# Effect of Floodplain Trees on Apparent Friction Coefficient in Straight Compound Channels

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**Abstract.** The interaction of water streams in channels with a complex cross-section, involving the exchange of water mass and momentum between slowly flowing water in the floodplains and fast water in the main channel, significantly depends on the diversification of the surface roughness between the main channel and floodplains. Additionally, trees strongly increase flow resistance on floodplains, but also significantly in the main channel by intensifying the interaction process. As a result, the water velocity and the discharge capacity of both parts of the channel decrease and at the same time, affecting the flow conditions in the main channel. The results of laboratory experiments were used to determine the effect of floodplain trees on the discharge capacity of the channel with diversified roughness. The reduction in velocity of the main channel caused by the stream interactions is described with the apparent friction coefficients introduced at the boundary between the main channel and the floodplain. The values of resistance coefficients and their changes as a result of the significant influence of trees on the interaction process were determined for different surface roughnesses of the main channel bottom.

## 1 Introduction

This paper is the result of a continuation of the study of the apparent friction coefficient at the main channel-floodplain interface for three variants of channel surface roughness described in the paper by Kubrak et al. (2019). It is well known that the very diversification of the bottom surface roughness intensifies the momentum exchange process along with the creation of vortex structures in the transition area between the floodplains and the main channel ("kinematic effect", Zheleznakov, 1971, nowadays is described as the streams interaction). An increase in channel surface roughness and consequent intensification of the process of vortices formation and secondary flows in the main channel results in a reduction in water velocity, changes in the turbulent flow pattern and affects the capacity of the channel with a complex cross-section (Shiono and Knight,1991; Tominaga and Nezu, 1991; Bousmar and Zech, 1999; Rowiński et al.,1998 and 2002; Van Prooijen et al., 2000; Czernuszenko et al. 2007; Tymiński, 2012; Tymiński and Kałuża, 2012; Kozioł and Kubrak, 2015). Floodplain trees further strongly increase the interaction between the main channel and the floodplain. Floodplain trees additionally cause a significant increase in flow resistance, a reduction in water velocity, a reduction in the capacity of both parts of the riverbed and especially a significant change in the turbulent flow structure (Kozioł, 2008, 2011, 2012, 2013, 2015 and 2019, Mazurczyk, 2007). The results of laboratory experiments (Kozioł, 2013) showed that trees on the floodplains did not result in significant changes in values of relative turbulence intensity in the whole compound channel, but they did result in significant changes in the vertical distributions of the relative turbulence intensities in all three directions on the floodplains and over the bottom of the main channel.

The main goal of this unique work was to determine the influence of floodplain trees on the value of the apparent resistance coefficient in a compound channel for the different roughness of the main channel bottom. The results of measurements from previous experimental studies in compound channels on the flow capacity and the turbulence structure were used to write this manuscript (Kozioł, 1999, 2012, 2013, 2019; Kubrak et al., 2019). Variants W 2.0 and W 3.0 from the Kubrak et al. (2019) study were used to show the impact of floodplain trees as reference.

The interaction between the main channel and the floodplain, especially in the transition zone, is a complex phenomenon. Traditionally, researchers have modelled this by separating the two zones, often represented by vertical lines. These lines represent boundaries where shear stresses are estimated and applied. Wright and Carstens (1970) introduced the concept of apparent shear stresses at these boundaries within compound channel cross-sections. Since the 1980s, consistent with the concept of apparent shear stress, a number of formulas based on hydraulic experiments in channels have been introduced to calculate flow resistance due to momentum transfer between the main channel and the floodplain (Myers, 1987; Wormleaton et al., 1982; Knight and Demetriou, 1983; Prinos and Townsend, 1984; Christodoulou, 1992). An overview of these formulas can be found in Moreta and Martin-Vide (2010).

Laboratory tests allow the determination of apparent shear stresses, which enable the determination of the values of dimensionless resistance coefficients used to calculate the average velocity $v_m$ in the steady uniform flow in the main channel of the compound cross-section, according to the Darcy-Weisbach formula:

$$v_m = \sqrt{\frac{8gR_mS_o}{f_m}}, \tag{1}$$

where: $v_m$ - average flow velocity in the main channel, $g$ - gravitational acceleration $R_m$ - hydraulic radius of the main channel cross-section, $S_o$ - longitudinal channel slope, $f_m$ - resistance coefficient for the main channel cross-section. The $f_m$ resistance coefficient is calculated for the wetted perimeter, taking into account the length of the cross-section division plane, side slopes and the bottom of the main channel.

The flow resistance coefficients at the division planes of the compound cross-section, calculated on the basis of apparent shear stresses, depend on the channel parameters given by Nuding (1998), but in the case of trees on the floodplain they also depend on additional parameters such as: $d$ - tree diameter, $A_v/A$ - the degree of cover of the cross-sectional area of the channel by trees, $a_x$ and $a_y$ - spacing of trees in the longitudinal and transverse directions. Then the relationship for flow resistance coefficients given in the work by Kubrak et al. (2019) should be supplemented with additional channel parameters (Fig. 1):

$$f_a = f\left(f_{mb}; \frac{H}{h_f}; \frac{b_m}{b_f}; 1{:}m; \frac{k_{mb}}{k_{fb}}; d; \frac{A_v}{A}; a_x \ and \ a_y\right), \tag{2}$$

where: $f_a$ - apparent coefficient of resistance at the boundary between the main channel and floodplain area, $f_{mb}$ - resistance coefficient of the main channel bottom, $f_{ms}$ - resistance coefficient of the main channel side slopes, $f_m$ - resistance coefficient in the main channel, $f_{fb}$ - resistance factor of the bottom of the floodplain, $H$ - water depth in the main channel, $h_f$ - water depth on the floodplain, $b_m$ - bottom width of the main channel, $b_f$ - floodplain width, $1{:}m$ - aspect of the side slope of the main channel and floodplains, $k_{mb}$ - absolute surface roughness of the main channel, $k_{ms}$ - absolute roughness of the main channel side slopes, $k_{fb}$ - absolute surface roughness of the floodplain, $k_{fs}$ - absolute roughness of the floodplain side slopes.

