EXPERIMENTAL STUDY AND NUMERICAL SIMULATION OF VEGETATED ALLUVIAL CHANNELS

by

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DEDICATION

To the soul of my Mother and Brother Nael

To my Father

To my Wife and Kids

To my Brothers and Sisters
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ABSTRACT

Vegetation in rivers increases flow resistance and bank stability, reduces bed resistance and flow conveyance, improves water quality, promotes habitat diversity, and alters both mean and turbulent flow. By reducing bed resistance and altering turbulent characteristics, vegetation can change the distribution of deposition and erosion processes.

To understand all above mentioned vegetation effects, more research is needed. The goal of this dissertation was to determine the impacts of vegetation on bed resistance and sediment transport and identify a best approach for quantifying vegetation induced friction resistance. To achieve this, both experimental study and numerical simulation were performed.

A series of laboratory experiments were conducted in an open channel flume to investigate the impacts of vegetation density on bed resistance and bed load transport for emergent vegetation condition. The bed resistance in a mobile bed channel is equal to the summation of grain and bed form resistances. An attempt has been made to make a separation between grain and bed form resistances, which is challenging and has never been reported in literature. An alternative approach is used to calculate the grain resistance. A new iterative method was derived to calculate the bed form resistance. Empirical relations were formulated to calculate the bed form resistance and bed load transport rate using a newly defined flow parameter that incorporates the vegetation concentration. The bed elevations and bed form height were measured by the Microsoft Kinect 3D Camera. It was found that the height of bed form depends on the vegetation concentration, which determines whether ripple/dune or scour holes are dominant on the bed surface. For sparsely vegetated flows, the bed form height and resistance are decrease rapidly as the
vegetation concentration was increased, and they decreased gradually when the vegetation concentration was high.

To quantify the vegetation induced friction resistance, a 3D numerical simulation was conducted using the Delft3D-FLOW open source program. The study area is Davis Pond freshwater marsh area near New Orleans, Louisiana. The dominant vegetation type for the study area is *Panicum hemitomon*. The study area was divided into several sub-areas depending on the existence of channels, overbanks, and vegetation height. Several approaches were used to approximate the vegetation roughness; a constant Manning’s $n$ coefficient, a time-varying $n$ or Chezy’s $C$ coefficient, and the modified momentum and $k$-$\varepsilon$ equations for each subarea. To quantify the time varying roughness coefficients, four equations for calculating $n$ values were incorporated in the Delft3D-FLOW program in addition to two options offered by this program to calculate $C$ values. It is concluded that the use of the time varying roughness coefficient gives better results than other approaches. Among the selected equations to calculate the time varying vegetation roughness, the equations that account for the effect of the degree of submergence and the vegetation frontal area per unit volume, symbolized as $a$, gave the closet matches with the observations. The sensitivity of modeling results to the selection of vertical grid ($\sigma$ –and Z-grids), $a$ value, and grid size were analyzed. It is found that using the $\sigma$-grid yielded more accurate results with less CPU times and the best range of $a$ value for the *Panicum hemitomon* vegetation type is from 8.160 to 11.220 m$^{-1}$. Also it was observed that the adoption of a coarse mesh gives reasonable simulation results with less CPU time compared with a fine mesh. A non-linear relation between the vegetation resistance, in terms of $n$ value, and degree of submergence was observed.
CHAPTER ONE
INTRODUCTION

1.1 Statement of the Problem

Flow in river channels and floodplains is highly complicated, and it is characterized by the interactions among the flow, boundaries, and vegetation canopy. Because of the importance of floodplain management and river restoration, an increase of interest has been raised to understand the impact of vegetation on flow hydraulics and river alluvial processes. Vegetation characteristics, such as vegetation type, distribution, density, flexibility, and degree of submergence all affect flow depth, velocity, hydraulic radius, and energy slope. The resistance to flow through vegetated areas is increased by an additional drag force exerted by vegetation (Fenzl 1962, Temple et al. 1987). Because of this drag, flow through vegetated areas decelerates, and the mean velocities reduce compared to unvegetated areas (Shi et al. 1995, Zhang et al. 2010). Vegetation also improves the water quality by removing nutrients and releasing oxygen to the waterbody, increasing bed and bank stabilization, and promoting habitat diversity.

Both emergent and submerged vegetation alter the time-averaged velocity profile in channels. Studies showed that the velocity profile in channels with submerged vegetation can be divided into four zones (Baptist et al. 2007): the first zone is the boundary layer flow near the bed, where the velocity distributions satisfies the logarithmic law; the second zone is inside the vegetation layer and sufficiently away from the bed and the top of the vegetation, and the velocity is uniformly distributed; the third zone is near the top of the vegetation having a transitional profile between the uniform velocity inside the vegetation
and the logarithmic velocity profile above it; and finally, the fourth zone is above the vegetation, and the logarithmic profile is observed.

Vegetation resistance has been approximated by means of resistance coefficients such as the Chezy, Darcy and Manning coefficients (e.g. Ree and Palmer 1949, Chow 1959, Petryk and Bosmaijan 1975, Shih and Rahi 1981, Klopstra et al. (1997), Green (2005a), Nikora et al. (2008), and Luhar and Nepf (2013)). Various empirical and analytical relations were derived to calculate these coefficients by correlating them with flow and vegetation properties. Since vegetation induces momentum loss and influences turbulence generation and dissipation, the vegetation effects can also be approximated by adding additional terms in the momentum equations and turbulent closure models, such as the kinetic energy \( (k) \) and energy dissipation \( (\varepsilon) \) model. The additional drag exerted by vegetation influences the transport of sediment and solutes by promoting sediment accumulation as the near-bed resistance reduces (Nepf 1999). Vegetation also changes near-bed turbulent characteristics, and significantly affects the scour formation around vegetation stems.

In vegetated channels, bed resistance is significantly smaller than that in an unvegetated channel at the same flow discharge. A simple schematic sketch has been plotted in Figure 1.1 to show the difference between flow through vegetated and unvegetated channels in steady uniform flow. For the same total resistance, bed resistance in the vegetated channel is less than that in the unvegetated channel. Eddies are generated between the vegetation stems, and their sizes depend on vegetation densities, which produce some degrees of turbulence that affect the erosion/deposition processes (sediment transport).
Bed resistance is equal to the summation of grain and bed form resistances in a mobile bed channel. On the fixed bed channel, it is equal to grain resistance, because there is no bed form resistance. Grain resistance is the friction due to bed surface roughness and it is a function of bed roughness height, while bed form resistance is a drag force due to flow separation at the lee side of bed form and is a function of bed form height.

![Diagram of Unvegetated Channel and Vegetated Channel](image)

Unvegetated Channel
- $\tau = Total\ Resistance$
- $\tau_b = Bed\ Resistance$
- $\tau_v = Vegetation\ Resistance$

Vegetated Channel
- Eddies

Figure 1.1 Comparison between vegetated and unvegetated channel flows

Although much research has been conducted to explore the effect of vegetation on hydraulic roughness coefficients (e.g. Ree and Palmer 1949, Chow 1959, Petryk and Bosmaijan 1975, Shih and Rahi 1981, Klopstra et al. (1997), Green (2005a), Nikora et al. (2008), and Luhar and Nepf (2013)), its influences on suspended and bed load sediment transport are less known. In open channel flow, many empirical equations have been proposed to relate sediment transport to flow characteristics, however they are not applicable for flow through vegetated channels because vegetation influences were not considered.
1.2 Literature Review

This section provides a brief state-of-the art review of research on (1) quantification of vegetation induced friction resistance by using empirical relations for roughness coefficients, (2) computational modeling of vegetation impact, (3) impact of vegetation on bed resistance in mobile bed channel, and (4) impact of vegetation on sediment transport.

1.2.1 Quantify Vegetation Induced Friction Resistance by Using Empirical Relations for Roughness Coefficients

Many approaches have been developed to calculate vegetation resistance. Among them, quantifying this resistance by means of friction coefficients, such as Chezy, Darcy and Manning coefficients, is a computational cost-effective method. Ree and Palmer (1949) conducted several experiments to study flow on trapezoidal and rectangular channels lined with natural grasses. They developed empirical curves that related Manning’s $n$ to the product of the average velocity and the hydraulic radius for various grass media. Cowan (1956) and Chow (1959) suggested values for $n$ by taking into account vegetation and several other factors. The $n$ value according to Cowan (1956) is adjustable and a function of a base $n$ value (a minimum value for a uniform shaped channel in natural material), channel surface irregularities, variation in channel cross section, obstruction, vegetation type and channel meandering. Petryk and Bosmaijan (1975) gave a guidance to calculate the $n$ value for emergent rigid vegetation. They found that the $n$ value, in the case of vertically uniform dense vegetation, increases in proportion to two-thirds power of the hydraulic radius and the square root of the vegetation density assuming that the channel boundary shear stress is negligible. A field study conducted by Shi and Rahi (1981) showed
that the \( n \) values in a subtropical marsh were significantly increased by vegetation. The \( n \) values are increased with a decrease in flow depth, and varied from 0.26 to 0.55 for *water hyacinth* and from 0.16 to 0.43 for mixed vegetation with flow depth ranging from 40 to 65 cm. Reed *et al.* (1995) suggested a formula to calculate the \( n \) value in a constructed wetland. This formula indicated that the \( n \) value is a function of flow depth and a resistance factor. The resistance factor is a function of vegetation density and flow depth.

Klopstra *et al.* (1997) derived an analytical model to calculate the Chezy’s \( C \) coefficient for submerged vegetation. The force balance was applied in the streamwise direction under the assumption of steady uniform flow. The Boussinesq concept was used to describe the shear stress, where the shear stress is equal to the product of eddy viscosity and velocity gradient. Klopstra *et al.* (1997) assumed that the eddy viscosity can be characterized by the product of a velocity scale and a length scale of large scale of turbulence, which is responsible for the vertical transport of momentum. Also they assumed that the velocity scale can be represented by the flow velocity profile, whereas the length scale is independent of the vertical direction. Under these assumptions, they found that the \( C \) value is a function of vegetation height and density, stem diameter, drag coefficient, and the characteristic length scale of large scale turbulence. An implementation based on Klopstra *et al.* (1996) has been added to the Klopstra *et al.* (1997) equation to calculate the \( C \) value for emergent vegetation (Deltares 2011). This \( C \) value is a function of bed coefficient, flow depth, drag coefficient, and vegetation frontal area per unit volume.

Wu *et al.* (1999) conducted an experimental work to investigate the variation of vegetative roughness coefficient with flow depth for emergent and submerged flow conditions. Their results revealed that the roughness coefficient reduces with increasing
flow depth under the emergent condition. However, when fully submerged, the vegetative roughness coefficient tends to remain constant or increase at low depths but then decrease to an asymptotic constant as the water level continues to rise.

