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Unsteady 1D flow model of a river with partly vegetated floodplains—application to the Rhine River

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Abstract

A relatively simple unsteady flow model was proposed which estimates velocities, friction factors and the components of discharge in the main channel and on the floodplains simultaneously. Bottom roughness of the main channel and the floodplains, the flow resistance of vegetation on the floodplains and the flow resistance caused by the momentum transfer between the main channel and the floodplains were included in the model using Nuding's method. A pre-processing program was developed to convert topographic field data that can be derived from a digital terrain model into cross-sectional input data of the flow model. The model was applied to a 28-km reach on the Upper Rhine for three steady flow cases and for two unsteady flood event cases to investigate resistance effects of partly vegetated floodplains. Computed discharges and water levels correlated well with the measured data. It was found that a significant component of discharge was transported by the floodplains in some cross-sections during high flows.

Keywords: Unsteady flow; Compound channel; Floodplain vegetation; Momentum transfer; Flow resistance

1. Introduction

Nowadays, environmental river engineering projects are often required to meet multiple objectives. These include sustaining the diversity of flow dynamics, flora and fauna; environmental flood management; providing for the passage of fish; preserving the recreational value and rising the ground water level. Local hydraulics and channel morphology are the primary determinants of the physical habitat that control ecosystem functioning. The local hydraulic conditions are determined by flow resistance and geometry of a channel (Broadhurst et al., 1997). Hence, simultaneously meeting multiple goals in both natural enhancement and flood management poses many difficulties in hydraulic design of channels.

According to Evans et al. (2001), among academics and river engineers, the following gaps exist in present knowledge on conveyance estimation: effect of vegetation on flow levels and extent of flooding, interaction between the main channel and the floodplain, and validity of different conveyance methods. The list can be further extended by including factors such as channel asymmetry and seasonal vegetation changes that complicate the conveyance estimation in a compound channel.

Rouse (1965) divided open channel flow resistance into surface or skin friction, form resistance or drag, wave resistance from free surface distortion and resistance due to flow unsteadiness. The flow resistance in a compound channel can be further subdivided into eight components: (1) grain roughness, (2) form resistance associated with acceleration or deceleration and flow separation over small-scale structures such as pebble clusters, (3) form resistance associated with large-scale bed undulations such as pools and riffles, (4) roughness height of flexible vegetation, (5) resistance of stiff vegetation, (6) resistance caused by the momentum exchange between the main channel and the floodplain, (7) resistance caused by the momentum exchange between vegetated and non-vegetated section, and (8) sinuosity (Lawless and Robert, 2001; Leopold et al., 1960; Nuding, 1991; Sellin, 1964).

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Nomenclature

A_i	the area of the cross-section [m^2]
A_i	the area of part of the cross-section [m^2]
a_X, a_Y	distances of the vegetation elements in flow direction and transverse direction [m]
a_Z	distance of branches in vertical direction [m]
b_{EFF}	contributing width of the floodplain [m]
b_M	width of the main channel [m]
c_{sh}	shape coefficient [–]
d_P	diameter of the plant [m]
d_Z	diameter of a branch of the plant [m]
f_i	friction factor for part of the cross-section [–]
f_J	friction factor for the imaginary boundary between main channel and floodplain [–]
f_{TOT}	composite friction factor for the whole channel cross-section [–]
g	acceleration due to gravity [m/s^2]
$H_{f,i}$	head loss of part of the cross-section [m]
$H_{f,M}$	head loss between two consecutive main channel cross-sections [m]
$h_{meas,j}$	the measured water depth for cross-section j
$h_{comp,j}$	the computed water depth for cross-section j
h_P	height of vegetation [m]
k	roughness of the bottom, roughness height of flexible vegetation [m]
k_M	roughness of the main channel bottom [m]
L_i	distance between the components of two consecutive cross-sections [m]
L_M	distance between two consecutive main channel cross-sections [m]
L_{TOT}	distance between two consecutive cross-sections [m]
R_i	the hydraulic radius of part of the cross-section [m]
R_{TOT}	the composite hydraulic radius for the whole cross-section [m]
S_0	the bottom slope [–]
S_f	the friction slope [–]
v_i	average velocity of part of the cross-section [m/s]
v_M	average velocity of the main channel [m/s]
Q	discharge [m^3/s]
Q_i	discharge component of part of the cross-section [m^3/s]
ω	Nuding's vegetation density parameter [–]
Ω	Pasche's vegetation density parameter [–]

Cross-sectional shape of natural channels is irregular and locally variable. Width–depth ratio is considered a general index to describe channel form (Knighton, 1984). Masterman and Thorne (1992) related the decrease in channel capacity to the width–depth ratio suggesting that vegetation effects are considerable if the width–depth ratio is less than 16. The width–depth ratio gives no indication of cross-sectional asymmetry, although the asymmetry is of great importance in connection with meanders, and Knighton (1981) therefore developed a method to estimate two different asymmetry parameters, i.e. areal asymmetry and vertical asymmetry. However, these are not adequate to describe the cross-sectional shape of a compound channel.

Estimation of discharge in compound channels is very complex because of the momentum transfer between the main channel and the floodplain, decreasing the discharge in the main channel and increasing the discharge on the floodplain (e.g. Lambert and Sellin, 1996). The lateral momentum losses can decrease the average velocity during rising stages as flow spills onto the floodplain. When the floodplain is narrow or heavily obstructed, channel velocities may continue to increase with rising stage (Copeland et al., 2001). However, the floodplains can account for conveying a significant component of discharge during high flows in a compound channel.

The coherence method of Ackers (1993) provides estimates of discharge within a few percent of measurements for most flow cases in compound channels. According to Samuels et al. (2002), the method is well established for compound channels with deviations of up to 10 degrees between main channel and floodplain alignment. However, it has limitations for natural rivers, because it requires simplification of the cross-sectional geometry to a double trapezoidal shape. The coherence method was further developed to get better estimates of discharge, but it does not predict the individual components of discharge in the main channel and the floodplains (Haidera and Valentine, 2002). The Shiono and Knight method (SKM) and the lateral division method (LDM) were developed to improve the coherence method (Knight, 2001). They are 2D methods, in which calibration coefficients are estimated for bed friction, lateral shear and secondary flow (the last one neglected in LDM). However, these methods are relatively complex in many practical applications.

Numerous steady flow models that take into account the flow resistance of vegetation and the additional resistance in the boundary between the main channel and the floodplain have been developed (Nuding, 1991, 1998; Mertens, 1989, 1994; Pasche, 1984; Pasche and Rouvé, 1985). These methods consider the boundary of vegetation as a very rough wall causing additional flow resistance in the main channel. They predict the components of discharge in the main channel and the floodplains, and furthermore, predict local average velocities and flow resistance coefficients that give information for habitat hydraulics. The problems with these models are that they are mainly calibrated with laboratory data having homogenous floodplains and stiff cylinders simulating vegetation, and the estimation of retention is not possible with steady flow models.

