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Unsteady 1D flow model of compound channel with vegetated floodplains

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Abstract

In areas that are occasionally inundated by floods, it is essential to know the quantity and density of vegetation that can be allowed while avoiding flooding beyond the intended floodplains. An unsteady flow model was developed for a channel with vegetated floodplains, to take into account the retention effects of the vegetated areas on flood wave conveyance. A one-dimensional (1D) unsteady flow model was combined with Nuding's method, which takes into account the friction caused by vegetation and the additional resistance caused by the interaction between the main channel and vegetated areas. Nuding's method was used to compute the total Darcy–Weisbach friction factor for each cross section and each water level as input data for each time step of the flow model. The model was applied to a double-trapezoidal channel, and the results were compared with a traditional model, in which floodplains were considered only as storage. Differences in the conveyance capacity of the channel were found between the models.

Keywords: Hydraulics; Rivers; Floodplains; Vegetation; Roughness

1. Introduction

Along with the general trend of environmental river engineering and restoration, more variation of geomorphic and biological elements is allowed in rivers, e.g. irregular cross sections, floodplains and vegetation. The flow physics of natural, irregular and meandering channels with floodplains and vegetation differ remarkably from the ones of straightened and regular channels and thus, cause large problems in channel design. Existing design methods are, to varying degrees, unreliable for versatile channel hydraulics. Therefore, more accurate methods are needed for hydraulic design of these channels.

In many areas, flooding cannot be allowed because of infrastructure. However, the channel cannot be oversized, because firstly, it can cause channel instabilities, erosion and sedimentation problems, and secondly, retention times may be reduced and flow may be accelerated due to reduced roughness and channel length. Locally that could solve the design problems, but may end up moving the problems downstream. Furthermore, it can totally isolate the channel flora and fauna from the surrounding environment and reduce the natural development of biodiversity (see e.g. Darby and Thorne, 1996). In such cases, a two-stage i.e. a compound channel may be an effective low-cost solution. In general, it provides adequate flood management allowing for morphological and hydraulic characteristics of the river during low flows. Additionally, in urban areas the flood plain has significant recreational value: e.g. in many Japanese cities, floodplains are effectively used for variable sports facilities.

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Nomenclature

A	cross-sectional area (m^2)
A_F	cross-sectional area of the floodplain (m^2)
A_M	cross-sectional area of the main channel (m^2)
A_{st}	total 'storage' area of cross section (m^2)
a_x, a_y	distances of the vegetation elements in x and y direction (m)
a_z	distances of the vegetation elements (branches) in z direction (m)
b_{eff}	contributing width of the floodplain (m)
b_F	width of floodplain (m)
b_M	width of main channel (m)
b_{st}	total 'storage' width of channel (m^2)
b_m	computational width of main channel (m)
c_D	drag coefficient (–)
c_{sh}	form coefficient (–)
d_P	diameter of a single vegetation element in x and y direction (m)
d_Z	diameter of a single branch in z direction (m)
f	Darcy–Weisbach friction factor (–)
f_F	D–W friction factor for the floodplain (–)
f_J	D–W friction factor for the boundary between main channel and floodplain (–)
f_M	D–W friction factor for the main channel (–)
f_V	D–W friction factor for the vegetation (–)
f_W	D–W friction factor for the wall or boundary (–)
g	acceleration due to gravity (m/s^2)
h	water depth (m)
h_J	water depth in the imaginary boundary between main channel and floodplain (m)
h_P	height of vegetation (m)
k	roughness (m)
k_F	wall roughness of the main channel (m)
k_M	wall roughness of the main channel (m)
p_F	wetted perimeter of the floodplain bottom (m)
p_M	wetted perimeter of the main channel (m)
Q	discharge (m^3/s)
Q_F	floodplain discharge (m^3/s)
Q_M	main channel discharge (m^3/s)
R	hydraulic radius (m)
R_F	hydraulic radius of the floodplain (m)
R_M	hydraulic radius of the main channel (m)
R_{MW}	hydraulic radius of the main channel computed without the wetted perimeter of the imaginary boundaries (m)
Re	Reynolds' number (–)
S, S_f	friction slope (–)
S_0	bottom slope (–)
v_M	velocity in main channel (m/s)
v_F	velocity on floodplain (m/s)
β	coefficient of non-uniform flow velocity distribution (–)
ϵ	density number of vegetation (–)
ω_V	vegetation parameter (–)

Design of compound channels with vegetation can be divided into several parts. First, there is a need for more accurate estimation of the resistance in vegetated areas of the channel and floodplain; and second, the interaction process between the main channel and the floodplain or vegetated area. Third, there is a need to estimate the retention volume of vegetated floodplains.

