead on the Raba River, a little mountain river which is located at the south of Krakow. The source of this river is in the Beskids mountains at nearly 750 m above sea level, between the towns of Rabka-Zdroj and Nowy-Targ. Then it flows to the north and the north east, before joining the Vistula river near to Uście Solne at 180 m above sea level, it is 132 kilometers long. Raba's catchment basin is 1537 square kilometres (as an example, the Vistula basin is 194 424 square kilometres). Its mean discharge is about 17 cubic meter per second at the Proszowki gauging station (data for the period 1951–90) [Rzeki polski info. Raba].

Although some devastating floods, such as in 1934 – during which 55 people died – or 1970, the Raba river and its tributaries – the Poniczanka, Słonka, Krzyworzeka, Mszanka, Kasinianka, Kaczanka, Krzczonówka, Trzemeśnianka, Stradomka and Babica Rivers – were very important for the development of the cities it goes through: Rabka-Zdrój, Mszana Dolna, Myślenice, Dobczyce and Bochnia. Indeed, in the past, it allowed to transport the salt form Wielicka and Bochnia, and the brine from Rabka. Nowadays, Raba valley is appreciated by tourists for its landscapes and by sports enthusiasts who can down it with canoes. The most important infrastructure on the Raba is the Dobczyce dam, an hydroelectric plant which provides Krakow with water too.

Before this dam, the Raba River shows all the characteristics of a mountain river: narrow valley, stones bed, strong stream and waterfalls. Nevertheless, this balance is a few changed after the dam.

METHODS

Among all the calculation methods of bankfull discharge, 4 of them were retained on this study: Gauckler-Manning formula, Williams' regression, Wolman and Leopold and Hey and Thorne's equations. For reasons of clarity, their theory were summed up and presented below.

- **Gauckler-Manning** [Radecki-Pawlik et al. 2015]

Gauckler and Manning [Chow 1959] describe bankfull discharge as a simple volume of water. So their theory is based on a formula which allows to calculate directly the wanted discharge:

$$Q_b = \frac{1}{n} \cdot A_b \cdot D_b^{\frac{2}{3}} \cdot S^{\frac{1}{2}}, \ \mathrm{m}^3 \cdot \mathrm{s}^{-1}$$

Here, Q_b is the bankfull discharge in cubic meters per second, A_b is the water area when its bankfull discharge (in square metres), D_b is the depth at bankfull (in metres), S is the slope of the river and n the roughness coefficient (Fig. 1) [Oregon department of transportation 2015].

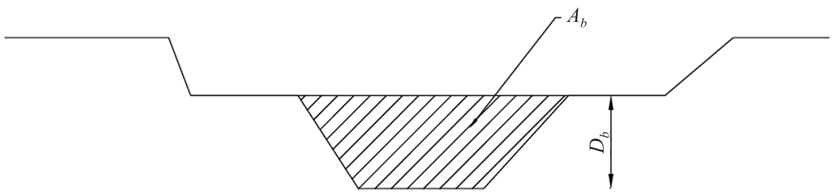

Fig. 1. Diagram trough with marked depth of bankfull water (D_b) and a surface area (A_b)
Ryc. 1. Schemat koryta z zaznaczoną głębokością wody brzegowej (D_b) oraz polem powierzchni (A_b)

- **Williams**

Williams method [1978] is just an evolution of the Gauckler-Manning [Chow 1959] formula which is the following equation:

$$Q_b = 4.0 \cdot A_b^{1.21} \cdot S^{0.28}, \ \mathrm{m}^3 \cdot \mathrm{s}^{-1}$$

- **Wolman and Leopold**

According to Wolman and Leopold [Leopold et al. 1964], bankfull discharge corresponds at the moment when river is flowing above its banks. As a consequence, their calculation method rests on exploiting some geometric characteristics of the river:

– Width (W), in metres
– Depth (D), in metres
– The ratio $R = W/D$

After drawing the curve D = f(R), a break in it, or when R comes to its minimum, indicates that critical depth has been reached. This critical depth corresponds to bankfull.