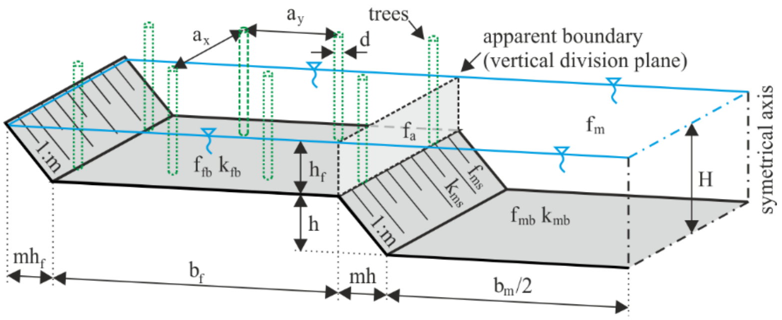

**Figure 1: Symbols used for dimensions of the compound cross-section of the channel.**

Bretschneider and Özbek (1997) used a large-scale hydraulic modeling approach to determine the apparent resistance coefficients at vertical division lines in compound channels. Their research, conducted as part of the Science and Engineering Research Council (SERC) program at the Hydraulic Research Laboratory in Wallingford, England, used measurements of: average water velocity in the main channel (this provided insight into flow characteristics within the main channel); apparent tangential stresses at the division boundary of the cross-section (these estimated shear stresses represent the interaction between the main channel and the floodplain). The study of the flow and structure of turbulent water flow in river channels with a compound cross-section is complex, incomplete and, despite considerable research interest in the subject, still requires detailed clarification in many areas of research, especially the influence of high vegetation. In recent years, there have been many important publications on the apparent roughness coefficient and apparent shear stress in a compound channel (Devi and Khatua, 2018; Fernandes, 2021; Devi et al., 2022; Khozani et al., 2022; Zhao et al., 2024). However, much of the research to date has been conducted on compound channels without tall vegetation (bushes and trees). Kubrak et al. (2019) performed research on a small-scale hydraulic model and the aim of their research was to explain how the surface roughness of the main channel and floodplains affects the values of apparent resistance coefficients. In contrast, the main objective of this unique work was to extend the knowledge by determining the effect of floodplain trees on the value of the apparent drag coefficient in a complex channel for the different bed roughness.

## 2 Study on Discharge Capacity of Channel with Compound Cross-Section with Floodplain Trees

A study on the capacity of the channel with the compound cross-section was carried out in the hydraulic laboratory of the Department of Water Engineering of the Warsaw University of Life Sciences. A straight open channel (16 m long and 2.10 m wide) with a symmetrically trapezoidal cross section was used for the laboratory variants (Fig. 2; Kozioł, 2013, Fig. 1; Kubrak et al., 2019, Figs. 2 and 3). Detailed information on the research model and measurement procedures can be found in the articles Koziol (1999, 2012, 2013, 2019) and Kubrak et al. (2019), while only the most relevant research parameters are included. The cross section halfway down the channel length was selected for velocity measurements (Fig. 2b and Kozioł, 2013, Fig. 1). Two devices were used to measure the components of the flow velocity: an electromagnetic PEMS probe and an acoustic Doppler velocity meter (ADV). At the beginning, the electrostatic PEMS probe was used, and then from the newly purchased acoustic ADV probe. The description of the electrostatic PEMS probe, the measurement technique and the method of determining the required length of the velocity measurements time series are presented in the work of Kubrak et al. (2019) and the ADV probe in the works of Kozioł (2012, 2019). The velocity measurements at a point by the PEMS probe were carried out in 77 measurement verticals and in nearly 500 cross-section points (Kubrak et al., 2019), and by the second probe at 250 points at 23 verticals — 6 on each floodplain and 11 in the main channel (Kozioł, 2012, 2019). The probes were mounted on a sliding measuring carriage. The differential pressure gauge and the probes were connected to a computer measurement logger. The results of measurements from two experimental studies in compound channels on the flow capacity (Kozioł, 1999; Kubrak et al.,2019) and turbulence characteristics of the water stream (Kozioł, 1999, 2012, 2019) were used to write this manuscript. Diversification of the surface roughness in the channel was obtained by painting the concrete of a blurred surface with paint (called a smooth surface), or by applying a terrazzo layer with a grain diameter of 6–12 mm (called a rough surface, Fig. 2).

The studies of the capacity of the compound channel and the analysis of the apparent friction coefficient at the apparent boundary between the main channel and the floodplain were carried out for six variants and three values of floodplain roughness. The test results of the first three variants without trees (W 1.0, W 2.0 and W 3.0) are described in detail in the article by Kubrak et al. (2019). This paper presents experiments of three variants with trees on floodplains for the following conditions:

1. In the fourth variant (W 2.T1, Figs. 2a and 2b), the surface of the main channel bed was smooth and made of concrete, whereas the floodplains were covered by cement mortar composed with terrazzo. The emergent vegetation (trees) growing on the floodplains were modelled by aluminum pipes of 0.8-cm diameter, placed with both longitudinal and lateral spacings of 10 cm. There were sixteen pipes in each of 161 cross sections. The treetops were emergent, and the pipes were not subject to any elastic strains caused by overflowing water.
2. In the fifth variant (W 2.T2, Fig. 2b), the covering of the floodplains was the same as in the variant W 2.T1, but emergent vegetation (trees) growing on the floodplains were modelled by half as much, placed with both longitudinal and lateral spacings of 20 cm (photo in Kozioł, 2013, Fig. 3). There were eight pipes in each of 80 cross sections.

3. In the sixth variant (W 3.T2, Fig. 2c), the floodplains and all sloping banks were covered by cement mortar composed with terrazzo, and the bottom of the main channel was smooth. The emergent vegetation (trees) growing on the floodplains were modelled in accordance with the variant W 2.T2, with spacings of 20x20 cm.

The list of tests performed during the experiments, the measured flow rates in the main channel and the adjacent floodplains are summarized in Table 1.