The aim of this research was to develop a one-dimensional unsteady flow model to predict average velocities, flow resistances and the components of discharge in the main channel and the floodplains. This is useful in conditions where both the flood management and local ecological aspects need to be taken into account simultaneously. The flow model takes into account the resistance of vegetation and the resistance caused by the momentum exchange between the main channel and the floodplain by combining Nuding's (1991) method into St. Venant equations. A method to compute the composite friction factor for a compound channel with imaginary boundaries between the main channel and floodplains was proposed, to be used in the unsteady flow model. In the Rhine River, significant flooding about 10 years ago launched several projects aiming at restoration of the retention volume of the floodplains. The model was applied to a 28-km reach on the Upper Rhine. In the Upper Rhine area, the goal is to increase retention by applying natural vegetation on the floodplains and therefore, a reliable method to estimate propagation of floods in vegetated floodplains and the retention effects of the natural vegetation is needed.

Formerly, compound channels were modelled so that the floodplains were treated only as storage areas with no conveyance and resistance coefficients (Helmiö, 2002). This was possible by inputting the cross-sectional parameters of the whole compound channel into the mass equation, but only ones of the main channel in the momentum equation. However, this kind of model does not compute velocities or friction factors on the floodplains. Comparisons were made between the proposed model and the traditional model in steady and unsteady simulations.

A minor aim of this research was to develop a pre-processing program of the cross-sectional coordinates and resistance parameters for a compound channel. The pre-processing program converts the complex field data, obtained from e.g. a digital terrain model, to a form suitable for input into the unsteady flow model. Thus, it assists flow modelling in compound channels with large topographic longitudinal and cross-wise deviations. This program was also used in the application of the flow model to the Rhine River.

2. Model development

A one-dimensional unsteady flow model was developed, solving St. Venant equations and using Nuding's (1991; Helmiö, 2002) method for computing flow resistance parameters for the main channel and the floodplains. Nuding's method is a calculation procedure for steady flow, in which for a known water level, the friction factors and the components of discharge in the main channel and each floodplain are computed separately, based on e.g. the shape and vegetation of the channel. The boundary between the main channel and the floodplain or the vegetated zone is treated as an imaginary wall, for which a separate Darcy–Weisbach friction factor is estimated.

The unsteady flow model with Nuding's method was divided into two independent modules: a pre-processing program and the unsteady model. In general, inputting complex field data such as coordinate points of cross-sections into St. Venant unsteady flow model is problematic. Therefore, a conceptual model was developed to describe cross-sectional geometry and flow resistance of a channel. This was the basis for the pre-processing program. The pre-processing program was developed to take in the field data on the complex channel cross-sections and process the data into a format that can more easily be input into the flow model.

2.1. Pre-processing program

The pre-processing program was developed to treat field data in the following form: measured cross-sections consisting of an arbitrary number of coordinate points and having five to seven vegetation parameters for each line segment between two adjacent coordinate points. The aim was to simplify the input of the complex field data into St. Venant unsteady flow model.

A conceptual model was developed from the components of both the geometry and the flow resistance and thus, it describes the local hydraulic conditions (Broadhurst, 1997). A compound channel was divided into six geometric components with five to seven different resistance parameters on the floodplains and one in the parts of the main channel. In many computational methods, e.g. Ackers (1993) and Darby and Thorne (1996), a compound channel is divided into three components based on its geometry: the main channel and the floodplains. The conceptual model for this pre-processor divides a compound channel or a channel with bank vegetation into six fundamental components that describe the whole channel: outer left and right floodplains (L1 and R1), inner left and right floodplains or vegetation zones (L2 and R2) and left and right parts of the main channel (M1 and M2) (Fig. 1). This division is based on the character of field data, and it allows for variability among the cross-sectional geometry and resistance coefficients. The resistance of vegetation on the floodplains and the additional resistance caused by the interaction processes

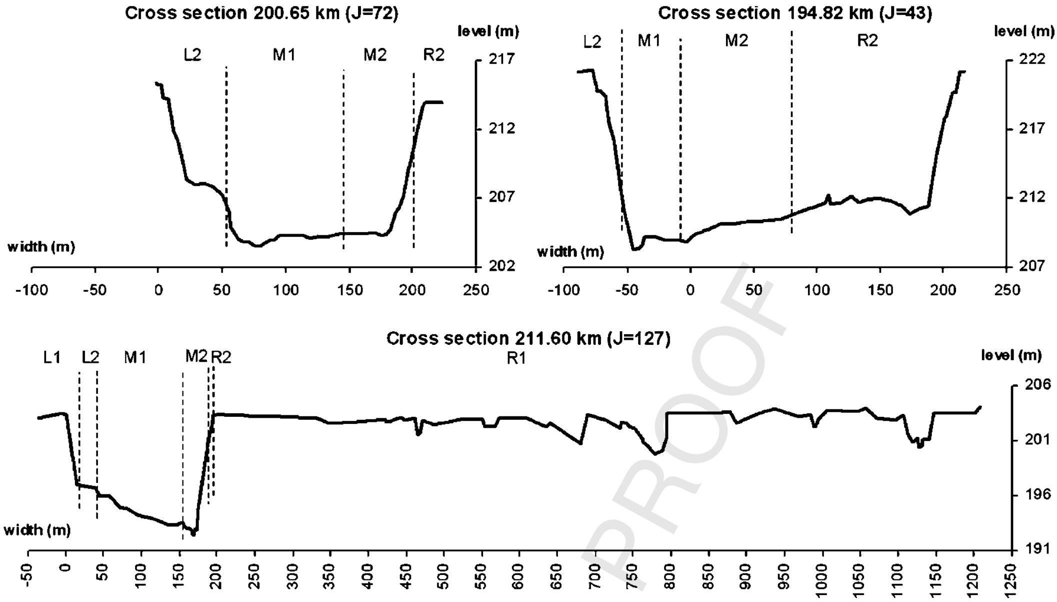

Fig. 1. The division of some cross-sections of the Upper Rhine into the outer and inner floodplains L1 and R1, and L2 and R2, respectively; and the main channel M1 and M2. Unnecessary sections are left out. Here, parts L2 and R2 are vegetated.

between a main channel and a floodplain, or between a vegetated zone and a non-vegetated zone, can be taken into account.

Assumption of no stiff vegetation in the main channel was made. Thus, the flow resistance of the main channel consists of the form resistance and resistance of flexible vegetation combined in a boundary roughness coefficient. In addition, the interaction process between a floodplain and a main channel must be taken into account in both sides of the main channel.

On the floodplains, the flow resistance can be simplified to a component of boundary roughness, including bottom grain roughness, form roughness and roughness height of flexible vegetation, and a component of stiff vegetation. The resistance of the imaginary boundary between the main channel and the floodplain is included in computing the main channel resistance. It can be neglected from the floodplain part because of low significance on floodplain discharge (Schumacher, 1995).