All traditional methods of estimating the resistance of channels with complex geometry and compound roughness are developed for either steady flow conditions or simple channel geometry or both, with the exception of the turbulence models that are used to model the lateral flow. They are closer to real physical flow behaviour, but are very complex and not easy to use in general channel design. However, there is a need to estimate the retention effects of the floodplains in unsteady conditions. Therefore, a simple unsteady 1D flow model was developed for a river channel with vegetated floodplains to take into account the retention effects of vegetation without neglecting the effects of lateral shear stress. The modelling was limited to rivers with mild slopes and sub-critical flow.

2. Hydraulics of compound channels

2.1. Compound channels without vegetation

Momentum transfer between the main channel and the floodplain decreases the discharge in the main channel and increases the discharge on the floodplain, ending up in decreasing the total discharge capacity of the channel. This was first recognised by Sellin in the 1960's (Lambert and Sellin, 1996). In recent decades, a significant amount of physical laboratory modelling has been carried out for compound channels with both double-rectangular and double-trapezoidal shapes of cross sections, to determine the flow behaviour in compound channels of different relative widths and depths. The most famous research facility may be the SERC flood channel facility in the UK (see e.g. Shiono and Knight, 1991; Myers and Lyness, 1997).

These measurements have helped in understanding the complex flow pattern, boundary shear stresses and the causes and consequences of the momentum transfer between the main channel and the floodplain. For example, Wormleaton et al. (1982), Knight and Demetriou (1983), and Stephenson and Kovlopoulos (1990) have studied in detail the flow pattern and the distribution of the boundary shear stresses in a double-rectangular channel. Shiono and Knight (1991) have broadened the analysis to all shapes of channels that can be discretised into linear elements. In addition to Shiono and Knight (1991), at least Prinos et al. (1985), Shimizu and Tsujimoto (1993), Lambert and Sellin (1996), and Sofialidis and Prinos (1999) have studied the structure of turbulence in compound channels. Myers and Lyness (1997) have researched the discharge ratios of compound channels, finding two significant key ratios to explain the flow behaviour: total-to-bankfull discharge and main-channel-to-floodplain discharge.

A large number of methods have been developed which attempt to take into account the energy dissipation due to shear stresses at the interface of the main channel and the floodplain, and the secondary flows caused by the shape of cross section. One of the first methods seems to be the *single-channel method* where the apparent shear stress in the interaction zone is taken into account in the roughness coefficient. According to Myers (1987; ref. Stephenson and Kovlopoulos, 1990), it underestimates the discharge. However, it is widely used in 1D flow computation of channels with floodplains (see e.g. Cunge et al., 1980) so that floodplains are considered only as storage areas with zero longitudinal velocity. In the *divided channel method*, the compound channel is divided into independent parts on some basis, like in modification of Posey (Myers and Lyness, 1997). In general, the discharge is overestimated because the reductions of the velocities due to the shear stresses at the interfaces are neglected. Both methods are very simple to use in channel design and widely used, but the physical background is very weak.

The physical background of *apparent shear stress methods* (e.g. Wormleaton et al., 1982; Knight and Demetriou, 1983) are closer to reality than the earlier methods, as they assume that the shear stress at the interface of the main channel and the floodplain is significantly higher than the boundary shear stress of the main channel or the floodplain. Although these methods are quite complex to use in computation, they are much simpler than turbulence models. Applying any of the aforementioned methods to

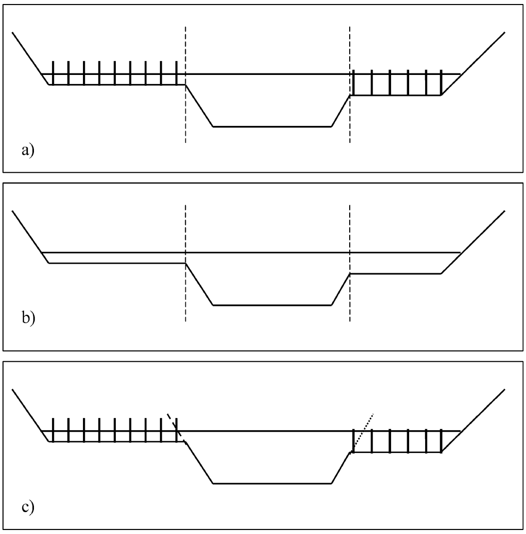

Fig. 1. The models that are compared: Model 1 combining St. Venant model with Nuding's method for vegetated floodplains; Model 2 combining St. Venant model with Nuding's method for floodplains without vegetation; Model 3 being a traditional version of St. Venant model for compound channel.

unsteady flow exacerbates the errors already present in the case of steady flow.