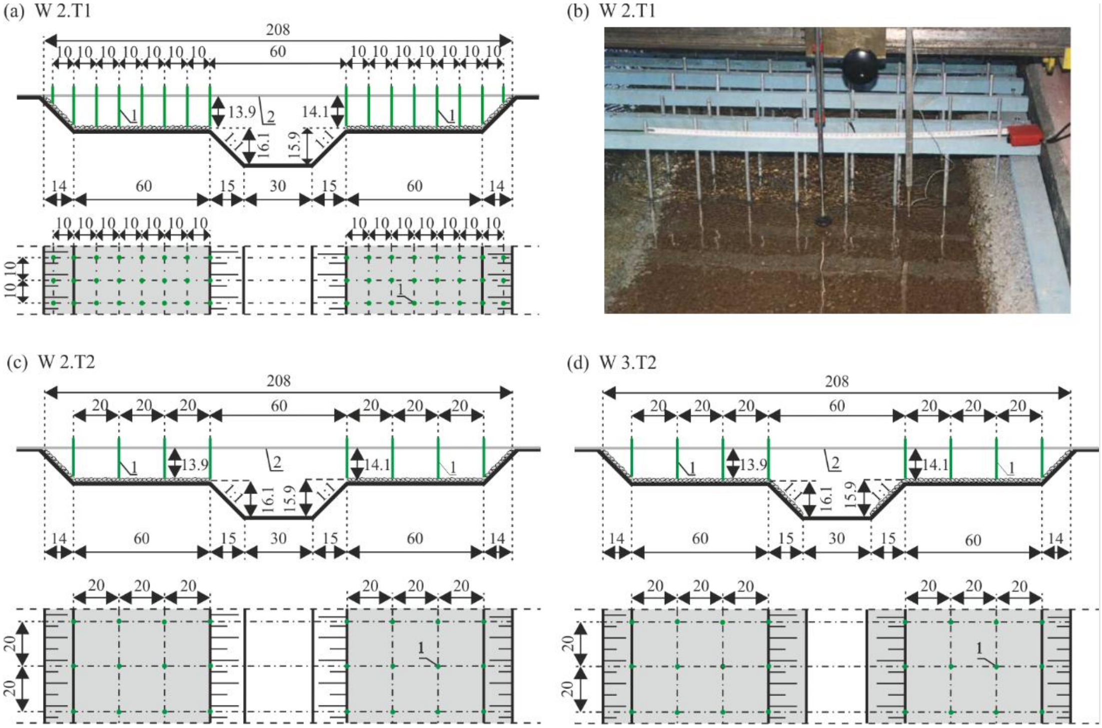

**Figure 2: Scheme of the cross-section of the channel in the variants analyzed (dimensions in cm) and a view of the model of the channel in the W 2.T1 variant.**

Based on the spot velocity measurements, it was possible to plot lines of constant velocities (isovels) in the cross-sections of the channel for all analyzed variants. Examples of isovels in the cross-section of the channel at a similar flow depth ($H \approx 0.25$ m) for variant W 2.0 and variants W 2.T1, W 2.T2 with trees on the floodplains are shown in Fig. 3. Figure 4 presents isovels in the cross-section of the channel with smooth surface of the bottom of the main channel, rough surface of the side slopes of the main channel and floodplains, for variant W 3.0 and variant W 3.T2 with trees on the floodplains ($H = 0.28$ m).

**Table 1: Hydraulic parameters of experiments (variants 2.0.7, 3.A1 and 3.A2 from research of Kubrak et al., 2019).**

| Parameter | Variant | | | | | | |
|---|---|---|---|---|---|---|---|
| | 2.0.7 | 2.T1 | 2.T2 | 3.A1 | 3.A2 | 3.T2.A1 | 3.T2.A2 |
| Discharge $Q$ [m$^3$s$^{-1}$] | 0.0808 | 0.0499 | 0.0613 | 0.0952 | 0.0811 | 0.0657 | 0.0589 |
| Discharge in the Main Channel $Q_m$ [m$^3$s$^{-1}$] | 0.0481 | 0.0401 | 0.0426 | 0.0500 | 0.0457 | 0.0386 | 0.364 |
| Discharge in the Left Floodplain $Q_{fl}$ [m$^3$s$^{-1}$] | 0.0150 | 0.0051 | 0.0095 | 0.0226 | 0,0180 | 0.0135 | 0.114 |
| Water depth $H$ [m] | 0.251 | 0.253 | 0.256 | 0.283 | 0.264 | 0.280 | 0.263 |
| Water depth in the Floodplain $h_f$ [m] | 0.091 | 0.093 | 0.096 | 0.123 | 0.104 | 0.12 | 0.103 |
| Reynolds Numbers in the Main Channel $Re_m$ | 202,824 | 149,136 | 157,071 | 160,460 | 149,521 | 122,133 | 119,100 |
| Reynolds Numbers on the Left Floodplain $Re_{fl}$ | 79,827 | 23,861 | 44,347 | 92,468 | 74,600 | 54,350 | 47,254 |
| Type of surface | smooth main channel and rough floodplains | | | rough floodplains and sloping banks of the main channel, with smooth bottom of the main channel | | | |
| The arrangement of trees [cm] | | 10x10 | 20x20 | - | - | 20x20 | 20x20 |
| Percentage reduction in flow $dQ_i$ [%] ($i$ – variant no) | | $dQ_{2.0.7\text{-}2.T1}$<br>-38.2 | $dQ_{2.0.7\text{-}2.T2}$<br>-24.1 | | | $dQ_{3.A1\text{-}3.T2.A1}$<br>-31.0 | $dQ_{3.A2\text{-}3.T2.A2}$<br>-27.4 |