Kouwen and Unny (1973) are the first to characterize the drag force induced by flexible vegetation. This drag is smaller than that for rigid upright vegetation because of the change of vegetation morphology (Vogel 1994). Kouwen and Fathi-Moghadam (2000) incorporated the vegetation flexibility to estimate the roughness coefficient, Darcy’s $f$ or $n$, for emergent vegetation on floodplains. The mathematical model (Kouwen and Fathi-Moghadam 2000) calculates roughness based on flow velocity, flow depth, and type of vegetation. The vegetation type is characterized by a vegetation index defined as a function of natural frequency, height, weight and length of plants.

Recently, Abood et al. (2006) conducted a laboratory study to analyze the effects of two types of vegetation, Napier grass and Cattail grass, on the $n$ value in an open channel, and then developed a relationship between vegetation characteristics (density, degree of submergence) and $n$. They found a logarithmic relation between $n$ and the degree of submergence, defined as the ratio of flow depth to the vegetation height. Their results showed that $n$ value for flows with high and low densities of Napier grass increased with the increase in flow depth for both submerged and emergent conditions. For the Cattail grass, the effect was reversed and a decrease in the $n$ value was found for both high and low grass densities. This was attributed to the physical characteristics of the Cattail grass, which has no branching stem and leave in addition to the rigidity of grass stems.

In engineering practice, the SED2D model, a two dimensional vertically averaged sediment transport model developed by Engineering Research and Development Center
(ERDC) of the US Army Corps of Engineers, adopted an empirical formula to calculate the $n$ value for vegetated channels. The Manning’s $n$ in SED2D model equation is a function of the maximum $n$ value for unvegetated water, vegetation height, maximum $n$ value of vegetated water, and flow depth (WexTech System, Inc. 2011).

Vegetation alters velocity profile and flow resistance in open channel flow through different scales ranging from individual branches and blades on a single plant, to a community of plants in a patch or canopy, to a channel reach (Nepf 2012). Vegetation resistance in a channel reach is determined primarily by the vegetation coverage or the blockage factor (Green 2005a). This factor is defined as the fraction of channel cross-section or surface area blocked by vegetation, or the fraction of channel volume occupied by vegetation (Green 2005a). It’s worth mentioning that Fisher (1992) first examined the surface area and volumetric blockage factors, and recommended the surface area blockage factor for calculating $n$ coefficient because it’s easier to be measured. Recently, Green (2005a), Nikora et al. (2008), and Luhar and Nepf (2013) used the cross-sectional blockage factor to calculate $n$ value. Since the cross-sectional blockage factor is a better representation of turbulence wake in vegetated zones, it’s more favored in literature than the surface blockage factor.

Green (2005a) conducted a field study to compute the $n$ values in channels containing submerged vegetation. They assumed that the vegetation component of the $n$ value is simply equals to the difference between the $n$ values for the total and the bed surface. At 35 river sites, the total $n$ values were calculated using the Manning equation, whereas the bed components were calculated using an equation that depends on the channel hydraulic radius, bed roughness height. He found that the cross-sectional blockage factor
better represented the vegetation component of the $n$ value compared with the other types of blockage factors. Nikora et al. (2008) conducted a field study to examine the vegetation effects on hydraulic resistance in small streams, and suggested to use the cross-sectional blockage factor to calculate the vegetation resistance for submerged flow condition. Luhar and Nepf (2013) developed equations to calculate the vegetation resistance in terms of the $n$ value for emergent and submerged flow conditions. They segregated flow field into two layers, vegetation and overflow layers, and applied the force balance principle at both layers for fully developed flow. They approximated the shear stress at the interface between the vegetation layer and the overflow layer by a weighting coefficient and the average of overflow velocity. The bed shear stress was approximated by the average velocity at the vegetated layer in addition to a weighting coefficient. Luhar and Nepf (2013) found that the $n$ value for emergent vegetation depends primarily on the vegetation drag, flow depth, and vegetation frontal area per unit volume. In addition to these factors, the $n$ value for submerged vegetation is a function of the blockage factor, vegetation height, and an interface shear stress parameter. Some of the commonly used relations are compiled in Table B-2.

1.2.2 Computational Modeling of Vegetation Impact

As stated earlier, vegetation affects the mean flow and turbulent structure. These effects range from small scaled eddies to large scaled bed form changes. In order to provide more details about these multi-scale effects, computational models were developed.

Wilson and Shaw (1977) developed a numerical model for simulating air flow within the vegetation canopies. They simulated the momentum loss and turbulence generation and dissipation by introducing a drag related sink term and drag related
turbulence production terms in the momentum and $k$-$\varepsilon$ turbulent transport equations, respectively. The model predicted mean wind velocity, Reynolds stress, and turbulent intensities for the region from the soil surface to twice of the canopies height. They are the first who recognized the importance of the spatial and temporal averaging of the governing equations for the proper representation of these types of the problems.

For aquatic vegetation, Shimizu and Tsujimoto (1994) and Lopez and Garcia (1997) followed the same Wilson and Shaw (1997) model to simulate steady uniform flow through vegetation of uniform density. The drag related sink term is incorporated in the Reynolds Average Navier Stokes (RANS) equations. This term is a function of drag coefficient, time averaged velocity, and projected vegetation area. The drag related production terms are functions of weighting coefficient, drag force, and time averaged velocity for $k$ and $\varepsilon$ equations. Differences between Shimizu and Tsujimoto (1994) and Lopez and Garcia (1997) numerical studies are how to deal with the drag coefficient and the weighting coefficients. Lopez and Garcia (1997) kept the drag coefficient as a constant, whereas Shimizu and Tsujimoto (1994) adjusted its value to get better matches with the measurements of velocity and Reynolds stress profiles. Lopez and Garcia (1997) used specific values for the weighting factors in the $k$ and $\varepsilon$ equations, whereas Shimizu and Tsujimoto (1994) used calibrated values.

Naot et al. (1996) carried out computational simulation to study the hydrodynamic response of turbulent flow in a partially vegetated compound channel. They simulated the vegetation by vertical round rods, positioned at two modes: an aligned homogenous array and a randomly distributed array. They modified the momentum and $k$-$\varepsilon$ equations by adding a drag related sink term and drag related turbulence production terms. Also they
introduced an algebraic stress model to take into account the non-isotropy of turbulence coming from the existence of vegetation.

Fischer-Antze et al. (2001) computed the velocity distribution in a channel partially covered with submerged vegetation using a three-dimensional model. They modified the momentum equation using a drag related sink term, while keeping the $k$-$\varepsilon$ equation unchanged to avoid any calibration for simulations of different flow situations. They assumed that the sink terms dominated the turbulent diffusive terms, so the values of $k$ and $\varepsilon$ within the vegetation layers did not affect the velocity. The numerical model was tested against three laboratory experiments from straight flumes with uniform flow, where vegetation partially covered the cross-section. The velocity and vegetation density varied in both vertical and horizontal directions in those cases. All tests gave fairly good correspondence between computed and measured velocity profiles.

Neary (2003) simulated open-channel flows with submerged vegetation using the $k$-$\omega$ (specific rate of dissipation or dissipation per unit kinetic energy) transport equations. He introduced the vegetation drag term to the one-dimensional RANS equation and also added turbulence production terms to the $k$-$\omega$ equations. Each turbulence production term has a weighting factor to characterize the turbulence production and dissipation. Neary (2003) adjusted these weighting factors to get reasonable predictions of streamwise velocity and Reynolds stress profiles compared with measurements.

Choi and Kang (2004) applied the Reynolds stress model to simulate open-channel flow with emergent and submerged vegetation. Their computed profiles were compared with the results from the $k$-$\varepsilon$ model and the algebraic stress model as well as the measured data available in the literature. Choi and Kang (2004) also used the non-isotropic model to
take into account the increase in the level of non-isotropy of turbulence due to vegetation. For open-channel flow with emergent vegetation, they observed that the Reynolds stress model is able to simulate the non-isotropic nature of the flow better than the algebraic stress model and the $k-\varepsilon$ model. For open-channel flow with submerged vegetation, they found that the Reynolds stress model predicts the mean velocity and turbulence quantities better than any other turbulence closure models.

Zhang et al. (2010) used the modified momentum and $k-\varepsilon$ equations to investigate the flow structure, velocity distribution, and mass transport process in a straight compound open channel and a curved open channel. They introduced an equation to simulate the anisotropy using the standard $k-\varepsilon$ model because the standard one does not have this capability. Their simulated results showed reasonable agreements with the experimental data. In a straight compound channel, all streamwise velocities follow the logarithmic distribution in the case of unvegetated floodplains. A S-shaped profile of velocity occurs at some place on the floodplain in the case of vegetated floodplains. In curved open channel flow, the peak values of turbulent kinetic energy occurred at the bottom and interfacial vegetation region. Velocity in the vegetated channel is smaller than that in the unvegetated one due to the impact of vegetation resistance.

1.2.3 Impact of Vegetation on Bed Resistance in Mobile Bed Channel

Resistance in vegetated channels is composed of resistances from the boundary and the vegetation stems. Boundary resistance consists of side wall, grain, and bed form resistances on mobile bed surface. Grain resistance is the friction due to bed surface roughness and is a function of bed roughness height, while bed form resistance is a drag
force due to flow separation at the lee side of bed form and is a function of bed form height. The summation of grain and bed form resistance is called the bed resistance.

In vegetated channels, bed resistance is significantly smaller than that in an unvegetated channel at the same flow discharge. Lopez and Garcia (1998) conducted a numerical simulation to represent the flow through rigid vegetation by modifying the governing momentum and \( k-\varepsilon \) equations. They found that the bed resistance in vegetated channels reduced steadily with the increase of vegetation roughness density, defined as \( aH \), where \( a \) is the vegetation frontal area per unit volume (m\(^{-1}\)), and \( H \) is flow depth. For channels with submerged vegetation having \( H/h_v=3 \), where \( h_v \) is the vegetation height, the bed resistance is reduced to just 10% of the bare bed value.

Jordanova and James (2003) and Kothyari et al. (2009a) calculated bed resistance by subtracting vegetation resistance from the total flow resistance when processing their laboratory experimental data. The vegetation resistance was determined by using the drag coefficient for a single cylindrical stem, but taking into account the effect of other adjacent stems. Jordanova and James (2003) used the equations proposed by Li and Shen (1973) to calculate the modified drag coefficient and the approaching velocity for the region located within multiple wakes of vegetation stems. The modified drag coefficient equation is a function of the drag coefficient for standard single cylindrical stem, average velocity and approaching velocity, whereas the approaching velocity equation is a function of stem diameter and spacing, and the average velocity. Kothyari et al. (2009a) used an equation proposed by Kothyari et al. (2009b) to calculate the drag coefficient, which is related to Froude number, Reynolds number as a function of stem diameter, staggering pattern, and, vegetation concentration, \( \phi \), defined as the fraction of bed area occupied by the vegetation.
stems. Jordanova and James (2003) found that the bed shear stress was reduced within stands of emergent vegetation through the absorption of momentum by the drag on the stems.