The vegetation parameters were primarily based on the method developed by Nuding (1991, 1998). Some features of vegetation parametrisation, however, were taken from the method of Mertens (1994). Every part of a cross-section has one bottom roughness height parameter (k). Additionally, the floodplain sections have four to six vegetation parameters each: the average plant height (h_P), and the average distances of the plants in flow direction (a_X) and in transverse direction (a_Y). The plant data can be input into the model in two different ways (Helmiö and Jolma, 2003):

(1) The average stem diameter d_P, the average branch diameters d_Z and the branch distances a_Z (Nuding, 1991), applicable mainly for bushes.
(2) The average plant diameter d_P, when d_Z and a_Z are assumed zero (Mertens, 1989), applicable for either single trees or large groups of trees and bushes.

The pre-processing program converts the topographic field data and single roughness parameters into approximations of geometric, friction and vegetation parameters for different water levels for each cross-section. The cross-sectional geometry and resistance parameters are computed as function of water depth, which can then be input into the unsteady flow model. This makes the data coming from different sources more uniform. Thus, the task of the pre-processor is to filter the complex data of natural irregular cross-sections into a simple, suitable input format with some degree of uniformity between different data sources.

In the computational procedure of the pre-processing program, the data of the cross-sections must be subdivided into parts by the user. Components that do not exist in a cross-section are left out. The properties and structure of the pre-processing program have been explained in more detail by Helmiö and Jolma (2003). The present version of the pre-processing program does not take into account a compound roughness inside each channel part, and thus the user must calculate the compound roughness coefficient for each part beforehand by e.g. Rouvé's (1987) method.

2.2. The unsteady flow model

The flow model proposed here was based on equations and the flow model presented in detail in Helmiö (2002). A McGormack two-step explicit scheme was used based on the conservative matrix form of St. Venant equations

$$\frac{\partial \mathrm{U}}{\partial t} + \frac{\partial \mathrm{F}}{\partial x} = \mathrm{G} \tag{1}$$

where the vectors are

$$\mathrm{U} = \begin{bmatrix} A \\ Q \end{bmatrix}, \ \mathrm{F} = \begin{bmatrix} Q \\ \boldsymbol{\beta}\frac{Q^2}{A} \end{bmatrix} \text{ and } \mathrm{G} = \begin{bmatrix} 0 \\ gA(S_0 - S_\mathrm{f}) \end{bmatrix} \tag{2}$$

and A is the cross-sectional area, Q is the discharge, β is the coefficient of non-uniform flow velocity distribution, g is the acceleration due to gravity, S_0 is the bottom slope and S_f is the friction slope. The computational procedure is presented in Fig. 2. The components of friction factors and discharges, and an average velocity for each part of cross-section after each time step were computed by Nuding's (1991) method.

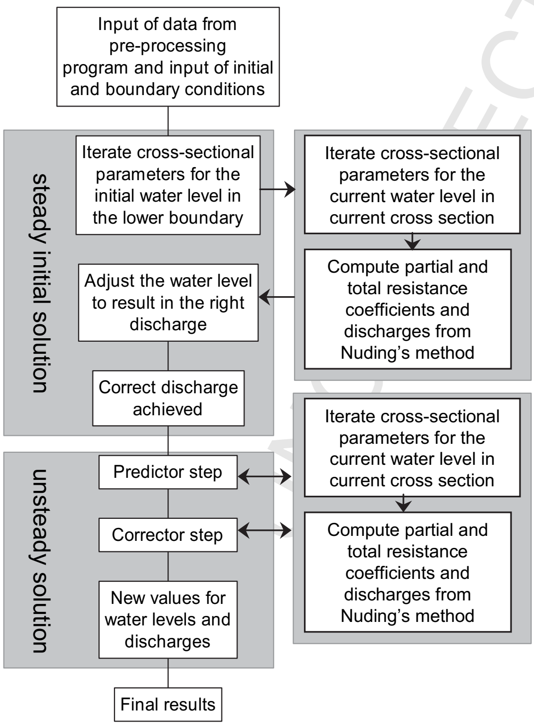

Fig. 2. A flow chart of the computational procedure of the flow model.

There were two main problems to be solved in combining Nuding's method and the St. Venant unsteady solution. First, Nuding's method gave friction factors for each part of a channel cross-section, and a composite friction factor is needed. Second, computation of the hydraulic radius was problematic. The traditional way of computing the hydraulic radius as a ratio of the total area of cross-section to the total wetted perimeter gave very low values and could not be used in the unsteady solution. In wide channels water depth h can be used instead of the hydraulic radius R. In complex cross-sections, it is very difficult to determine a relevant water depth for the floodplain and even more difficult for the whole compound channel.

Therefore, a procedure was developed to estimate the composite hydraulic radius and composite friction factor by assuming that the water level and the water surface slope in every part of each cross-section must be the same. The procedure was based on the uniform flow equation. An effective hydraulic radius for each part of each cross-section was calculated as

$$R_i = \frac{f_i v_i^2 L_i}{8gH_{\mathrm{f},i}} \tag{3}$$

where f is the Darcy–Weisbach friction factor, v is the average velocity, L is the reach length, and H_f is the total head loss, and the subscript i denotes the main channel, outer floodplain or inner floodplain part of the cross-section. This was based on the assumption that the water surface slope in each part of the cross-section has the same head loss term and it can be computed from the head loss of the main channel as

$$\frac{8gH_{\mathrm{f},i}}{L_i} = \frac{8gH_{\mathrm{f,M}}}{L_\mathrm{M}} = \frac{f_\mathrm{M} v_\mathrm{M}^2}{R_\mathrm{M}} \tag{4}$$

The composite hydraulic radius was then

$$R_\mathrm{TOT} = \frac{\sum_{i=1}^{5} R_i Q_i^2}{\sum_{i=1}^{5} Q_i^2} \tag{5}$$

and the composite friction factor was computed as

$$f_\mathrm{TOT} = \frac{8gH_\mathrm{f} R_\mathrm{TOT} \left(\sum_{i=1}^{5} A_i \right)^2}{L_\mathrm{TOT} \left(\sum_{i=1}^{5} Q_i \right)^2} \tag{6}$$

Using the uniform flow equation neglects the effect of changes in velocity head and acceleration that are also present in unsteady flow. However, their effect can be significant in some conditions where the changes in cross-section size and elevation are very large.

3. Application of the model to the Rhine River

The Rhine has a total length of 1320 km and a catchment area of 185,000 km^2. The model was applied to a 28-km long reach (186.156 km–214.244 km downstream from Lake Constance) in the Upper Rhine area, between Rheinweiler (upper end of the reach) and Hartheim (lower end). The reach has 140 cross-sections, 100–320 m apart from each other, each cross-section having 42–227 coordinate points. Along most of the reach there is a vegetated bank on the left (French) side and a vegetated floodplain on the right (German) side of the main channel. Most cross-sections were divided only into the main channel and the inner floodplain sections, because the floodplain and/or the riverbank is completely vegetated (Fig. 1, cross-sections 43 and 72) and thus, the outer floodplain sections were not needed. Some cross-sections had very wide shallow floodplains without vegetation (Fig. 1, cross-section 127) that were included as the outer floodplains.