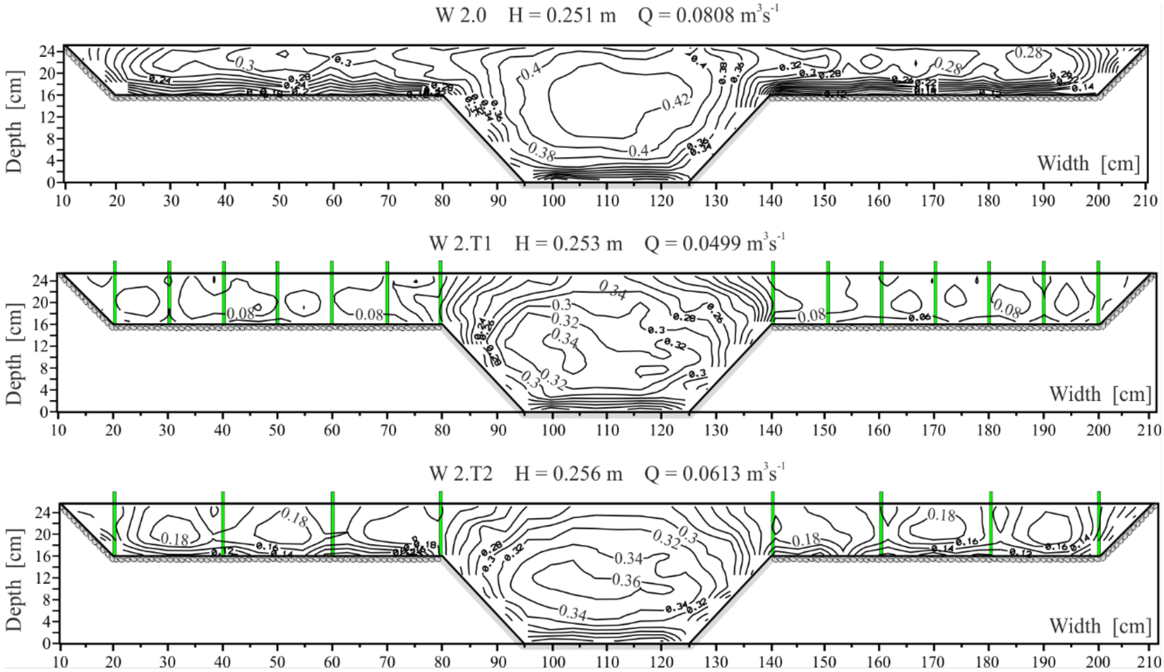

**Figure 3: Isovels in the cross-section of the channel at similar depth for variant W 2.0 and variants W 2.T1, W 2.T2 with trees on the floodplains (variant W 2.0 from research of Kubrak et al., 2019).**

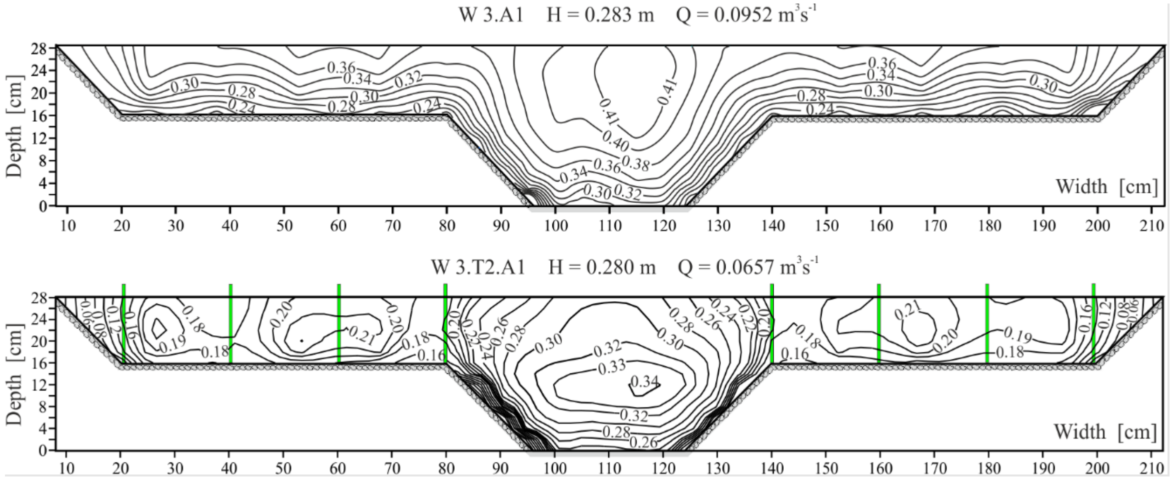

**Figure 4: Isovels in the cross-section of the channel at similar depth for variant W 3.A1 and variant W 3.T2.A1 with trees on the floodplains (variant W 3.A1 from research of Kubrak et al., 2019).**

## 3 Resistance Coefficients in the Main Channel with the Influence of the Floodplain Trees

In the variant with trees in the floodplain, as in the variant without trees (Kubrak et. al., 2019), the values of the dimensionless resistance coefficients in the main channel with different bottom and slope roughness and the resistance coefficients in the distribution plane of the channel cross-section were calculated using the Einstein method (Einstein, 1934). This method is based on a simplified approach in which the flow can be found for each surface roughness along the perimeter of the cross section, where this roughness determines the flow conditions (Fig. 5). The Einstein method simplifies the flow analysis by assuming uniform average velocities within subsections defined by surface roughness along the channel perimeter. These areas are identified using isovel plots (Fig. 5), which represent lines of equal velocity. The method divides the cross section with lines perpendicular to the isovels, starting from the wetted perimeter. This approach assumes that the dividing lines are free of shear stress and that no forces are transmitted between the separated areas.

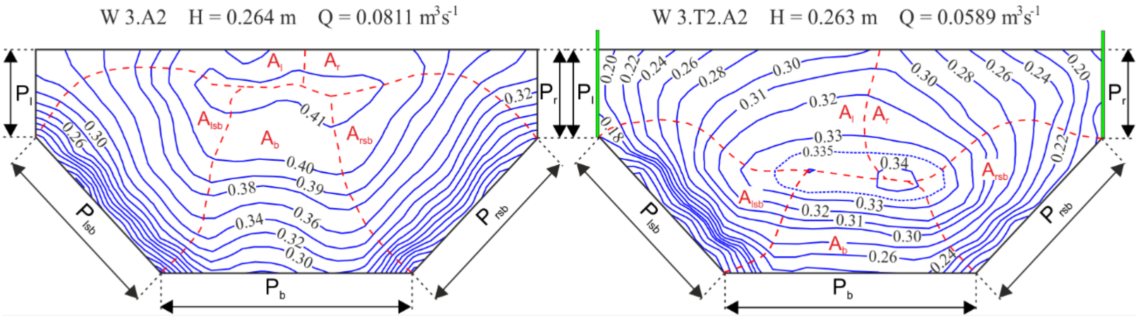

**Figure 5: Surface areas of stream cross-sections $A_i$ in which the flow conditions are shaped under the influence of a constant roughness over the length of the wetted perimeter $P_i$ (variant W 3.A2 from research of Kubrak et al., 2019).**

