Author’s response to Editor decision and comments from Reviewers

Methods of estimation of resistance to flow under unsteady flow conditions

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We would like to thank the Editor for giving us the opportunity to re-submit the manuscript. Our main problem was to find a compromise among altogether 4 reviews which were not very consistent and had different overtones. We have changed the text substantially mainly following the comments of the most critical Reviewer#1 of the last version of the paper. Accordingly, we have changed the title to reflect the objectives of the manuscript. The manuscript is now entitled: “A methodological approach of estimating of resistance to flow under unsteady flow conditions.”

To be honest we strongly disagree with the statement of the reviewer that we should change the direction away from the shear velocity approach. We may agree that the concept of replacing well established formulae of Manning, Chezy or Darcy-Weisbach is somewhat vague and this has been changed but we cannot agree that studies of shear velocity do not make sense. This is an absolutely crucial and physically well justified value in hydraulic research and very rich literature in this respect is a remarkable evidence of it. Also the studies of the shear velocity under unsteady flow conditions from various perspectives are undertaken in many research centres all over the world and reasonable evaluation of the shear velocity in such conditions may substantially improve our predictive capabilities of sediment transport, turbulent characteristics of flow etc. The thorough discussion of our paper, however made us to rethink our approach and we are very grateful to all Reviewers for this. In this letter we will attend to the remarks of two Reviewers of the last version of the paper. Let us thank Reviewer#1 for encouraging us to look at our analysis from another perspective. We are also very grateful to Reviewer#2 for encouraging comments and detailed suggestions on technical issues.

We have kept the structure of the paper, but, as suggested we have shortened the text by removing excessive references and description of theory which was not directly applied in the study. We decided to present the problem of resistance evaluation from different angle. In the revised version friction slope, friction velocity and Manning n are presented as three widely used ways of expressing resistance. We stress that friction slope and friction velocity is critical and applied amply in studies on hydrodynamic problems in unsteady flow, and for this reason reliable method of evaluation is necessary. On the other hand, Manning n is parameter used in flood routing. We resigned from proving superiority of one approach over another. Instead, we discuss the strengths and weaknesses of each approach and give recommendations on how to improve reliability of results. In the revised version some figures have been improved, and some new figures have been added.

We provide answers to comments from Reviewers below. For clarity each answer is structured as follows: (1) RC# comments from Referees, (2) AR# author's response. Below please find attached a marked-up version of the manuscript.

Answers to Comments of Anonymous Reviewer #1

The following should be considered for improving this article:

RC#1. It does not make much sense to replace a resistance parameter with another one. The idea to replace Manning n with the shear velocity is redundant. The essence of resistance to flow relationships is to define the relationship between the mean flow velocity V and the shear velocity u*. For instance, the Darcy Weisbach friction coefficient f is defined as f = 8 (u*/V)2. The Manning formula is somewhat similar but involves a function of flow depth to the power 1/6. So the resistance coefficients already have a built in function of the shear velocity. So for the above example, to replace f with a function of u* does not simplify things, it also requires measurements of the mean flow velocity V, which is usually what we are looking for. In an ideal world where all parameters are known, the author's idea may make some sense, but in most practical applications where V is the unknown, knowledge of both f and u* or n, u* and h are required. In other words, the approach of the authors does not make much practical sense.

AC#1. We have changed the way of presenting resistance to flow parameters. In the revised version we do not judge about their applicability. Instead, we present them as equal ways of resistance evaluation but used in different kinds of problems. We would like to stress that friction velocity is an extremely important variable necessary in a number of studies on unsteady flow, and there is still a lot of inconsistence in literature on how to evaluate it reliably. We believe that our study is valuable in this regard. When it comes to Manning n, we present it as modelling parameter and do not suggest to abandon it. We have performed new analysis (results shown in Fig. 11) which demonstrated that Manning n is less sensitive on unsteadiness of flow than other discussed variables, and this is its asset as modelling parameter.

RC#2. The use of Manning n (or Chezy C or Darcy-Weisbach f) will not disappear from engineering practice. These methods have been applied for a long time and practitioners have a good feel for what is a high or low Manning n value. The authors suggesting a use of u* instead will have to define what is a high u* and what is a low u* value. There is only doubt that this will prove to be a successful method on the long run. My point here is that the authors are facing strong headwinds and their paper is not very convincing to change well established understanding of rivers.

AC#2. As presented in the previous answer, we removed all recommendations of replacing Manning n by friction velocity. Friction velocity is crucial in another kind of studies – experimental research on unsteady flow, e.g. sediment transport. In such studies it is necessary to evaluate friction velocity by methods dedicated to unsteady flow to apply the results to further analyses.

RC#3. There is data of seemingly good quality during flood propagation, but I do question whether these can be called river flows. I thought something was missing when I noticed discharges less than 1 m3/s in some graphics. The graphs are misleading, and it is misleading to call this river flows in the first place. This looks like a small drainage at best.

AC#3. In fact Olszanka is a small watercourse and we avoided naming it a river. We emphasized it in a revised manuscript. We also added a photo. Let us, however, mention that the language is quite vague in this respect. Very often creeks, brooks and rivulets are called small rivers but this paper is definitely not a good place to discuss this nomenclature.

RC#4. The drainage network presented in Figure 3 seems rather complex. There are forks and tributaries coming into play and the cross-section geometries are not that simple. It is not clear at all that the flows are exactly described by simple equations. Also, the trapezoidal channel geometries raise questions regarding how the shear velocity values are determined. Are those the cross section average value or the values of shear stress (velocity) at the deepest point.

AC#4. The network is quite complex in fact, but tributaries are not so significant as it might have seem from the figure. We decided the figure might have been misleading, and narrowed the width of lines representing tributaries.
Shear velocity has been determined as average cross-sectional value, as velocity used for calculations was cross-sectionally averaged and hydraulic radius was applied in relations on resistance.

RC#5. One of the problems with the shear velocity concept is that it is not clear what method should be used. The authors are well read and provide several good methods for evaluating the shear velocity in gradually varied unsteady flows. It is not clear which of these methods would be best for all cases.

AC#5. In the revised version we stress that we describe and apply only one method – relations derived from flow equations. We mention some other methods to illustrate how important and widely studied is the problem of evaluation of friction velocity. In fact, other methods are not feasible to be applied during flood wave propagation, e.g. turbulence measurements under unsteady flow conditions in natural watercourses are extremely rare. In the recommended method only mean velocity or flow rate and water stage (in a few cross-sections) are necessary.

RC#6. I wish I could see a photo of this site, but I can imagine that there is vegetation involved and it is not clear how the vegetation factors are taken into account in different seasons.

AC#6. In this study we applied data for the beginning of vegetation season. We have added the photo to the manuscript (Fig. 3).

RC#7. There are several cases OL 1-4 and I am not sure they are all needed. Would one or two be sufficient to make the case.

AC#7. We have reduced the number of cases. We have chosen Ol-1 and Ol-2 as representative cases. They represent data from the same experiment in two cross-sections.

RC#8. The article is quite long and this should be shortened quite substantially.

AC#8. The manuscript has been substantially shortened. Excessive passages and references have been removed.

RC#9. There are tons of references all the way to the conclusions and the reader gets lost as to what is the main contribution of the authors as compared to what can be found in the literature. I would think that the number of references could be reduced by at least 50%.

AC#9: We have reduced the number of references.

RC#10. The peak values of resistance coefficients may be the most important for engineering design. What is the difference in predicted stage values with the Manning n approach versus the u* approach that is proposed. By the way, I am still not clear as to what is the correct method for the evaluation of u* that the authors propose.

AC#10. The reviewer raised here a very important issue. It goes, however far beyond the scope of this paper. It was not our aim to discuss the models for predicting the water stages and it may constitute a subject of completely different study.
RC#11. In summary, there is some interesting information in this article but it would need quite a bit of work before publication. There should be a clear presentation of a proposed method. I am sure that a method based on shear velocity will not lead anywhere, and if it is still the intent of the authors after modification of this article, I doubt I would recommend publication. The presentation on the definition of shear velocity in trapezoidal channels with vegetation (at least during some time of year) is quite complex and cannot be over-simplified with a simple analysis of the Saint-Venant equations.
In conclusion, this article is not ready for publication and quite a bit of work would be required per the above discussion. There should be a change of direction away from the shear velocity approach. An analysis of the Saint-Venant terms seems promising and may have more value that the shear velocity. It could be combined with Manning n or Chezy C for instance, but again, the idea of shear velocity seems dead-ended. With modifications along this line and a better description of the site and tremendous reduction in the number of references and redundant text, and a reduction of the number of cases (OL-1-4) to focus on the main ones would be desirable. I would think that a clear explanation of the method of analysis of trapezoidal channels with vegetation – I guess pls show a picture – would be a nice addition. If this is possible from the authors, I would gladly re-review this manuscript. I definitely would like major changes to this paper. If the authors insist on their views with the shear velocity approach, it is likely to end up a useless exercise to ask my opinion about it.
I cannot recommend publication of this article in the present form, but see potential for major changes and improvement of this manuscript. I sincerely hope that the authors will have the courage to thoroughly rework this manuscript, with my best regards.

AC#11. We did our best to follow suggestions of the Reviewer wherever possible. We hope that our revision and explanation are enough for positive recommendation.

Answers to Comments of Anonymous Reviewer #2

RC#1. Lines 64-67: The authors present the different designations of shear stress existing in the literature. Also they state that Prokrajac et al. (2006) present different definitions of shear velocity. Finally in lines 189-193 the authors present their definition. I it pertinent to analyse how this definition relates with the others from the literature?

AC#1. Unfortunately, there are no data available from this experiment to apply other methods. There are only data on mean velocity and water stage which are not sufficient to discuss this important issue Various definitions and methods of determination of shear velocities were the subject of another paper of one of the authors (see Rowiński P.M., Aberle J., Mazurczyk A., 2005, Shear velocity estimation in hydraulic research, Acta Geophysica Polonica 4, pp. 567-583.)

RC#2. Line 98: "This paper is structured as follows." Should not be a period but ":".

AC#2. Corrected.

RC#3. Line 127: What justifies the smaller velocities for Ol-4?

AC#3. It was due to smaller amount of water released in this dam-break experiment compared to other experiments. In revised version this case has been removed.

RC#4. Line 155: Geek letters to Greek letters

AC#4. Corrected.

RC#5. Line 208: Why is the Dey and Lamber (2005) equation omitted?

AC#5. This equation is very long, and is not applied in this study. Finally, as suggested by Reviewer 1 we removed the majority of equations that are not directly applied in the analysis presented in the paper for better clarity.

RC#6. Line 285: Equation 18 is valid for rectangular channels. Does it constitutes a good approximation for the case of a trapezoidal channel?

AC#6. It is a simplification but seems to be very reasonable.

RC#7. Section 3.3.4. An analysis to the relative order of magnitude could have been presented in order to identify which are the terms that contribute more for the uncertainty.

AC#7. We discussed this aspect in the text based on the results presented in the figure with terms of momentum balance equation.

RC#8. Figure 6: Ol-4 ranges up to almost 10000 s. But in Figure 3 it ranges to 8000 s. Although the datasets refer to different experimental conditions, they should be uniform whenever possible.

AC#8. In revised manuscript we present results only for Ol-1 and Ol-2, as Reviewer#1 suggested reduction of data sets. But we have paid attention to this issue in other figures.

RC#8. Figure 7: Why are the dependent variables plotted in the horizontal axis? If these plots represent discrete values the red and black lines should be discrete as well.

AC#8. We have corrected the figure, as suggested.

RC#9. Figure 9: There are error bars missing for Ol-2 and Ol-3.

AC#9. They were hidden behind other lines. In revised version, we decided that it is correct to show error bars only for the results obtained from dynamic wave relations, and we changed it in all figures.

RC#10. Figure 10. Similarly to Figure 9, the error bars should be plotted. Also Ol-4 horizontal axis goes up to almost 10000.

AC#10. In revised version we have added uncertainty analysis of Manning n.

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~~Methods~~ A methodological approach of ~~estimation~~ estimating of resistance to flow under unsteady flow conditions

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Abstract. ~~The paper discusses methods of expressing and evaluating~~ This paper presents evaluation and analysis of resistance to flow ~~in an unsteady flow. Following meaningful trends in hydrological sciences, the paper suggests abandoning, where possible, resistance coefficients in favour of physically based variables such as shear stress and friction velocity to express flowresistance. Consequently, an acknowledged method of flow resistance evaluation based on the relations derived from flow equations is examined. The paper presents both a theoretical discussion of various aspects of flow resistance evaluation and the application of the method to field data originating from~~ expressed as friction slope, friction velocity and Manning n in unsteady flow. Measurements of flow parameters obtained from artificial dam-break flood waves in a small lowland ~~river. As the method is prone to many errors due to the scarcity and the uncertainty of measurement data, the aim of the paper is to provide~~ watercourse have made it possible to apply relations for resistance derived from flow equations. The first part of the paper provides suggestions on how to apply ~~the method to enhance the correctness~~ this method to minimize the uncertainty of the results. ~~The main steps in applying the method include consideration of the shape of the channel, the type of wave, the method of evaluating the gradient of the flow depth, and the assessment of the uncertainty of the result. Friction velocity and the Manning coefficient are compared in terms of resistance to flow variability during flood wave propagation. It is concluded that the Manning coefficient may be a misleading indicator of the magnitude of resistance in unsteady flow , and to be inferior to physically based variables in such cases~~Proposed methodology enhances the reliability of resistance evaluation in unsteady flow, and may be particularly useful in research investigating impact of flow unsteadiness on hydrodynamic processes. In the second part of the paper, the results of friction slope, friction velocity and Manning n are analysed. The study demonstrates that unsteadiness of flow has larger impact on friction slope and friction velocity than on Manning n. Manning n, adequate as flood routing parameter, may

appear to be misleading when information on unsteadiness of flow is crucial. Then friction slope or friction velocity seems to be better choice.

