An Extended Mathematical Model for Shallow Water Flows in Vegetated Open Channels

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Abstract: An extended mathematical model governing shallow water flows in vegetated open channels, referred to as the 1-D extended shallow water equations (1-D ESWEs), is presented in this paper as a physically more consistent alternative to the conventional 1-D SWEs. Emerged and submerged aquatic plants in channels are considered in the 1-D ESWEs as momentum sinks with appropriately defined water fractions. The 1-D ESWEs improve the double-counting problem on the momentum losses in the 1-D SWEs originating from the additivity assumption of the wall friction and vegetation drag forces without considering the water fraction. The 1-D ESWEs are applied to steady and unsteady numerical simulation of water flows in an agricultural drainage canal in Japan. The computational results demonstrate advantages of the 1-D ESWEs over the 1-D SWEs, reducing overestimation of the water depth. Impacts of the vegetation modeling on the flows in the canal are also assessed through the unsteady simulation.

Keywords: Open channel; Agricultural drainage canal; Aquatic plants; Shallow water equations; Extended shallow water equations

1 Introduction

Analysis of water flows in an agricultural drainage system is an essential step toward better assessment of its hydraulics. Computational fluid dynamics (CFD) is an effective tool for that purpose, providing useful information to operate and maintain the agricultural drainage system.

Water flows in agricultural drainage canals are reasonably described with a cross-sectionally averaged 1-D mathematical model. The 1-D shallow water equations (1-D SWEs), in which the incompressibility of water and the hydrostatic pressure distribution are assumed, have served as one of the most successful models for the open channel flows (Cunge et al., 1980; Szymkiewicz, 2010). The 1-D SWEs are a nonlinear hyperbolic system of partial differential equations (PDEs) with source terms. Analytical solutions to the 1-D SWEs are available only for limited number of cases (Stoker, 1957; Thacker, 1981; Chen et al., 2011; Delestre et al., 2013). Numerical methods have therefore been utilized to solve the 1-D SWEs in applications. A number of numerical methods have been proposed; major numerical methods, such as finite element methods (FEMs), finite volume methods (FVMs), discontinuous Galerkin FEMs, lattice Boltzmann methods, and Lagrangian particles methods, are reviewed in the literatures (Toro, 2010; Delis et al., 2011; Lai and Khan, 2012; Vacondio et al., 2012; Van Thang et al., 2012). The finite element/volume methods (FEMs) and the dual FVMs (DFVMs) have been developed by the authors to solve the 1-D SWEs with transitions and shocks (Yoshioka and Unami, 2012; Yoshioka et al., 2013c, 2014a). The selective lumping method (SELUM), an improved FEVM equipped with a stable and computationally efficient temporal discretization algorithm, has also been developed (Yoshioka et al., 2014d). These methods have been applied to a number of benchmark and experimental cases to demonstrate their versatility.

An important issue relevant to analyzing some surface water flows is the existence of aquatic plants, which are patchy-distributed on the channel bed affecting physical processes in the flows (Chen et al., 2012). Franklin et al. (2008) reviewed the roles of aquatic plants in lowland rivers on controlling hydro-environments. Montakhab et al. (2012) reviewed sedimentation processes around vegetation in open channel flows summarizing past works and future challenges on their modelling. In the context of shallow water theory, vegetation is treated as macroscopic obstacle causing the momentum losses. A number of researches for vegetation modeling have been conducted since the comprehensive research of Nepf (1999) who discussed mass and momentum transport phenomena in the flows with vegetation. Vegetation in the flows can be categorized broadly into the two types; one of them is emerged case and the other is submerged case (Nepf, 2012). In the former case, vegetation is treated as a semi-infinite length of cylinders not significantly enhancing vertical mixing. On the other hand, in the latter case, vegetation is treated as a set of the cylinders with finite heights smaller than water depth creating strong vertical mixing around the plant canopy layer (Huai et al., 2013; Nikora et al., 2013). Sand-Jensen (2003) measured reconfigurations of five flexible macrophytes in experimental open channel flows and proposed power-law formulae to predict the drag coefficient. Tanino and Nepf (2008a) measured the drag coefficient for random arrays of stiff, emerged cylinders in open

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channel flows to obtain its dependence on the local Reynolds number. Aberle and Järvelä (2013) proposed a drag formula for emerged vegetation with the Leaf Area Index as a control variable. Some researchers applied shallow water models to the flows with vegetation, most of which focused on controlled (laboratorial or idealized) conditions, and only a few on uncontrolled (field) conditions.