1.2.4 Impact of Vegetation on Sediment Transport

Bed resistance and turbulence intensity have significant effects on sediment transport in vegetated channels. Specht (2002) conducted several laboratory experiments to investigate bed load transport in a bare bed channel with emergent vegetation on the banks. Since flow velocity on the vegetated banks is less than that in the channel, a secondary current is generated with the direction towards the channel center at the bottom, but outwards at the free surface, resulting in a scour hole at the bank toe. This secondary flow circulation considerably affects the direction of bed load transport. Based on the experimental results, Specht (2002) developed a vegetation parameter that can be used with the existing bed load transport formulae to account for the effect of vegetated banks on bed load transport. Later, Jordanova and James (2003) and Kothyari et al. (2009a) correlated sediment transport in vegetated channels with bed resistance. However, the results of Jordanova and James (2003) are not generic because they are based on only one sediment size, one stem diameter, and one vegetation density. Recently, Kothyari et al. (2009a) studied the effect of emergent vegetation on bed load transport. They observed that sediment transport rate in vegetated channels is smaller than that in unvegetated ones. The sediment transport relationship by Hashimoto and Hirano (1996), originally for sediment transport in unvegetated channels, was modified in Kothyari et al. (2009a). They found sediment transport in vegetated channels is a function of bed resistance and critical shear stress of bed sediment. Schmid et al. (2005) developed a mathematical model to describe
sediment transport and deposition in the constructed wetland ponds with emergent vegetation. Flow through wetland ponds is characterized by slow flow in the transition regime between laminar and turbulent, and this results in a significant effect on the deposition of suspended sediment. They assumed the uniformly distributed streamwise velocity through the emergent vegetation to simplify the mathematical modeling of transport process.

Although most previous studies observed enhanced depositions within the vegetated bed surface, the opposite trend has also been observed (Nepf 2012). Baptist (2003) conducted experiments of sediment transport on channels with flexible submerged vegetation. The results showed an increase in suspended sediment transport rate compared to a case without vegetation. The increased turbulence levels in between the vegetation stems are capable of picking up the sediment more effectively, and thus bringing the sediment in suspension. Follett and Nepf (2012) observed the erosion and deposition patterns formed in an experimental sand bed around a circular patch of emergent vegetation imitated by rigid cylinders. All of their measurements showed some degrees of scouring within the patch. This was attributed to the higher level of turbulence within the vegetation patch. Sediment scoured from the sparse patch was mostly deposited within one patch diameter downstream of the same patch. Additional deposition occurred further downstream, but at the sides of the turbulence wake, creating an open bed formation (Figure A-1 (a)). For a dense patch, flow experiences greater resistance, sediment scoured from this patch was carried further downstream before depositing along the patch centerline. Consequently, a closed bed formation was created (Figure A-1 (b)).
1.3 Format of Dissertation

The format of this dissertation is defined by The University of Arizona Graduate College’s Manual for Theses and Dissertations and is, therefore, subject to some repetitions of information. It includes a first chapter ‘INTRODUCTION’ describing the relevance of this research, in the context of previous research, and a second chapter ‘CURRENT STUDY’ that briefly summarizes the objectives, methodology and results of the three manuscripts included in Appendices A, B, and C, and potential future work of the current study. Appendix A is a scientific manuscript regarding a series of experiments to study the grain and bed resistances and bed load transport in an open channel flume with emergent vegetation, and it has been presented in the ASCE EWRI Congress 2015 and also submitted to the Journal of Hydraulic Engineering. Appendix B is a scientific manuscript regarding the numerical simulation (1st part) of hydrodynamic flow field in the vegetated marsh area by introducing empirical roughness coefficients for each subarea, and it has been published in the Proceedings of ASCE EWRI Congress 2014 and also submitted to the Journal of Waterway, Port, Coastal and Ocean Engineering. Appendix C is a scientific manuscript regarding the numerical simulation (2nd part) of tidal flow in vegetated marsh area in which the time varying roughness coefficients and the modified momentum and k-ε equations were used for each subarea to simulate the vegetation resistance, and has been published by the Journal of Hydraulic Engineering.
CHAPTER TWO
CURRENT STUDY

2.1 Objective

The main objective of this study is to quantify vegetation impacts on flow resistance and sediment transport. In order to achieve this, the following specific tasks were completed:

- Conduct a series of laboratory experiments to investigate grain and bed form resistances, and bed load transport in a vegetated mobile bed channel. An attempt was made to separate grain and bed form resistances, which is challenging and has never been reported in literature. Bed surface elevations and bed form height were captured by the Microsoft Kinect (Microsoft 2013) 3D Camera. Bed sediment size, flow condition, and vegetation density were varied in the experiments. Empirical relations to determine bed form resistance and bed load transport rate were derived from the experimental data. Both were correlated with a dimensionless flow parameter that depends on vegetation concentration using the experimental data from this and other studies.

- Simulate flow hydraulics in an estuarine fresh water marsh using Delft3D-FLOW model (rigid bed). This task was divided into two parts:
  - 1st part: Two approaches were used to approximate the vegetation roughness: a constant Manning’s $n$ coefficient, and a time-varying $n$ or Chezy’s $C$ coefficient for each sub-area. Observed water surface elevations were used for model validation and verification. It is concluded that the use of time varying
roughness coefficient gives better simulated results comparing with the observations. Several equations were used to quantify the time varying roughness coefficients. It is found that the equations that account for the effect of the degree of submergence and the vegetation frontal area per unit volume give the closet matches with the observations.

- 2nd part: The time varying roughness coefficients approach and the modified momentum and $k$-$\varepsilon$ equations approach for approximating vegetation induced resistance were evaluated. Research from 1st part was extended by using fine meshes and additional methods. Observed flow rate in addition to water surface elevations were used for model validation and verification. The best empirical equations identified in the 1st part gave better results than other equations as well as the method for modifying the momentum and $k$-$\varepsilon$ model.

### 2.2 Methodology

The impacts of vegetation on flow resistance and sediment transport were studied through a series of laboratory experiments of variable vegetation densities (Appendix A). Numerical simulation using the Delft3D-FLOW model is used to evaluate various equations for calculating flow resistance in the vegetated channel. Different methods for calculating vegetation induced roughness were implemented in Delft3D model (Appendices B and C).

#### 2.2.1 Experimental Study (Appendix A)

The impacts of vegetation on bed resistance and bed load transport were studied. The vegetation stems were simulated by arrays of emergent PVC rods. Three different
staggered vegetation concentrations and two groups of uniformly sized sediment were used. The total flow resistance was divided into bed and vegetation resistance, and bed resistance is further separated into grain and bed form resistances. Bed load transport rate was measured by a bed load sampler.

### 2.2.1.1 Grain Resistance in Vegetated Channel Flow

Nepf (2012) summarized several methods to measure bed resistance without the presence of bed form in vegetated channel by using: (See Appendix A for variable notations)

1. The spatial averaged viscous stress on bed surface ($\mu \frac{\partial v}{\partial z}$).

2. The near bed turbulent kinetic energy (TKE) ($0.2 \rho [0.5(u'^2 + v'^2 + w'^2)]$).

3. The near bed Reynolds stress ($\rho u'w'$) or by extrapolating the linear profile of Reynolds stress to the bed; and

4. An alternative approach based on the ratio of the mean velocity in vegetated layer and the stem diameter, $(2.0 \pm 0.2)^2 (\mu \frac{U_r}{d})$, for $aH \geq 0.3$.

To calculate grain resistance using methods (1), (2) and (3), the measurements must be made within the viscous sublayer (usually less than 1.0 mm in hydraulic rough flows). This type of fine-scaled measurement is difficult for flow through a vegetated mobile bed. If the measurement location is beyond the viscous sublayer, turbulence generated from bed forms and vegetation stems are also included, which means the measured TKE and Reynolds stresses are not appropriate for calculating the grain resistance. This leaves method (4), the only method to estimate the bed resistance in vegetated channel. Without the presence of bed form, the bed resistance calculated from method (4) is essentially the
grain resistance. Therefore, in this study, method (4) was used to calculate the grain resistance.

The mean velocity over the vegetation layer, \( U_v \), is equal to the mean pore velocity over the entire cross section, \( V_v = Q/(BH(1-\phi)) \) because vegetation is emerged in this study (Kothyari et al. 2009a, Cheng and Nguyen 2011). Therefore, the grain resistance is calculated based on method (4) as:

\[
\tau_g = (2.0 \pm 0.2)^2 (\mu V_v / d), \quad \text{for } aH \geq 0.3
\]  

(2.1)

2.2.1.2 Bed Form Resistance in Vegetated Channel Flow

The mathematical equation for the force balance in steady uniform open channel flow with vegetation is: (See Appendix A for variable notations)

\[
\gamma \forall S = (\tau_g + \tau_{bf})A_{bed} + F_D
\]  

(2.2)

The drag force acting on the vegetation stems in Eq. (2.2), \( F_D \), can be calculated as:

\[
F_D = \frac{1}{2} \rho C_D N B d H V_v^2
\]  

(2.3)

To calculate the bed form resistance using Eqs. (2.2) and (2.3), the value for \( C_D \) needs to be calculated first. Cheng (2013) developed an approach to calculate the vegetation drag coefficient for a cylinder located in arrays of emergent cylinders using the pseudo-fluid model. An analogy was made between the cylinder-induced drag in an open channel flow with that induced by the cylinder settling in a stationary fluid. The \( C_D \) value calculated by Cheng (2013) is applicable for a wide range of vegetation concentrations and Reynolds numbers, and different vegetation configurations.
To calculate the bed form resistance, a new trial and error method is adopted because $C_D$ is a function of $r_m$, which depends on the bed form resistance itself. The detailed procedure is as follows:

**Step #1:** Calculate $\tau_g$ using Eq. (2.1), and convert it into the $f_g$, using $f_g = (8 \tau_g / (\rho V_v^2))$.

**Step #2:** Calculate $r_v$ value using $r_v = (\pi/4) (1 - \phi) d / \phi$ (Cheng and Nguyen 2011), $r$ value using $r = [(1/H) + (1/r_v)]^{-1}$, and $f$ value using $f = (8 g r S / V_v^2)$.

**Step #3:** Assume $f_b$. For the first trial, this guess must be greater than $f_g$. Then, perform the following steps to recalculate the bed friction coefficient.