Three steady flow cases were computed and compared to measured data: (a) $Q = 680\ m^3/s$, water level near the floodplain level, (b) $Q = 1430\ m^3/s$, water on the floodplains, and (c) $Q = 3040\ m^3/s$, water on the floodplains. The topographic and discharge-water level data were received from the Upper Rhine water administration (Gewässerdirektion Südlicher Oberrhein/Hochrhein), project group of Breisach. The determination of the roughness and vegetation parameters was carried out by Hartmann et al. (1998). The roughness values in the main channel were calibrated by the measurement of a steady discharge rate of 680 m^3/s because at that discharge rate the water levels were mostly below bankfull levels. Yoshida and Dittrich (2002) calibrated the same reach with the same discharge rate of 680 m^3/s, assuming that the floodwater flowed only in the main channel, and the momentum exchange was not taken into account. In this application, the additional resistance of the momentum exchange was included in the calibration, because clearly there was floodplain flow already with this discharge. It should be noted that the division of the channel into the main channel and the floodplains in the proposed model is not necessarily the same as in the model of Yoshida and Dittrich (2002). The channel cross-sections could also be divided by the channel topography (geometry), but in this application, it was divided mainly by the location of vegetation zones. The calibrated roughness values for the main channel are presented in Table 1. They were in the range of 40–70% of the values used by Yoshida and Dittrich (2002). However, the total friction factor of the main channel was about the same in both applications.

Table 1
Calibrated roughness values for the main channel of the reach of the Upper Rhine

Cross-sections (km)	k_M (m)
186.15–189.04	0.06
191.66–191.47	0.04
191.66–193.01	0.12
193.19–199.18	0.21
199.42–207.77	0.12
208.03	0.16
208.18–214.20	0.18

In this application, the momentum transfer between the floodplain and the main channel explains the rest of the friction factor of the main channel. The values of vegetation parameters and floodplain roughness were the same as in Yoshida and Dittrich (2002).

The model was used to simulate two unsteady flood event cases. In case 1, the discharge rate decreased from 790 m^3/s to 387 m^3/s, then increased to 1670 m^3/s and decreased back to 766 m^3/s (2–5 November 1998). Case 2 was a flood event with two peaks, with discharge rate increasing first from 412 m^3/s to 2014 m^3/s, decreasing to 1220 m^3/s, again increasing to 2407 m^3/s, and finally decreasing to about 700 m^3/s in total in 100 h (20–24 February 1999).

Two kinds of stage–discharge data from the River Rhine were available: (a) water levels during steady discharges along the whole reach, and (b) a hydrograph measured in both ends of the reach. In the computation of all (both steady and unsteady) cases, the discharge was used as the upper boundary condition, and the water level in the upper boundary was computed from the mass conservation equation. The discharge-rating curve determined from the hydrograph of the lower end of the reach was used as the lower boundary condition. It should be noted that during the time when the discharge was at a rate of 680 m^3/s the water level was about 60 cm lower in the steady state data than in the hydrograph at the lower end of the reach. This discrepancy in the values was probably due to different time period of determining the stage–discharge relationships for steady and unsteady data, as the measurements have been carried out during several decades. Thus, when the discharge-rating curve for the lower boundary was computed from the unsteady hydrograph, the computed water level ended up being 60 cm higher than the measured value in steady state in the lower end of the channel, which effects the results of the steady state calculations.

Along an increase in the vegetation density at the boundary of the main channel and the floodplain, the friction factor of the imaginary boundary increases as well, until it reaches a certain density in which the vegetation begins to dampen the momentum exchange (Pasche, 1984). In Mertens' (1989) and Nuding's (1991) method, this is not taken into account, but the friction factor is infinitely growing. Pasche (1984) has presented maximum values for some conditions. He related the friction factor of the boundary to a vegetation density parameter and the effective widths of the floodplain and the main channel as

$$\frac{1}{\sqrt{f_J}} = -2.03\log\left(0.065\left(\frac{b_{EFF}}{b_M}\right)^{0.9}\Omega\right) \tag{7}$$

where Ω is a vegetation density parameter computed from vegetation parameters, wake widths and lengths of the plants, and the main channel flow velocity. Based on the data of River Rhine ($a_X = 5.6$ m, $a_Y = 10.3$ m, $d_P = 1.0$ m, $v_M = 0.6$ to 2.3 m/s), the average vegetation density parameter Ω was estimated to be about 2.0 and the ratio of floodplain and main channel widths $b_{EFF}/b_M = 0.15$ to 1.3, and thus the friction factor of the boundary should not significantly exceed $f_J = 0.40$. This was set as an upper limit in the model. The drag coefficient of vegetation was given a constant value of 1.5 suggested by e.g. Mertens (1989) and Nuding (1991) for mixed vegetation, and verified by Järvelä (2002) for leafless willows.

The results of the proposed model were compared to the results of a traditional unsteady flow model in which the floodplains were treated only as storage areas with no conveyance. In the traditional method, only the main channel bottom roughness is included in the computation, but no flow resistance of vegetation on the floodplains or resistance due to momentum exchange is included.

4. Results and analysis

The water levels from the steady state simulation are presented in Fig. 3. A root mean square error for each water level computation was calculated from Eq. (8)

$$\mathrm{RMSE} = \sqrt{\frac{1}{N}\sum_{j=1}^{N}(h_{\mathrm{meas},j} - h_{\mathrm{comp},j})} \tag{8}$$

where $h_{\mathrm{meas},j}$ is the measured water depth and $h_{\mathrm{comp},j}$ is the computed water depth for cross-section $j = 1, \ldots, N$. The lowest discharge rate of 680 m^3/s was used for calibration of the main channel roughness height. The RMSE of 0.37–0.46 m of the proposed model was considered to be acceptable (Table 2). With the traditional model, the water levels at the calibration discharge rate of 680 m^3/s were very accurate with RMSE of 0.16 m, but with higher discharge rates of 1430 m^3/s and 3040 m^3/s the error was significant, RMSE of 1.23 m and 1.96 m, respectively. The RMSE of Yoshida and Dittrich (2002) varied, but was lower with higher discharge rates, from only 0.19 m to 0.28 m, respectively. The high values of RMSE obtained with the proposed model were partly due to the difference in the water levels in the lower boundary caused by the discharge-rating curve.