Helmio (2005) used the 1-D SWEs to simulate river flows with partially vegetated floodplains. Fathi-Moghadam et al. (2011) applied the 1-D SWEs to sub-critical water flows in a river with dense submerged vegetation specifying the Manning’s coefficient depending on the vegetation density. Katul et al. (2011) performed mathematical and numerical analyses on the impacts of the submerged vegetation on flood routing to relate microscopic turbulent mechanisms with the resulting macroscopic hydrological variables. In these literatures, vegetation effect on the mass transport is neglected and the effect on the momentum equation is simply lumped into the friction slope, which does not explicitly separate the momentum losses from the wall friction and vegetation drag forces.

Previous researches revealed that the 1-D SWEs are sufficiently accurate for steady flows in vegetated open channels (Wakazono et al., 2013; Yoshioka et al., 2014c); however, their drawbacks in the mathematical formulation should be addressed. First drawback is the neglect of the water fraction in the flows, which will contribute to errors for the flows with dense vegetation. Second drawback is a double-counting problem on the momentum losses originating from the additivity assumption of the wall friction and vegetation drag forces. The purpose of this paper is to develop 1-D extended SWEs (1-D ESWEs) that improve the above-mentioned drawbacks. The extension is performed so that the flows with vegetation are more appropriately described without significantly increasing model complexity. An application example of the 1-D ESWEs to water flows in an agricultural drainage canal is presented to demonstrate their advantages over the 1-D SWEs in simulating transient flows with vegetation. Impacts of the vegetation modeling on the flows in the canal are also assessed through the unsteady numerical simulation.

The remainder of this paper is organized as follows. The shallow water models used in this paper is presented in Section 2. Steady and unsteady numerical simulation with the shallow water models is performed in Section 3. Section 4 gives conclusions of this paper.

2 Shallow water models
The 1-D SWEs and the 1-D ESWEs are presented in this section. Throughout this paper, cross-sectional shape of channel is assumed to be uniformly rectangular and channel bed is assumed to be fixed. Momentum exchanges between main stream and lateral inflows are not explicitly taken into account in the models because only right-angled inflows are considered in this paper. In addition, vegetation in water flows is assumed to be stiff.

2.1 1-D SWEs
The 1-D SWEs (Yoshioka et al., 2014c) consist of the continuity equation and the momentum equation, which are given by

\[ T \frac{\partial \eta}{\partial t} + \frac{\partial Q}{\partial x} - q = 0 \]  
\[ \frac{\partial Q}{\partial t} + \frac{\partial F}{\partial x} + g A \left( \frac{\partial \eta}{\partial x} + S_i + S_v \right) = 0 \]

with the momentum flux

\[ F = \frac{\beta Q^2}{A}, \]

respectively where \( t \) is the time, \( x \) is the 1-D abscissa taken along the channel, \( A \) is the cross-sectional area of flow, \( T \) is the width of the channel, \( \eta \) is the water surface elevation, \( Q \) is the discharge, \( q \) is the lateral inflow, \( g \) is the gravitational acceleration, \( \beta \geq 1 \) is the momentum coefficient, and \( S_i \) is the friction slope given by the Manning’s formula

\[ S_i = \frac{n^2 Q^2}{A R^{5/3}} \]

where \( n \) is the Manning’s coefficient and \( R \) is the hydraulic radius. The term on the momentum losses due to the existence of vegetation \( S_v \), referred to as drag slope in this paper, is modeled with the semi-empirical quadratic type formula (Nepf, 1999)

\[ S_v = \frac{\min \{ h, h_e \} C_d a Q^2}{2 g A^2} \]

where \( h_e \) is the effective vegetation height, \( C_d \) is the drag coefficient and \( a = \lambda d \) is the vegetation density with the number of stems per unit area \( \lambda \) and the effective di-
ameter of the stem \( d \). The condition \( 0 < h < h_e \) corresponds to the emerged case and \( h > h_e \) to the submerged case (Figure 1). Although empirical formulae for \( h_e \) are available (Wang et al., 2010), this paper assumes it as a constant parameter to see its impacts on the water flows with a brief sensitivity analysis as presented in a later section. In the 1-D SWEs of Wakazono et al. (2013), the effective vegetation height is taken as \( h_e = +\infty \), which reduces Eq.(5) to

\[
S_v = \frac{C_o a Q |Q|}{2 g A^2},
\]  

resulting in an overestimation of the drag force caused for the flows with submerged vegetation.  