2.2. Compound channels with floodplain vegetation

One-dimensional methods for steady flow have been developed to take into account the lateral shear stress between the main channel and vegetated floodplain (Pasche, 1984; Pasche and Rouvé, 1985), between vegetated and non-vegetated zones of cross sections (Nuding, 1991, 1998), or between the main channel and vegetated banks (Mertens, 1989, 1994). Darby and Thorne (1996) developed a method to predict stage-discharge curves for straight gravel-bed channels with flexible vegetation on the floodplains and steady, uniform flow, using an eddy viscosity model and Kouwen's (1988) roughness estimation methods of flexible vegetation. Later Darby (1999) included computation of sand bed and rigid floodplain vegetation in the model.

The common thread in the methods of Mertens, Pasche and Nuding is that the boundary between the main channel and floodplain or vegetated zone is treated as an imaginary wall, for which a separate Darcy–Weisbach friction factor is estimated. According to Pasche (1984) and Pasche and Rouvé (1985), the friction factor of the boundary depends mainly on the relationships of plant diameter and plant distances (d_p/a_x and d_p/a_z), and the contributing width of the floodplain that has influence in the interaction process (b_{eff}). The same conclusions are made by Mertens (1989, 1994), although the calculation procedure is different. According to Nuding (1991, 1998), the friction factor of the boundary depends on the relationship of the ideal velocity in the main channel without the effects of interaction and floodplain velocity ($v_{M\text{-ideal}}/v_f$), the relationship between the hydraulic radius of the floodplain and the depth of the imaginary boundary (R_f/h_J) and relationship between the contributing width of the floodplain and the computational main channel width (b_{eff}/b_m). Also Naot et al. (1996a) and Thornton et al. (2000) explain that the apparent shear stress at the interface of the main channel and the floodplain can be quantified as a function of the local turbulence at the interface; and it is influenced by the main channel and floodplain velocities, flow depth and vegetation density.

The denser the floodplain vegetation, the further the point of maximum velocity moves away from the floodplain (Naot et al., 1996a). Furthermore, the denser the floodplain vegetation is, the more the turbulence energy is reduced on the floodplain and still more at the boundary of the main channel and the floodplain. When there is no floodplain vegetation, the slope of the bank between the main channel and the floodplain and furthermore, the width of floodplain have a significant effect on the shear stress at the interface; but when floodplain is vegetated, the slope has no significant influence on the shear stress (Pasche and Rouvé, 1985). Naot et al. (1996b) found out that the shear layer that develops at the boundary of vegetation can develop an oscillatory pattern of longitudinal vortices.

Naot et al. (1996a) found that the behaviour of the flow in a compound channel with rigid floodplain vegetation depends mainly on two vegetation parameters: the shading factor and the wake length. The shading factor increases with increases in vegetation diameter and density, and the wake length increases with increasing vegetation diameter and decreasing vegetation density. The effect of the wake length is included in the computational method of Pasche.

Pasche and Rouvé (1985) also found out that when the vegetation is very dense, the friction factor at the boundary of the main channel and the floodplain might increase when the width of floodplain decreases. Therefore, the velocity reduction due to vegetation on the floodplain is not sufficient to describe the change in the friction factor of the boundary.

3. Model development

Two different types of models were implemented to take into account the effects of the lateral shear stress on the total friction factor and thus on the flow retention. First, in a basic unsteady flow model, a steady computational method was included that estimates the resistance due to vegetation and the resistance due to the apparent shear stress in the boundary between the main channel and the floodplain or vegetation zone (Fig. 1). Secondly, a basic unsteady flow model in which the floodplains were treated only as storage areas was made for comparison. The models were tested for a compound channel that had two vegetated floodplains.

3.1. Models (1) and (2): 1D unsteady flow model with Nuding's method

Model (1) was a 1D unsteady flow model for a compound channel with vegetated floodplains. Model (2) was the same as model (1), except that the floodplain vegetation was left out and only bottom roughness was included.