1. Calculate $r_m$ value using $r_m = r_v \left[ 1 - \left( \frac{f_b}{H} \frac{r}{f} \right) \right]$ (Cheng and Nguyen 2011).

2. Calculate $R'_e$ using $R'_e = \frac{1+S}{1+80\phi} \frac{V_v d}{\nu} \frac{r_m}{r_v}$ (Cheng (2013)).

3. Calculate $C'_D$ using $C'_D = 11 R'_e^{-0.75} + 0.9 \left[ 1 - e^{-\left( \frac{1000}{R'_e} \right)} \right] + 1.2 \left[ 1 - e^{-\left( \frac{R'_e}{4500} \right)} \right]$ (Cheng (2013)).

4. Calculate $C_D$ using $C_D = \frac{1+S}{1-\phi} C'_D$ (Cheng (2013)).

5. Calculate $F_D$ using Eq. (2.3).

6. Calculate $\tau_{bf}$ using Eq. (2.2).

7. Calculate $f_{bf}$ using $f_{bf} = (8 \tau_{bf} / (\rho V_v^2))$. 
8- Re-calculate \( f_b \) using \( f_b = f_g + f_{bf} \).

9- Repeat step #3 until the difference between the calculated and the assumed values of \( f_b \) is within a desired tolerance.

2.2.1.3 Bed Surface Elevation

Bed surface elevation was captured by the Microsoft Kinect (Microsoft 2013) 3D camera (Figure 2.1). Microsoft Kinect is a motion sensing device designed initially for video gaming and introduced in November 2010. It was found later that it has many other applications (Voullieme et al. 2014, Kahn et al. 2013, Azzari et al. 2013, Mankoff and Russo 2013). It is composed of RGB-D (Red Green Blue + Depth) sensors. These sensors can produce a RGB visible light image and a depth-coded image from the structured infrared light. The bed surface elevation and bed form height were captured by the depth sensor. The basic principle of the depth sensor is to emit an infrared light pattern and calculate depth from the light reflection at different positions (Andersen et al. 2012). This allows to generate a depth-coded image that consists of dots with known coordinates and depths. Kinect is supported in MATLAB (version 2013a), and its data can be acquired using the MATLAB Image Acquisition Toolbox.

After each experimental run, water is slowly drained out of the flume. When the bed surface was still wet, vegetation stems were removed carefully to make this region clear for taking images (Figure 2.2 (a)). Microsoft Kinect together with the MATLAB Image Acquisition Toolbox was used to capture a depth image for the bed surface. Using the MATLAB program, we converted the depth-coded image, and stored it as point clouds.
Each point in the cloud has $X$, $Y$, and $Z$ values representing its position in space ($X$ and $Y$) as well as its distance or depth ($Z$) from the Kinect depth sensor (Figure 2.2 (b)).

Because the bed surface has longitudinal and transverse slopes, these slopes will affect the distance ($Z$-value) from each point on the bed surface to the Kinect depth sensor (Figure A-4 (a)). In order to remove these effects (bias) another MATLAB program was used for leveling the bed surface (Figure A-4 (b)).

Finally, the average of the bed form height can be calculated by $\sqrt{\frac{1}{n} \sum_{i=1}^{n} (Z_i - \bar{Z})^2}$. Also the bed surface elevation contours can be drawn as shown in Figure 2.2 (c).

Figure 2.1 Microsoft Kinect (http://www.pcmag.com/article2/0,2817,2402520,00.asp)
Figure 2.2 Steps to capture bed surface elevations and bed form height
2.2.2 Numerical Simulation (Appendices B and C)

In order to simulate tidal flow in an estuarine marsh area, a three dimensional hydrodynamic simulation using the Delft3D-FLOW open source program was performed. Delft3D-FLOW is capable of simulating three dimensional (3D) unsteady incompressible flow and transport phenomena resulting from tidal and/or meteorological forcing (Deltares 2011). It solves the RANS equations, under shallow water (hydrostatic pressure) assumption, on a structured staggered curvilinear grid using a finite-difference scheme (Stelling and van Kester 1994). The governing equations are solved with an Alternating Direction Implicit (ADI) technique (Stelling 1984). In the vertical direction, Delft3D-FLOW offers two different vertical grid system, the σ coordinate system (σ-grid) and the Cartesian coordinate system (Z-grid) (Deltares 2011). In the σ-grid, the vertical layers bounded by two sigma planes, which are not strictly horizontal but follow the bottom topography and free surface. Because the σ-grid is boundary-fitted both to the bottom and to the moving free surface, a smooth representation of the topography is obtained. In the Z-grid, the layer thickness is fixed and the number of active layers varies with the depth. The layer thickness at the top, however, is determined by the actual water level and at the bottom by the local topography. The RANS equations under hydrostatic pressure assumption were solved for both σ and Z-grids. An extension for solving non-hydrostatic pressure has been added to Z-grid. Delft3D-FLOW offers four turbulence closure models: constant eddy viscosity coefficient, algebraic eddy viscosity model, k-L model, and k-ε model.

Delft3D-FLOW has a facility to define the bed and flow resistance on each sub-grid using a function called Trachytopes (Deltares 2011). Three classes are available in the
Trachytopes function: area, line, and point class. The area class has three types: the first type is a constant coefficient for bed roughness, such as White Colebrook, Chezy, and Manning’s coefficients, the second type accounts for the form resistance resulting from sand dunes, and the third type is for the roughness coefficient in vegetated channels. In a simulation run, the roughness coefficient often remains a constant with time if choosing the first type of area class while for the second type, it is determined by dune height, and the third by vegetation properties. The line class of the Trachytopes function can be used to approximate flow resistance for elements with hedge, bridge piers, and other structures. The point class can be used to represent a set of point flow resistance elements, such as groups of individual tree or small plant.

The vegetation effects have been incorporated in Delft3D-FLOW by applying an adjusted bed roughness, such as using the Klopstra et al. (1997) equation, or adding an artificial term to account for extra momentum loss due to vegetation using the Baptist (2005) equation. Also, the momentum and $k$-$\varepsilon$ turbulent closure model equations in Delft3D-FLOW have been modified by including the vegetation induced momentum loss as well as the influences of vegetation on turbulence generation and dissipation. The influence of the vegetation upon the momentum equations is given by the vegetation drag force \( F = \frac{1}{2} \rho C_D a u^2 \) in which \( \rho \) is water density (kg/m$^3$) and \( u \) is the horizontal flow velocity. The influence of vegetation on vertical mixing is reflected in an extra source terms \( T \) and \( T \tau^{-1} \) in the \( k \) and \( \varepsilon \) equations, respectively, where \( T = (F u) \) is the work spent on the fluid and \( \tau \) is the minimum of the dissipation time scale of free turbulence \( \tau_{free} = (1/c_{2\varepsilon}) \cdot (k/\varepsilon) \) and the dissipation time scale of eddies between the vegetation \( \tau_{veg} = [1/(c_{2\varepsilon} \sqrt{C_\mu})] \cdot \varepsilon^3 (L^2 / T) \), where \( C_\mu \) and \( c_{2\varepsilon} \) are constants and equal to 0.09 and
1.92, respectively, \( L = (C_l \sqrt{(1 - A_p)/N}) \) is the smallest distance in between the stems; \( A_p = (\pi / 4)W_v^2 N \) is the vegetation horizontal cross sectional area; \( W_v \) is the average width of vegetation; \( N \) is the number of vegetation per unit bed area; and \( C_l \) is a constant and equals 0.8.

In Appendix B, two approaches were used for calculating vegetation induced roughness: a constant Manning’s \( n \) coefficient and time varying \( n \) or Chezy’s \( C \) coefficient for each sub-grid. Therefore, the first and third types of the area class of the Trachytopes function in Delft3D model were adopted. Four empirical relations to calculate the time varying roughness coefficients were programmed in Delft3D-FLOW program in addition to two empirical relations offered by this program to calculate the \( C \) value (Table B-2). Observed water surface elevations were used for model validation and verification. The \( \sigma \) and \( Z \) grids were used in the vertical direction. The RANS equations under hydrostatic pressure assumption were solved when using the \( \sigma \) grid, whereas the hydrostatic and non-hydrostatic pressures were solved when using the \( Z \)-grid. The sensitivity of modeling results to the variation of \( a \) and vertical grid selection were analyzed.

In Appendix C, the time varying roughness equations and the modified momentum and \( k-e \) equations were used for calculating vegetation induced roughness for each sub-grid. A finer mesh was used compared with that in the Appendix B. Observed flow rate in addition to water surface elevations were used for model validation and verification. The \( \sigma \) grid was used in the vertical direction. The RANS under hydrostatic pressure assumption was solved. The variation of vegetation roughness coefficient with the degree of submergence is handled in more details. The spatially and temporally variation of
vegetation roughness and Reynolds number are also explained, and the sensitivity of modelling results to the variation of grid size was analyzed.

2.3 Results

2.3.1 Experimental Study (Appendix A)

A set of 18 experimental runs were conducted in an open channel flume to study grain and bed form resistances and bed load transport in vegetated mobile bed. The vegetation stems were simulated by arrays of emergent PVC rods. The stems were arranged in a regular staggered grid with three concentrations 3.3%, 1.4%, and 0.5%. Two groups of uniform sized sediments with the mean sizes of 0.45 mm and 1.6 mm were used. Three flow discharge values were used for each vegetation concentration and sediment group with overall range of 0.01 to 0.04 m$^3$/s. Microsoft Kinect (Microsoft 2013) was used to capture a depth image of bed surface for determining bed elevations and bed form heights.

The following conclusions were obtained in this study:

1- The height of bed form depends on the vegetation concentration, which determines whether ripple/dune or scour holes are dominant on bed surface.

2- For sparsely vegetated flows, the bed form height and resistance decrease rapidly as the vegetation concentration is increased, and they decreased gradually when the vegetation concentration is high.

3- Sand dunes started to appear when the vegetation was sparse, and their sizes were increased as the flow velocity was increased.

4- Based on the experimental data from this and other studies, poor correlations were found between the grain resistance and the bed load transport rate and a similar
trend was found for the correlation between the total resistance and the bed load transport rate. This means that the bed load transport rate in vegetated channel should be correlated with other variables.

5- Empirical relations were formulated to calculate the bed form resistance and bed load transport rate using a newly defined flow parameter. This parameter is a function of flow characteristics, energy slope, vegetation concentration, vegetation stem diameter, and sediment sizes.