As shown in Eqs.(1) and (2), the 1-D SWEs consider vegetation effects solely by the drag slope \( S_v \), neglecting the occupied volume of the vegetation in the flows. The 1-D SWEs may therefore lead to erroneous results for the flows with densely vegetated areas. In addition, they overestimate the net friction force for the flows with vegetation as shown in the next sub-section.  

### 2.2 1-D ESWEs

The 1-D ESWEs proposed in this paper consist of the continuity equation

\[
\phi_v \frac{\partial \eta}{\partial t} + \frac{\partial (\phi_v Q)}{\partial x} - q = 0
\]  

and the momentum equation

\[
\frac{\partial (\phi_v Q)}{\partial t} + \frac{\partial (\phi_v F)}{\partial x} + g A \left( \phi_v \frac{\partial \eta}{\partial x} + \phi_s S_i + S_r \right) = 0
\]

with the momentum flux \( F \) defined in Eq.(3). The 1-D ESWEs have the additional variables \( \phi_s \) and \( \phi_i \). \( \phi_s \) is the fraction of water on the plane \( z = \eta \) (water surface) and \( \phi_i \) is the fraction of water within the cross-section. Based on a geometrical consideration (Figure 1), the fraction \( \phi_s \) is expressed with the fraction of water on the channel bed, denoted by \( \phi_y \), as

\[
\phi_s = \frac{1}{2} (1 + \text{sgn} \{ h - h_i \}) + \frac{1}{2} (1 - \text{sgn} \{ h - h_i \}) \phi_y
\]

and \( \phi_i \) with \( \phi_y \) as

\[
\phi_i = \min \left\{ \frac{h_i}{h} \phi_y, \max \left\{ 0, 1 - \frac{h_i}{h} \right\} \right\}.
\]

The fractions \( \phi_v \), \( \phi_s \), and \( \phi_i \) are thus related with each other through the parameters \( \lambda \) and \( d \). By the definition, these fractions satisfy

\[
0 < \phi_v, \phi_s, \phi_i \leq 1.
\]

If \( \phi_v = \phi_s = \phi_i = 1 \), namely if there is no vegetation in the flows, the 1-D ESWEs accordingly reduce to the 1-D SWEs. Assuming the statistically uniform vegetation distribution on channel bed yields the expression of \( \phi_y \) as (Tanino and Nepf, 2008b)

\[
\phi_y = 1 - \frac{\pi}{4} \lambda d^2.
\]

Substituting Eq.(12) to Eqs.(9) and (10) leads to analytical expressions of \( \phi_s \) and \( \phi_i \), respectively.

Multiplication of the water fraction \( \phi_s \) by \( S_v \) in Eq.(8) is justified because the net cross-sectional area in the flow is \( \phi_s A \leq A \). The 1-D SWEs therefore overestimate the net cross-sectional area for the flows with vegetation. Another major difference between the 1-D SWEs and the 1-D ESWEs is the spatial differential terms involved in Eqs.(1) and (7). The net mass flux of water along the channel in Eqs.(1) and (7) are \( Q \) and \( \phi_s Q \), respectively. The 1-D ESWEs thus conserve the net discharge \( \phi_s Q \) but not the conventional discharge \( Q \), both of which are defined analogously to the Darcy’s flux for porous media flows.

An important difference between the proposed 1-D ESWEs and the published similar models (Guinot and Soares-Frazão, 2006; Cea and Vázquez-Cendón, 2010) is that the former can handle patchy-distributed vegetation (spatially discontinuous water fractions) as found in real problems (Chen et al., 2012) but the latter cannot due to the assumed smoothness of \( \phi \). Another difference between them is that the proposed 1-D ESWEs do not a priori assume the equality

\[
\phi_y = \phi_s = \phi_i,
\]

which is violated for the flows with submerged vegetation where \( \phi_s \) equals to 1 but \( \phi_y \) and \( \phi_i \) are smaller than 1.