Last step is to determine the corresponding discharge using the equation of discharge:

$$Q = V \cdot A_b, \ \ \mathrm{m^3 \cdot s^{-1}}$$

Where V is the speed of water in metres per seconds. V can be calculated following this equation:

$$V = \frac{1}{n} \cdot R_h^{\frac{2}{3}} \cdot I^{\frac{1}{2}}, \ \ \mathrm{m^3 \cdot s^{-1}}$$

- **Hey and Thorne** [Radecki-Pawlik et al. 2015]

Hey and Thorne [Thorne et al. 1997] method, well-known as *Hey and Thorne's equations* consists in several equations which allow to calculate many geomorphological characteristics of the river (meander arc length, sinuosity, pool and riffles) according the vegetation type.

However, what is important for this study is the two following equations with which bankfull discharge was determinated in the research areas:

$$\textit{Bankfull mean depth}\text{: } d = 0.22 \cdot Q^{0.37} \cdot D_{50}^{-0.11}, \ \ \mathrm{m}$$

$$\textit{Bankfull maximum depth}\text{: } d_m = 0.20 \cdot Q^{0.36} \cdot D_{50}^{-0.56} \cdot D_{84}^{0.35}, \ \ \mathrm{m}$$

Of course, they both need some granulometric data (D_{50} and D_{84}) which have been obtained on the laboratory. Then, it consists in calculating these depths for a chosen scale of discharges and look the correspondence between discharge and depths.

For our study in terms of bankfull discharge of the Raba River, six research areas were chosen: four before the Dobczyce dam – Rabka-Zdrój, Mszana Dolna, Kasinka Mała and Stróża – and two after it – Dobczyce and Proszówki. They are almost fairly distributed all along the river, as it is showed on fig. 2.

On every research area were taken geomorphologic and topographic data [Henry n.d.]. Cross-sections of the river were made by the radiation method to obtain the riverbed topography, also were determined granulometry – at the laboratory by sieving, slope and roughness – using Manning's table [Oregon Department of Transportation 2015]. These data are presented in the following table.