1 Introduction

Resistance is one of the most important factors affecting the flow in open channels. In simple terms it is the effect of water viscosity and the roughness of the channel boundary which result in friction forces that retard the flow. The largest input into the resistance is attributed to water-bed interactions.

~~The resistance and its impact on flow parameters is traditionally characterised by resistance coefficients such as Manning n, Chezy C or Darcy-Weisbach f. However, their application has been challenged in recent years (Carrivick, 2010; Ferguson, 2010; Knight and Shino, 1996; Lane, 2005; Strupczewski and Szymkiewicz, 1996a, b; Wh The strongest critique is directed towards the most popular resistance coefficient~~ Resistance to flow is expressed by friction slope S which is dimensionless variable or boundary shear stress τ which refers directly to the shearing force acting on the channel boundary, with the dimension of Pascal [Pa]. Alternatively, shear stress is expressed in velocity units $[\mathrm{m\,s^{-1}}]$ by friction (shear) velocity u_*, which is related to the shear stress and friction slope by the equation:

$$u_* = \sqrt{\frac{\tau}{\rho}} = \sqrt{gRS}, \tag{1}$$

where g – ~~Manning n. This was supposed to be invariant with the water stage; however, in practise~~ gravity acceleration $[\mathrm{m\,s^{-2}}]$, ρ – density of water $[\mathrm{kg\,m^{-3}}]$. Shear stress and friction velocity are crutial in research on hydrodynamics problems such as bed load transport (?), rate of erosion (Garcia, 2007), contaminants transport (Kalinowska and Rowiński, 2012; Kalinowska et al., 2012), turbulence characteristics of flow (Dey et al., 2011).

On the other hand, in engineering practice the resistance is traditionally characterised by Manning n~~very often varies (Ferguson, 2010). It is not clear how to interpret this variability in the light of resistance definition~~, Chezy or Darcy-Weisbach coefficients. The flow resistance equation (Eq. 1) relating flow parameters through Manning n was originally derived for steady uniform flow conditions:

$$n = \cancel{\frac{1}{U}R^{2/3}}\frac{R^{2/3}}{U}S^{1/2}, \tag{2}$$

where R – hydraulic radius $[\mathrm{m}]$, ~~S – friction slope –,~~ U – mean cross-sectional velocity $[\mathrm{m\,s^{-1}}]$. ~~For this reason, the resistance coefficient is meaningful only in such cases. However, its~~ Its application is accepted for gradually varied flows ~~, especially in flood wave modelling. Constant values of~~ for which friction slope can be approximated by bed slope I. Manning n ~~are usually applied in such studies; a procedure which has been questioned (Julien et al., 2002), as resistance coefficients have been shown to vary during flood wave propagation (Fread, 1985; Julien et al., 2002). However, in such cases resistance coefficients are mainly model parameters, since physical interpretation of~~

~~variable Manning n is not obvious. Further aspect of possible misinterpretation of variable Manning n is the fact that~~ was supposed to be invariant with the water stage; however, research has shown that the resistance coefficient very often varies (Ferguson, 2010; Fread, 1985; Julien et al., 2002) . Furthermore, the trend of n versus flow rate Q may be falling or rising depending on the geometry of wetted area. Fread (1985) reported, based on computations of n from extensive data of flood waves in American rivers, that the trend is falling when inundation area is relatively small compared to inbank flow area; in reverse case the trend is rising. ~~This inconsistency stems from the fact that~~

In unsteady flow additional factors affect flow resistance ~~in unsteady flow~~ compared to steady flow. As Yen (2002) presents after Rouse (1965), besides water flow-channel boundary interactions represented by skin friction and form drag, resistance has two more components: wave resistance from free surface distortion and resistance due to local acceleration or flow unsteadiness. ~~The concept of resistance coefficients is not able to reflect the variability of the resistance in such cases.~~ Consequently, in order to evaluate resistance in unsteady flow it might be not sufficient to approximate friction slope S by bed slope I.

~~Many authors argue that the description of resistance to flow is unsatisfactory (Beecham et al., 2005; Chaudhry, 2011; Knight, 2013a~~ ~~For the above reasons, it seems more meaningful to consider friction force, rather than resistance coefficients, as a basic term expressing resistance to flow. In this respect, resistance is represented by boundary shear stress τ which refers directly to the shearing force acting on the channel boundary, with the dimension of Pascal . Alternatively, shear stress is expressed in velocity units by friction (shear) velocity u_*, which is related to the shear stress and friction slope by the equation:~~

$$\cancel{u_* = \sqrt{\frac{\tau}{\rho}} = \sqrt{gRS},}$$

~~where g – gravity acceleration , ρ – density of water . As shear stress and friction velocity describe directly physical processes, there are no background theoretical doubts about their soundness in unsteady flow unlike in the case of Manning n. Moreover, interpretation of their variability is straightforward – they rise with rising resistance to flow.~~

~~The proper definition and understanding of shear stress and friction velocity is of great importance, since shear stress is an intrinsic variable in a number of hydrological problems, such as bed load transport, rate of erosion and contaminants transport (Garcia, 2007; Julien, 2010; Kalinowska and Rowiński, 2012; Kalinowska et al.,~~ ~~Boundary shear stress is expressed on a range of spatial scales from a point value to a global one (Yen, 2002) . The following types of boundary shear stress are defined: local bed shear stress (Khodashenas et al., 2008) , average bed shear stress; average wall shear stress (Khiadani et al., 2005) ; and finally average boundary shear stress, i.e. averaged over a wetted perimeter (Khiadani et al., 2005) . It should be noted that the nomenclature is inconsistent, and other authors may use different terminology (Ansari et al., 2011; Khiadani et al., 2005; Khodashenas et al., 2008; Knight et al., 1994) . Moreover, a number of definitions of friction velocity exist (Pokrajac et al., 2006) . Hence, for clarity a reference to a definition is necessary in each study.~~

~~It is difficult to measure bed shear stress directly. The direct method, which uses a floating element balance type device, enables the measurement of the force acting tangentially on a bed, and is used in both field (Gmeiner et al., 2012) and laboratory studies (Kaczmarek and Ostrowski, 1995) ; however, the results are prone to high uncertainty~~Large variety of methods of bed shear stress and friction velocity evaluation have been devised in order to study the flow resistance experimentally. The majority of methods measure bed shear stress indirectly, e.g. using hot wire and hot film anemometry ~~(Albayrak and Lemmin, 2011; Nezu et al., 1997)~~ (Albayrak and Lemmin, 2011) , a Preston tube ~~(Molinas et al., 1998; Mohajeri et al., 2012)~~ (Mohajeri et al., 2012) , methods that take advantage of theoretical relations between shear stress and the horizontal velocity distribution ~~(Graf and Song, 1995; Khiadani et al., 2005~~ methods based on Reynolds shear stress ~~(Biron et al., 2004; Campbell et al., 2005; Czernuszenko and Rowiński, 2008; Dey and Barbh~~ turbulent kinetic energy ~~(Galperin et al., 1988; Kim et al., 2000; Pope et al., 2006)~~ (Pope et al., 2006) , or methods that incorporate double-averaged momentum equation (Pokrajac et al., 2006). ~~Despite the fact that there is a variety of methods , a handful of them are feasible for application in unsteady flow conditions.~~

~~In this paper we apply formulae derived from flow equations to evaluate both friction velocity and Manning n, because these formulae require input variables which are feasible to be monitored during passage of a flood wave – flow rate or velocity and water stage. They have been claimed to be reasonable means of friction velocity assessment in unsteady flow by~~ These methods are impractical or even impossible to be applied during flood wave propagation. Instead, a number of authors ~~, e.g. Afzalimehr and Anctil (2000); De Sutter et al. (2001); Ghimire and Deng (2011, 2013); Graf and Song (1995); Guney et al. (2013); R~~ formulae derived from flow equations (Ghimire and Deng, 2011; Graf and Song, 1995; Guney et al., 2013; Rowiński et al., 2000) ; nonetheless, ~~in-depth analysis is still needed because this method provides uncertain results when measurement data are scarce. For this reason , the paper aims to complement the existing research studies in this field~~this method needs further development because scarce measurement data very often restrict the relationships on resistance to simplified forms which provide uncertain results. Among simplifications applied in literature there are simplifications of momentum balance equation terms and simplifications that refer to the evaluation of $\frac{\partial h}{\partial x}$. This method requires flow velocity and flow depth as input variables and for this reason its practical application is restricted. However, it is a good choice for research purposes.

In this study we apply formulae derived from flow equations to obtain values of friction slope, Manning n and friction velocity given data on flow parameters. The objectives of this paper are twofold: (1) to ~~describe how to determine friction velocity for unsteady flow with critical review of existing methods based on flow equations, (2) to provide methodology to minimise uncertainty of~~ enhance the evaluation of resistance to flow ~~evaluated by relationships~~ by relations derived from flow equations ~~, (3) to illustrate inconsistency between the results of friction~~ and by providing relevant methodology, (2) to analyse to what extent friction slope, friction velocity and Manning n ~~results in the context of resistance evaluation in unsteady flow.~~ vary in unsteady flow. The first objective could be valuable for those who would like to apply relations derived from flow equations to evaluate resistance and its impact on hydrodynamic processes, e.g. sediment transport, while the other could be of interest to those who use resistance coefficients in modelling practice.

The paper is structured as follows~~.~~: Section 2 presents settings of dam-break field experiment and measurement data. Methodology of evaluation of friction slope, friction velocity and Manning n in unsteady flow with focus on detailed aspects of application of formulae derived from flow equations is outlined in Sect 3. In Sect 4 results of computations of friction slope, friction velocity and Manning n are presented for field experiment. In Sect 5 conclusions are provided. The problem presented herein has been partially considered in the unpublished Ph.D. thesis of the first author of this paper (Mrokowska, 2013).

2 Experimental data

The data originate from an experiment carried out in the Olszanka ~~River~~ which is a small lowland ~~river~~ watercourse in central Poland (see upper panel of Fig. 1) convenient for experimental studies. The aim of the experiment was to conduct measurements of hydraulic properties during artificial flood wave propagation. To achieve this goal, a wooden dam was constructed across the ~~river~~channel, then the dam was removed in order to initiate a wave. Then, measurements were carried out at downstream cross-sections. Two variables were monitored: the velocity and the water stage. Velocities were measured by propeller current meter in three verticals of a cross-section at two water depths. Water stage was measured manually by staff gage readings. Geodetic measurements of cross-sections were performed prior to the experiment. An in-depth description of the experimental settings in the Olszanka ~~River~~ watercourse may be found in (Szkutnicki, 1996; Kadłubowski and Szkutnicki, 1992), and a description of similar experiments in the same catchment is presented in (Rowiński and Czernuszenko, 1998; Rowiński et al., 2000).

In the study, two cross-sections, denoted in Fig. 1 as CS1 and CS2, are considered. Cross-section CS1 was located about 200 m from the dam, and cross-section CS2 about 1600 m from it. The shape of the cross-sections is presented in the bottom panel of Fig. 1. Both were of trapezoidal shape with side slopes of $m_1 = 1.52$, $m_2 = 1.26$ and $m_1 = 1.54$, $m_2 = 1.36$ for CS1 and CS2, respectively (Fig. 2). The bed slope I was 0.0004 for CS1 and 0.0012 for CS2.

~~Four~~ Two data sets are used in this study, denoted as follows: Ol-1, Ol-2~~, Ol-3, Ol-4~~. Other data sets provided qualitatively similar results and therefore, for simplicity, are not presented herein. The first set was collected in cross-section CS1 and the ~~others~~ other in cross-section CS2 ~~. Data sets Ol-1 and Ol-2 were collected~~ during the passage of the same wave on 26 April ~~1990. Data set Ol-3 was collected on 27 April~~ 1990 ~~, and Ol-4 on 9 May 1991. Measurement data used in this paper were collected~~ at the beginning of vegetation season when banks were slightly vegetated ~~.~~(Fig. 3). The bed was composed of sand and silt with no significant bed forms. Figure ~~3~~ 4 illustrates the results of the measurements – the temporal variability of mean velocity (U) and flow depth (h). Mean velocity has been evaluated by the velocity-area method from propeller current meter readings and flow depth has been calculated from geodetic data and measurements of water stage. Please note the time lag between maximum values of U and h, which indicates the non-kinematic character of the waves. ~~Similarly, the time lag may be observed in the data of Shen and Diplas (2010) .~~ Consider that waves represent a ~~gradually-varied~~ one-dimensional subcritical flow, with a Froude number ($\mathrm{Fr} = U/\sqrt{gh}$) smaller than 0.33. The loop-shaped relationship between flow rate (Q) and water stage (H) may be observed in Fig. ~~4~~5. From the figure it can be seen that the rating curves are not closed~~for Ol-1, Ol-2 and Ol-3~~, which is probably caused by too short series of measurement data.