### 3 Application

#### 3.1 Study area

The two shallow water models are applied to steady and unsteady numerical simulation of water flows in a vegetated agricultural drainage canal in Katsura district of Imazu-cho, Takashima City, Shiga Prefecture, Japan. Figure 2 depicts a sketch of the study area. Pumping water from Lake Biwa is applied to farmlands in the study area. Water flows (Kinjo et al., 2013) and solute transport phenomena in the drainage canal (Yoshioka et al., 2013a-b, 2014b) were numerically analyzed without considering the vegetation. The canal is a concrete-made channel with bottom and sidewalls having a rectangular cross-section with the width of 1.7 (m). The water in the canal originates from a spring located upstream of the canal. The downstream-end of the canal is connected to Eigo River via a hydraulic drop. Eigo
River pours to Sakai River, one of the rivers flowing into Lake Biwa.

A field survey of the agricultural drainage canal was conducted on June 18, 2013. Bottom topography, water surface profile, and discharge in the canal and lateral inflows from the paddy fields were measured in the survey. No rainfall was observed and the flows in the canal were almost steady during the survey. The canal drained from 44 farmlands, 28 of which were along the canal and the other 16 along its upstream reach. 14 of the farmlands along the canal were irrigated paddy fields. The water surface and bed elevations in the canal were measured with a GPS instrument (GPS900, Leica). Figure 3 shows the measured bed topography of the canal. The locations of the lateral inflowing points from the farmlands and the vegetated areas in the canal are also plotted in the figure. Aquatic plants in the canal were patchy vegetated as shown in Figure 3. Vegetation in each patch was almost uniformly distributed in the lateral direction. The discharge at the downstream-end of the canal was estimated assuming a critical flow condition. The lateral inflows from the irrigated paddy fields were directly measured with a cup. The lateral inflows were assumed to be steady because the paddy fields were irrigated continuously during the observation. The discharge at the upstream-end was consequently estimated by subtracting the lateral inflow discharges from the outflow discharge. According to another field survey on August 28, 2013, the aquatic plants found in the canal were identified as Elodea nuttalli and Sparganium sp., the latter being predominant species in the canal. These aquatic plants were found in gently flowing areas with sediment deposition. The effective vegetation height $h_v$ in the canal was estimated to be between 0.15 (m) and 0.25 (m).

3.2 Computational conditions
The Manning's coefficient $n$ in the canal is set as 0.02 (s/m$^{1/3}$) since the canal is concrete-made with slight degradation. The momentum coefficient $\beta$ is set as 1.1 in the entire canal. Computational mesh used in this paper is same with that of Wakazono et al. (2013) where the canal is divided into 606 elements with 607 nodes. Both the 1-D SWEs and the 1-D ESWEs are numerically solved with the SELUM (Yoshioka et al., 2014d), in which each water fraction attributed to the elements. The time increment for temporal integration is 0.025 (s). Overtopping of the water from the canal is not considered in this paper.

3.3 Steady simulation
Steady simulation is performed to identify the values of the model parameters for vegetation, which are assumed to be constant in the canal. In the steady simulation, the effective vegetation height $h_v$ is assumed to be larger than the water depth $h$ since almost all of the aquatic plants in the vegetated areas were emerged at the field investigation. Consequently, the parameters to be identified are the water fraction $\phi_v$, the drag coefficient $C_d$, and the vegetation density $a$. The product $b = C_d a$ is regarded as one variable to reduce the number of unknown parameters (Yoshioka et al., 2014c). This procedure is physically justified since the inverse of $b$ serves as a dominant length scale for mass and momentum transport phenomena in vegetation (Tanino and Nepf, 2008b; King et al., 2012). Identification of the values of the parameters $\phi_v$ and $b$ is performed with the 1-D ESWEs because of the insensitivity of $\phi_v$ for the steady flow in the canal. In fact, differences between the water depths with the 1-D SWEs and the 1-D ESWEs were at the order of 10$^{-4}$ (m), several order smaller than the water depths. Parameter identification is carried out with a try and error approach so that the root mean square error between the computed and measured water depths is minimized (Yoshioka et al., 2014c).

Figure 4 shows the computed water surface profiles with the 1-D SWEs and 1-D ESWEs with the identified parameter values $\phi_v = 0.90$ and $b = 5$ (m$^{-1}$). The maximum water depth in the canal was 0.21 (m), which is smaller than the maximum of the observed effective vegetation height $h_v = 0.25$ (m), supporting the validity to assume the emergence of vegetation. The computed water surface profile well captures the measured one. Discrepancy between the computed and observed results is considered due to measurement errors and the uniform assumption of the vegetation parameters.