The basic form of the hyperbolic, non-linear St Venant equations was used in the models. The equations can be presented in a conservative matrix form

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

where the vectors are

$$\mathbf{U} = \begin{bmatrix} A \\ Q \end{bmatrix}, \tag{2}$$

$$\mathbf{F} = \begin{bmatrix} Q \\ \beta \dfrac{Q^2}{A} \end{bmatrix} \tag{3}$$

and

$$\mathbf{G} = \begin{bmatrix} 0 \\ gA(S_0 - S_f) \end{bmatrix}, \tag{4}$$

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 and S_0 is the bottom slope. The upper terms of the vectors in Eqs. (2)–(4) form the continuity equation and the lower ones the momentum equation. The friction term in the momentum equation can be expressed as

$$-gAS_f = -f\frac{Q|Q|}{8AR}, \tag{5}$$

where R is the hydraulic radius and f is the Darcy–Weisbach friction factor.

In the models, a McCormack two-step explicit finite differentiation scheme was used, because of the simplicity of combining it with Nuding's method. The scheme is accurate to the second order in space and time. The computational procedure used was the following:

The values of the predictor step are computed as (Tseng, 1999)

$$\mathbf{U}_i^p = \mathbf{U}_i^n - \frac{\Delta t}{\Delta x}(\mathbf{F}_{i+1}^n - \mathbf{F}_i^n) + \Delta t\mathbf{G}_i^n \tag{6}$$

and the values of the corrector step from the predictor values as

$$\mathbf{U}_i^c = \mathbf{U}_i^n - \frac{\Delta t}{\Delta x}(\mathbf{F}_i^p - \mathbf{F}_{i-1}^p) + \Delta t\mathbf{G}_i^p \tag{7}$$

New values are then the averages of the predictor and the corrector steps

$$\mathbf{U}_i^{n+1} = \tfrac{1}{2}(\mathbf{U}_i^p + \mathbf{U}_i^c). \tag{8}$$

To deal with the vegetal roughness and the lateral shear stress in the boundary between main channel and floodplain, a method of Nuding (1991, 1998) was built into the unsteady flow model. It is a calculation procedure, in which for a known water level, the contribution of the main channel and each floodplain to the discharge is computed separately, based on e.g. the shape and vegetation of the channel.

Nuding's method was chosen because it requires less iteration compared to methods of Mertens and Pasche, which makes it easier to implement in the unsteady flow model. In Nuding's method, some parameters are highly simplified, compared to the methods of Pasche and Mertens, but this also makes the computation procedure much simpler in practise. There are many empirical coefficients in all three methods.

Nuding's method was initially developed for a partly vegetated channel (Nuding, 1991), but further applied to a compound channel (Nuding, 1998). The method has the following limitations:

- contributing width of the floodplain must be less than 1/5 of the main channel width
- flow must be subcritical
- vegetation parameter ω_V must be less than 9,6 1/m
- friction factor of the imaginary boundary must be larger than friction factor of the bottom of the main channel

In the method, the maximum width for floodplains is not limited, but only the contributing width that depends on vegetation density. However, it must be noted, that in case of extremely wide floodplains the assumption of 1D flow is even less correct.

3.1.1. The computational procedure of Nuding's method

(a) In the beginning, the compound channel is divided into three parts. The water depths at the boundaries between the main channel and the floodplains i.e. the imaginary boundaries h_J are determined. Then for the main channel (M) and the floodplains (F), the wetted perimeters (p_M and p_F), widths (b_M and b_F), boundary i.e. wall roughness (k_M and k_F), cross sectional areas (A_M and A_F) and hydraulic radii (R_M and R_F) are computed. The Darcy–Weisbach friction factors for a rough wall are computed from

$$\frac{1}{\sqrt{f}} = 2.03\ \lg\left(\frac{4 \times 3.71\ c_{sh}\ R}{k}\right) \tag{9}$$

where R is the hydraulic radius and k is the boundary roughness. The form coefficient c_{sh} can be estimated for the main channel or floodplain from

$$c_{sh} = \begin{cases} \left(\dfrac{1.629\ h/b}{1+2\ h/b}\right)^{0.25} & \text{when } 0.05 < h/b < 0.62 \\ 0.52 & \text{when } h/b \le 0.05 \text{ (wide channel)} \\ 0.82 & \text{when } h/b \ge 0.62 \text{ (narrow channel)} \end{cases} \tag{10}$$

where h is the water depth and b is the surface width of the zone.