The Einstein method assumes a simplified approach where the average flow velocity within each subsection, $A_i$, is equivalent to the average velocity across the entire main channel cross-section ($v_i = v_m$). Under this assumption, the Darcy-Weisbach equation can be applied, leading to the following relationship (Kubrak et. al., 2019):

$$\sqrt{\frac{8gR_iS_o}{f_i}} = \sqrt{\frac{8gR_mS_o}{f_m}} \Longrightarrow f_i = f_m\frac{R_i}{R_m}, \tag{3}$$

where: $R_i$ is the hydraulic radius of the cross-sectional area per given roughness ($R_i = A_i/P_i$), $R_m$ - the hydraulic radius of the entire cross-section of the main channel ($R_m = A_m/P_m$), $f_i$ - the resistance coefficients of the subsection, $f_m$ is the average Darcy's friction factor in the main channel - being the substitutionary coefficient of resistance for the cross-section of the main channel calculated for the wetted perimeter $P_m$, which includes the lengths of the section dividing lines ($P_m = P_l + P_{lsb} + P_b + P_{rsb} + P_r$). The coefficient of resistance $f_m$ in the cross-section of the main channel is calculated on the basis of the average velocity ($v_m = Q_m/A_m$). The determined areas of the cross-section $A_i$ (Fig. 5) were used to calculate the hydraulic radius $R_i$ and the resistance coefficients $f_i$.

In Fig. 6, the calculated values of apparent resistance coefficients $f_a$ (subscripts $l$ and $r$ - the left and the right side, respectively) and resistance coefficients of the main channel $f_m$ as well as of the bottom $f_{mb}$, the side slope of the main channel $f_{ms}$, the bottom of the floodplain $f_f$, of the compound cross section in experiments made in variants W 2.0, W 2.T1, W 3.T2, W 3.0 and W3.T2 are presented as a function of the depth ratio $(H\text{-}h)/H$. The values of the apparent resistance coefficients $f_a$ for the compound cross-section in variants W 2.0 and W 3.0, and resistance coefficients of the bottom of the floodplain $f_f$ with high roughness (in variants W 2.0 and W 3.0) decrease with the increase of the flow depth (also with increase of the ratio $(H\text{-}h)/H$) (Fig. 6). The presence of trees and the interaction process in variants W 2.T1, W 2.T2 and W 3.T2, in contrast to variants W 2.0 and 3.0, contributes to the fact that there is a significant increase of apparent resistance coefficients values above the depth of $(H\text{-}h)/H = 0.2$.

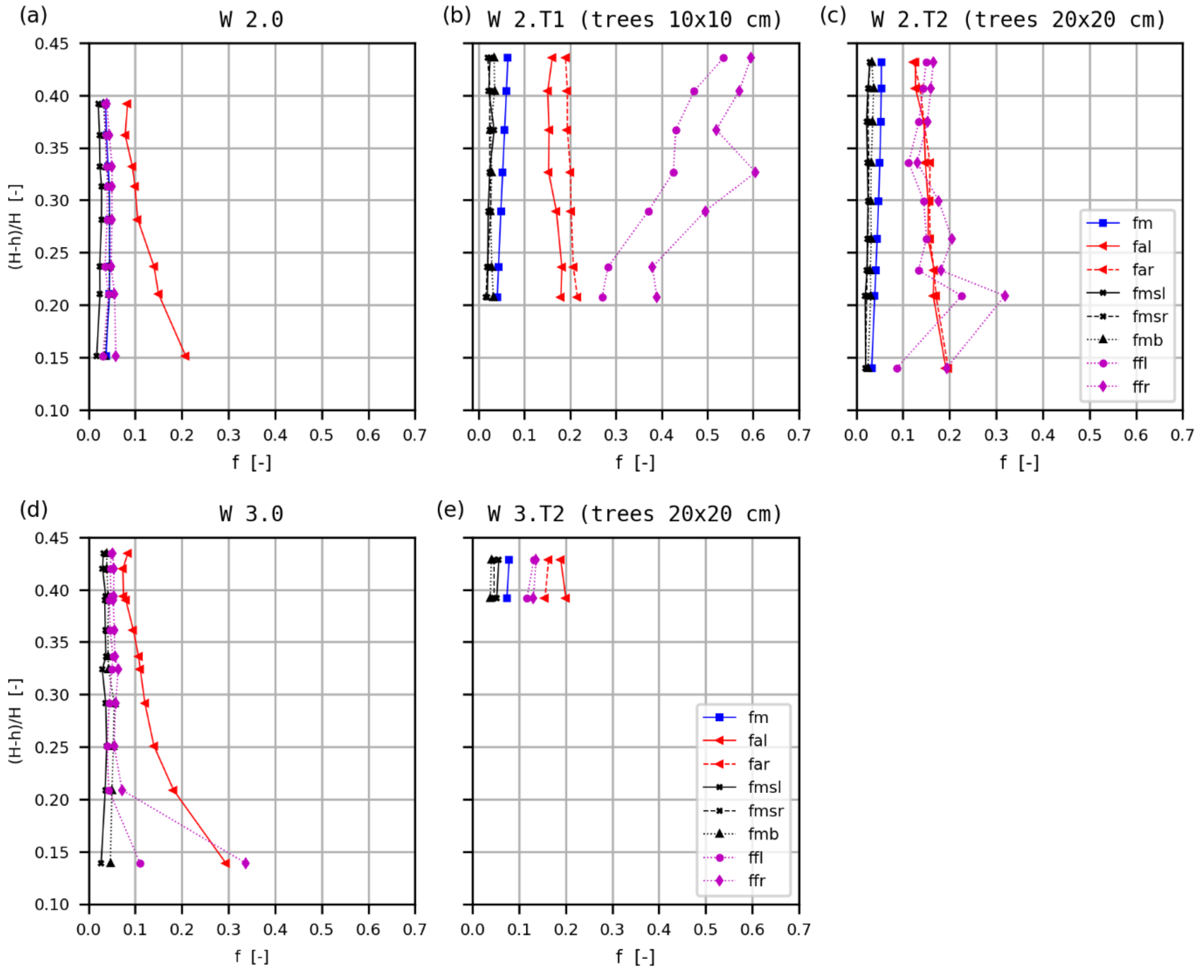

**Figure 6: Variability of resistance coefficients in the cross-section of the compound cross-section in variants: (a) W 2.0, (b) W 2.T1, (c) W 2.T2, (d) W 3.0, and (e) W 3.T2 (variants without floodplain trees W 2.0 and 3.0, Kubrak et al., 2019).**