The water depths in the main channel and in the boundaries of the main channel and each floodplain or bank are shown in Table 3, giving an overview of the channel dimensions and variation of cross-sections. The components of the discharge on the floodplains are presented in Fig. 4. It is seen that water was conveyed

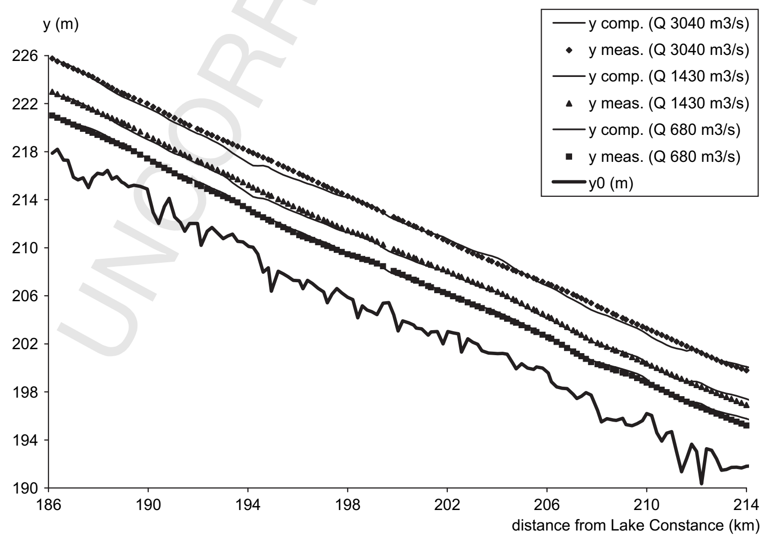

Fig. 3. Computed water levels compared with measured levels for discharges of 680 m^3/s, 1430 m^3/s and 3040 m^3/s.

Table 2
The root mean square errors for steady state computation for different discharges using the proposed model and the traditional method

Q (m^3/s)	Nuding and St. Venant method	Traditional method
	RMSE (m)	RMSE (m)
680	0.37	0.16
1430	0.40	1.23
3040	0.46	1.96

better on the right bank or floodplain because of lower elevation and thus, larger cross-sectional area. For example, in cross-section 43 (Fig. 1) the right floodplain conveyed up to 26% of total discharge when at the high discharge rate of 3040 m^3/s. In the left bank, however, the discharges computed were insignificant when compared to the total.

Average velocities are shown in Figs. 5–7 for discharge rates of 680 m^3/s, 1430 m^3/s and 3040 m^3/s, respectively, and presented in Table 3. It can be observed that although the discharges were very low in the left side, velocities are higher than on the right-side floodplains in every discharge computed. This is because of the large cross-sectional area and low elevation of the floodplain. Significant reduction in computed velocities was observed in the main channels of cross-sections 41–42 and 128–129 during higher discharges. The reach at cross-sections 41–42 has a sudden increase in the cross-sectional area. The reach at 128–129 has very big changes up and down in the bottom elevation.

Table 3 shows the friction factors for the main channel and the floodplains for discharge rates of 680 m^3/s, 1430 m^3/s and 3040 m^3/s, respectively. The main channel friction factors include the friction factor of the imaginary boundary between the floodplain and the main channel.

The simulations of unsteady flood event cases 1 and 2 are shown in Figs. 8 and 9, respectively. With the proposed model, relative errors of discharges were 1.89% and 5.41% and relative errors of peak discharges were 0.29% and 5.78%, respectively (Table 4). The relative error in case 2 was about the same size as the one of Yoshida and Dittrich (2002). Yoshida and Dittrich (2002) did not present all the results of case 1, but only a short time section from 48 h to 72 h. Surprisingly, the difference of results between the proposed model and the traditional model are almost negligible in unsteady cases, unlike the steady cases. In both simulations, the computed discharges and water levels were higher than the measured ones during very high discharge, and lower during low discharges.

5. Discussion

It was recognized that in the derivation of St. Venant equations, flow is assumed one-dimensional with uniform velocity distribution. Yet it is known that flow in a compound channel is never purely one-dimensional because of the intensive vorticity shedding in the boundary between the main channel and the floodplain. Despite these facts, the aim was to test if it is possible to simplify the flow into one dimension by considering the major flow distortions as additional friction, i.e. the resistance caused by the momentum exchange and the resistance caused by the wakes induced by stif vegetation. This simplification gave relatively good results compared to the measured values in the Rhine River in both steady and unsteady simulation. The used McCormack two-step explicit scheme was found relatively stable although there was very high variation in cross-sectional sizes and shapes in the computed reach.

Table 3
Summary of computed main channel water depths h_M, depths of the imaginary boundaries h_J, velocities v, and friction factors f on the reach of the Upper Rhine (f_M includes the friction factors of the imaginary boundaries)

	h_{JL}	h_M	h_{JR}	v_L	v_M	v_R	f_{L1}	f_{L2}	f_M	f_{R2}	f_{R1}
$Q = 680\ m^3/s$											
Average	1.80	3.77	0.44	0.51	1.73	0.34	0.00	0.29	0.06	0.39	0.00
Std dev	0.63	0.71	0.50	0.19	0.24	0.29	0.00	0.16	0.01	1.74	0.00
Min	0.28	2.32	0.00	0.16	0.58	0.00	0.00	0.10	0.04	0.00	0.00
Max	3.21	6.65	2.08	1.00	2.30	1.96	0.00	0.93	0.08	20.00	0.00
$Q = 1430\ m^3/s$											
Average	3.37	5.36	1.58	0.73	2.09	0.56	0.00	0.23	0.06	0.26	0.00
Std dev	0.67	0.74	0.87	0.14	0.29	0.24	0.00	0.05	0.01	0.10	0.00
Min	1.75	3.94	0.00	0.27	0.78	0.00	0.00	0.13	0.04	0.00	0.00
Max	4.84	8.36	3.99	1.09	2.60	1.72	0.00	0.38	0.07	0.53	0.00
$Q = 3040\ m^3/s$											
Average	6.05	8.03	4.13	1.06	2.41	0.63	0.00	0.23	0.06	0.51	0.00
Std dev	0.70	0.77	1.13	0.19	0.37	0.24	0.00	0.06	0.01	0.18	0.00
Min	4.53	6.51	0.00	0.36	0.87	0.00	0.00	0.16	0.04	0.00	0.00
Max	7.80	10.98	6.79	1.51	3.07	1.25	0.00	0.41	0.07	0.90	0.00