(b) The friction factor in the vegetated floodplain can be estimated as a sum of the friction factors of the bottom (excluding the imaginary boundary) and the vegetation

$$f_F = f_W + f_V. \tag{11}$$

In the case of dense vegetation, the boundary friction factor is difficult to determine and it can be assumed that the boundary roughness has no significant effect on the friction factor. The density of vegetation is determined as

$$\omega_V = \frac{d_P + d_z\ a_y/a_z}{a_x a_y}, \tag{12}$$

where a_y and a_x are average distances of the vegetation elements, d_P is the diameter of a single element, a_z is the average distance of branches in vertical direction and d_z is the diameter of a single branch.

If $\omega_V < 1.0$ (sparse vegetation), the flow velocity is

$$v_F = \sqrt{\frac{1}{f_F}}\sqrt{8gR_F S}, \tag{13}$$

where $R_F = A_F/p_F$, p_F is the wetted perimeter of the vegetated zone without the imaginary boundary and

$$\sqrt{\frac{1}{f_F}} = \sqrt{\frac{1-\epsilon}{f_W(1-\epsilon)+f_V}}, \tag{14}$$

in which the density number of the vegetation (the volume relationship of Kaiser) is computed from

$$\epsilon = \sum V_V/V_F \tag{15}$$

where V_V is the volume of vegetation elements and V_F is the total volume of the floodplain. The friction factor of the vegetation is computed from

$$f_{\mathrm{V}} = 4\frac{h_{\mathrm{P}}d_{\mathrm{P}}}{a_x a_y}c_{\mathrm{D}}\cos\alpha \tag{16}$$

where h_{P} is the height of vegetation, the drag coefficient c_{D} varies between 1.0 and 1.5, and α is the slope of the floodplain bank ($\cos\alpha \approx h/b$). The vegetation parameter in Eq. (16) can be simplified as

$$\frac{h_{\mathrm{P}}d_{\mathrm{P}}}{a_x a_y} = \omega_{\mathrm{V}}h_{\mathrm{J}}. \tag{17}$$

If $\omega_{\mathrm{V}} \geq 1.0$ (dense vegetation), the flow velocity is

$$v_{\mathrm{F}} = \sqrt{\frac{2gS}{c_{\mathrm{D}}\omega_{\mathrm{V}}}} \tag{18}$$

where S is the friction slope. Thus, the discharge for the whole vegetated floodplain is

$$Q_{\mathrm{F}} = A_{\mathrm{F}}v_{\mathrm{F}}. \tag{19}$$

For exceptions of very narrow vegetation zones or single vegetation elements, see Nuding (1991).

(c) In the main channel, an ideal flow velocity without the effects of the interaction process can be estimated as

$$v_{\mathrm{M,ideal}} = \sqrt{\frac{1}{f_{\mathrm{M,ideal}}}}\sqrt{8gR_{\mathrm{MW}}S}, \tag{20}$$

where $f_{\mathrm{M,ideal}}$ is estimated from Eq. (9) and the hydraulic radius is

$$R_{\mathrm{MW}} = A_{\mathrm{M}}/p_{\mathrm{M}} \tag{21}$$

where p_{M} is the wetted perimeter of the main channel excluding the imaginary boundaries.

The friction factor for the imaginary boundary can be calculated from

$$f_J = 4\left[\lg\left(\frac{v_{\mathrm{M,ideal}}}{v_{\mathrm{F}}}\right)\right]^2\frac{R_{\mathrm{F}}}{h_{\mathrm{J}}}\frac{b_{\mathrm{EFF}}}{b_{\mathrm{m}}} \tag{22}$$

where $b_{\mathrm{m}} = A_{\mathrm{M}}/h_{\mathrm{J}}$and h_{J} is the water depth in the imaginary boundary between the main channel and the floodplain. If the computed value of b_{m} is greater than the width of the main channel, b_{m} is the main channel width (Nuding, 1998). The width of the interaction zone is

$$b_{\mathrm{EFF}} = 3.2\sqrt{a_z c_{\mathrm{D}} d_x}, \tag{23}$$

where an estimation for the drag coefficient $c_{\mathrm{D}} = 1.0$ can be used, when Reynolds number is large. In case of no vegetation on the floodplains, a value $b_{\mathrm{EFF}} = 0.15h_{\mathrm{J}}$ can be used.