~~Data set Ol-1 was applied in (Mrokowska and Rowiński, 2012; Rowiński et al., 2000) , and data set Ol-4 in (Mrokowska et al., 2013) , and to the authors knowledge, none of the data sets have been utilised elsewhere in the context of the evaluation of friction velocity.~~

3 Methods

~~Formulae for friction velocity under unsteady flow conditions are usually~~ The methodology of evaluating resistance to flow from flow equations is proposed. It comprises four questions that need to be answered to obtain reliable values of resistance:

1. What is the shape of the channel – is simplification of the channel geometry applicable?
2. Is it admissible to apply simplified formula with regard to the type of wave?
3. What methods of evaluating input variables, especially $\vartheta = \frac{\partial h}{\partial x}$, are feasible in the case under study?
4. What is the uncertainty of the input variables, and which of them are most significant?

In proceeding sections a thorough review of each questioned issue is given. Methods used in the literature are facilitated with critical analysis, and some new approaches are proposed by the authors.

3.1 Relations for resistance in unsteady non-uniform flow derived from flow equations

In this study, resistance to flow is evaluated by formulae derived from flow equations – the momentum conservation equation and the continuity equation~~in both forms: the 2D Navier-Stokes Reynolds averaged equations (Dey and Lambert, 2005; Graf and Song, 1995; Nezu et al., 1997) and 1D St. Venant model (Ghimire and Deng, 2011; Rowiński et al., 2000; Shen and Diplas, 2010) . Despite the fact that there are many ways of deriving the formulae, when the same assumptions of flow conditions are made, the formulae are equivalent. Please note that the same approach may be applied to evaluate Manning n from flow equations.~~

~~The~~ . Here we propose to evaluate resistance to flow for dynamic wave from the relations derived from the St. Venant model for ~~a rectangular channel which comprises Eqs. (3) and (4) is the most frequently used mathematical model to derive formulae on resistance:~~ trapezoidal channel (Mrokowska et al., 2013) :

$$U(b+mh)\frac{\partial h}{\partial x}+\left(b+\frac{m}{2}h\right)h\frac{\partial U}{\partial x}+(b+mh)\frac{\partial h}{\partial t}=0, \tag{3}$$

$$\frac{\partial h}{\partial x}+\frac{U}{g}\frac{\partial U}{\partial x}+\frac{1}{g}\frac{\partial U}{\partial t}+S-I=0, \tag{4}$$

where ~~I – bed slope -,~~ t – time [s], x – longitudinal coordinate [m]~~.~~, b – width of river bed [m], h – here: the maximum flow depth in the channel section (trapezoidal height) [m], $m=m_1+m_2$, m_1 and m_2 – side slopes [-] defined as $m_1=l_1/h$ and $m_2=l_2/h$. The cross sectional shape with symbols is depicted in Fig. 2. Equation (3) is the continuity equation and Eq. (4) is the momentum balance equation which the terms represent as follows: the gradient of flow depth (hydrostatic pressure term), advective acceleration, local acceleration, friction slope and bed slope. Further on, derivatives will be denoted by ~~Geek~~ Greek letters to stress that they are treated as variables, namely $\zeta=\frac{\partial U}{\partial t}$ [m s^{-2}], $\eta=\frac{\partial h}{\partial t}$ [m s^{-1}], $\vartheta=\frac{\partial h}{\partial x}$ [-].

~~To evaluate Manning n or friction velocity, friction slope S is extracted from the above~~ The friction slope derived analytically from the set of equations ~~and~~ is represented by the following formula:

$$S=I+\left(\frac{U^2}{g}\frac{b+mh}{bh+m\frac{h^2}{2}}-1\right)\vartheta+\frac{U}{g}\frac{b+mh}{bh+m\frac{h^2}{2}}\eta-\frac{1}{g}\zeta \tag{5}$$

To evaluate friction velocity and Manning n Eq. (5) is incorporated into Eq. (1) ~~or~~ and Eq. (2), respectively~~. We would like to stress again that it is questionable if this way of S assessment in evaluation of Manning n is meaningful. However, relationships derived this way are applied in this paper for comparative purposes~~:

$$u_*=\left[gR\left(I+\left(\frac{U^2}{g}\frac{b+mh}{bh+m\frac{h^2}{2}}-1\right)\vartheta+\frac{U}{g}\frac{b+mh}{bh+m\frac{h^2}{2}}\eta-\frac{1}{g}\zeta\right)\right]^{\frac{1}{2}}. \tag{6}$$

$$n=\frac{R^{2/3}}{U}\left(I+\left(\frac{U^2}{g}\frac{b+mh}{bh+m\frac{h^2}{2}}-1\right)\vartheta+\frac{U}{g}\frac{b+mh}{bh+m\frac{h^2}{2}}\eta-\frac{1}{g}\zeta\right)^{\frac{1}{2}}. \tag{7}$$

Equations (5, 6 and 7) are considered in this study, as Olszanka watercourse has nearly trapezoidal cross-section.

~~Scarce and uncertain measurement data very often restrict the relationships on resistanceto simplified forms. Among simplifications applied in literature there are simplifications of momentum balance equation terms (i.e. type of wave) and simplifications of channel geometry that affect the number of~~

~~terms in the relationships. Another simplification which is very often applied due to limited spatial data refers to the evaluation of $\frac{\partial h}{\partial x}$. Simplified methods are welcome, especially for practitioners.However, they must be justified properly, and there seems to be a gap here.It is crucial to choose the best method for a case under study. In proceeding sections a thorough review of each aspect of simplifications, description of uncertainty evaluation and finally a methodology for evaluation of resistance to flow is given. One may choose the best method to considered case from the presented herein. To the best of our knowledge such analysis is presented for the first time.~~ Flow equations for rectangular channel or unit width are the most frequently used mathematical models to derive formulae on resistance. A number of formulae for friction velocity has been presented in the literature, e.g.:

- Graf and Song (1995) derived the formula from the 2D momentum balance equation:

$$u_* = \left[ghI + \left(-gh\vartheta(1-(\mathrm{Fr})^2)\right) + (\eta - h\zeta)\right]^{\frac{1}{2}}, \tag{8}$$

- Rowiński et al. (2000) , and next Shen and Diplas (2010) applied the formula derived from the St. Venant set of equations:

$$u_* = \left[gh\left(I + \left(\frac{U^2}{gh} - 1\right)\vartheta + \frac{U}{gh}\eta - \frac{1}{g}\zeta\right)\right]^{\frac{1}{2}}. \tag{9}$$

- Tu and Graf (1993) derived the equation from the St. Venant momentum balance equation:

$$u_* = \left[gh\left(I + \frac{1}{C}\eta - \frac{1}{g}\zeta\left(1 - \frac{U}{C}\right)\right)\right]^{\frac{1}{2}}, \tag{10}$$

where C – wave celerity $[\mathrm{m\,s^{-1}}]$.

3.2 ~~Simplification~~ Simplifications of ~~momentum balance equation terms (~~relations with regard to type of ~~wave)~~flow

~~Equations (3) and (4) in the full form represent a dynamic wave.~~ If the acceleration terms of ~~Eq. (~~momentum balance equation for dynamic wave (Eq. 4) are negligible, they may be eliminated, and the model for a diffusive wave is obtained. Further omission of the hydrostatic pressure term leads to the kinematic wave model, in which only the term responsible for gravitational force is kept. ~~The simplifications of the St. Venant model have been investigated in many papers in the context of flood wave modelling (Aricó et al., 2009; Dooge and Napiórkowski, 1987; Moussa and Bocquillion, 1996; Yen and Tsai, 2001) . Some authors have concluded that the diffusive approximation is satisfactory in the majority of cases (Ghimire and Deng, 2011; Moussa and Bocquillion, 1996; Yen and Tsai, 2001) , especially for lowland rivers. However, according~~ According to Gosh (2014); Dooge and Napiórkowski (1987); Julien (2002), in the case of upland rivers, i.e. for average bed slopes, it could be necessary to apply the full set of St. Venant equations. Aricó et al. (2009) have pointed that this may be the case for mild and small bed slopes. Moreover, artificial flood waves, such as dam-break-like waves (Mrokowska et al., 2013), and waves due to hydro-peaking ~~(Shen and Diplas, 2010; Spiller et al., 2014)~~ (Shen and Diplas, 2010) , are of a dynamic character. On the other hand, when the bed slope is large, then the gravity force dominates and the wave is kinematic (Aricó et al., 2009). Because of the vague recommendations in the literature, we suggest analysing whether simplifications are admissible separately in each studied case.

~~The friction velocity derived from the Eqs. (3) and (4) represents the value averaged over a wetted perimeter: the bulk variable. If the channel width is much larger than the flow depth, the mean cross-sectional velocity U is equivalent to the depth-averaged velocity above any location of the bed, and the hydraulic radius R may be substituted by the flow depth h. Consequently, the bulk friction velocity is equivalent to the bed friction velocity.~~

~~Formulae for friction velocity encountered in the literature may be classified into five groups according to the type of flow. They are the formulae on both bed $u_{*\mathrm{b}}$ and bulk $u_{*\mathrm{a}}$ friction velocity. They may be recalculated to Manning n if necessary. Formulae for unsteady non-uniform flow in a rectangular channel (dynamic wave): Graf and Song (1995) derived the formula from the 2D momentum balance equation:~~ Below we provide simplified relations for diffusive wave which are applied in this study:

$$u_{*\mathrm{b}} S = ghI + - ghI - \vartheta(1-(\cancel{\mathrm{Fr}})^2) \pm \eta - h\zeta^{\frac{1}{2}}, where \mathrm{Fr} - - Froude number - .$$ Rowiński et al. (2000) , $and next$ Shen and Diplas (201

~~Tu and Graf (1993) derived the equation from the St. Venant momentum balance equation:~~

$$u_{*\mathrm{b}} = \left[gh\left(I + \frac{1}{C}\eta - \frac{1}{g}\zeta\left(1 - \frac{U}{C}\right)\right)\right]^{\frac{1}{2}},$$

~~where C – wave celerity . Dey and Lambert (2005) derived the formula from the 2D Reynolds equations which incorporated data on bed roughness. To see the equation please refer to (Dey and Lambert, 2005) .~~

~~Formulae for diffusive wave approximation: Guney et al. (2013) applied the formula derived from the St. Venant momentum balance equation:~~

$$u_{*\mathrm{a}} = [gR(I - \vartheta)]^{\frac{1}{2}}.$$

~~Ghimire and Deng (2011) combined the diffusive wave formula with the kinematic wave assumption to assess ϑ, and obtained the following formula:~~

$$u_{*\mathrm{a}} = \left[gR\left(I + \frac{1}{BC^2}\frac{\partial Q}{\partial t}\right)\right]^{\frac{1}{2}},$$

~~where B – width of rectangular channel m, Q – flow rate . Formula for steady non-uniform flow derived by Afzalimehr and Anctil (2000) from the 1D continuity and momentum balance equations:~~

$$u_{*\mathrm{b}} = \left[gh\left(I - \vartheta\left(1 - (\mathrm{Fr})^2\right)\right)\right]^{\frac{1}{2}}.$$

~~Formula for flow with negligible advective acceleration derived by Nezu et al. (1997) for $\frac{\tau}{\rho} = u_*^2$ from the 2D momentum and continuity equation:~~

$$\frac{\tau}{\rho} \cong gS_{\mathrm{w}}R - \frac{1}{B}\frac{\partial Q}{\partial t},$$

~~where S_{w} –~~ which is equivalent to water surface slope~~$S_{\mathrm{w}} = I - \vartheta$. Formula for steady flow or kinematic wave which neglect all variables responsible for the temporal and spatial variability of flow:~~

$$u_* = [gRI]^{\frac{1}{2}}.$$

3.3 ~~Cross-sectional channel geometry~~

$$u_* = [gR(I - \vartheta)]^{\frac{1}{2}}, \tag{12}$$

~~Besides a rectangular channel, another widely analysed channel shape is a trapezoidal one. The distribution of the shear stress in the steady flow along the boundary of a trapezoidal channel has been studied experimentally (Knight et al., 1992, 1994) and theoretically (Ansari et al., 2011) . The bulk friction velocity for a dynamic wave in a trapezoidal channel may be evaluated from the relation derived from the St. Venant model (Eqs. 13 and 14) (Mrokowska et al., 2013) . The cross sectional shape with symbols is depicted in Fig. 2.~~

$$U(b+mh)\frac{\partial h}{\partial x} + \left(b + \frac{m}{2}h\right)h\frac{\partial U}{\partial x} + (b+mh)\frac{\partial h}{\partial t} = 0,$$

$$\frac{\partial h}{\partial x} + \frac{U}{g}\frac{\partial U}{\partial x} + \frac{1}{g}\frac{\partial U}{\partial t} + S - I = 0,$$

~~where b – width of river bed , h – here: the maximum flow depth in the channel section (trapezoidal height) , $m = m_1 + m_2$, m_1 and m_2 – side slopes -defined as $m_1 = l_1/h$ and $m_2 = l_2/h$. The friction velocity derived analytically from the set of equations is represented by the following formula:~~

$$n = \frac{R^{2/3}}{U}(I - \vartheta)^{\frac{1}{2}}. \tag{13}$$

Relations for steady flow are as follows:

$$u_{*\mathrm{a}}S = gRI \pm \frac{U^2}{g}\frac{b+mh}{bh+m\frac{h^2}{2}} - 1\vartheta + \frac{U}{g}\frac{b+mh}{bh+m\frac{h^2}{2}}\eta - \frac{1}{g}\zeta^{\frac{1}{2}}., \tag{14}$$