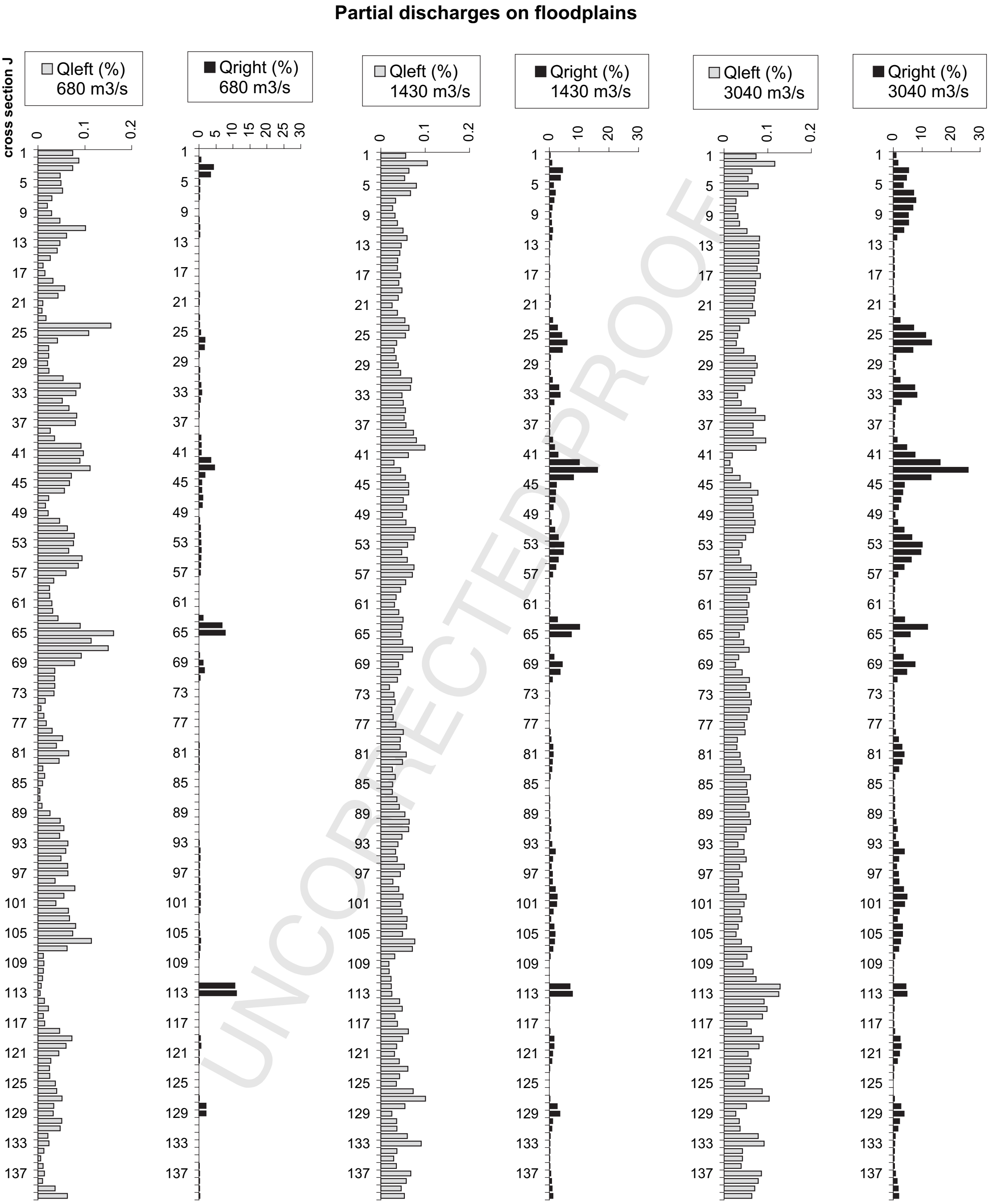

Fig. 4. Percentages of discharge flowing on the river floodplains or banks. Note different scale in right and left floodplains.

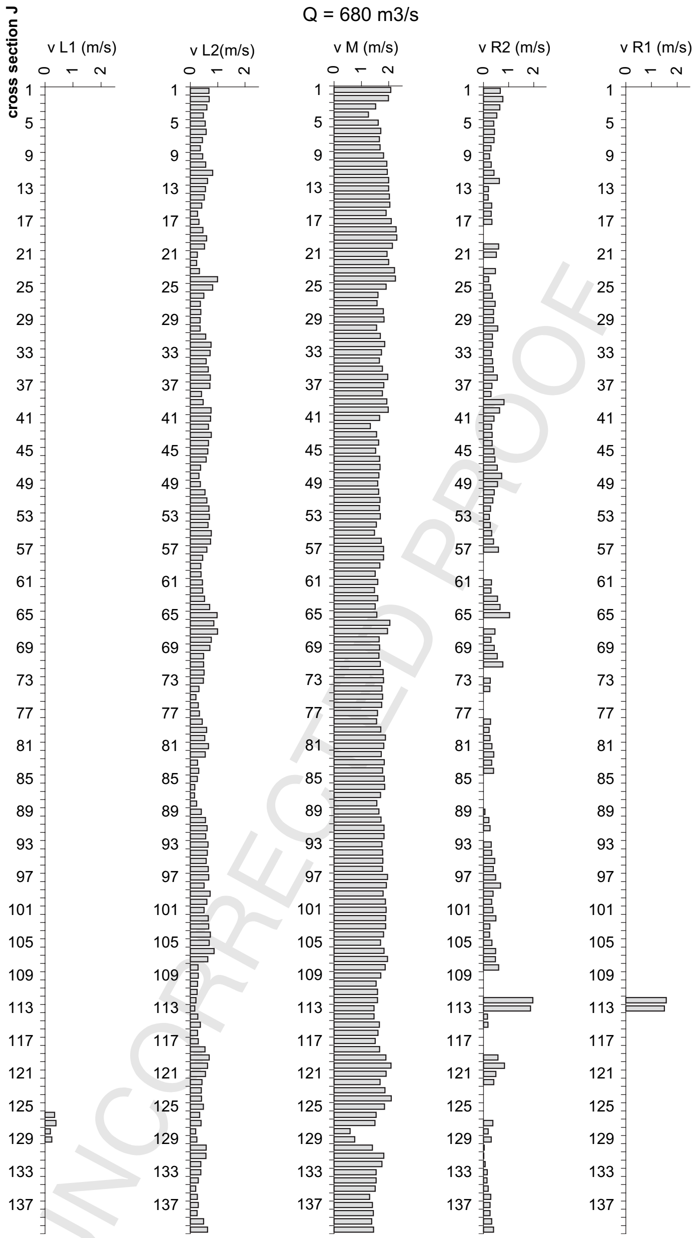

Fig. 5. Computed average velocities during discharge 680 m^3/s in different channel parts: outer and inner left floodplain (L1, L2), the main channel (M), and inner and outer right floodplain (R2, R1).

Because the resistance effect of the momentum exchange process is limited to a certain region on both sides of the imaginary boundary between the main channel and the floodplain, it is quite realistic to assume it as an additional boundary resistance. The wakes induced by the stiff vegetation mainly reduce the flow velocity on the floodplains and can therefore be considered as additional resistance on the floodplains.