The friction factor for the walls of the main channel is iterated from Eq. (9) and

$$R_{\mathrm{M}} = \frac{f_{\mathrm{MW}}A_{\mathrm{M}}}{\sum f_{\mathrm{MWi}}p_{\mathrm{Mi}} + \sum f_{\mathrm{J}}h_{\mathrm{J}}} \tag{24}$$

so that the friction factors f_{MW} and f_{MWi} are computed from Eq. (9) and used as input into Eq. (24), from which R is input to Eq. (9) and a new value for friction factor is obtained. The iteration is carried out until the hydraulic radii and friction factors are constant.

The total Darcy–Weisbach friction coefficient for the main channel is

$$\frac{1}{\sqrt{f_{\mathrm{M}}}} = \sqrt{\frac{p_{\mathrm{M}} + \sum h_{\mathrm{J}}}{(f_{\mathrm{M}}p_{\mathrm{M}}) + \sum(f_{\mathrm{J}}h_{\mathrm{J}})}} \tag{25}$$

and the flow velocity is

$$v_{\mathrm{M}} = \sqrt{\frac{8gR_{\mathrm{M}}S}{f_{\mathrm{M}}}}. \tag{26}$$

The discharge of the main channel is thus

$$Q_{\mathrm{M}} = A_{\mathrm{M}}v_{\mathrm{M}} \tag{27}$$

and the total discharge is

$$Q_{\mathrm{total}} = Q_{\mathrm{M}} + \sum Q_{\mathrm{F}}. \tag{28}$$

Schumacher (1995) compared methods of Mertens, Pasche and Nuding with independent data. According to him, Nuding's method underestimates the friction factor of the imaginary boundary and thus, the method is unreliable, but Nuding (1998) explains that Schumacher did not realise that in Eq. (22) the computational value of b_{m} cannot exceed the physical width of the main channel.

In the models presented in this paper, Nuding's method was used as a subprogram to compute the total Darcy–Weisbach friction factor f for the whole compound channel with the help of discharges computed for the main channel and the floodplains. The total Darcy–Weisbach f was input into the St Venant computation in Eq. (5). It was computed separately for each cross section and for each water level both in the predictor and in the corrector step of the scheme. Also the water levels in the initial state were computed using Nuding's method.

The boundary conditions were dealt with using the continuity equation such that the discharge was given as the upper boundary condition, and the stage–discharge curve was used as the lower boundary condition.

3.2. Model (3): 1D unsteady flow model for a compound channel—traditional approach

As presented in Cunge et al. (1980), a traditional way to deal with floodplains in 1D modelling is to use the total widths and areas of the cross-sections in the continuity equation

$$\frac{\partial A_{\mathrm{St}}}{\partial t} + \frac{\partial Q}{\partial x} = 0 \quad (29)$$

where the storage area can be presented with the help of the storage width as

$$\frac{\partial A_{\mathrm{St}}}{\partial t} = b_{\mathrm{St}} \frac{\partial h}{\partial t} \quad (30)$$

However, only the width and area of the main channel are included in the momentum equation (Fig. 1). This way, it is assumed that main channel transports all the water in the longitudinal direction. Therefore, the floodplains are considered only as storage areas with zero longitudinal velocities, and thus don't contribute to the overall momentum flux in the cross section. A model of this type was compared to the unsteady model combined with Nuding's method. The same McCormack scheme was used with one roughness value k for each cross section and with the same boundary conditions.

4. Results

Due to a great number of parameters in the models, only a few of them were selected for investigation in this early phase of the study. The parameter values were not changed along the length of the channel, although it was made possible in the model. The following channel dimensions were fixed during the model testing: the main channel width was set to $b = 10$ m and side slopes of both the main channel and floodplains to 2:1. The bottom roughness of the main channel and the floodplains was set to $k = 0.02$ m. Both floodplains were at a level of 2 m from the bottom of main channel; although in the model it is possible to set the floodplains on different levels in each side of the channel and vary the slope of the floodplain bottom in longitudinal direction. Effects of variation in floodplain widths, vegetation density and longitudinal slope were tested. Water levels and discharges were compared between the following models:

Model (1): Nuding's method and St Venant equations with plants
Model (2): Nuding's method and St Venant equations without plants on floodplain
Model (3): Traditional St Venant calculation with floodplains as storage areas

In the model (3), it is not possible to make a difference in the computation between vegetated and non-vegetated floodplains.