Figures 7a and 7b present the influence of floodplain trees on the values of the resistance coefficients $f_m$ in the main channel in the second and third variants. In variant W 2.0 the values of resistance coefficients $f_m$ would first increase above $(H-h)/H$ = 0.25 and then start to decrease. Trees from floodplains intensify the increase in resistance and subsequent reduction in flow. In variant W 2.T1 (trees 10x10 cm) at approximately $H$ = 0.25 m ($(H-h)/H$ = 0.4), the value of the coefficient $f_m$ increased by approximately 48 % in the main channel and the flow reduction was approximately 38.2 % in the entire channel (Table 1). In variant W 2.T2, with a larger spacing (20x20 cm) and fewer trees, the $f_m$ value increased by approximately 36 % in the smooth main channel and the flow reduction was 24.1 % in the entire channel. The values of the resistance coefficients $f_m$ in variants with trees (W 2.T1 and W 2.T2) increase with the increase of the flow depth (Fig. 7a). The increase in the roughness of the main channel slopes in variant W 3.0 resulted in a significant increase in the $f_m$ value in the main channel (Fig. 7b), for $H$ =

0.251 m by approximately 32 % ((*H-h*)/*H* = 0.36) and for *H* = 0.262 m by approximately 36 % ((*H-h* )/*H* = 0.39), while the flow reduction in the entire channel was approximately 12.9 % and 15 %, respectively. Figure 7b presents the influence of floodplain trees (20x20 cm) on values of resistance coefficients $f_m$ in the main channel in the third variant. In variant W 3.T2, the $f_m$ value in the main channel increased by approximately 57 % for *H* = 0.263 m ((*H-h*)/*H* = 0.39) and for *H* = 0.28 m ((*H-h*)/*H* = 0.43) by approximately 70 %, while the flow reduction in the entire channel was approximately 27.4 % and 31 %, respectively (Table 1).

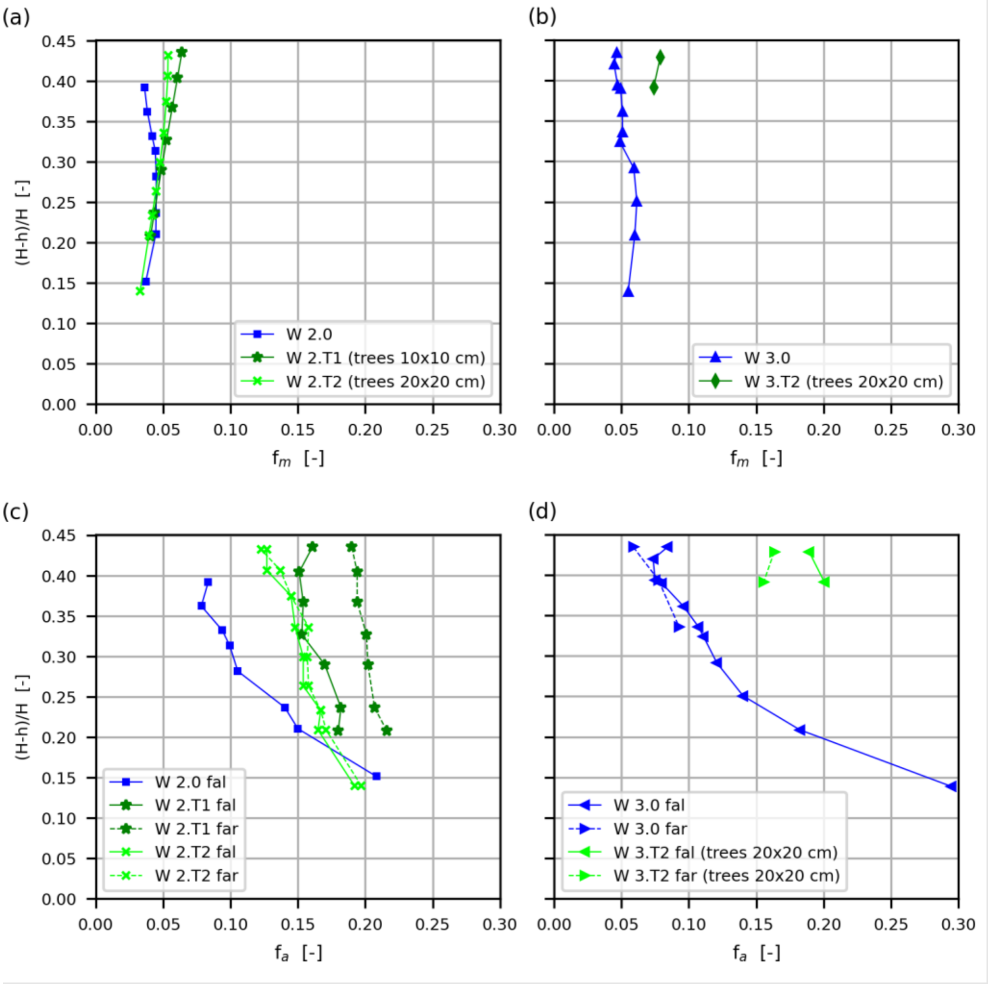

**Figure 7: Variability of resistance coefficients $f_m$ in the main channel and apparent resistance coefficients $f_a$ at the boundary between the main channel and the floodplain as a function of the flow depth (variants without floodplain trees W 2.0 and 3.0, Kubrak et al., 2019).**

Figures 7c and 7d present the influence of floodplain trees on the apparent resistance coefficients $f_a$ at the boundary between the main channel and floodplain in the second and third variants. In variant W 2.0 without trees at the analyzed flow depth