2.3.2 Numerical Simulation (Appendices B and C)

Results from numerical modeling studies are summarized in Appendices B and C. In Appendix B, the preliminary numerical simulation was focused on the difference between a constant and time varying roughness coefficient for simulating hydrodynamic flow field in vegetated marsh area. Further research suggested more advanced methods to simulate the impacts of vegetation in open channel flow, such as the method for modifying the momentum and $k$-$
$ model. However, the simulation results showed that the advanced method did not provide more accurate results than using the empirical relations for varying roughness in time and space. Detailed conclusions from numerical simulation are as follows:

1- For the constant Manning’s $n$ approach, the simulated results are underestimated when using the Manning roughness coefficient for unvegetated channels, whereas they are overestimated when using the Manning’s roughness for vegetated channels. Several $n$ values between the above two $n$ values were selected to re-run the model. However, there are no general improvements of modeling results. This
excludes the feasibility of using a constant roughness for simulating flow hydrodynamics in a freshwater marsh.

2- The time varying roughness coefficient equations, especially those (best) equations that take into account the degree of submergence and the vegetation frontal area per unit volume (a value), gave better matches of simulated results with the observations compared with the simulation results using a constant roughness coefficient and modified momentum and k-ε equations.

3- The a value must be calculated by considering the vegetation stem diameter, leaf width and number. The best range for the dominant grass in the study (Panicum hemitomon) is 8.160 to 11.220 m⁻¹.

4- Adopting the σ-grid model in the vertical direction gave better simulation results compared with the two options of the Z-grid. This study recommends the use of the σ-grid for shallow water marsh application.

5- When using the best time varying roughness coefficient equations, the simulation results agreed very well with the observations for both fine-and coarse-grid meshes.

6- Adoption of coarse mesh gave reasonable simulation results with less CPU time.

7- A non-linear relation between the vegetation resistance (in terms of n value) and degree of submergence was observed with an opposite trend for emergent and submerged vegetation conditions.

8- In the case of emergent vegetation, as the degree of submergence is increased, the vegetation resistance is increased owing to the increase of vegetation frontal area.

9- In the case of submerged vegetation, the vegetation resistance decreases with the increasing degree of submergence due to the reduction in the relative roughness
(vegetation height/water depth) and the bending of the nonrigid plants. As the degree of submergence increases further, the vegetation layer acts as a rough surface, and the vegetation resistance becomes constant.

### 2.4 Future Works

Vegetation induced resistance is highly variable in the field due to the complex vegetation types, density, height, and flexibility. Therefore, more research is needed to quantify those varieties and their effect on flow resistance and sediment transport in vegetated channels. The following works are recommended for the future:

- It is found that the vegetation frontal area per unit volume, symbolized as $a$, is considered one of the important factors to quantify vegetation properties. This value is equal to the product of frontal area and vegetation density. Several factors affect the vegetation frontal area, such as vegetation stem size, leaf width, number of leaves, flexibility, and flow depth and velocity. This means that the $a$ value is varying in the vertical direction. Further research to better quantify the vegetation characteristics, the $a$ value, in both horizontal and vertical spaces are needed for improving the numerical models.

- Although relations of bed form resistance and sediment transport rate in a vegetated mobile bed channel were derived through a series of experiments, those equations can be implemented in the Delft3D model to improve its capability for simulating flow and sediment transport in vegetated mobile bed channels.

- Additional research can also be performed by using advanced Computational Fluid Dynamics Models, such as Direct Navier Stokes (DNS) equation solution, or Large Eddy Simulations (LES). This research allows the tracking of sediment particle...
motion through complex turbulence flow fields within the vegetation stems. However, High Performance Computers (HPC) will be needed for those simulations.
Appendix A: Experimental Study of Bed Resistance and Bed Load Transport in Vegetated Channel

Khalid Al-Asadi¹, Jennifer G. Duan²

Abstract

A set of laboratory experiments were conducted to study the impact of vegetation density on bed resistance and bed load transport in mobile bed channel. The vegetation stems were simulated by arrays of emergent PVC rods. Three different staggered vegetation configurations and two groups of uniformly sized sediment were used. Bed elevation was measured by the Microsoft Kinect 3D Camera. The total flow resistance was divided into bed and vegetation resistance, and bed resistance is further separated into grain and bed form resistances. Based on the experimental data from this and other studies, empirical relations were formulated to calculate the bed form resistance and bed load transport rate. We found bed form resistance and bed load transport rate in vegetated mobile bed channels is a function of a newly derived flow parameter that incorporates the influence of vegetation concentration.

Introduction

Flow in vegetated rivers is characterized by the interactions among the flow, channel boundary, and vegetation canopy. Vegetation characteristics, such as vegetation type, distribution, density, flexibility, and degree of submergence, all affect flow depth,

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velocity, hydraulic radius, and energy slope. The resistance to flow through vegetated areas is increased by an additional drag force exerted by vegetation (Fenzl 1962, Temple et al. 1987). Because of this drag, flow through vegetated reaches decelerates, and the mean velocity is smaller than those in unvegetated reaches (Shi et al. 1995, Zhang et al. 2010). This additional drag also influences the transport of sediment and solutes by promoting sediment accumulation as the near-bed shear resistance reduces (Nepf 1999). Vegetation also changes near-bed turbulent characteristics, and significantly affects the scour formation around vegetation stems.

Resistance in vegetated channel is composed of resistances from the boundary and the vegetation stems. Boundary resistance consists of side wall resistance, grain and bed form resistances on mobile bed surface. Grain resistance is the friction due to bed surface roughness, and it is a function of bed roughness height. While bed form resistance is a drag force due to flow separation at the lee side of bed form, and it is a function of bed form height. The summation of grain and bed form resistance is called the bed resistance. In vegetated channels, bed resistance is significantly smaller than that in an unvegetated channel at the same flow discharge. Jordanova and James (2003) and Kothyari et al. (2009a) calculated bed resistance by subtracting vegetation resistance from the total flow resistance when processing their laboratory experimental data. The vegetation resistance was determined by using the drag coefficient for a single cylindrical stem, but taking into account the effect of other adjacent stems (Eq.5 in Jordanova and James 2003 and Eq.4 in Kothyari et al. 2009a). Numerical modeling study (Lopez and Garcia 1998) found bed resistance in vegetated channels reduced steadily with the increase of vegetation roughness density, defined as $aH$, where $a$ is the vegetation frontal area per unit volume ($m^{-1}$), and
$H$ is flow depth. For channels with submerged vegetation having $H/h_v = 3$, where $h_v$ is the vegetation height, the bed resistance is reduced to just 10% of the bare bed value.

Bed resistance and turbulence intensity have significant effect on sediment transport in vegetated channels. Specht (2002) conducted several laboratory experiments to investigate bed load transport in a bare bed channel with emergent vegetation on the banks. Since flow velocity on the vegetated banks is less than that in the channel, a secondary current is generated with the direction towards the channel center at the bottom, but outwards at the free surface, resulting in a scour hole at the bank toe. This secondary flow circulation considerably affects the direction of bed load transport. Based on the experimental results, Specht (2002) developed a vegetation parameter that can be used with the existing bed load transport formulae to account for the effect of vegetated banks on bed load transport. Later, Jordanova and James (2003) and Kothyari et al. (2009a) correlated sediment transport in vegetated channels with bed resistance. However, the results of Jordanova and James (2003) are not generic because they are based on only one sediment size, one stem diameter, and one vegetation density. Recently, Kothyari et al. (2009a) studied the effect of emergent vegetation on bed load transport. They observed that sediment transport rate in vegetated channels is smaller than that in unvegetated ones. The sediment transport relationship by Hashimoto and Hirano (1996), originally for sediment transport in unvegetated channels, was modified in Kothyari et al. (2009a). They found sediment transport in vegetated channel is a function of bed resistance and critical shear stress of bed sediment.

Although most previous studies observed enhanced deposition within vegetated bed surface, the opposite trend has also been observed (Nepf 2012). Follett and Nepf (2012)
observed the erosion and deposition patterns formed in an experimental sand bed around a circular patch of emergent vegetation imitated by rigid cylinders. All of their measurements showed some degrees of scouring within the patch. They attributed that to the higher level of turbulence within the vegetation patch. Sediment scoured from the sparse patch was mostly deposited within one patch diameter downstream of the same patch. Additional deposition was occurred further downstream, but at the sides of the turbulence wake, creating an open bed formation (Figure A-1 (a)). For dense patch, flow experiences greater resistance, sediment scoured from this patch was carried further downstream before depositing along the patch centerline. Consequently, a closed bed formation was created (Figure A-1 (b)). The density of vegetation is apparently a key factor that influences sediment transport and the resulted erosion/deposition pattern in vegetated channels. However, this subject has not been thoroughly studied in literature.

Therefore, the objective of this study is to conduct a series of laboratory experiments to investigate bed form resistance and bed load transport in vegetated mobile bed channel. Sediment sizes, flow conditions, and vegetation densities were varied in the experiments. Empirical relations to determine the bed form resistance and bed load transport rate were derived from the experimental data. Both were correlated with a vegetation concentration dependent dimensionless flow parameter using the experimental data from this and other studies.
Experimental Setup

Flume Setup

A set of 18 experimental runs were conducted in an open channel flume at the Department of Civil Engineering and Engineering Mechanics, University of Arizona. The flume is 0.6 m wide and 12.2 m long with a flat bed. A large water tank was used to provide water to the flume, and the flow rate was controlled by a valve installed at the inlet pipe. A sharp crested suppressed rectangular weir located at the end of the flume was used to measure flow rate. The vegetation stems were simulated by emergent PVC rods of 16 mm outside diameter. The stems were inserted into holes drilled into a 1.5 cm thick and 4.8 m long coated wood board, as shown in Figure A-2. The stems were arranged in a regular staggered grid (Figure A-3). Three different staggered vegetation configurations were used with three concentrations: 3.3%, 1.4%, and 0.5%, respectively. The vegetation concentration, \( \phi \), is defined as the fraction of bed area occupied by the vegetation stems = \( N \left( \frac{\pi}{4} \right) d^2 \), where \( N \) is the number of stems per unit bed area, and \( d \) is the outside diameter of the stem.

Two groups of uniformly sized sediment with mean sizes, \( d_{50} = 0.45 \) mm and 1.6 mm, were used. The standard deviations of these two sediment mixtures, \( \sigma_g = (d_{84} / d_{16})^{0.5} \), are 1.47 and 1.35 for sediment sizes of 0.45 mm and 1.6 mm, respectively. Sediment mixtures with the value of \( \sigma_g \) less than 1.6 can be considered as uniformed (Parker 2008). The density of sediment, \( \rho_s \), is equal to 2,650 kg/m\(^3\). Before each experimental run, sediment was saturated and placed evenly among the vegetation stems at a depth of 10 cm (Figure A-2).
Water depth was measured at an interval of 0.45 m along the vegetated reach using a fine-scaled ruler of 1 mm accuracy. When the measured flow depths were nearly constant along the study reach, the flow is considered as steady uniform. After each experiment, bed elevations were also measured by a laser level (accuracy 1 mm) at an interval of 0.45 m and 0.1 m in the streamwise and transverse directions within the vegetated reach, respectively. Bed elevation at each cross section is the average of all the measured elevations in the transverse direction. The longitudinal bed slope was obtained by fitting the bed elevations at each cross section with a straight line. The water surface elevations at each cross section were calculated as the summation of water depth and bed elevation. Then, the friction (energy) slope was calculated by fitting the water surface elevations with a straight line. For all the experimental runs, the correlations of curve fitting for calculating bed and friction slopes are greater or equal 0.84. Results showed the friction slopes are nearly equal to the measured bed slopes for all the experiments.