The results with the traditional method, where the floodplains are considered only as storage areas, were very similar to the ones with the proposed model. However, the proposed model computes velocities,

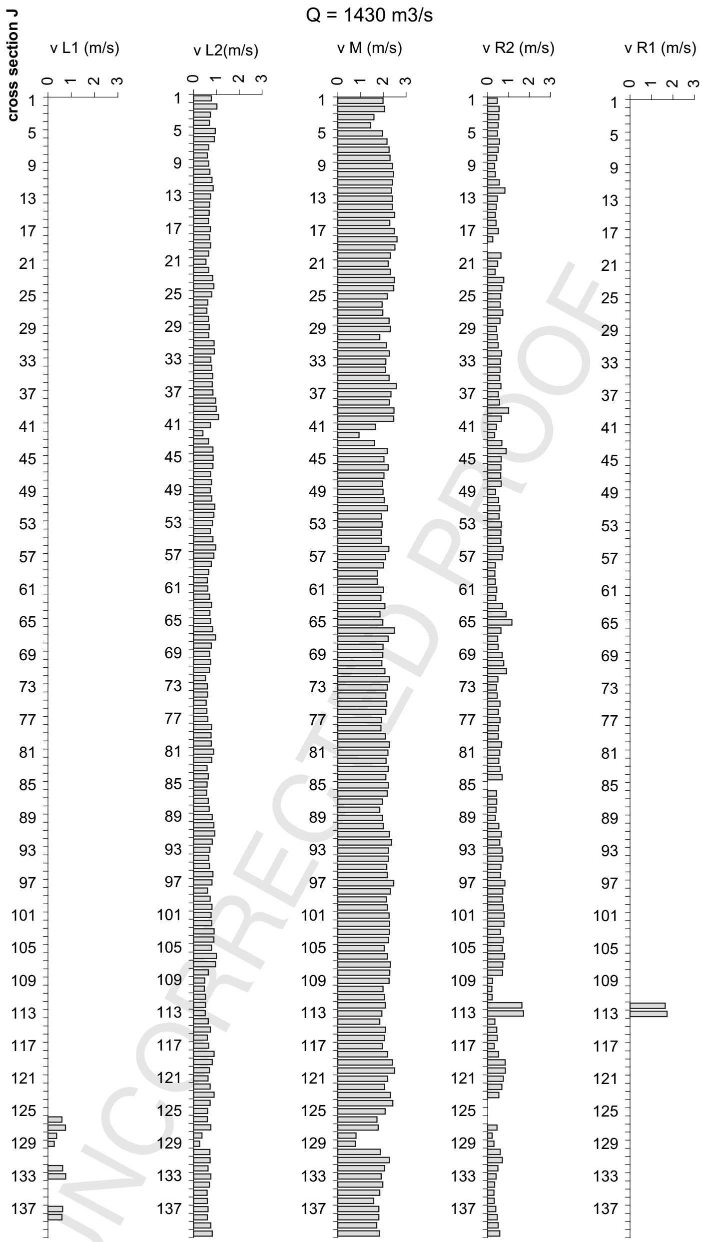

Fig. 6. Computed average velocities during discharge 1430 m^3/s in different channel parts.

discharges and friction factors separately for the main channel and the floodplains, which has significant value in estimating local conditions for erosion and sedimentation, and for different habitat. And clearly, the conveyance capacity of the floodplains was considerable, up to 26% of the total discharge in some cross-sections.

The maximum values for the friction factor of the boundary between the main channel and the floodplain, f_J, were estimated from Pasche's (1984) method. Limiting the resistance coefficient in some way was essential due to a combination, in some cross-sections, of very dense vegetation and very low water depths, which can rise the value of the friction factors up to 20 or even 50. The

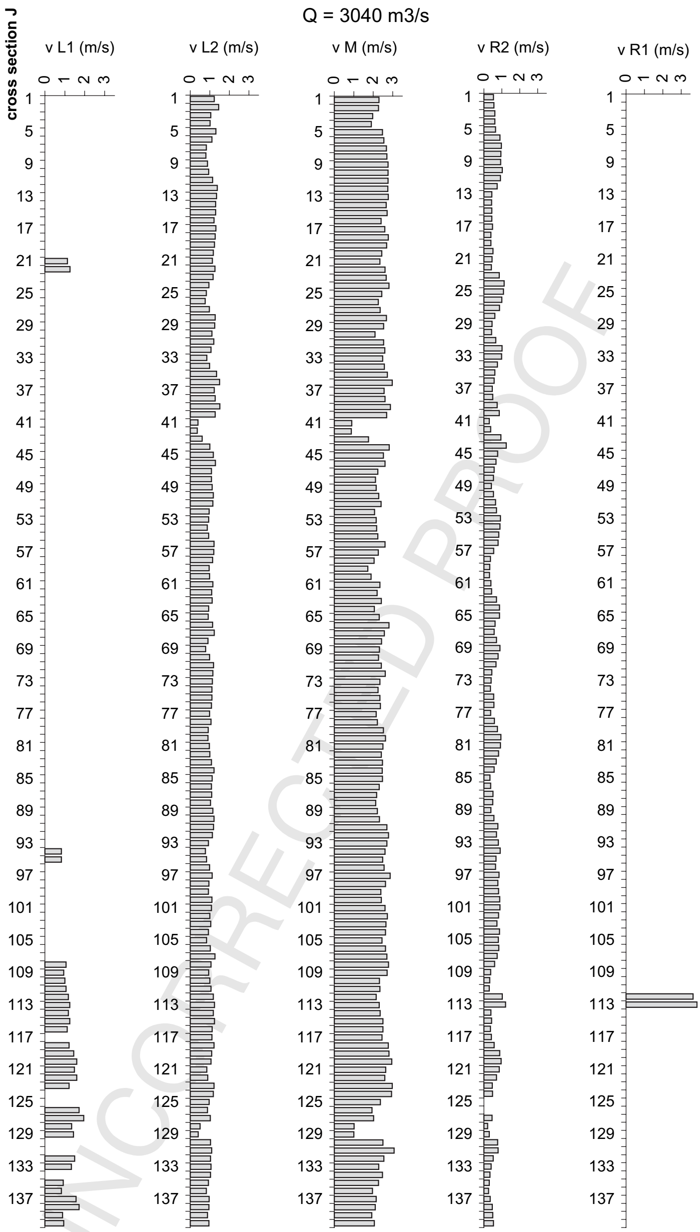

Fig. 7. Computed average velocities during discharge 3040 m^3/s in different channel parts.

estimation method used, however, was not very accurate as it was based only on some local average values. Therefore, further development of the method is recommended.