(Fig. 7c) the $f_a$ values decrease quite rapidly with increasing depth. However, in the variants with trees (W 2.T1 and W 2.T2), the $f_a$ values decrease slowly with increasing depth. In variants with trees the $f_a$ values increase compared to the variant without trees. In both cases, the increase in the $f_a$ value is the smallest at low depths on the floodplain, and increases with depth, which is the result of the increase in interactions between the main channel and the tree-covered floodplain. At the depth of $H = 0.20$ m ($(H\text{-}h)/H = 0.21$) in variant W 2.T1 in the left division plane, the $f_{al}$ coefficient value increased by 20 % (Fig. 8c). In the right division plane, the $f_{ar}$ coefficient value is even higher than the left one by 24 %, which indicates asymmetric flow in the main channel, higher flow velocities on the left side of the main channel (Fig. 3, W 2.T1). It is similar at the entire depth, but the variation in the coefficient value increases. At the depth of $H = 0.26$ m ($(H\text{-}h)/H = 0.39$) in the left division plane, the $f_{al}$ coefficient value in variant W 2.T1 increased by about 81 % and the $f_{ar}$ coefficient value is even higher than the left one by 52 %. In variant W2.T2, with a larger spacing (20x20 cm) and fewer trees, the $f_a$ values are similar on the left and right sides of the main channel, and at the depth of $H = 0.20$ m ($(H\text{-}h)/H = 0.21$), the $f_a$ coefficient value increased by about 12 % and at $H = 0.26$ m ($(H\text{-}h)/H = 0.39$) by about 58 % (Fig. 7c). The increase in the roughness of the main channel slopes in variant W3.0 caused the greatest increase in the $f_{al}$ value at small flow depths in the division planes (about 41 %, $H = 0.18$ m, $(H\text{-}h)/H = 0.14$) and decreased with increasing depth (about 22 %, $H = 0.25$ m, $(H\text{-}h)/H = 0.36$) until the values become equal (Fig. 7d). Trees from floodplains in variant W 3.T2 (20x20 cm) at greater depths ($(H\text{-}h)/H \geq 0.39$) resulted in a more than two-fold increase in the $f_a$ value. In the left division plane, the $f_a$ value increased by 168 % at $H = 0.26$ m ($(H\text{-}h)/H = 0.39$) and by 125 % at $H = 0.28$ m ($(H\text{-}h)/H = 0.43$), while in the right division plane by 101 % and 178 % respectively.

An increase in the flow depth in the floodplain resulted in an increase in the influence of the floodplain trees on the flow conditions in the main channel and on the values of the apparent resistance coefficients $f_a$ at the apparent boundary between the main channel and the floodplain (Fig. 7). However, at small flow depths ($(H\text{-}h)/H < 0.2$), the bottom roughness generally determines the coefficient values.

Figure 8 presents the influence of floodplain trees on the values of the resistance coefficients for the bottom $f_{mb}$ and the side slopes $f_{ms}$ of the main channel in the second and third tests. Figure 8a shows that in the W2.0 variant without trees on the floodplains, the $f_{mb}$ coefficient values initially increase slightly and then decrease with increasing depth on the floodplains. The influence of trees in the W2.T1 and W2.T2 variants resulted in the greatest decrease in the value of the $f_{mb}$ coefficient at small flow depths on the floodplain. With increasing flow depth, the value of the coefficient increases and already at approximately (H-h)/H = 0.39 the value is the same as in the variant without trees. Figure 8b shows that the increase in the roughness of the main channel side slopes in variant W 3.0 resulted in a slight increase in the $f_{mb}$ value. However, the floodplain trees in variant W3.T2 (20x20 cm) at higher flow depths ($(H\text{-}h)/H = 0.39\text{-}0.43$) did not result in a change in the $f_{mb}$ value for the bottom of the main channel.

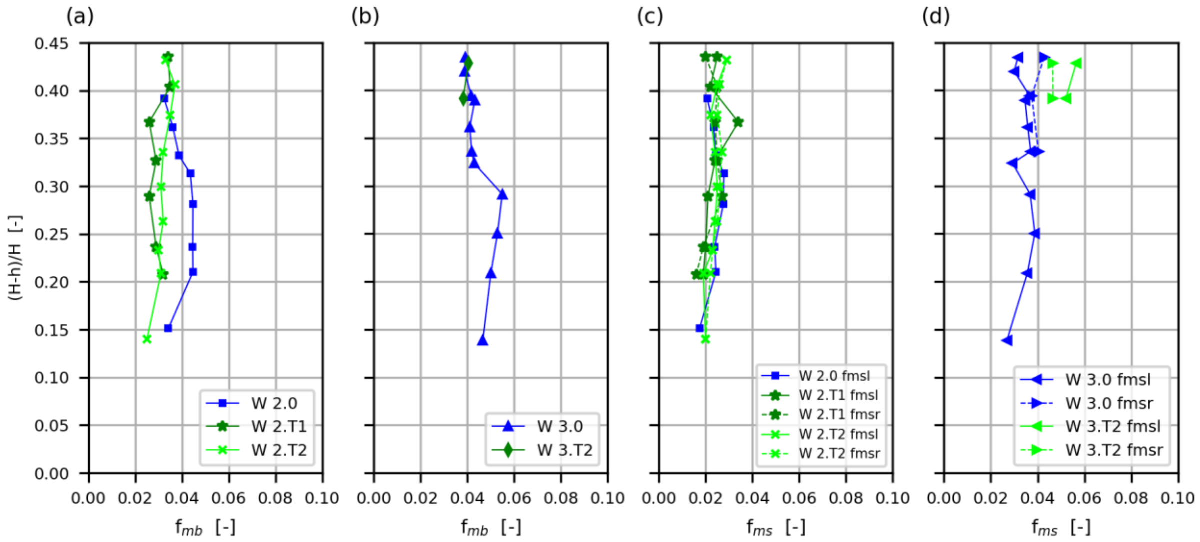

**Figure 8: Variability of resistance coefficients for the bottom $f_{mb}$ and the side slopes $f_{ms}$ of the main channel as a function of the flow depth (variants without floodplain trees W 2.0 and 3.0, Kubrak et al., 2019).**

Figure 8c shows that the influence of trees in the smooth main channel (W2.T1 and W2.T2) resulted in only a slight decrease in $f_{ms}$ values at low flow depths in the floodplain, while at higher depths the coefficients did not change. Figure 8d shows that the increase in the surface roughness of the sloping banks of the main channel (W3.0) resulted in an increase in the $f_{ms}$ value coefficient, also with an increase in the flow depth. The influence of trees in the main channel with rough sloping banks (W3.T2) resulted in different increase in $f_{msl}$ and $f_{msr}$ values at higher flow depths ($(H\text{-}h)/H$ = 0.39-0.43).