~~Equation (15) is considered in this study, as Olszanka River has nearly trapezoidal cross-section.~~

$$u_* = (gRI)^{1/2}. \tag{15}$$

$$n = \frac{R^{2/3}}{U} I^{1/2}, \tag{16}$$

3.3 Evaluation of the gradient of flow depth ϑ

The ~~gradient of flow depth $\vartheta = \frac{\partial h}{\partial x}$ is a significant variable in both dynamic (Eqs. 5, 6, 15) and diffusive (Eq. 8) friction velocity formulae. Moreover, the~~ evaluation of ϑ is widely discussed in hydrological studies on flow modelling and rating curve assessment ~~(Dottori et al., 2009; Perumal et al., 2004; Schmidt and Yen, 2008)~~ (I
The gradient of flow depth is evaluated based on flow depth measurements at one or a few gauging stations. Due to the practical problems with performing the measurements, usually only one or two cross-sections are used. ~~This constitutes one crucial obstacle when seeking friction velocity.~~

3.3.1 Kinematic wave concept

According to the kinematic wave concept, the gradient of flow depth is evaluated implicitly based on measurements in one cross-section~~by Eqs. (16) or (17) (Graf and Song, 1995; Perumal et al., 2004) .~~ :

$$\vartheta_{\text{kin}} = \frac{\partial h}{\partial x} = -\frac{1}{C}\frac{\partial h}{\partial t}. \tag{17}$$

$$\vartheta_{\text{kin}} = \frac{\partial h}{\partial x} = -\frac{1}{BC^2}\frac{\partial Q}{\partial t}. \tag{18}$$

This approach is encountered in friction velocity assessment studies ~~(De Sutter et al., 2001; Graf and Song, 1995; Ghimire and Deng~~
However, this method has been challenged in rating-curve studies ~~(Dottori et al., 2009; Perumal et al., 2004; Schmidt and Yen, 2008)~~ (I
to its theoretical inconsistency. As Perumal et al. (2004) presented, Jones introduced the concept in 1915 in order to overcome the problem of $\frac{\partial h}{\partial x}$ evaluation in reference to looped rating curves, i.e. non-kinematic waves. The looped shape of non-kinematic waves results from the acceleration of flow and the gradient of flow depth ~~(Henderson, 1963; Silvio, 1969)~~ (Henderson, 1963) . The kinematic wave, on the other hand, has a one-to-one relationship between the water stage and flow rate, which is equivalent to a steady flow rating curve. Both rating curves are illustrated in the upper panel of Fig. ~~5~~ 6 after (Henderson, 1963). ~~The kinematic wave concept results in the Jones formula which is applied in this study:~~

$$\vartheta_{\text{kin}} = \frac{\partial h}{\partial x} = -\frac{1}{C}\frac{\partial h}{\partial t}.$$

~~Furthermore, ϑ may be expressed by the temporal variation of the flow rate instead of the flow depth (Ghimire and Deng, 2011; Julien, 2002) , which leads to the following approximation :~~

$$\vartheta = \frac{\partial h}{\partial x} = -\frac{1}{BC^2}\frac{\partial Q}{\partial t}.$$

In this study, the impact of kinematic wave approximation on arrival time of $\frac{\partial h}{\partial x} = 0$ is analysed. Both approximations, Eqs ~~. (16~~(17) and (~~17~~18), affect the time instant at which $\frac{\partial h}{\partial x} = 0$. As shown in the upper panel of Fig. ~~5~~6, in the case of a non-kinematic subsiding wave, the peak of the flow rate $\frac{\partial Q}{\partial t} = 0$ in a considered cross-section is followed by the temporal peak of the flow depth $\frac{\partial h}{\partial t} = 0$, while the spatial peak of the flow depth $\frac{\partial h}{\partial x} = 0$ is the final one. The bottom panel of Fig. ~~5~~ 6 presents schematically the true arrival time of $\frac{\partial h}{\partial x} = 0$ for the non-kinematic wave, and the arrival time approximated by the kinematic wave assumption in the form of Eq. (~~16~~17) and Eq. (~~17~~18). Both formulae underestimate the time instant at which $\frac{\partial h}{\partial x} = 0$. As a matter of fact, from the practical point of view, the evaluation of the friction velocity is exceptionally important in this region, as intensified transport processes may occur just before the wave peak ~~(Bombar et al., 2011; De Sutter et al., 2001; Lee et al., 2004) . Consequently, it seems that the admissibility of the kinematic wave assumption should be thoroughly verified for a wave under consideration.~~ (Bombar et al., 2011; De Sutter et al., 2001) .

In order to apply the kinematic wave approximation, the wave celerity must be evaluated. Celerity can be assessed by the formula ~~for a wide rectangular channel~~ derived from the Chezy equation (Eq. ~~18) (Henderson, 1963; Julien, 2002)~~ 19) (Henderson, 1963) , and it is applied in this study.

$$C = \frac{3}{2}U. \tag{19}$$

~~Tu (1991); Tu and Graf (1993)~~ Tu and Graf (1993) proposed another method for evaluating C:

$$C = U + h\frac{\partial U}{\partial t} / \frac{\partial h}{\partial t}. \tag{20}$$

However, we would like to highlight the fact that in Eq. (20) $\frac{\partial h}{\partial t}$ is in the denominator, which constrains the application of the method. As a result, a discontinuity occurs for the time instant at which $\frac{\partial h}{\partial t} = 0$. When the results of Eq. (20) are applied in Eq. (~~16~~17), the discontinuity of ϑ as a function of time occurs at the time instant at which $C = 0$, which is between $t(\frac{\partial U}{\partial t} = 0)$ and $t(\frac{\partial h}{\partial t} = 0)$. This effect is illustrated in the section on field data application (Sect 4.1).

We propose another approach for evaluation of ϑ, which is compatible with the kinematic wave concept, but does not require the evaluation of temporal derivatives, and for this reason may appear to be easier to be used in some cases. Let us assume a reference cross-section P0 and two cross-sections P1 and P2 located at a small distance Δs downstream and upstream of P0, respectively. Knowing the $h(t)$ relationship, let us shift this function to P1 and to P2 by $\Delta t = \frac{\Delta s}{C}$ in the following way: $h_1(t) = h_0(t - \Delta t)$, and $h_2(t) = h_0(t + \Delta t)$. The spatial derivative $\frac{\partial h}{\partial x}$ is next evaluated as follows:

$$\vartheta_{\mathrm{wt}} = \frac{\partial h}{\partial x} = \frac{h_2(t) - h_1(t)}{2\Delta s}. \tag{21}$$

The method is denominated as wave translation method~~and is denoted as ϑ_{WT}~~, and is applied in this study.

3.3.2 Linear approximation based on two cross-sections

Because of the drawbacks of kinematic wave approximation, it is recommended to evaluate the gradient of the flow depth based on data from two cross-sections ~~(Aricó et al., 2008, 2009; Dottori et al., 2009; Julien, 2002; Warmink et al.,~~ which is, in fact, a two-point difference quotient (backward or forward). Nonetheless, a number of problematic aspects of this approach have been pointed out. Firstly, Koussis (2010) has stressed the fact that flow depth is highly affected by local geometry~~; hence, the proper location of the cross-sections is a difficult task~~. Moreover, Aricó et al. (2008) have pointed that lateral inflow may affect the evaluation of the gradient of flow depth, and for this reason the cross-sections should be located close enough to each other to allow the assumption of negligible lateral inflow. On the other hand, the authors have claimed that the distance between cross-sections should be large enough to perform a robust evaluation of the flow depth gradient. The impact of distance between cross-sections on the gradient of flow depth has been studied in (Mrokowska et al., 2015) with reference to dynamic waves generated in a laboratory flume. The results have shown that with a too long distance, the gradient in the region of the wave peak is misestimated due to the linear character of approximation. On the other hand, with a too short distance, the results may be affected by fluctuations of the water surface which in such case are large relative to the distance between cross-sections.

Another drawback of the method is the availability of data. Very often, data originate from measurements which have been performed for some other purpose. Consequently, the location of gauging stations and data frequency acquisition do not meet the requirements of the evaluation of the gradient of flow depth (Aricó et al., 2009). The latter problem applies to the case studied in this paper.

3.3.3 ~~Higher order approximation~~

Due to the linear character of a two-point (backward and forward) difference quotient, it is not able to represent properly the peak region of a flood wave. ~~The better approximation of the derivative requires a difference quotient of a higher order. Then, the question arises as to how many measurement cross-sections are necessary to properly reflect the realistic value of the derivative.~~ In (Mrokowska et al., 2015) it has been stated that for better representation of ϑ the central difference quotient ~~(Eq. ??)~~ should be applied~~:~~

$$\frac{\partial h}{\partial x} \approx \frac{h(x+\Delta x)-h(x-\Delta x)}{2\Delta x},$$

~~where Δx – distance between cross-sections . It is difficult to draw conclusions about the application of the method in natural conditions, as similar problems to those described in Sect 3.3.2 are likely to occur. The feasibility of the application of the method in the field requires further analysis. .~~ Due to not enough measurement cross-sections ~~, this approach could not be tested for data sets from the Olszanka River~~for Olszanka watercourse, in this study only two-point difference quotient is applied.

3.3.3 ~~Uncertainty of input data and the results~~

3.4 Uncertainty of resistance evaluation

The ~~friction velocity, as with other physical variables,~~ results of resistance evaluation should be given alongside the level of uncertainty~~of the results (Fornasini, 2008) . The uncertainty of results depends on the evaluation method and the quality of the data. As shown in the proceeding sections, neither of these is perfect when a friction velocity assessment is performed. For this reason, an appropriate method of uncertainty evaluation must be chosen in order to obtain information about the quality of the result. Friction velocity is usually applied to further calculations, and for this reason information about the uncertainty of results is of high importance.~~ . In the case of unrepeatable experiments Mrokowska et al. (2013) have suggested applying deterministic approach – the law of propagation of uncertainty (Holman, 2001; Fornasini, 2008)~~, which for Eq. (15)takes the form of Eq. (3.4)~~. Let us denote dependent variable as Y (here: S, n or u_*), and independent variables as x_i. Then maximum deterministic uncertainty of Y is assessed as: {~~multline~~equation $\Delta u Y_{*\max} \simeq$

$$\sum_{i=1}^{n} \left| \frac{\partial u_*}{\partial I} \frac{\partial Y}{\partial x_i} \right| \Delta I + \frac{\partial u_*}{\partial R} \Delta R + \frac{\partial u_*}{\partial U} \Delta U + \frac{\partial u_*}{\partial h} \Delta h + + \frac{\partial u_*}{\partial \zeta} \Delta \zeta + \frac{\partial u_*}{\partial \eta} \Delta \eta + \frac{\partial u_*}{\partial \vartheta} \Delta \vartheta + \frac{\partial u_*}{\partial b} \Delta b + \frac{\partial u_*}{\partial m} \Delta m x_i . multline equation$$

The method is valid under the assumption that the functional relationship describes correctly the dependent variable. In this method the highest possible values of uncertainty of input variables are assessed based on the knowledge of measurement techniques and experimental settings. Hence, ~~this method~~ it provides maximum uncertainty of a result.

3.4.1 ~~Suggestions on the application of formulae on resistance to flow – methodology~~

~~The preceding sections have demonstrated that the application of friction velocity formulae requires a thorough analysis of flow conditions and available methods. To sum up, the following issues should be considered during the evaluation of resistance to flow from flow equations: What is the shape of the channel – is simplification of the channel geometry applicable? What methods of evaluating input variables, especially~~ $\cancel{\vartheta = \frac{\partial h}{\partial x}}$~~, are feasible in the case under study? Is it admissible to apply simplified formula with regard to the type of wave? What is the uncertainty of the input variables, and which of them are most significant?~~

~~Although the above considerations seem to be quite universal, their significance will be illustrated based on a set of data from an experiment carried out in natural settings. The detailed analyses shown for these practical cases may provide advise on how to proceed in similar situations.~~

4 Results

~~Methods described in Sect 3 are applied to experimental data from the Olszanka River. As in the case under study, the channel is of a trapezoidal shape with a small width to depth ratio, Eq. (15) is applied.~~

4.1 Evaluation of the gradient of flow depth

As presented in Sect 2 a number of measurements were performed in ~~the Olszanka River~~Olszanka watercourse. Nonetheless, the location and the number of cross-sections constrain the evaluation of spatial derivative ϑ. It is feasible to use the data from only two subsequent cross-sections: for data set Ol-1, ϑ could be evaluated based on cross-sections CS1 and CS1a located 107 m downstream of CS1, and for ~~the other data sets~~ Ol-2 based on CS2 and CS2a located 315 m upstream of CS2 (upper panel of Fig. 1).

The following methods of evaluating ϑ are examined and compared:

- Linear approximation denoted as ϑ_{lin}
- Kinematic wave approximation in the form of the Jones formula (Eq. ~~16~~17), denoted as ϑ_{kin} with C evaluated from Eq. (~~18~~19)
- Wave translation (Eq. 21) denoted as ϑ_{wt} proposed in this paper with Δs = 10 m, and C evaluated from Eq. (~~18~~19)
- ~~Method presented by Tu (1991); Tu and Graf (1993) based on Eq.~~ Kinematic wave approximation (Eq. 17) with C evaluated from Eq. (20) which is denoted as $\vartheta_{\text{Tu\&Graf}}$.