3.4 Unsteady simulation
The purpose of the unsteady simulation is to assess impacts of the vegetation modeling on the flows in the canal focusing on a real event responsible for reliability of the drainage canal. The unsteady simulation focuses on a flash flood caused by the 18th typhoon in 2013 on September 15 and 16 in the year. According to the data from Automated
Meteorological Data Acquisition System (AMeDAS) at Imazu observation station (1.9 km south-southwest of the downstream-end of the drainage canal), total rainfall during the above-mentioned two days was 239 (mm) (Japan Meteorological Agency, 2014), exceeding the designed daily rainfall intensity of the canal 180 (mm/d). The maximal hourly rainfall intensity was 22.5 (mm/h). A public relation magazine from the government of Takashima City reported that the city was damaged by the typhoon, suffering from river bank collapses, inundation and soil losses of farmlands, inundation of canals, and more than 280 inundations of households above or below floor level (The government of Takashima City, 2013).

The simulation period is three days, September 15 AM 00:00 ($t = 0$ (d)) to 17 PM 24:00 ($t = 3$ (d)) in 2013. The water dropping ports of all the farmlands are assumed to be open. The farmlands are assumed to be initially dry since the study area is non-irrigated during September. Lateral inflow from each farmland is calculated with the lumped model of water balance (Kinjo et al., 2013) driven by the measured rainfall data from AMeDAS data with 600 (s) intervals. The effective vegetation height $h_e$ is set as 0.15 (m) based on the field survey results. Steady flow with no lateral discharge from the farmlands is specified as the initial condition in the canal at the time $t = 0$ (s).

Figure 5 shows the computed water surface profiles at the peak rainfall (AM 06:40 on September 16, 2013) with the 1-D SWEs and 1-D ESWEs. Figures 6 and 7 show comparisons of the computed water depths at $x = 293.0$ (m) (in a non-vegetated area) and at $x = 126.1$ (m) (in a vegetated area). As shown in Figures 5 through 7, the computed water depth with the 1-D SWEs is much deeper than that of the 1-D ESWEs during the period of relatively strong rainfall in particular. Difference between the computed water depths is significant during the period from $t = 1$ (day) to $2$ (day) where the water depths are larger than 0.20 (m). The maximum difference between the water depths at $x = 293.0$ (m) is 0.17 (m) that corresponds to the relative difference of 0.36. This difference results from the fact that the former neglect submergence of the vegetation, while the latter account for it improving the double counting problem with the appropriately defined water fractions and the effective vegetation height. Figure 7 shows a similar tendency on the difference between the water depths at $x = 126.1$ (m) with their maximum difference of 0.35 (m) that corresponds to the relative difference of 0.34. Figure 8 shows the computed hydrographs at the downstream-end of the canal. The hydrographs with the two shallow water models are not distinguishable; maximum difference between them is 0.01 (m$^3$/s) at the rising limb of the hydrograph that corresponds to the relative difference of 0.07.

Unsteady numerical simulation with the 1-D ESWEs for different values of $h_e$ is also performed to see their impacts on the flows in the canal. The six values of $h_e$ from 0.00 (m) through 0.25 (m) ($h_e = 0.05i$ (m) for $0 \leq i \leq 5$) are considered where the cases with which are referred to as Cases 0 through 5, respectively. Case 3 ($h_e = 0.15$ (m)) corresponds to the previous computational case. No vegetation is assumed in Case 0 ($h_e = 0.00$ (m)), which is equivalent to solving the 1-D SWEs. Figure 9 shows a comparison of the water surface profiles in the canal at the peak rainfall. Figure 9 shows that the water...
depth in the canal almost monotonically increase (decrease) in accordance with the increase (decrease) of \( h_i \).

4 Conclusions

The 1-D ESWEs governing the water flows in vegetated open channels were presented and applied to steady and unsteady numerical simulation of the flows in an agricultural drainage canal. The SELUM is utilized in the numerical simulation so that the shallow water models are accurately solved. The computational results showed clear differences between the 1-D SWEs and 1-D ESWEs for the unsteady case in particular. The 1-D SWEs predicted deeper water depth than the latter, which is due to the neglect of the submergence of vegetation, while the 1-D ESWEs account for it with the physically-based more appropriate vegetation modelling. A brief sensitivity analysis for the effective vegetation height was also performed. The results obtained in this paper indicated potential applicability of the 1-D ESWEs to analysis of the flows in open channels with vegetation. Future research will focus on modeling flexible vegetation from both theoretical and experimental point of views. Application of the 1-D ESWEs to numerical simulation of water flows in the agricultural drainage system extending over the study area will also be performed.

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