The influence of trees on the flow in a compound channel is very significant and the most common observed effect is a large decrease in the water flow value (Table 1) and clear changes in the distribution of the depth average velocity in the cross-section of the compound channel (Fig. 9). It can be observed from the presented results that the influence of trees changes the values of resistance coefficients in the main channel to varying degrees, and the size of the changes depends on the surface roughness. Generally, the influence of trees in the smooth main channel resulted in a large increase in the apparent resistance coefficient but a slight decrease in the value of the bottom resistance coefficient with an almost unchanged resistance coefficient of the main channel side slopes. However, the influence of trees in the channel with the rough surface of the main channel side slopes also resulted in a large increase in the apparent resistance coefficient and a small increase in the value of the resistance coefficient of the main channel side slopes with an unchanged bottom resistance coefficient at large flow depths ($(H\text{-}h)/H$ = 0.39-0.43). The value of the apparent resistance coefficient depends on the surface roughness of the channel bottom, the density of trees and the depth of flow. Changes in the values of the apparent resistance coefficients can be explained by a change in the interaction between the parts of the compound channel, which depends on the magnitude of changes in the average depth velocity in the main channel and on the floodplain (Fig. 9). If the values of the apparent resistance coefficients are all the greater, the greater are the differences between the flow velocities in the main channel and the floodplain.

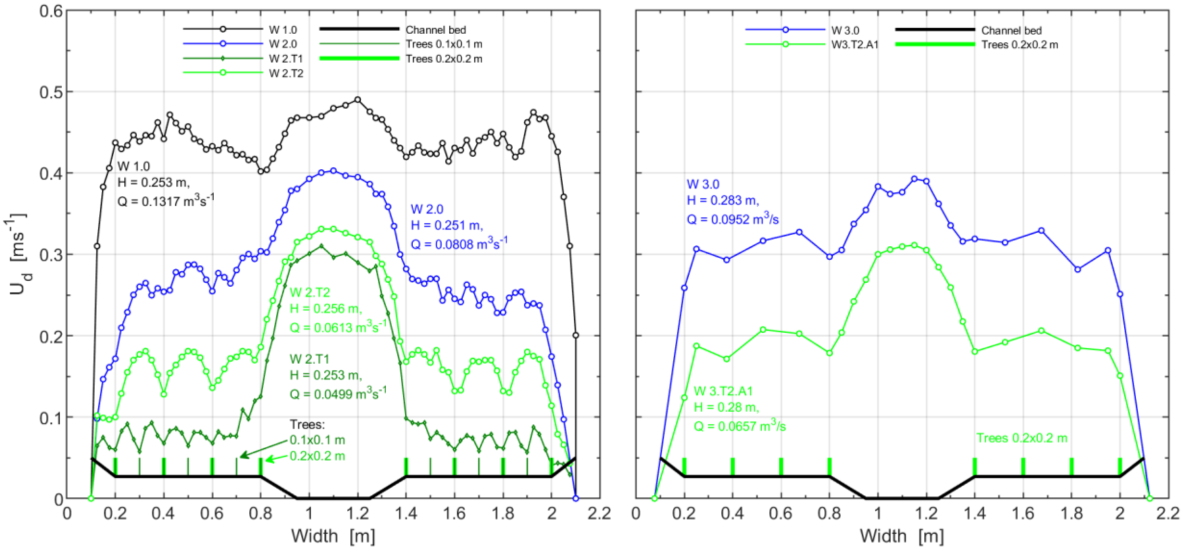

**Figure 9: Distribution of average velocity in verticals in variants W 1.0, W 2.0 and W 3.0 with similar flow depths in the compound channel (The variants without floodplain trees, designated W 1.0 /smooth channel/, 2.0 and 3.0, are derived from the study by Kubrak et al., 2019).**

## 4 Conclusions

The analysis of the values of resistance coefficients determined for the main channel in the compound channel with different bottom roughness with and without trees on floodplains showed that:

1) Floodplain trees cause an increase in floodplain interaction on flow conditions in the main channel, to varying degrees for different coefficients depending on flow depth. The effect of floodplain trees on the value of the resistance coefficient for the entire smooth main channel was observed above the flow depth $(H-h)/H = 0.25$. In contrast, an effect on the value of the apparent resistance coefficient was already observed above the flow depth $(H-h)/H = 0.15$. The values of the apparent resistance coefficient differ little or are identical at very small flow depths in floodplains in variants without and with trees in floodplains (the rough surface of the channel bottom generally has more influence than trees). As the flow depth increased, the trees resulted in a significant increase in the value of the apparent resistance coefficient and reached even twice as high values.

2) Floodplain trees in the channel with rough floodplains and rough sloping banks of the main channel, at large flow depths resulted in a more than two-fold increase in the value of the apparent resistance coefficient.

3) The values of the apparent resistance coefficients decrease with increasing flow depth, slower with trees on floodplains and faster without trees.

4) In the straight compound channel in the main channel (Kubrak et al., 2019) the values of the flow resistance coefficient increase with the flow depth up to (H-h)/H = 0.25, and then the values decrease. The floodplains trees resulted in a continuous increase in the value of the flow resistance coefficient with the flow depth.

5) The values of apparent resistance coefficients are several times greater than the resistance coefficients for side slopes and bottoms of the main channel. The floodplains trees in the smooth main channel resulted in a decrease the value of the resistance coefficients for bottoms of the main channel below depth $(H-h)/H < 0.4$ and only a slight decrease the value for side slopes of the main channel.

## Author contributions

AK, AKi and MK: conceptualisation. AK, AKi, MK, EK, JK, GM and MB: methodology and investigation. AK, AKi and MK: writing – original draft. AK, AKi, MK, GM and MB measuring and analysis of data.

## Competing interests

The contact author has declared that none of the authors has any competing interests.

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