As can be seen from Fig. ~~6~~7, ϑ_{kin} and ϑ_{wt} provide compatible results. Nonetheless, huge discrepancies in the ϑ_{lin} values are evident compared to ϑ_{kin} and ϑ_{wt}. The reason for this is that the linear method is applied to data from two cross-sections, which are located at a considerable distance apart. Moreover, due to the linear character of this method, ϑ_{lin} is unsuitable to express the variability of the flood wave shape. As a result, it overestimates the time instant at which $\vartheta = 0$ when the downstream cross-section is taken into account (as in Ol-1), and underestimates the time instant when the upstream cross-section is used (as in Ol-2~~, Ol-3, Ol-4~~). Next, the lateral inflows might have an effect on the flow, and thus the estimation of ϑ by the linear method. When it comes to $\vartheta_{\text{Tu\&Graf}}$, the results are in line with ϑ_{kin} and ϑ_{wt} except for the region near the peak of the wave where discontinuity occurs. This occurs due to the form of Eq. (20), which cannot be applied if $\frac{\partial h}{\partial t} = 0$, as was theoretically analysed in Sect 3.3.1. Consequently, the method must not be applied in the region of a rising limb in the vicinity of the wave peak and in the peak of the wave itself.

4.2 Evaluation of resistance to flow

Friction slope S, friction velocity u_* and Manning n are evaluated by formulae for dynamic, diffusive waves and steady flow. Wave translation method is used to assess ϑ. Results evaluated by formulae for dynamic wave are presented with uncertainty bounds, which allow to assess if the results obtained by simplified methods lie within the acceptable bounds or not. Uncertainty bounds are evaluated by the law of propagation of uncertainty. The uncertainties of the input variables are assessed based on knowledge of measurement techniques and experimental settings as follows: $\Delta h = 0.01$ m, $\Delta U = 10\%\ U$ (measurement performed by a propeller current meter), $\Delta R = 0.01$ m, $\Delta\zeta = 0.0001$ $[\mathrm{m\,s^{-2}}]$, $\Delta\eta = 0.0001$ $[\mathrm{m\,s^{-1}}]$, $\Delta\vartheta - 0.00001$ [-], $\Delta I = 0.0001$, $\Delta m = 0.001$, $\Delta b = 0.01$.

4.3 ~~Type of wave~~

4.2.1 Evaluation of friction slope

In order to assess to which category of flood wave (dynamic, diffusive or kinematic) the case under study should be assigned, the terms of the momentum balance equation are compared. The results are shown in Fig. ~~7~~8. All terms are evaluated analytically from measurement data. ~~The results for data sets Ol-2, Ol-3, Ol-4 are similar, as they originate from the same cross-section. The bed slope is of magnitude 10^{-3}, ~~For data set Ol-1, the bed slope and the maximum flow depth gradient ~~is~~ are of magnitude 10^{-4}, and the ~~other terms are negligible. On the other hand, for data set Ol-1, the bed slope and~~ acceleration terms reach the magnitude of 10^{-4} along the rising limb. For Ol-2 bed slope is of magnitude 10^{-3}, the maximum flow depth gradient ~~are~~ is of magnitude 10^{-4}~~. Moreover, the acceleration terms reach the magnitude of 10^{-4} along the rising limb~~, and other terms are negligible. However, the acceleration terms are of opposite signs, and the overall impact of flow acceleration on the results might not be so pronounced. The comparison between Ol-1 and Ol-2 ~~, which originate from the same experiment,~~ shows that in cross-section CS1, which is closer to the dam, more terms of the momentum balance equation are significant. From the results for CS2 it may be concluded that the significance of the temporal variability of flow parameters decreases along the channel.

~~It may be concluded that the waves from cross-section CS2, i.e. Ol-2, Ol-3, and Ol-4, are of a diffusive character. Consequently, the formula for diffusive waves, Eq. (8), may be applied, and friction slope (indicated by the red line in Fig. 7) is well approximated by the water surface slope.~~ In the case of data set Ol-1, along the rising limb local acceleration term is slightly bigger than the advective one, which may indicate dynamic character of ~~a wave.~~

~~Another method which may be used to identify the type of wave is analysis of the sensitivity of friction velocity to input variables (Mrokowska and Rowiński, 2012; Mrokowska et al., 2013) or a kind of stability analysis in which one observes the impact of a small change in the value of the input variable on the friction velocity value (Mrokowska et al., 2013)~~ the wave. On the other hand, it may be concluded that the wave for Ol-2 is of a diffusive character.

4.3 ~~Evaluation of friction velocity~~

~~Figure 8 presents the results for the friction velocity evaluated using the formula for the dynamic wave~~ Fig. 9 presents comparison between the results of friction slope evaluated by formulae for dynamic wave S_{dyn} (Eq. ~~15), using different methods to evaluate ϑ. As can be seen from the figure, $u_{*\mathrm{kin}}$ and $u_{*\mathrm{wt}}$ agree well with each other. There is also good agreement with $u_{*\mathrm{Tu\&Graf}}$ along the falling limbs of waves. In Ol-1~~5), diffusive wave S_{dif} (Eq. 3.2) and approximated by bed slope I (Eq. 14). Values of S_{dyn} range in the following intervals: [0.00027, 0.00085] for Ol-1 and [0.0013, ~~Ol-3, and Ol-4 it is observed that the discontinuity occurs between~~ 0.0015] for Ol-2 with the ~~time instants of maximum U and maximum h, as is noted in~~ maximum before the peak of wave. Difference between values of S_{dyn} for Ol-1 and Ol-2 is affected to large extent by difference of bed slope between cross-sections CS1 and CS2.

In the case of data set Ol-1 S_{dif} slightly differs from S_{dyn} along the rising limb of the wave. There are regions in which the results for diffusive wave lie outside the uncertainty bounds of friction slope evaluated by formula for dynamic wave. This is another argument for choosing the formula for dynamic wave along the rising limb of the wave in Ol-1. For the falling limb formula for diffusive wave may be applied. Steady flow approximation is not recommended in this case as the values of bed slope fall outside the uncertainty bounds in both rising and falling limb. In the ~~theoretical part of this paper (Sect 3.3.1). The effect of the discontinuity depends on the time step appliedin the analysis, and when the step is large enough, as in the~~ case of Ol-2 ~~, the discontinuity may be overlooked. When it comes to $u_{*\mathrm{lin}}$, it deviates to high extent from the previous results, and is considered as not reliable due to the comments on ϑ_{lin} presented in Sect 3.3.2~~results of friction slope for both approximations – diffusive wave and steady flow are within uncertainty bounds. However, the formula for diffusive wave is recommended, as it reflects the temporal variability of friction slope. With steady flow formula the information about friction slope variability during the propagation of wave is not provided. Before the peak of wave $S_{\mathrm{dyn}} > I$ and after the peak $S_{\mathrm{dyn}} < I$.

~~Figure 9~~

4.2.1 Evaluation of friction velocity

Figure 10 presents the comparison of the results of friction velocity evaluated by dynamic $u_{*\mathrm{dyn}}$ (Eq. ~~15~~6), diffusive $u_{*\mathrm{dif}}$ (Eq. ~~8~~12) and steady flow $u_{*\mathrm{st}}$ (Eq. ~~12~~15) formulae. ~~Additionally, uncertainty bounds are presented for each result. Uncertainty bounds are represented by the maximum deterministic uncertainty evaluated by the law of propagation of uncertainty (Eq. 3.4). The uncertainties of the input variables are assessed based on knowledge of measurement techniques and experimental settings as follows: $\Delta h = 0.01$, $\Delta U = 10\%\ U$ (measurement performed by a propeller current meter), $\Delta R = 0.01$, $\Delta\zeta = 0.0001$~~ The results for friction velocity are in line with the results of friction slope. Values of $u_{*\mathrm{dyn}}$ range in the following intervals: [~~, $\Delta\eta = 0.0001$~~ 0.031, 0.052] ~~, $\Delta\vartheta = 0.00001$~~ for Ol-1 and [~~, $\Delta I = 0.0001$.~~ 0.057, 0.061] for Ol-2 with the maximum before the peak of wave.

As can be seen from Fig. ~~9~~10, the results for friction velocity in Ol-1 obtained by the formula for dynamic ~~waves (Eq. 15)~~ wave and the formula for diffusive ~~waves (Eq. 8)~~ wave agree well with each other along the falling limb. The slight difference along the rising limb of the wave between the results occurs~~in data set Ol-1~~, as $u_{*\mathrm{dif}}$ falls outside uncertainty bounds. This is caused by the acceleration terms, which appear to be significant in Ol-1 along the leading edge (Fig. ~~7~~8). Consequently, in this region, the application of ~~Eq. (15)~~ formula for dynamic wave may be considered~~. However, the results of Eq. (8) lie within the uncertainty bounds of the results of Eq. (15); hence, the application of the simplified~~ , while for falling limb formula for diffusive wave ~~is acceptable.~~

~~On the other hand, the results obtained by Eq. (15) and by formula for steady flow (Eq. 12)~~ may be applied. In the case of Ol-1 $u_{*\mathrm{dyn}}$ and $u_{*\mathrm{st}}$ differ from each other. ~~For Ol-1, Ol-2 and Ol-4 the results of Eq. (12)~~ The results for steady flow formula fall outside the uncertainty bounds ~~of Eq. (15)~~ along the substantial part of ~~leading edge of the waves. In data set Ol-4, the time period could be observed in which the uncertainty bounds of Eq. (15) and Eq. (12) do not overlap. The significant discrepancies along the leading edge of a flood wave indicate~~ the wave, which indicates that the application of ~~Eq. (12) in this region~~ steady flow approximation is incorrect. In the case of Ol-2 diffusive wave formula may be applied, as $u_{*\mathrm{dyn}}$ and $u_{*\mathrm{dif}}$ agree well with each other. Moreover, discrepancy between results for dynamic wave and steady flow is smaller, and steady flow approximation might be considered in friction velocity evaluation. However, then the information on maximum value of resistance along rising limb is missing.

4.3 ~~Analysis of the Manning coefficient~~

4.2.1 Evaluation of the Manning coefficient

Figure 5 presents the comparison of the results of Manning n ~~is calculated from Eq. (1) with S derived analytically from the St. Venant model for data sets Ol-1, Ol-2, Ol-3 and Ol-4. In fact, Manning n may be also recalculated from friction velocity results. All analyses of simplifications and evaluation of ϑ presented above apply to evaluation of Manning n, as well. Figure 10 presents the results of n for ϑ evaluated by the wave translation (n_{wt}) and linear approximation (n_{lin}) methods. In addition, n_{st} is evaluated for $S = I$. Discrepancies between n_{st} and n_{wt} result from the difference between I and S depicted in Fig. 7, and the discrepancies are most pronounced for Ol-1. Moreover, it can be seen that n_{lin} differs considerably from the other results in all cases. This indicates that the method of evaluating ϑ may have a significant effect on n. Note that Manning n_{st} reaches its minimum value at the time instant of maximum U, hence it decreases with increasing velocity. On the other hand, it may not be true for n_{wt} and n_{lin}, because their values depend additionally on variable S.~~ evaluated by dynamic n_{dyn} (Eq. 7), diffusive n_{dif} (Eq. 13) and steady flow n_{st} (Eq. 16) formulae.

Values of ~~n_{wt}, which are reference values here,~~ n_{dyn} range in the following intervals: [0.015, 0.039] for Ol-1 ~~,~~ and [0.024, 0.032] for Ol-2~~, 0.025, 0.033for Ol-3, and 0.053, 0.095for Ol-4~~. The values of Manning n ~~for data sets Ol-1, Ol-2, and Ol-3~~ correspond with the values assigned to natural minor streams in the tables presented in (Chow, 1959). The minimum values of Ol-2 ~~and Ol-3~~ correspond with "clean straight, full stage, no rifts or deep pools", while the minimum value of Ol-1 does not match n for natural streams presented in the tables. The maximum values may be assigned to "same as above, but more stones and weeds". The ~~minimum value of n for Ol-4 may be assigned to "sluggish reaches, weedy, deep pools" and the maximum value to "vary weedy reaches, deep pools". The higher values of n for data set Ol-4 compared to the other data sets result from the fact that U is smaller than in the other cases (Fig. 4). The~~ Manning n coefficients have been evaluated in a completely different way for the measurement data from this field site by Szkutnicki (1996); Kadłubowski and Szkutnicki (1992). In that study, n was treated as a constant parameter in the St. Venant model, and its value was assessed by optimising the model performance. The authors have reported that for spring conditions, $n \in [0.04, 0.09]$. In this analysis, the results ~~for~~ are smaller.

Results for n_{dyn}, n_{dif} and n_{st} follow the same trend achieving minimum values for time instant of U_{max}. The results for Manning n obtained by the formula for dynamic wave and the formula for diffusive wave agree well with each other in both cases: Ol-1 ~~, Ol-2, Ol-3 are smaller,~~ and ~~the results for Ol-4 fall within the mentioned bounds.~~ Ol-2. Results obtained by formula for steady flow differ slightly from n_{dyn} along the rising limb of Ol-1, and lie on the edge of uncertainty bounds, while n_{st} agree well with n_{dyn} in the case of Ol-2. Consequently, Manning n may be approximated by formula for diffusive wave along the rising limb of Ol-1, while along the falling limb of Ol-1 and for Ol-2 steady flow approximation may be applied.