The Eqs. (3)–(6) developed to compute the composite hydraulic radius and composite friction factor gave relatively good values. Even so, in the reach between 193 km and 197 km, there was a big sag in the water levels in the steady state. In this river reach, the vegetated areas are very large and of low elevation, thus having a high value for water depth. The sag indicates that in this reach the composite friction factor was underestimated. Increasing the maximum limit of f_J increased the composite friction factor, but it did not

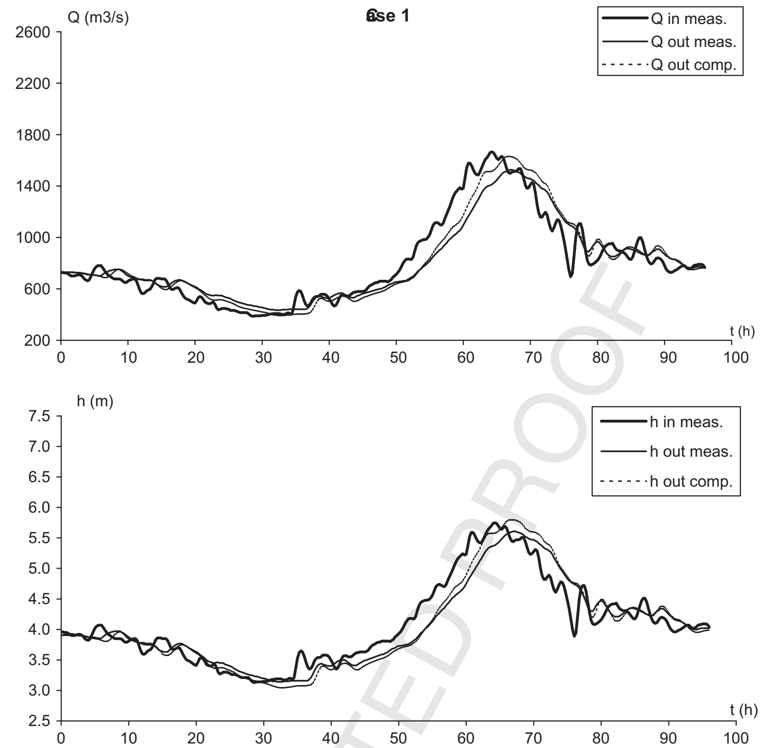

Fig. 8. The measured and simulated discharges and water levels in unsteady case 1.

reduce the sag. The composite friction factors were still underestimated in some reaches while allowing great overestimation in other reaches. The results indicate that the method may underestimate the friction factors of vegetated areas and momentum exchange for high water depths and overestimate resistance values for low water depths. Furthermore, not taking into account the effects of changes in velocity head and acceleration terms in Eqs. (3)–(6) may have significant effect on some reaches with variable cross-sectional size.

In Nuding's method, the Darcy–Weisbach friction factors are computed from the Colebrook equation, including a shape coefficient c_{sh}. Depending on the depth–width ratio of the channel, the values of the coefficient vary from 0.52 in a wide channel to 0.82 in a narrow channel (see Helmiö, 2002, eqs. (9) and (10)). This coefficient had a significant effect on the friction factors, because when neglecting it and using instead coefficients determined for pipe flow, the friction factor of each part could be up to 39% lower compared to cases when shape coefficient was included. Therefore, caution should be taken if selecting the shape coefficient from several presented in literature.

In this model, the additional resistance caused by the sinuosity was neglected because in a large river, it has relatively small effect compared to the resistance of vegetation. It could be included in the flow model by estimating additional bottom roughness to the channel (e.g. Fisher, 2001). Alternatively, the sinuosity could be taken into account in Eqs. (3) and (4) by giving a different distance L_i between the two consecutive cross-sections for each part. The effects of the form resistance associated with large-scale bed undulations such as pools and riffles were not investigated in the model. The flow resistance caused by pool-riffle-variation could be estimated by selecting representative cross-sections for the model, but it was not investigated whether the effects could be seen with this cross-sectional data or not.

6. Conclusions and future development

An unsteady flow model was proposed to compute partial discharges, velocities and friction factors for the main channel and the floodplains. Taken into account were the resistance of vegetation on the floodplains, and the additional resistance caused by the interaction processes between a main channel and a floodplain, or between a vegetated zone and a non-vegetated zone. This model is a valuable tool for assessing local hydraulic

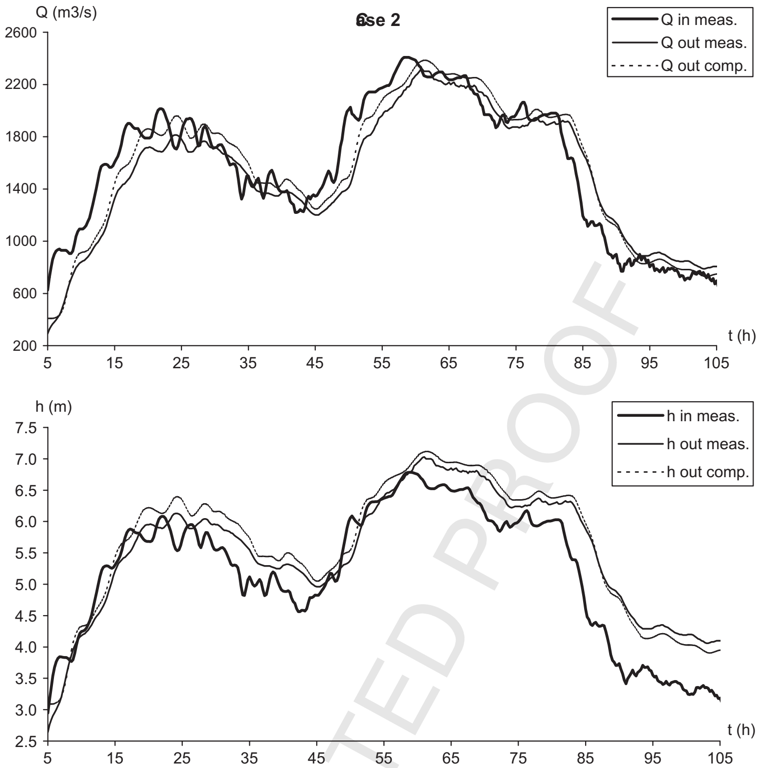

Fig. 9. The measured and simulated discharges and water levels in unsteady case 2.

conditions in compound channels, to ensure suitable conditions for habitat diversity in projects of environmental flood management. A program was developed to pre-process the complex field data, obtained from e.g. a digital terrain model, to yield a form suitable for input into the unsteady flow model.

The model was applied to a reach on the Upper Rhine. Despite the inexact simplification of one-dimensional flow in a compound channel, the measured hydrographs were simulated reasonably well. In addition, the model is relatively simple and easy to apply compared to multi-dimensional flow models. Thus, it can be reliably used as a tool to estimate time-dependent stage–discharges and furthermore, the discharge components.

Table 4
The relative error of discharges and of peak discharge for the unsteady flood event cases using the proposed model and the traditional model

	Nuding and St. Venant model		Traditional St. Venant model	
	RE (%)	REp (%)	RE (%)	REp (%)
Case 1	1.9	0.3	1.9	0.8
Case 2	5.4	2.9	5.6	2.0

Further development of Nuding's method is recommended to estimate resistance of vegetation and momentum exchange more accurately in the extreme water levels. Furthermore, the velocity head and the acceleration terms should be implemented in the procedure (1)–(4). The computed average velocities on the floodplains in the unsteady state ought to be verified with ones computed with the help of a 2D model or measured velocities, and the model should further be tested in rivers of different sizes and shapes.

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