4.1. Comparison in steady state

At the beginning, the models were compared having steady flow 50 m^3/s as an upper boundary condition in the channel, and the following parameter values were set: $a_x = a_y = 1$ m, $h_{\mathrm{p}} = 2$ m, $d_{\mathrm{p}} = 0.1$ m, $d_z = 0.02$ m, $a_z = 0.2$ m, $b_{\mathrm{fl}} = b_{\mathrm{fr}} = 10$ m, $S_0 = 0.001$. The initial conditions were $h_{\mathrm{end}} = 1$ m and $Q_{\mathrm{up}} = 50\ \mathrm{m}^3/\mathrm{s}$.

In model (3), water level was about 2.15 m, i.e. about 20 cm lower than in models (1) and (2). It is presumed in the traditional model (3) that no flow is transported longitudinally on the floodplains. However, models (1) and (2) differ from this assumption. In model (1) over 5% of the total discharge was transported on the floodplains and in model (2) almost 7% of the total discharge. The differences were quite small between the models (1) and (2), i.e. the versions with and without floodplain vegetation, respectively. This is due to the fact that water levels on floodplains were quite low and thus, the lateral shear stress played a more significant role than the effects of vegetal resistance.

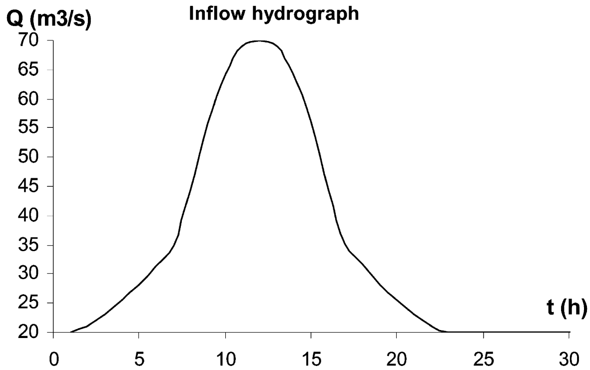

Fig. 2. Assumed inflow hydrograph for model testing.

4.2. Comparison in unsteady state

In the next phase, an unsteady flood event due to rainfall in typical Finnish conditions was simulated: flood runoff 100 l/s/km^2, catchment area 700 km^2, mean discharge 20 m^3/s, rising to peak discharge 70 m^3/s during 12 h and decreasing back to 20 m^3/s during another 12 h (Fig. 2). The initial conditions were $h_{\mathrm{end}} = 1$ m and $Q_{\mathrm{up}} = 20$ m^3/s. In Finland, it is typical that floodplains are very wide and shallow. Several computations were carried out with different floodplain widths ($b_{\mathrm{F}} = 3–100$ m), vegetation densities ($\omega_{\mathrm{V}} = 0.04–3.5$) and the longitudinal bottom slope ($S_0 = 0.001–0.0015$). Crosswise effects of changes in the parameters were not investigated.

In general, the water levels were estimated to be higher with the traditional model (3). In computed examples, the difference in water levels was from a few millimetres up to 10 cm.

4.2.1. Effect of vegetation density

The changes in water levels of model (1) due to vegetation density were from a few millimetres to a few centimetres. Changes in a_z and h_{P} had no significant effect in the example, because of the low water levels on the floodplains, whereas changes in a_x and a_y affected the contributing width of floodplain b_{EFF}, and thus the water levels considerably. When vegetation was very dense, the vegetated portion transported only a small fraction of the total discharge. When the density was slightly decreased, the total channel conveyance increased, i.e. maximum water levels decreased (Fig. 3). However, when the vegetation density ω_{V} was further decreased, the contributing width of the floodplain increased and

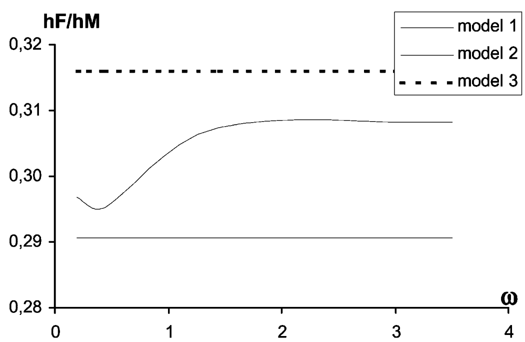

Fig. 3. Effect of vegetation density ω_{V} on maximum water levels computed by different methods.