4.3 The variability of resistance to flow during flood wave propagation~~– comparison between friction velocity and Manning n~~

The variability of resistance ~~to flow~~ in unsteady flow is very often analysed in terms of flow rate Q, and Manning n is considered as a reference variable (Fread, 1985; Julien et al., 2002). It ~~should be emphasised that variable n is against the idea behind the derivation of the Manning resistance relation, and it is difficult to interpret the values in terms of resistance to flow.~~

~~On the other hand, friction velocity provides straightforward interpretation, as we discussed in the introduction. To illustrate the inconsistency of such analysis, the comparison between~~ seems reasonable to compare Manning n and friction velocity vs. flow rate Q. The comparison is illustrated in Fig. ~~5~~12. As can be seen from the figure, ~~the~~ Manning n decreases with increasing flow rate. This trend is characteristic of the majority of streams with inbank flow (Chow, 1959), which has been observed by Fread (1985) when the inundation area was relatively small compared to inbank flow area. This is the case considered herein, as the experiment was performed under inbank flow conditions. The reverse trend has been observed by Julien et al. (2002) for flood waves in the River

Rhine. The authors discussed extensively impact of bed forms on Manning n. However, we would like to emphasise another aspect – the shape of inundation area which determines the reverse trend. In (Julien, 2002) interpretation of rising n as rising resistance is qualitatively correct, while in the case of ~~the Olszanka River~~ Olszanka watercourse false conclusions may be drawn from the analysis of Manning n, that the bulk resistance decreases with flow rate. As the results for friction velocity show, the maximum values of resistance are in the rising limb of the waves, before the maximum flow rate Q.

5 Concluding remarks

~~In the paper, two methods of expressing flow resistance in unsteady flow are considered, namely the physically based variable which is friction velocity, and the Manning coefficient. Both,~~ Relations for friction slope, friction velocity and the Manning coefficient ~~, are~~ have been derived from flow equations. ~~The analysis proved that friction velocity is superior to the Manning coefficient when the physical interpretation of resistance is necessary. The advantage of friction velocity lies in the fact that it refers directly to the friction force; hence, the variability of friction velocity (or alternatively shear stress) may be interpreted in a straightforward way. On the other hand, when the Manning coefficient is considered, its interpretation is subjective to a great extent, as a number of factors affect the coefficient, e.g. roughness, vegetation and meandering. Discrepancy between trends of Manning n versus flow rate for the Olszanka River studied herein and the River Rhine reported in (Julien et al., 2002) is most likely due to different geometry of inundation area between these two cases. Resistance cannot be compared between these two cases based on Manning n. Moreover, the comparison between the results for friction velocity and Manning n has shown that the theoretical interpretation of n in unsteady flow should be avoided. However, this remark does not apply to modelling studies, where n is treated as an optimisation parameter. For the above reasons, following a large group of researchers, we suggest considering friction velocity (or shear stress) as a reference parameter for resistance to flow.~~

~~As friction velocity is recommended to express flow resistance, the method of friction velocity derived from flow equations is scrutinised. It also applies to Manning n. Analysis of resistance evaluation in the Olszanka River shows that friction velocity is~~ Analyses based on experimental data have shown that resistance is highly uncertain and difficult to determine. However, we believe that when ~~friction velocity~~ resistance relations are applied with an awareness of their constraints, and proper effort is made to minimise the uncertainty of the input data, the method of ~~friction velocity~~ resistance evaluation is likely to provide reliable results. For this reason, in-depth description of how to determine ~~friction~~ resistance for unsteady flow has been provided. The ~~suggestions on the evaluation of friction velocity given~~ methodology proposed in the paper should be helpful in reaching a compromise between scarcity of data and the correctness of simplifying assumptions. ~~We have~~

~~demonstrated that some simplifications such as linear approximation for $\frac{\partial h}{\partial x}$ evaluation may result in high incorrectness of results. On the other hand, as simplified methods are very often a must when data are scarce, when data from only one cross-section are available we recommend the translation method, introduced in this paper, to evaluate $\frac{\partial h}{\partial x}$~~ Beside critical analysis of existing methods we have proposed some new approaches: the formulae for friction slope, friction velocity and Manning n for trapezoidal channel and translation method instead of Jones formula ~~. The simplifications applied and their possible impact on the assessed value of the friction velocity should be clearly stated when the results are presented. The~~ to evaluate $\frac{\partial h}{\partial x}$.

The paper has demonstrated the application of ~~friction velocity~~ resistance relations to experimental data; hence, the detailed conclusions drawn in the study apply to similar cases. Analysis of terms of momentum balance equation has revealed that in the first case – Ol-1, which is closer to the dam, the wave has dynamic character along rising limb and diffusive character along falling limb. In the second case - Ol-2, the wave is of diffusive character with relatively small difference between water slope and bed slope.

Comparison between the results of simplified formulae for S, u_* and n has shown that evaluation of friction slope and friction velocity is more sensitive to flow unsteadiness than Manning n. For this reason S and u_* should not be approximated by formulae for steady flow, and the type of flow (dynamic or diffusive) should be carefully studied, and it is strongly recommended to apply the methodology presented in this paper. The reliability of resistance expressed by friction slope and friction velocity is critical for studies on the impact of variability of flow resistance on hydrodynamic phenomena, e.g. sediment transport, which are amply represented in literature.

When it comes to Manning n, in the case presented in this study the steady flow approximation is admissible when the wave is of diffusive character, and diffusive approximation is satisfactory for dynamic flow. This weak effect of flow unsteadiness on Manning n is an asset when n is considered as a parameter in flood routing practice, because the reliability of the results is less dependent on quality and quantity of data used. However, it constrains its application in studies on variability of resistance in unsteady flow. Moreover, trend of Manning n with flow rate does not provide unique information on the variability of resistance.

Flood wave phenomena are so complex that it is currently impossible to provide a comprehensive analysis, and the problem of resistance to flow in unsteady non-uniform conditions still poses a challenge. For this reason, more research on resistance in unsteady non-uniform conditions is necessary.

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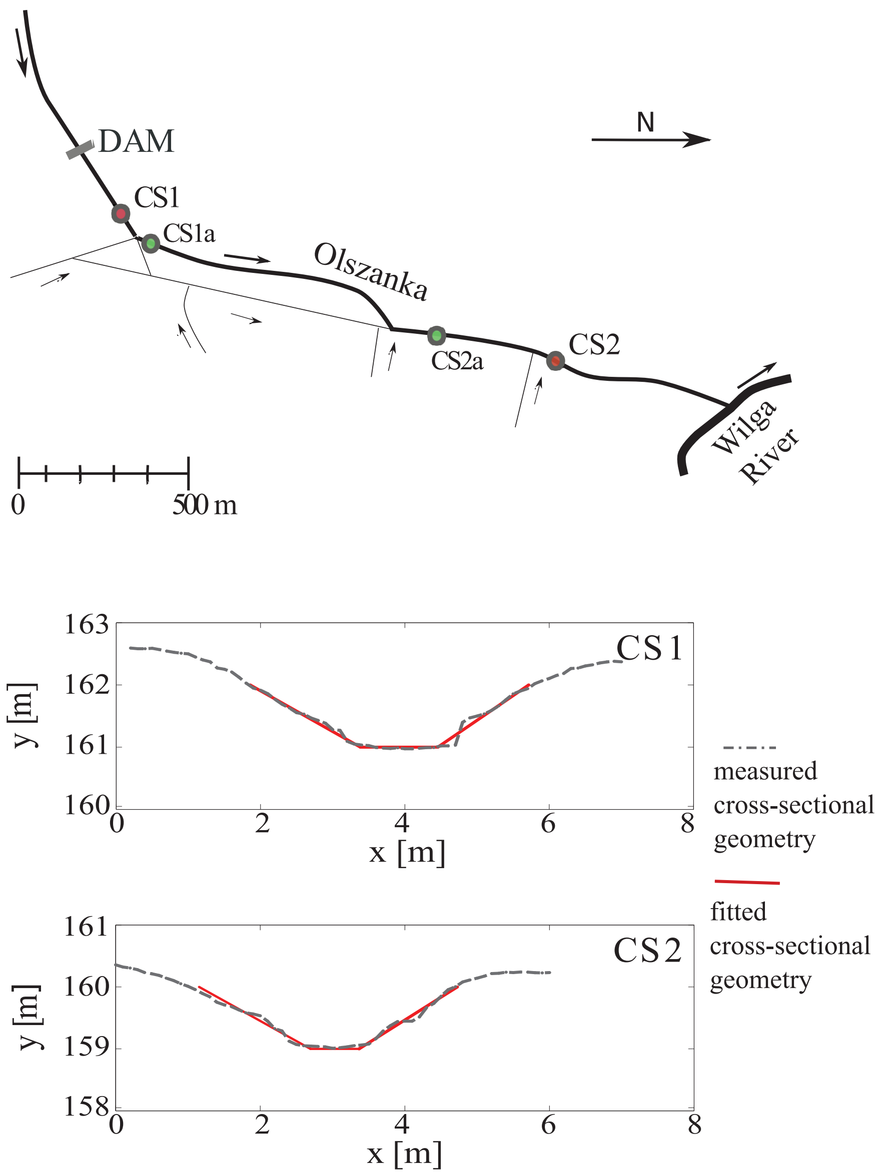


Figure 1. The site of the experiment in Olszanka ~~River~~ watercourse (upper panel), and the shape of measurement cross-sections CS1 and CS2 (lower panel).

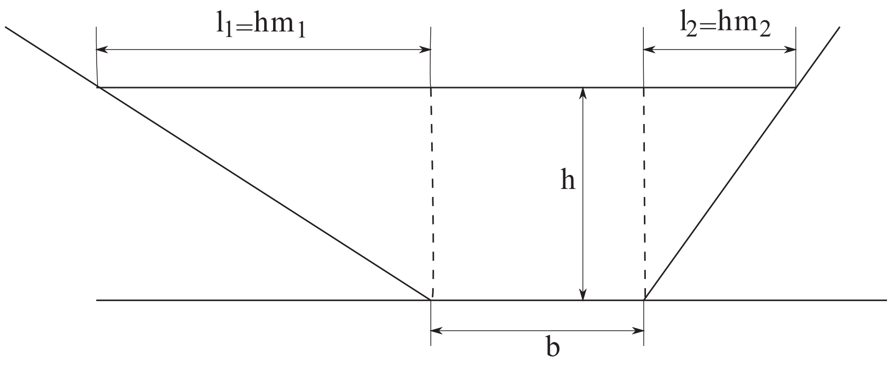


Figure 2. Trapezoidal cross-section of a channel with definitions of symbols used in the text.

Figure 3. Experimental reach of Olszanka watercourse. (courtesy of Jerzy Szkutnicki)

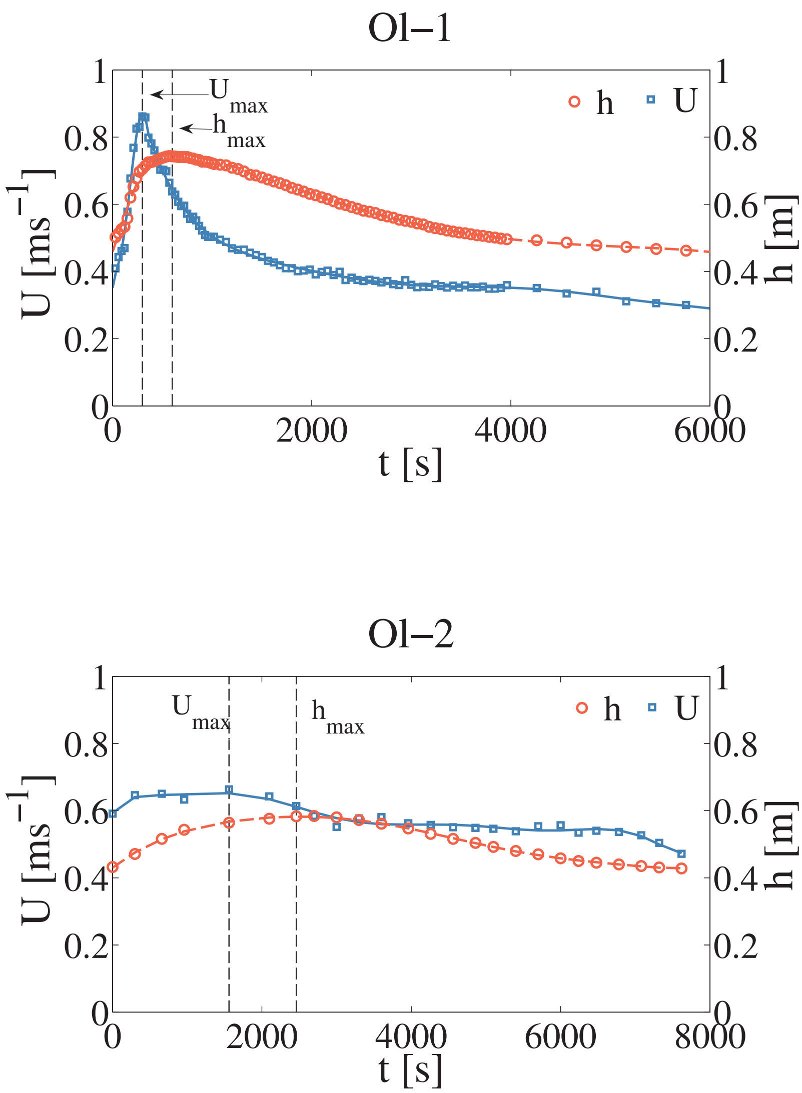


Figure 4. Temporal variability of flow depth h and mean velocity U for experimental flood waves in ~~the~~ Olszanka ~~River~~watercourse.