Bed load transport rate, $q_b$, was measured by a bed load sampler at the end of vegetated reach. The sampler nozzle is 4.5 cm high and 25 cm wide, and mounted on a rod. The collection bag has a mesh size of 0.2 mm. The sampling time interval ranged from 1 to 8 minutes. Then, the bed load was dried and weighted. Bed load transport rate was first calculated as weight per unit time, and then converted to the volume per unit time per unit channel width ($m^2/s$).

All the measurements in Table A-1 were taken after the flow has reached the steady state. During each experimental run, sediment was supplied from time to time at the upstream end of the flume to supplement the sediment being washed out of the flume, and to keep approximately the steady state flow condition.
Bed Surface Elevation

Microsoft Kinect (Microsoft 2013) was used to capture a depth image of bed surface for determining bed elevations of scoured vegetated reach. Microsoft Kinect was initially designed for gaming, but it has many other applications (Voullieme et al. 2014, Kahn et al. 2013, Azzari et al. 2013, Mankoff and Russo 2013). It is composed of RGB-D (Red Green Blue + Depth) sensors. These sensors can produce a RGB visible light image and a depth-coded image from the structured infrared light. The bed elevation deviations are captured by the depth sensor. The basic principle of the depth sensor is to emit an infrared light pattern and calculate depth from the light reflection at different positions (Andersen et al. 2012). This allows to generate a depth-coded image that consists of dots with known coordinates and depths. Kinect is supported in MATLAB (version 2013a), and its data can be acquired using the MATLAB Image Acquisition Toolbox.

Data Processing

Grain Resistance

Nepf (2012) summarized several methods to measure bed resistance without the presence of bed form in vegetated channel by using: (i) the spatial averaged viscous stress on bed surface \( \left( \mu \frac{\partial v}{\partial z} \right) \), where \( \mu \) is the dynamic viscosity of water \( (N \cdot s/m^2) \), and \( \frac{\partial v}{\partial z} \) is the velocity gradient within the laminar sub-layer; (ii) the near bed turbulent kinetic energy (TKE) \( (0.2 \rho [0.5(u'^2 + v'^2 + w'^2)]) \), where \( \rho \) is the water density; \( u' \), \( v' \), and \( w' \) are the fluctuating velocities in the streamwise, transverse, and vertical directions, respectively, and the overbar means time-average; (iii) the near bed Reynolds stress \( (\rho u' w') \) or by extrapolating the linear profile of Reynolds stress to the bed; and (iv) an
alternative approach based on the ratio of the mean velocity in vegetated layer and the stem
diameter, \((2.0 \pm 0.2)^2 \left( \mu \frac{U_v}{d} \right)\), for \(aH \geq 0.3\), where \(U_v\) is the mean velocity in vegetated layer.

To calculate grain resistance using methods (i), (ii) and (iii), the measurements must be made within the viscous sublayer (usually less than 1.0 mm in hydraulic rough flows). This type of fine-scaled measurement is difficult for flow through vegetated mobile bed. If the measurement location is beyond the viscous sublayer, turbulence generated from bed forms and vegetation stems are also included, which means the measured TKE and Reynolds stresses are not appropriate for calculating the grain resistance. This leaves method (iv), the only method, to estimate the bed resistance in vegetated channel. Without the presence of bed form, the bed resistance calculated from method (iv) is essentially the grain resistance. Therefore, in this study, the (iv) method was used to calculate the grain resistance. The mean velocity over the vegetation layer, \(U_v\), is equal to the mean pore velocity over the entire cross section, \(V_v = \frac{Q}{BH(1-\phi)}\) because vegetation is emerged in this study, where \(B\) is channel width (m) (Kothyari et al. 2009a, Cheng and Nguyen 2011). Therefore, the grain resistance is calculated based on method (iv) as:

\[
\tau_g = (2.0 \pm 0.2)^2 \left( \mu \frac{V_v}{d} \right), \quad \text{for } aH \geq 0.3
\]  

(1)

Because grain resistance directly affects bed load transport, this study aims to separate grain resistance from the total flow resistance. The calculation of grain resistance in vegetated mobile bed channel is a challenge, which has never been reported in literature. In this study, we made an attempt that uses method (iv) in Nepf (2012) to calculate the grain resistance. However, we noticed that some of our experimental data, as well as data used in this study have the vegetation roughness density \((aH)\) less the lower limit for Eq.(1).
Therefore, we assumed Eq. (1) is valid for lower vegetation roughness density although the original experimental data (Nepf 2012) doesn’t contain those data.

**Bed Form Resistance**

The mathematical equation for the force balance in steady uniform open channel flow with vegetation is:

\[
\gamma \forall S = (\tau_g + \tau_{bf})A_{bed} + F_D
\]

(2)

where \( \gamma \) is the specific weight of water (N/m\(^3\)), \( \forall \) is the volume of water (m\(^3\)) \( = A_{bed} \cdot H \) in which \( A_{bed} \) is bed surface area (m\(^2\)), \( S \) is friction slope, \( \tau_{bf} \) is bed form resistance (N/m\(^2\)), and \( F_D \) is the vegetation drag force (N). The bed surface area for a reach of unit length and width, \( B \), is \( A_{bed} = B(1-\phi) \). The friction force on the side wall is neglected because it is several orders of magnitude smaller than other forces (Jordanova and James 2003, Kothyari et al. 2009a).

The drag force acting on the vegetation stems in Eq. (2), \( F_D \), can be calculated as:

\[
F_D = \frac{1}{2} \rho C_D N B d H V_v^2
\]

(3)

where \( C_D \) is the vegetation drag coefficient. From Eqs.(2) and (3), by knowing \( H, S, \frac{\tau_g}{\tau}, B, d, \phi, \) and \( Q \), the coefficient of vegetation drag must also be known in order to find the bed form resistance (\( \tau_{bf} \)). Cheng (2013) developed an approach to calculate the vegetation drag coefficient for a cylinder located in arrays of emergent cylinders using the pseudo-fluid model. An analogy was made between the cylinder-induced drag in an open channel flow with that induced by the cylinder settling in a stationary fluid. The drag coefficient can be calculated as follows:
\[
C_D = \frac{1+S}{1-\phi} C_D',
\]

where \( C_D' \) is the drag coefficient for the pseudo fluid model, and defined by:

\[
C_D' = 11 R_e^{r-0.75} + 0.9 \left[ 1 - e^{\left(\frac{1000}{R_e'}\right)} \right] + 1.2 \left[ 1 - e^{\left(\frac{R_e'}{4500}\right)^{0.87}} \right]
\]

where \( R_e' \) is Reynolds number for the pseudo fluid model, and can be calculated by:

\[
R_e' = \frac{1+S}{1+80\phi} \frac{V_m}{\nu} \frac{r_m}{r_v}; \quad r_v = \frac{\pi}{4}(1-\phi) d / \phi
\]

where \( r_v \) is the vegetation-related hydraulic radius for the vegetated flows if only considers vegetation resistance; \( r_m \) is the modified vegetation-related hydraulic radius, and calculated by taking the effect of vegetation and bed resistances into consideration (Cheng and Nguyen 2011):

\[
r_m = r_v \left[ 1 - \left( \frac{f_b}{f} \right) \right]
\]

where \( f \) is the Darcy-Weisbach friction coefficient due to vegetation and bed resistances; \( f_b \) is the bed friction coefficient, and equal to the summation of grain and bed form friction coefficients \([=f_g + f_{bf}]\); \( r \) is the total hydraulic radius including both vegetation and bed resistances:

\[
r = \left( \frac{1}{H} + \frac{1}{r_v} \right)^{-1}
\]
In order to calculate the bed form resistance from measured flow properties (e.g., $H, S$) and vegetation parameters ($\phi, d$), and channel geometry ($B$) using Eq.(2), the trial and error method is adopted because vegetation drag coefficient $C_D$ is a function of $r_{im}$, which depends on the bed form resistance itself. The detailed procedure is as follows:

Step #1: Calculate the grain resistance using Eq.(1), and convert it into the Dracy-Weisbach grain friction coefficient using $f_g = (8 \tau_g / (\rho V_g^2))$.

Step #2: Calculate the vegetation-related hydraulic radius using $r_v = (\pi / 4)(1 - \phi) d / \phi$, the total hydraulic radius, $r$, using Eq. (8), and $f$ value using $f = (8 grS / V_r^2)$.

Step #3: Assume the Darcy-Weisbach bed friction coefficient, $f_b$. For the first trial, this guess must be greater than $f_v$. Then, perform the following steps to recalculate the bed friction coefficient.

1- Calculate the modified vegetation-related hydraulic radius, $r_{im}$, using Eq. (7).

2- Calculate Reynolds number for the pseudo fluid model, $R'_e$, using Eq. (6).

3- Calculate the drag coefficient for the pseudo fluid model, $C'_D$, using Eq. (5).

4- Calculate the vegetation drag coefficient, $C_D$, using Eq. (4).

5- Calculate the vegetation drag force, $F_D$, using Eq. (3).

6- Calculate the bed form resistance, $\tau_{bf}$, using Eq. (2).

7- Calculate the Dracy-Weisbach bed form friction coefficient using $f_{bf} = (8 \tau_{bf} / (\rho V_v^2))$.

8- Re-calculate the Darcy-Weisbach bed friction coefficient using $f_b = f_g + f_{bf}$. 

9- Repeat #3 until the difference between the calculated and the assumed values of $f_b$ is within a desired tolerance.

The calculated $\tau_g$, $V_s$, $C_p$, and $\tau_{bf}$ values for all the experiments are shown in Table A-2. All the experimental flows are subcritical with Froude number ($F_r$) ranging from 0.162 to 0.343. The Reynolds number ($R_H$) based on flow depth are ranging from 16,775 to 68,018.

**Bed Form Height**

After each experimental run, water is slowly drained out of the flume. When the bed surface was still wet, vegetation stems were removed carefully to make this region clear for taking images. Microsoft Kinect together with the MATLAB Image Acquisition Toolbox was used to capture a depth image for the bed surface at the region indicated above. Using the MATLAB program, we converted the depth-coded image, and stored it as point clouds. Each point in the cloud has $X$, $Y$, and $Z$ values representing its position in space ($X$ and $Y$) as well as its distance or depth ($Z$) from the Kinect depth sensor.