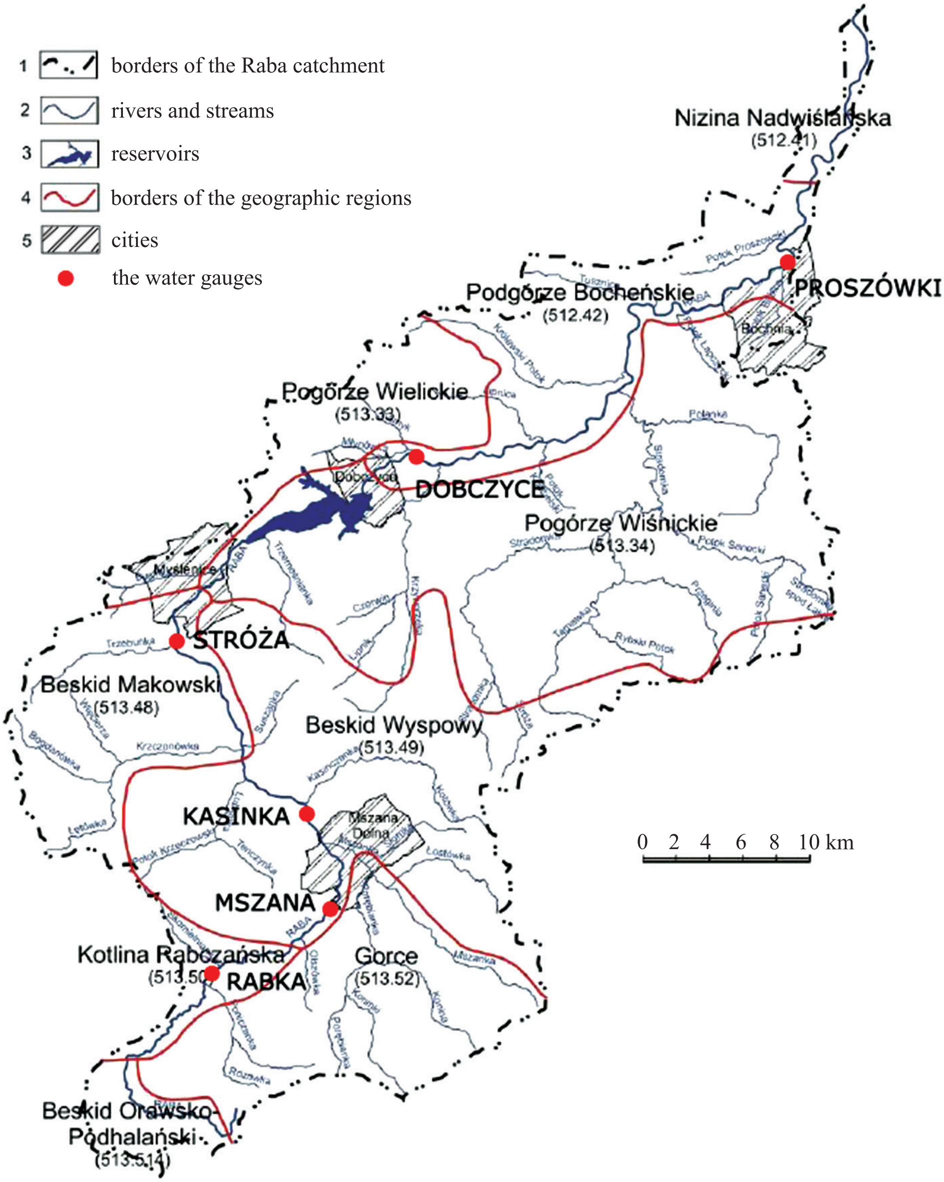

Fig. 2. Research areas along the Raba River [based on Paszkiewicz 2009]
Ryc. 2. Obszar badań wzdłuż rzeki Raby [oprac. na podstawie Paszkiewicz 2009]

Table 1. Characteristics of the Raba River on the research sites
Tabela 1. Charakterystyka przekrojów badawczych na rzece Rabie

	Roughness			Slope	Granulometry				
Gauge station	left bank	bed	right bank	promil	D_{20} mm	D_{30} mm	D_{50} mm	D_{80} mm	D_{90} mm
Rabka-Zdrój	0.03	0.02	0.03	0.86	19	31	62	123	131
Mszana Dolna	—	0.04	0.11	2.7	23	33	54	103	121
Kasinka Mała	0.025	0.04	0.025	11,4	24	35	57	112	134
Stróża	0.02	0.035	0.03	3.92	24	36	60	120	147
Dobczyce	0.035	0.04	0.03	2.6	10	22	42	80	102
Proszówki	0.035	0.03	0.035	0.97	11	18	33	54	65

RESULTS AND DISCUSSION

For each research area, critical depth was determined by Wolman and Leopold method, but also corrected by studying the topography of the riverbed. Hence the results showed in the following table 2, obtained using the methods previously detailed:

Table 2. Bankfull discharge on the Raba River, $m^3 \cdot s^{-1}$
Tabela 2. Przepływ brzegowy na rzece Rabie, $m^3 \cdot s^{-1}$

	Bankfull discharge Q, $m^3 \cdot s^{-1}$						Depth m
	Method of calculation	Gauckler--Manning	Williams	Wolman and Leopold	Hey and Thorne		
					Mean depth	Max depth	
Gauge station	Rabka-Zdrój	21	11	20	54	18	1,3
	Mszana Dolna	54	50	49	106	37	1,7
	Kasinka Mała	228	133	203	165	59	2,0
	Stróża	278	189	244	220	72	2,2
	Dobczyce	338	241	276	640	205	3,4
	Proszówki	485	276	371	1750	627	5,0

On a global scale, one can notice the scattering of results in terms of obtained bankfull values using different methods. But there is even so some regularity. Excepted Hey and Thorne method which is growing exponentially, the three others – Gauckler-Manning, Williams and Wolman-Leopold – are quite linear and their final results are close.

On a more limited scale, we can distinguish several cases. First, for small critical depths and weak streams – less or around 2 meters and 50 cubic meters per second – results are very close each other, excepted for Hey and Thorne with mean depth. This is due to the fact that as critical depth D_b is not very high, it doesn't make a big difference in the calculation. The Hey and Thorne mean depth result is twice any other result, exactly because we are using mean depth, and not critical depth.