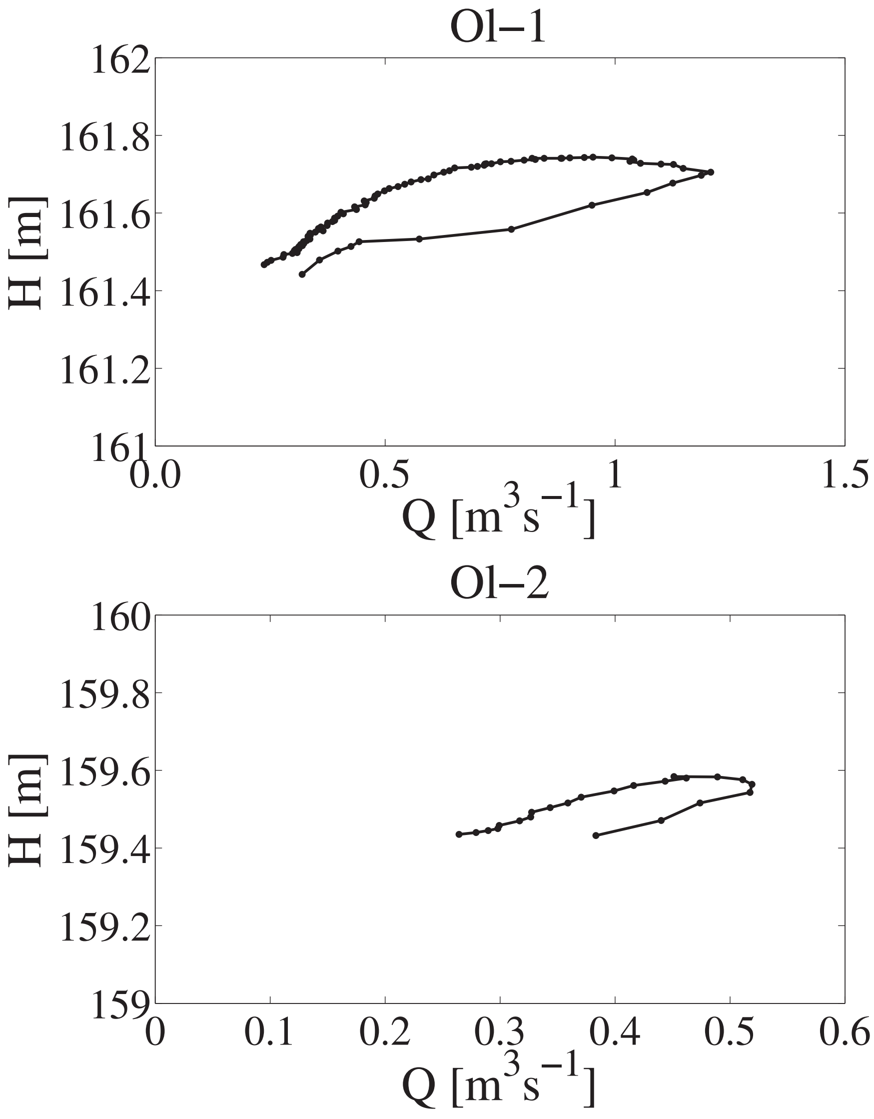


Figure 5. Rating curves of experimental flood waves in ~~the~~ Olszanka ~~River~~watercourse.

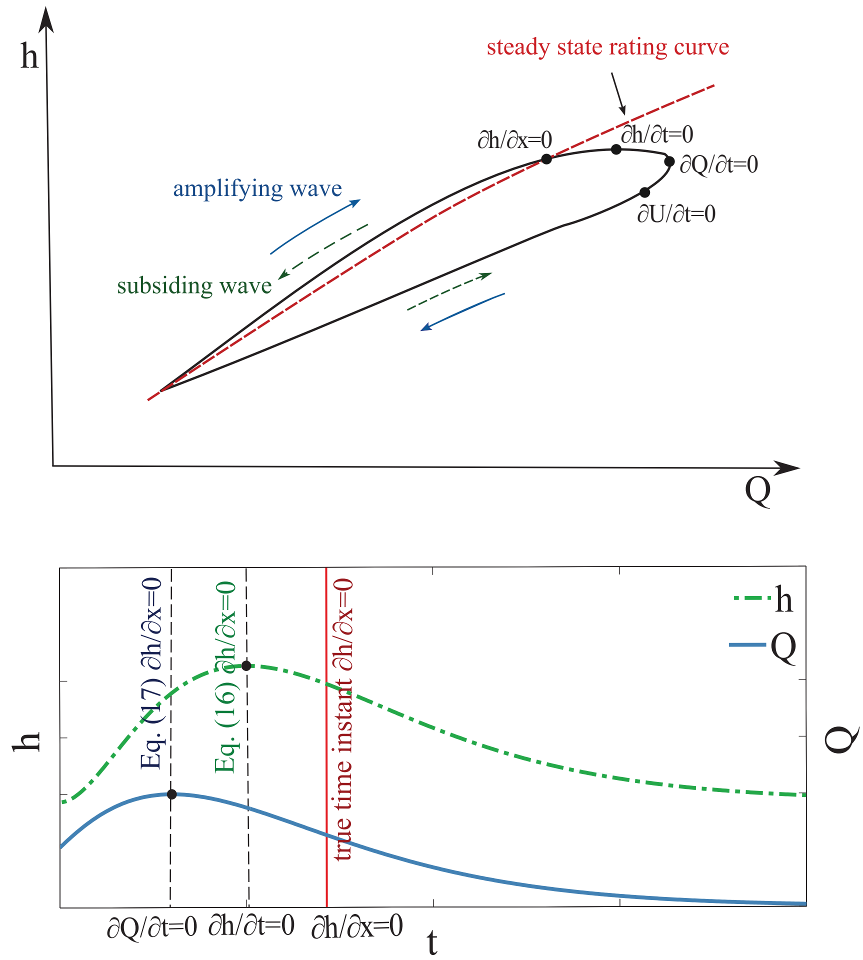


Figure 6. Comparison between rating curve for flood wave and steady flow with characteristic points, based on (Henderson, 1963) (upper panel), and impact of kinematic wave approximation (Eqs. (~~16~~17) and (~~17~~18)) on the assessment of time instant at which $\frac{\partial h}{\partial x} = 0$ (lower panel).

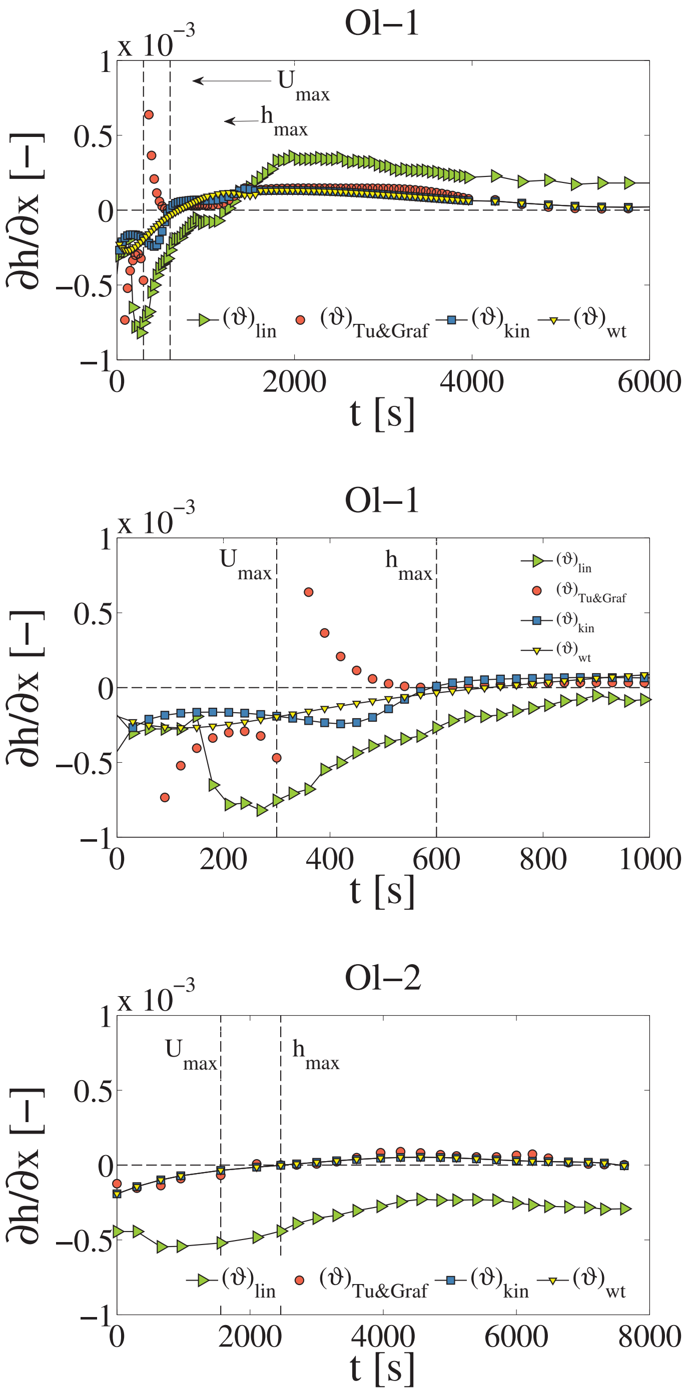
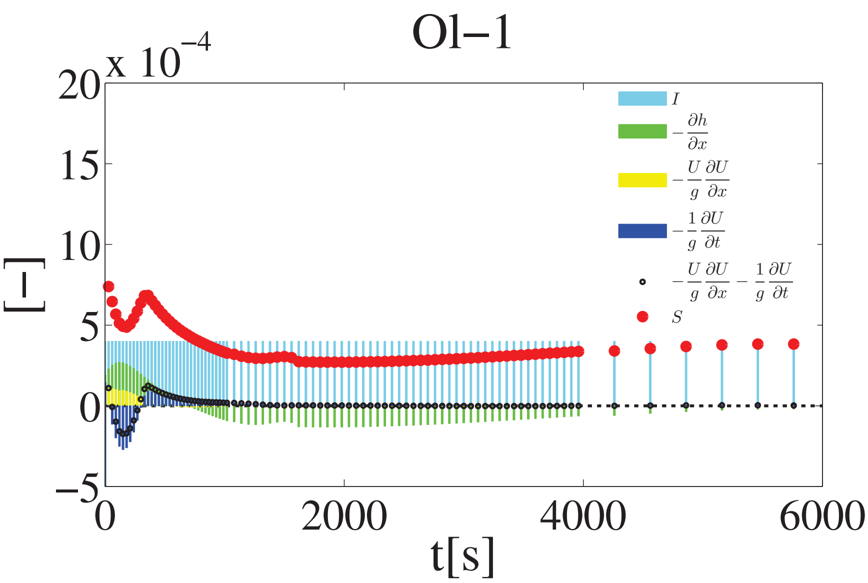


Figure 7. Temporal variability of gradient of flow depth $\vartheta = \frac{\partial h}{\partial x}$ for experimental flood waves in ~~the~~ Olszanka ~~River~~watercourse. Middle panel shows a zoom of the rising limb of the wave for Ol-1.



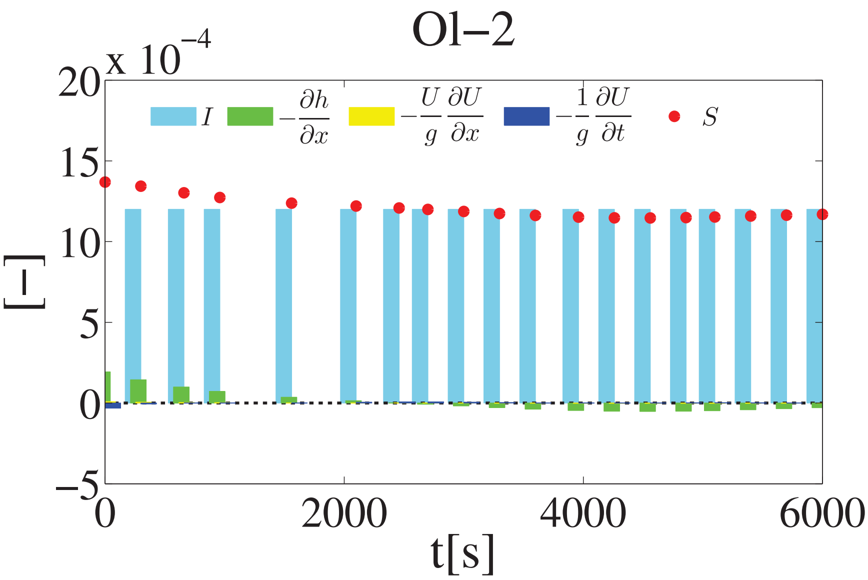


Figure 8. Comparison of terms of the momentum balance equation for experimental flood waves in ~~the~~ Olszanka ~~River~~watercourse.

