Influence of Vegetated Floodplains on Compound Channels Discharge Capacity in 1D Modelling

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Abstract

Three different types of models were applied to compare an impact of floodplain treatment in 1D modelling on compound channels discharge capacity and retention volume of vegetated floodplains. The tested models are based on 1D St Venant equations with the Darcy-Weisbach friction law. A traditional way in which floodplains in 1D modelling are considered storage areas was compared to a model with conveyance of vegetated floodplain and a model with lateral shear stress between the channel and floodplain section, proposed in the Pasche approach. The models were applied to a steady flow in a 50 km long double trapezoidal channel, and differences in rating curves, retention volume of vegetated floodplains, and discharge distribution in a cross-section, were found between the models.

1. Introduction

Designing of compound channels, as well as projects of environmental flood management require in many cases estimating discharge capacities of compound channels and retention volume of vegetated floodplains. One dimensional hydrodynamic models are widely applied for solving these problems. This type of models is based on the assumptions of 1D flow, with the most relevant believing that the water level and discharge vary only in the longitudinal direction. Flow processes in channels with local flood berm vegetation between the main channel and floodplains are very complex.

When water overflowing the main channel and overbank flow occurs, processes, such as interaction between the main channel and floodplain flows, significant variation of resistance parameters with depth and flow regimes, distribution of boundary shear stresses and effects of vegetation on retarding flow (Knight 2001), will be considered. A traditional way to deal with floodplains in 1D modelling is considering floor-
lains retention areas with zero longitudinal velocities. In a one-dimensional model, floodplains geometry is accounted for in only one of Saint Venant’s equations – a continuity equation, and the momentum equation reduces that to hydraulic parameters within the main channel geometry (Cunge et al. 1980). In another simplified approach widely used in solving river flow, cross-section conveyance is solved as the sum of conveyance of the main channel and left and right floodplain, and water level calculated for the cross-section is considered constant across the cross-section. A zero shear stress assumption is made for a vertical division between a channel and floodplain section. Although these methods are attractive in their simplicity, they ignore secondary effects due to the interaction between high velocities in the main channel and low velocities on the floodplain, and in consequence, overestimation of discharge capacity (Ackers 1993). Presently one-dimensional methods for water level calculation have been developed which take into account a lateral shear stress between the main channel and vegetated floodplain (e.g., Pasche 1984, Nuding 1998) and are capable of considering a momentum transfer between the main channel and the floodplain.

2. Developed models

Three different types of models were applied to compare an impact of floodplain treatment in 1D modelling on compound channels discharge capacity and retention volume of vegetated floodplains. Water levels, discharge distribution between the main channel and floodplain, as well as retention volume were compared for the following models:

- model DW_FA_P: Vegetated floodplain and St Venant equations with the Pasche’s method for description of a momentum transfer between the main channel and floodplain (Swiatek 2007),
- model DW_FA: Vegetated floodplain and St Venant equations with a zero lateral shear stress between the channel and a floodplain section,
- model DW_FIN: St Venant equations with floodplains as storage areas.

Both models, DW_FA_P and DW_FA, enable accounting for flow resistance resulting from vegetation covering a compound channel with floodplain in unsteady flow calculations. Moreover, the DW_FA_P allows to consider a momentum exchange between the main channel and floodplains, proposed in the Pasche approach (Pasche 1984). In the DW_FIN model it is only possible to take into account flow resistance caused by the main channel vegetation. The floodplain is considered only a storage area with zero velocities, and thus will not contribute to the overall momentum flux in a cross section.

A basis for calculations in the three models is the friction law of Darcy-Weisbach and the conveyance factor $K$, expressed as

$$K = A \left( \frac{8gR}{\lambda} \right)^{1/2},$$

where: $A$ = cross area of flow; $g$ = gravitational acceleration; $R$ = hydraulic radius; $\lambda$ = friction factor.
Flow resistance in parts of channel sections overgrown with vegetation depends on both vegetation and bed roughness and is calculated as a sum of channel bed $\lambda_s$ and submerged vegetation $\lambda_v$ friction factors (Indlekofer 1981). Friction factors for high vegetation $\lambda_v$ were the aim of investigations by Kaiser (1984), Lindner (1982) and Pasche (1984), and are computed according to the concept issued by these authors. The lateral shear stress between the main channel and vegetated floodplain is taken into account in the model DW_FA_P. In this model, a compound river cross section is divided into sections with vertical imaginary walls between the main channel and neighbouring floodplains. The heights of these boundaries are taken into consideration in calculations of the wetted perimeter of the main channel, and separate Darcy-Weisbach friction factors are estimated for these imaginary walls. According to Pasche (1984), a friction factor of the boundary depends mainly on relationships of a plant diameter and distances between individual plants, and the contributing width of the floodplain that has influence on the interaction process. This process decreases the discharge in the main channel and increases the discharge on the floodplain.

The total conveyance (Eq. 1) for a compound cross section in models DW_FA_P and DW_FA is obtained by summing the subdivision conveyances of the channel and floodplains. The total conveyance $K$ is introduced to the St V rentant equations.