Because the bed surface has a longitudinal and transverse slopes, these slopes will affect the distance ($Z$-value) from each point on the bed surface to the Kinect depth sensor (Figure A-4 (a)). In order to remove these effects, hereafter, called bias, another MATLAB program was used for leveling the bed surface (Figure A-4 (b)).

The height of bed elevation, $\Delta Z$, shown in Table A-2, is defined as the average bed form height, calculated by $\sqrt{\frac{\sum (Z_i - \bar{Z})^2}{n}}$, where $Z_i$ is the bed elevation at point $i$; $\bar{Z}$ is the mean bed elevation (m), which is a constant for a horizontal plane; $n$ is the total number of
measurement points. Typical bed surface elevation contours, such as run #7 and #18, are shown in Figure A-5 (a) and A-5 (b), respectively.

For $\phi = 3.3\%$ and 1.4%, scour holes were observed around each vegetation stem with a depositional bed form in between (Figure A-5 (a)). These bed forms are formed by the high level of turbulence from overlapping wakes and horseshoe vortices generated by each stem. Regardless of flow properties and sediment sizes, the $\Delta Z$ values for $\phi = 3.3\%$ were nearly the same (Table A-2), and the same trend was noticed for $\phi = 1.4\%$. This means that the bed form height is only dependent on vegetation concentration. The mean values of bed form height, $\Delta Z_{avg}$, for $\phi = 1.4\%$ and 3.3% are equal to 7.0 and 5.7 mm, respectively. This indicates that the bed form height is slightly decreased with the increasing of vegetation concentration.

For $\phi = 0.5\%$, because of the formation of sand dunes, the $\Delta Z_{avg}$ value is equal to 12 mm, larger than that for other $\phi$ values. For $d_{50}=0.45$ mm, as shown in Table A-2, the $\Delta Z$ value is slightly increased because smaller sized sand dunes were observed. When $d_{50}=1.6$ mm, as shown in Figure A-5 (b) and Table A-2, the $\Delta Z$ values are increased as the flow velocity are increased due to the increasing of sand dunes’ sizes. This implies that the sand dunes are generated through the sparse vegetation as flow velocity increases.

The variation of $\Delta Z_{avg}$ versus $\phi$ was shown in Figure A-6. This figure indicated that the $\Delta Z_{avg}$ is decreased rapidly as the $\phi$ value increased from 0.5% to 1.4% and then decreased gradually as the $\phi$ value increased from 1.4% to 3.3%. This trend is consistent with the evolution of bed form from sand dunes at low vegetation concentration to fully developed scour holes around each vegetation stem at high concentration.
Results

Bed Form Resistance Relation

In addition to data from this study, data from Jordanova and James (2003) and Kothyari et al. (2009a) in Table A-3 were also included for analysis. The value of bed resistance, $\tau_b$, shown in Table A-3 is the sum of the grain ($\tau_g$) and bed form ($\tau_{bf}$) resistances, which were calculated and given in their papers. By knowing the grain resistance ($\tau_g$) value (Eq.1) and the bed resistance ($\tau_b$). Then, the bed form resistance ($\tau_{bf}$) value is simply the difference between $\tau_b$ and $\tau_g$. A non-dimensional bed form resistance is defined as $\tau_{bf}^* = \tau_{bf} / \{(G_s - 1) \gamma d_{s0}\}$, where $G_s$ is the specific gravity of sediment, and equal to 2.65. In this study, through dimensional analysis, we formulated a non-dimensional flow parameter as a function of flow characteristics, energy slope, vegetation concentration, vegetation stem diameter, and sediment sizes, and defined by $\eta$

$$\eta = S \left( \frac{d}{d_{s0}} \right) \left( \frac{V_s^2}{2 g H \phi} \right)^{0.18}.$$ Regression analysis showed that $\tau_{bf}^*$ is correlated well with $\eta$ for all the datasets considered (Figure A-7). The correlation coefficient is $R^2 = 0.77$. Therefore, the dimensionless bed form resistance can be estimated using the dimensionless flow variable, $\eta$, as:

$$\tau_{bf}^* = 1.033 \ \eta^{0.94} \quad (9)$$

From Eq.(9), the vegetation concentration is one major factor affecting the bed form resistance. When only changing the $\phi$-value, but keeping all other variables constant, the changes of bed form resistance with vegetation concentration $\phi$ is shown in Figure A-8. This figure has the same trend as the one in Figure A-6, which indicated that the bed form...
resistance increases with bed form height. The bed from resistance decreases rapidly with the increase of vegetation concentration at low vegetation concentration ($\phi < 1.4\%$), and then decreases gradually as the concentration increases for high vegetation concentration.

**Bed Load Transport Relation**

The dimensionless bed load transport rate is defined as $q_b^* = q_b / \sqrt{(G_s - 1)g d_{50}^3}$. The non-dimensional grain resistance is defined as $\tau_g^* = \tau_g / [(G_s - 1)\gamma d_{50}]$, and the non-dimensional total resistance is defined as $\tau_t^* = HS / [(G_s - 1)d_{50}]$. The dimensionless bed load transport rate is traditionally correlated with the dimensionless grain resistance. Figure A-9 (a) showed the relation of $q_b^*$ versus $\tau_g^*$, apparently a poor correlation. Then, the correlation between $q_b^*$ versus the total resistance, $\tau_t^*$ was plotted in Figure A-9 (b), apparently is still very poor correlation. This means that the bed load transport rate in vegetated channel should be correlated with other variables.

**Variation of Bed Load Transport with Flow Parameter**

The dimensionless flow parameter, $\eta$, has incorporated the vegetation concentration effect into flow properties. Since bed load transport rate is dependent on the vegetation concentration, we plotted the variation of $q_b^*$ versus $\eta$ in Figure A-10. Regression analysis using the available datasets yielded the correlation coefficient of $R^2=0.78$. The empirical relation was formulated from the curve fitting as:

$$q_b^* = 3.763 \eta^{2.206} \quad (10)$$
Equation (10) indicates that the bed load transport rate decreases with the increasing of vegetation concentration. This relation is consistent with previous research observations (e.g. Abt et al. 1994, Nepf 1999, Cotton et al. 2006) that the sediment transport is reduced in vegetated channel because of the additional drag exerted by the vegetation. However, some other researchers observed the opposite trend of sediment transport due to the effect of vegetation on turbulence characteristics. For sparse vegetation (low $\phi$-value), individual vegetation behaves independently, the influence of vegetation concentration on bed load transport is negligible. As vegetation concentration increases, bed load transport rate will decrease due to the drag force induced by vegetation stems that reduces the resistance acting on bed surface. However, as vegetation becomes more dense, turbulence intensity will continue to increase, and more sediment will be entrained from bed surface. An increase of suspended load was observed by some researchers (Baptist 2003). However, the vegetation stem generated turbulence does not affect bed load transport, so that the bed load transport rate will remain unchanged. Eq. (10) is valid when the vegetation concentration changes from low to high and bed load transport is dominant.

**Conclusions**

A series of laboratory experiments were conducted in an open channel flume to study bed form resistance and bed load transport in vegetated mobile bed channel. An alternative approach based on the ratio of the average pore velocity, $V_v$, and the stem diameter is used to calculate the grain resistance. The bed form evolves from sand dunes to structured scour holes around the vegetation stems overlapped on ripples or dunes as vegetation concentration increases. The height of bed form depends on the vegetation concentration, which determines whether ripple/dune or scour holes are dominant on bed
surface. A new iterative method was derived to calculate the bed form resistance. For sparsely vegetated flows, the bed form height and resistance decrease rapidly as the vegetation concentration is increased, and they decreased gradually when the vegetation concentration is high. In our experiments, sand dunes started to appear when the vegetation was sparse, and their sizes were increased as the flow velocity was increased. Empirical relations were also formulated to calculate the bed form resistance and bed load transport rate using a newly defined flow parameter that incorporates the vegetation concentration. All empirical relations were verified by experimental data from this and other studies.
Notation

The following symbols are used in this paper:

\( a \) = vegetation frontal area per unit volume (m\(^{-1}\))

\( aH \) = vegetation roughness density (-)

\( A_{bed} \) = bed surface area (m\(^2\))

\( b \) = channel width (m)

\( C_D \) = drag coefficient for a cylindrical emergent stem

\( C_D' \) = drag coefficient for the pseudo fluid model

\( d \) = vegetation stem diameter (mm)

\( d_{16}, d_{84} \) = sizes for which 16 % and 84 % of the sediment are finer than \( d_{16} \) and \( d_{84} \) respectively (mm)

\( d_{50} \) = median sediment size (mm)

\( F_D \) = vegetation drag force (N)

\( f \) = Darcy-Weisbach friction coefficient due to vegetation and bed resistances

\( f_b \) = bed Darcy-Weisbach friction coefficient = \( f_g + f_{bf} \)

\( f_g, f_{bf} \) = grain and bed form Darcy-Weisbach friction coefficients respectively

\( Fr \) = Froude number

\( g \) = gravity acceleration (m/s\(^2\))

\( G_s \) = specific gravity of the sediment

\( H \) = flow depth (m)

\( N \) = number of stems per unit bed area (m\(^2\))

\( n \) = total number of bed elevation points
\( Q \) = flow rate \((m^3/s)\)

\( q_b \) = bed load transport rate \((m^3/s)\)

\( q_b^* \) = non-dimensional bed load transport

\( R_e \) = Reynolds number for the pseudo fluid model

\( R_H \) = Reynolds number based on flow depth

\( r \) = total hydraulic radius that taking into account the vegetation and bed resistances \((m)\)

\( r_v \) and \( r_{vm} \) = vegetation-related, and modified vegetation-related hydraulic radii respectively \((m)\)

\( S \) = friction slope (-)

\( S_s \) = vegetation stem spacing \((mm)\)

\( V_v \) = mean pore velocity \((m/s)\)

\( X, Y, and Z \) = position of the bed points (points clouds) in space and distance (depth) \((m)\)

\( Z_i \) = bed elevation at any point \(i\) \((m)\)

\( \bar{Z} \) = mean bed elevation of original bed surface \((m)\)

\( \Delta Z \) = bed form height \((mm)\)

\( \Delta Z_{avg} \) = average of the bed form height for each \(\phi\) value \((mm)\)

\( \phi \) = vegetation concentration (-)

\( \gamma \) = specific weight of water \((N/m^3)\)

\( \mu \) = water dynamic viscosity \((N \cdot s/m^2)\)

\( \rho, \rho_s \) = water and sediment density respectively \((kg/m^3)\)