About medium critical depths – between 2 and 4 meters, in our study 2.2 and 3.4 – Wolman and Leopold and Williams methods are nearby but Gauckler-Manning is sensibly higher than them. These differences are in one hand because Williams' regression is a better approximation for little depths and in the other hand because critical depth influence in Gauckler's formula is stronger than in Wolman's.

The difference between the two calculation methods: Gaucklera-Manning and Wolman, shows the difference between one parameter. Comparing the two pattern we conclude that the decisive parameter is the depth of the channel (in the formula $Q_{\text{Gaucklera-Manning}}$ $D_b^{\frac{2}{3}}$ and $D_b^{\frac{1}{2}}$ for Q_{Wolman}).

For high critical depths – above 4 meters, here 5 – we can notice the same trend. However, the two Hey and Thorne results are now rocketing. This is because the growing influence of critical depth accentuated by the exponent in the reversed formulas which are following:

$$\textit{Bankfull mean depth}: Q = \left(4.55 \cdot d \cdot D_{50}^{0.11}\right)^{\frac{1}{0.37}}, \ \mathrm{m}^3 \cdot \mathrm{s}^{-1}$$

$$\textit{Bankfull max depth}: Q = \left(5 \cdot d \cdot D_{50}^{0.56} \cdot D_{84}^{0.35}\right)^{\frac{1}{0.36}}, \ \mathrm{m}^3 \cdot \mathrm{s}^{-1}$$

Furthermore, bankfull discharge with max depth is smaller than with bankfull discharge with mean depth because of the exponents $\left(D_{50}^{0.56} \cdot D_{84}^{0.35} < D_{50}^{0.11} \text{ and } \frac{1}{0.36} < \frac{1}{0.37}\right)$.

The main conclusion after viewing all the obtained results of bankfull for the five used methods is that there is not one of them which should be used preferably for determining its value. Each method has its principles, based on different theories. Of course, in every one is a common thing, the margin of error, due to the field measurements or the choices made by the user. As seen previously, all the methods are really close for small depths and streams but then they are pulling away. Williams' regression does not fit as proximate for high depths as it is for small ones, Wolman results are slackening while Hey and Thorne's ones are increasing faster and faster – this can be linked to the growing influence of sediment discharge, Hey and Thorne being the only ones to consider it. Finally, bankfull results are shaping a wide range of flows delimited by Williams at the bottom and Hey and Thorne on the top, Wolman-Leopold and Gauckler-Manning being that we can call "medium values".

Then, bankfull should not be seen as a single value, but as a range of flows. Indeed, each method has its privileged applications, varying from what we want to take into account, and so they gave a wide range of results. It should not be true to say that one value obtained by this or that method is the only right bankfull discharge. Hence it is more correct to consider that bankfull discharge is within a range of flows flooding the banks of the river.

CONCLUSIONS

From the above discussion, we can reach the following conclusions:

1. There no precise analytical method for determining bankfull, even though there are good approximation.
2. Many of these approximation are depending on the user's perception and choices. A little change at the beginning of the study can have significant influence on the final result.
3. General methods such as Williams' regression are more justified for little depths and flows.
4. Bankfull discharge should not be defined as a single value, but as a discharge within a range of values.

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WARTOŚCI PRZEPŁYWU BRZEGOWEGO W PRZEKROJACH STACJI POMIAROWYCH RZEKI RABY – POLSKIE KARPATY

Strszczenie. W artykule zaprezentowano porównanie różnych metod obliczeń przepływu brzegowego. Zastosowano metody oparte na wzorze Gauckler-Manninga, a także metody Wiliamsa, Wolmana i Leopolda, oraz Heya i Thorna. Obliczenia wykonano dla rzeki Raby.

Wyniki pokazują, że nie ma jednej metody, która byłaby najlepszą, a wyniki różnią się w zależności od metody i zastosowanych parametrów obliczeniowych.

Słowa kluczowe: przepływ brzegowy, przepływ, obliczenia.

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