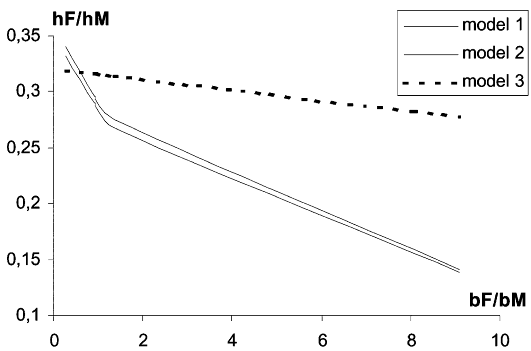

Fig. 4. Effect of floodplain width on maximum water levels computed by different methods.

thus the main channel conveyance decreased causing a decrease in the total conveyance as well. Changes in a_y alone had no significant effect because it has little effect on the contributing width of floodplain.

4.2.2. Effect of floodplain width

The changes in water levels due to the variation of the floodplain width were some dozens of centimetres. As seen in Fig. 4, widening the floodplains decreased the water level more in models (1) and (2) than in the traditional model (3), because not only the storage capacity but also the transport capacity of the channel increased. This is valid also without floodplain vegetation. In the case of very narrow floodplains (3 m), water levels were estimated to be higher in models (1) and (2) than in the traditional model (3), contrary to general cases. This is due to the fact that the interaction process plays a more significant role than the vegetal resistance, and the interaction process is neglected in model (3). When the floodplains were widened from 3 to 10 m, the water level dropped almost 10 cm in models (1) and (2), and when further widened to 15 m, the water level dropped 5 cm more. When floodplains were widened to 100 m, the water level further dropped more than 25 cm. This also caused error in the computation procedure, as the water level no longer decreased below 2 m after the peak flood. Already, with the width of 10 m, some numeric error could be seen. In the traditional model (3), the water levels were almost the same for every floodplain width, with differences of only a few millimetres. However, the traditional model (3) was also slightly unstable when the floodplain width was 100 m.

4.2.3. Effects of longitudinal bottom slope

Increase in the longitudinal bottom slope increased the difference of estimated water levels between the methods. With a higher slope, model (1) gave higher water levels than the traditional model (3). This indicates that during high flow velocities, the differences between model (1) and model (3) are even greater.

In total, the differences between model (1) and model (2), i.e. Nuding's method with and without floodplain vegetation, were far smaller than expected. The traditional model (3) neglected the effects of vegetation totally. As the transport capacity of the floodplains was zero, the water levels were, for the most part, estimated to be higher than in models (1) and (2).

5. Conclusions and future development

The models (1) and (2) in which Nuding's method was combined with St Venant equations were relatively stable and computationally fast. However, the models are still very preliminary and have some defects in the basic assumptions. For example, the contributing width b_{EFF} depends only on the vegetation density on the floodplains, but not on the water depth at the imaginary boundary or on the widths of the main channel and the floodplain. Furthermore, some numeric errors were seen in the models when water was just rising to floodplains. The spreading of water on floodplains caused rapid increase in the total friction factor and thus a reduction in the conveyance capacity of the channel. A flaw is made in computing the total Darcy–Weisbach friction factor from the friction factors for the floodplains and main channel. Due to the estimation of f, the sum of discharge fractions for the floodplains and main channel i.e. the total discharge calculated by Nuding's method was somewhat higher than the discharge computed from St Venant equations. To correct this, discharges from Nuding's method and St Venant equations should be iterated to match with each other.

In model (1), the changes in vegetation density and floodplain width had quite a significant effect on the transport capacities of the main channel and floodplains. The changes due to vegetation density are totally neglected in the traditional model (3), where floodplains are used as storage; and furthermore, the effect of floodplain width is very small in this method. Therefore, the proposed unsteady model combined with Nuding's method, i.e. model (1), are better applicable to compound channels with vegetated floodplains, especially with higher flow velocities.

In the next version of the model, some main improvements will be made:

(1) The discharges in Nuding's method and St Venant equations will be iterated to match each other.
(2) The contributing widths will be iterated based on

the shapes of cross sections and the relative water depths. This is done by either using a method of Mertens or Pasche, or combining some parts of them with the present application of Nuding's method.

(3) Real field measurement data of the Rhine River will be used for calibration and verification of the model.

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