### 3. Results

In order to compare a compound channel discharge capacity and retention volume of vegetated floodplains, three models were applied to a steady flow in a double trapezoidal channel. The channel length was $L = 50$ km and bottom slope $J = 0.0005$. A compound river cross-section was stable and its geometry and growth of vegetation as presented in Fig. 1. The left floodplain was 60 m wide and covered with shrubs of $d_p = 1.0$ m of diameter and an average distance between individual shrubs of $a_x = a_y = 2.5$ m. A part of the left channel slope was covered with low vegetation of roughness $k_s = 0.5$ m. The bottom of the main channel was covered with small and medium-grain sand of roughness $k_s = 0.05$ m. The right channel slopes were covered with low vegetation of roughness $k_s = 0.09$ m. The right floodplain was 60 m wide and planted with shrubs and trees of an average diameter of $d_p = 0.04$ m, and average spacing $a_x = a_y = 0.3$ m. The floodplains roughness was 0.10 m.

![Fig. 1. A sketch of a compound cross-section.](image-url)
A numerical mesh with a constant space step $\Delta x = 1000$ m and 51 nodes was used. Simulations for a steady flow were performed for different values of discharge ranging from 2 m$^3$/s to 35 m$^3$/s, and then rating curves were elaborated for the tested models (Fig. 2).

In model DW_FIN, water level at discharge of 35 m$^3$/s was about 0.57 m and 0.36 m higher than in models DW_FA and DW_FA_P (Fig. 2). It is so because in model DW_FIN only the main channel transports all the water in the longitudinal direction. The lateral shear stress assumed in model DW_FA_P causes the water level to be 0.21 m higher than in model DW_FA. The differences in water levels vary from 0.06 m at discharge of 10 m$^3$/s to 0.21 m at 35 m$^3$/s. The water depth on floodplains varies from 0.24 m to 1.64 m for the studied range of discharges (model DW_FA_P). The ratio of differences in water levels in models DW_FA_P and DW_FA as referred to water depths on floodplains shows that for low water levels on floodplains, the lateral stress played a significant role. In Fig. 3, retention volume of floodplains is shown for the tested models. In model DW_FIN, the maximum retention volume is about 19% higher than in model DW_FA_P, and 31% higher than in model DW_FA (Table 1).

<table>
<thead>
<tr>
<th>Q [m$^3$/s]</th>
<th>$V_{DW_FA_P}/V_{DW_FIN}$ %</th>
<th>$V_{DW_FA}/V_{DW_FIN}$ %</th>
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<tbody>
<tr>
<td>10</td>
<td>72</td>
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<td>15</td>
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<td>35</td>
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Fig. 2. Rating curves for tested models.
Models DW_FA_P and DW_FA allow to take into account longitudinal velocities on floodplains. Calculated discharges for the main river channel and left and right floodplains are shown in Figs. 4-6. At the total discharge of 35 m$^3$/s, in model DW_FA_P over 31% of this value, was transported on the floodplains and in model DW_FA – about 26% (Table 2). Highest differences (Table 2) are at low water levels on floodplains. This is due to the fact that the impact of resistance of the vegetated floodplain is lower than that of the lateral shear stress.

4. Conclusions

A traditional model in which floodplains are considered to be the only storage areas significantly overestimates a discharge capacity in relation to a model with conveyance of vegetated floodplain, and model with lateral shear stress between the channel and
Fig. 5. Discharges $Q_{CH}$ in the main channel calculated in models DW_FA_P and DW_FA.

Fig. 6. Discharges $Q_{RF}$ in the right floodplain calculated in models DW_FA_P and DW_FA.

Table 2
Percentages of discharge on the floodplains and in the main channel in models DW_FA_P ($Q_P$) and DW_FA ($Q_F$)

<table>
<thead>
<tr>
<th>Q [m³/s]</th>
<th>$Q_{PCH}/Q_{TOT}$ %</th>
<th>$Q_{PLRF}/Q_{TOT}$ %</th>
<th>$Q_{FCH}/Q_{TOT}$ %</th>
<th>$Q_{FLRF}/Q_{TOT}$ %</th>
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the floodplain. Percentage differences in water depth for a studied example in which floodplain is covered with shrubs and trees achieve 40% and 22%, respectively, at high water levels on floodplains. In the model with vegetated floodplain conveyance and lateral shear stress between the channel and floodplain, the water depth on floodplains is about 15% higher than in the model in which only vegetated floodplain conveyance is considered. The differences in water levels and discharge distribution in the floodplains in these two models depend on, which factor, the lateral stress or the effects of vegetal resistance of high plants, played a more significant role.

Contrary to the traditional approach where floodplains are considered storage areas, models with floodplain conveyance compute velocities, discharges, and friction factors for each specified part according to the type of vegetation in floodplains and the main channel. They may be used to estimate a new water surface level for renaturalized rivers, especially for flood conditions, as well as, to ensure suitable conditions for habitat diversity in projects of environmental flood management. They are an appropriate tool to estimate floodplain vegetation influence on flow conditions.

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References


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