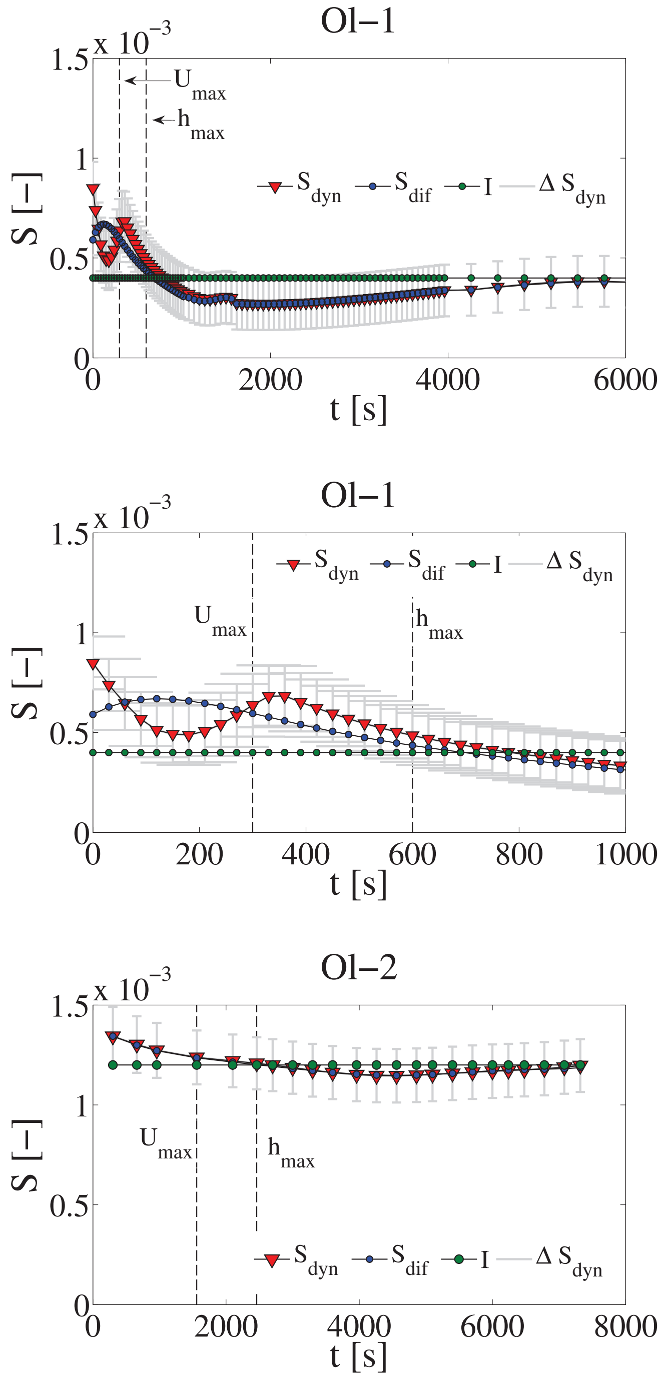


Figure 9. Comparison of friction ~~velocity u_*~~ slope evaluated by ~~different methods (symbols defined in the text)~~ formulae for dynamic S_{dyn}, diffusive wave S_{dif} and steady flow I with uncertainty bounds ΔS_{dyn} for experimental flood waves in ~~the~~ Olszanka ~~River~~watercourse. Middle panel shows a zoom of the rising limb of the wave for Ol-1.

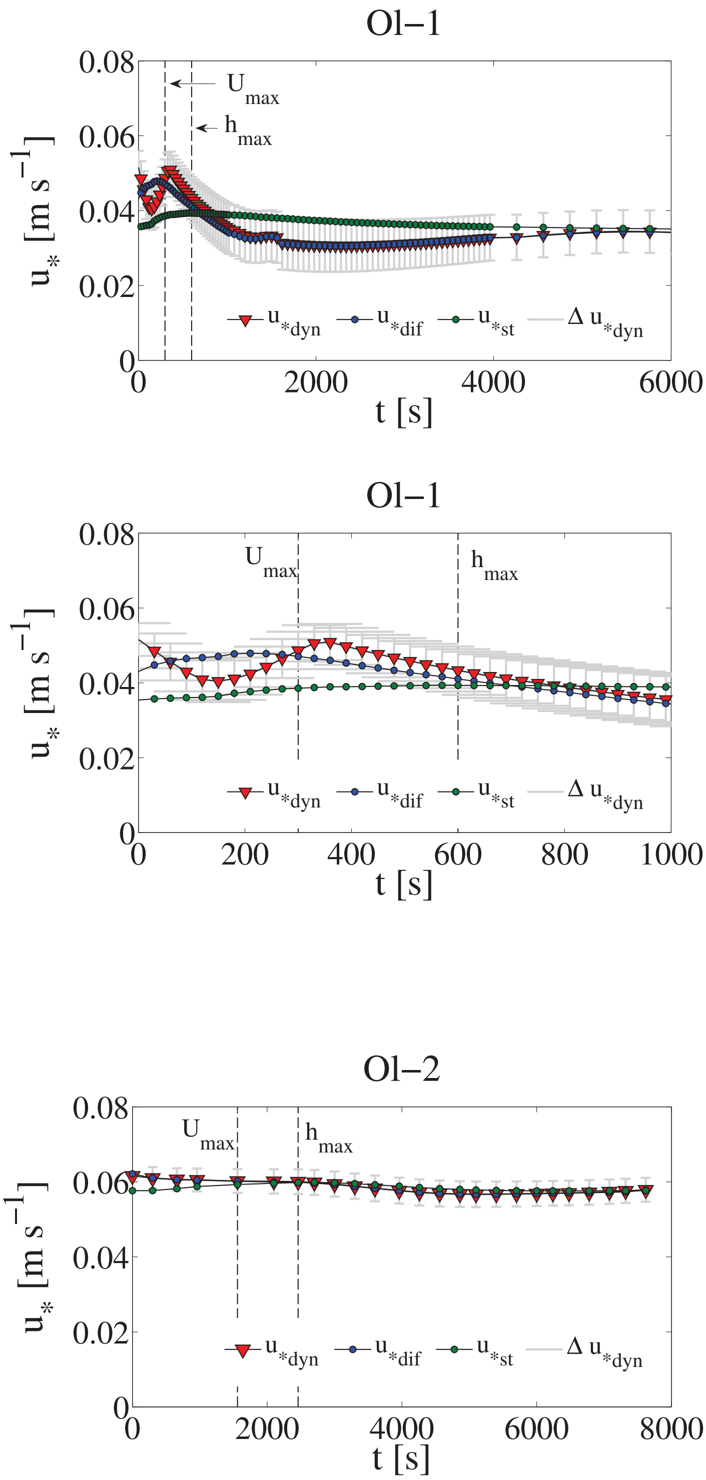
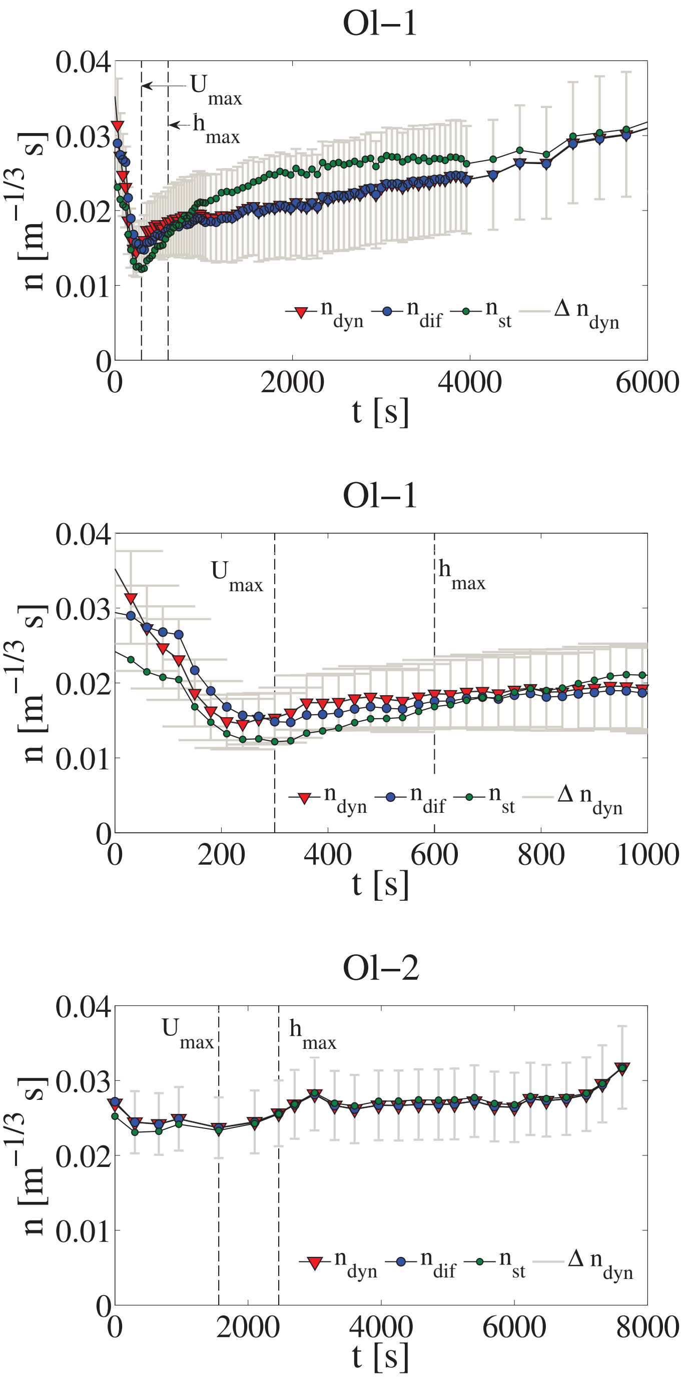


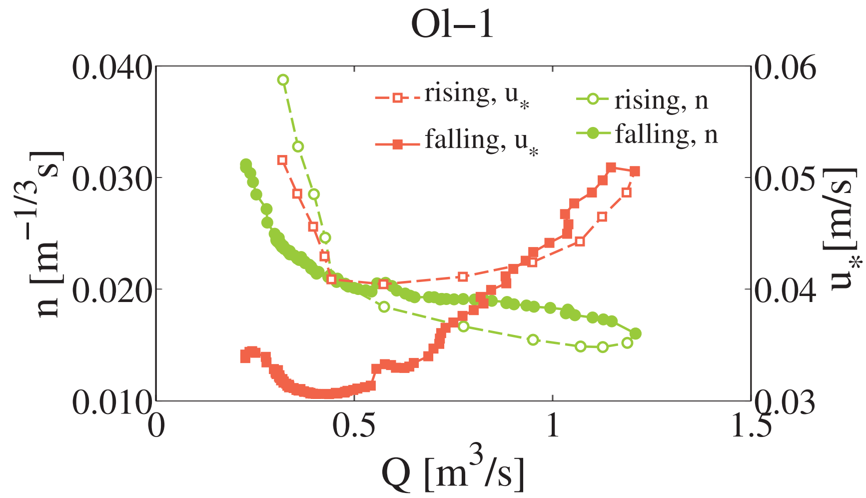
Figure 10. Comparison of friction velocity evaluated by formulae for dynamic $u_{*\mathrm{dyn}}$, diffusive wave $u_{*\mathrm{dif}}$ and steady uniform flow $u_{*\mathrm{st}}$ with uncertainty bounds $\Delta u_{*\mathrm{dyn}}$ for experimental flood waves in ~~the~~ Olszanka ~~River~~watercourse. Middle panel shows a zoom of the rising limb of the wave for Ol-1.



~~Comparison~~ Middle panel shows a zoom of the ~~relation of Manning n vs flow rate Q and friction velocity u_* vs Q along~~ rising ~~and falling limbs~~ limb of ~~waves for experimental flood waves in~~ the ~~Olszanka River~~wave for Ol-1.

~~Comparison~~ Middle panel shows a zoom of the ~~relation of Manning n vs flow rate Q and friction velocity u_* vs Q along~~ rising ~~and falling limbs~~ limb of ~~waves for experimental flood waves in~~ the ~~Olszanka River~~wave for Ol-1.

Figure 11. ~~Temporal variability~~ Comparison of Manning n evaluated by formulae for ~~different assumptions about friction slope S~~ dynamic n_{dyn}, diffusive wave n_{dif} and steady uniform flow n_{st} with uncertainty bounds Δn_{dyn} for experimental flood waves in ~~the~~ Olszanka ~~River~~watercourse.



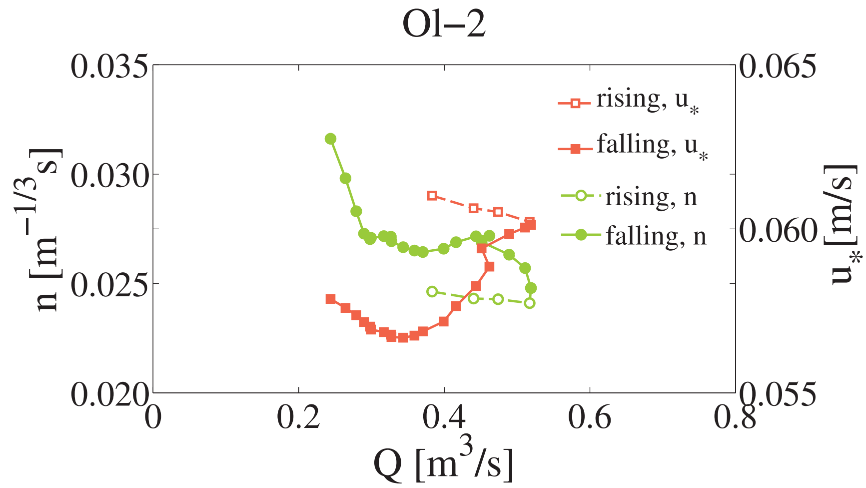


Figure 12. Comparison of the relation of Manning n vs flow rate Q and friction velocity u_* vs Q along rising and falling limbs of waves for experimental flood waves in the Olszanka watercourse.