\( \sigma_s \) = standard deviation of sediment mixture
\[ \tau_b = \text{bed resistance (N/m}^2\text{)} = \tau_g + \tau_{bf} \]

\[ \tau_g, \tau_{bf} = \text{grain and bed form resistances respectively (N/m}^2\text{)} \]

\[ \tau_{bf}^*, \tau_g^*, \text{ and } \tau^* = \text{non-dimensional bed form, grain, and total resistances respectively} \]

\[ \forall = \text{volume of water (m}^3\text{)} \]
## Tables

Table A-1. Experimental runs

<table>
<thead>
<tr>
<th>Run</th>
<th>$d$ (mm)</th>
<th>$d_{50}$ (mm)</th>
<th>Stem spacing ($S_i$) (mm)</th>
<th>$N$</th>
<th>$\phi$ (%)</th>
<th>$S$ (%)</th>
<th>$H$ (cm)</th>
<th>$Q \times 10^3$ (m$^3$/s)</th>
<th>$q_b \times 10^6$ (m$^2$/s)</th>
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Table A-2. Experimental runs processing data

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<th>$V_r$ (cm/s)</th>
<th>$C_D$</th>
<th>$\tau_{bf}$ (N/m$^2$)</th>
<th>$\Delta Z$ (mm)</th>
<th>$F_r$</th>
<th>$R_H$</th>
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Table A-3. Ranges of literature test data considered

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<th>Investigator</th>
<th>$d$ (mm)</th>
<th>$d_{so}$ (mm)</th>
<th>$\phi$ (%)</th>
<th>$S$ (%)</th>
<th>$H$ (cm)</th>
<th>$V_r$ (cm/s)</th>
<th>$\tau_b$ (N/m$^2$)</th>
<th>$F_r$</th>
<th>$q_b \times 10^6$ (m$^2$/s)</th>
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</thead>
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<tr>
<td>Kothyari et al. (2009a)</td>
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<td>0.55 to 5.9</td>
<td>0.2 to 1.2</td>
<td>1.7 to 20.8</td>
<td>2.78 to 6.08</td>
<td>33.6 to 94.2</td>
<td>1.70 to 59.43</td>
<td>0.44 to 1.77</td>
<td>0.5 to 8121</td>
</tr>
<tr>
<td>Jordanova &amp; James (2003)</td>
<td>5.0</td>
<td>0.45</td>
<td>3.14</td>
<td>1.18 to 1.84</td>
<td>2.05 to 11.1</td>
<td>15.1 to 18</td>
<td>0.51 to 1.32</td>
<td>0.16 to 0.37</td>
<td>1.89 to 6.94</td>
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</table>
Figures

Figure A-1. Schematic drawing for (a) open bed formation, (b) closed bed formation

Figure A-2. Flume set-up
Figure A-3. Vegetation stems arrangement

Figure A-4. Kinect Z-values, (a) with bed surface slope, (b) leveling bed surface
Figure A-5. Bed surface elevation contours (a) run #7 \( \phi = 1.4\% \), (b) run #18 \( \phi = 0.5\% \)
Figure A-6. Variation of $\Delta Z_{\text{avg}}$ versus $\phi$

Figure A-7. Variation of $\tau_{bf}^*$ versus $\eta$
Figure A-8. Variation of $\tau_{bf}$ versus $\phi$
Figure A-9. (a) Variation of $q_b^*$ versus $\tau_g^*$, (b) Variation of $q_b^*$ versus $\tau_i^*$.
Figure A-10. Variation of $q_b^*$ versus $\eta$

Our Data
Kothyari et al. (2009)
Appendix B: Simulation of Tidal Flow through a Vegetated Marsh Area Using Delft3D-FLOW Model

Khalid Al-Asadi¹, Jennifer G. Duan²

Abstract

This paper reported the simulation of tidal flow in an estuarine marsh area using the Delft3D-FLOW open source program. The study area was divided into several sub-areas depending on the existence of channels, overbanks, and vegetation height. Two approaches were used to approximate the vegetation roughness: a constant Manning’s $n$ coefficient and a time-varying $n$ or Chezy’s $C$ coefficient for each sub-area. To quantify the time varying roughness coefficients for each sub-area, four empirical equations for calculating $n$ values are incorporated in the Delft3D-FLOW program in addition to two options offered by this program to calculate $C$ values. Water surface elevations (WSE) at eleven locations within the study area are calculated and compared with the corresponding field observed data measured by stream gauges. It is concluded that the use of time varying roughness coefficient gives better results than those using constant values. Among the selected empirical equations to calculate the vegetation roughness, the equations that account for the effect of the degree of submergence and the vegetation frontal area give the closet matches with the field observed data. The vegetation frontal area for freshwater marsh grass dominated by Panicum hemitomon type ranges from 8.160 to 11.220 m$^{-1}$.

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Introduction

Vegetation alters the velocity profile and flow resistance in open channel flow through different scales ranging from individual branches and blades on a single plant, to a community of plants in a patch or canopy, to a channel reach (Nepf 2012). Vegetation resistance in a channel reach is determined primarily by the vegetation coverage, or the blockage factor (Green 2005a). This factor is defined as the fraction of channel cross-section or surface area blocked by vegetation, or the fraction of channel volume occupied by vegetation (Green 2005a). It’s worth mentioning that Fisher (1992) first examined the surface area and volumetric blockage factors, and recommended the surface area blockage factor for calculating Manning’s $n$ coefficient because it’s easier to be measured. Recently, Green (2005a), Nikora et al. (2008), and Luhar and Nepf (2013) used the cross-sectional blockage factor to calculate $n$ value. Since the cross-sectional blockage factor is a better representation of turbulence wake in vegetated zones, it’s more favored in literature than the surface area blockage factor.

Early researchers (e.g., Ree and Palmer 1949, Cowan 1956, Chow 1959, Petryk and Bosmaijan 1975) formulated various empirical relations for Manning’s roughness coefficient by correlating $n$ value with flow and vegetation properties. However, the applications of those relations are limited by vegetation types and experimental flow conditions. To avoid the dependence of roughness coefficient on experimental conditions, Klopstra et al. (1997) derived an analytical model to calculate the Chezy’s $C$ coefficient for submerged vegetation. They found that the $C$ value is a function of vegetation height and density, stem diameter, drag coefficient, and the characteristic length scale of large scale turbulence. Wu et al. (1999) investigated the variation of vegetative roughness
coefficient in emergent and submerged flow conditions and developed a model for the drag coefficient of vegetal element, and then converted it into Manning’s $n$ value. Recently, Abood et al. (2006) analyzed the effects of two types of vegetation, Napier grass and Cattail grass, on the Manning roughness coefficient in an open channel, and then developed a relationship between vegetation characteristics (density, degree of submergence and distribution) and Manning’s $n$. They found a linear relationship between Manning's $n$ and grass density for both vegetation types in both submerged and emergent flow conditions.

In engineering practice, the SED2D model, a two dimensional vertically averaged sediment transport model developed by Engineering Research and Development Center (ERDC) of the US Army Corps of Engineers, adopted an empirical formula to calculate $n$ value for vegetated channels. The Manning’s $n$ value in SED2D model is a function of the maximum $n$ value for unvegetated water, vegetation height, maximum $n$ value of vegetated water, and flow depth (WexTech System, Inc. 2011).

When Acoustic Doppler Velocitimeter (ADV) and Laser Doppler Velocitimeter (LDV) are available to measure turbulence around vegetation, researchers (e.g., Nepf et al. 1997, Nepf 1999) found the production of turbulence near the bed region is affected by bed shear stress, while far away from that region, the stem wake turbulence dominated (Nepf et al. 1997). Vortex generation by stem wake extracts energy from the mean flow, and feeds it into the turbulence kinetic energy (Nepf 1999). Consequently, the turbulence intensity initially increases with the increasing stem density but eventually decreases as the density reaches a given value (Nepf et al. 1997).

However, up to date, there is no consensus on which method is the most feasible for calculating Manning’s $n$ roughness in freshwater marsh areas. Vegetation induced
resistance is highly variable in the field due to the complex vegetation types, density, and height. To quantify those varieties, this study used the product of frontal width and vegetation density, defined as the vegetation blockage index, symbolized as $a$, as the key factor to quantify vegetation property. Then, various methods for quantifying vegetation-induced roughness were examined using field observed water surface elevations.

**Study Area Location and Characteristics**

The study area is Davis Pond located on the west bank of the Mississippi River, two miles from Luling City in the Southwest of New Orleans, Louisiana (Figure B-1). Natural and man-made levees have reduced freshwater, sediment, and nutrient inputs from the Mississippi River to the surrounding estuarine-marsh areas (McAlpin *et al*. 2008). This causes an intrusion of saltwater that threatens the existing freshwater habitat. To reduce the effects caused by the saltwater intrusion, freshwater needs to be diverted from the Mississippi River into the adjacent estuarine areas. To achieve this purpose, the Davis Pond freshwater diversion project was constructed. When the project began to operate, a problem of high water level was recognized throughout the study area. Water level was raised much bigger than anticipated. McAlpin *et al*. (2008) simulated the study area using the RMA2 model, a depth-averaged 2D model developed by ERDC in the US Army Corps of Engineers, to find a solution to lower the water levels. McAplin *et al*. (2008) validated their model by comparing the simulated WSE with the observations, and then proposed 12 alternatives to reduce the water level throughout the study area.

The study area is enclosed by guided levees on the North, East, and West, and by a gabion rock weir on the South edge, along the shoreline of Lake Cataouatche. The inlet canal delivers freshwater to the pond and then drains into Lake Cataouatche. The area is
covered with a significant amount of floating freshwater marsh of typical vegetation, such as *Panicum hemitomon*, *Sagittaria Lancifolia*, *Eleocharis Baldwinii*, or *Cladium Mariscus ssp. Jamaiscence* (Sasser et al. 2008). O’Neil (1949) found that *Panicum hemitomon* is the dominant vegetation for freshwater marshes in the Mississippi River delta. The stem height for the mature *Panicum hemitomon* is about 0.762 m (USDA http://plants.usda.gov) and its diameter ranges from 1 to 6 mm (Turner 1994). The leaf blade is 20 to 30 cm long and 1.25 cm wide, rough on the upper side, smooth on the lower side, and grows along its stem (Leithead et al. 1971) (Figure B-2). For maidencane (*Panicum hemitomon*) marshes, the averaged stem density is 255 stems per square meter; for deep marshes, stem densities are only 18 per square meter; and in mixed shallow marshes (*Eleocharis elongata*, *Sagittaria lancifolia*, *Panicum hemitomon*, and *Pontederia cordata*) its average density is 286 stems per meter square (Turner 1996). The Davis Pond Marsh is apparently a maidencane (*Panicum hemitomon*) marsh, therefore the averaged stem density is 255 stem/m². A field data showed that Manning’s $n$ values in a subtropical marsh are varied from 0.26 to 0.55 for water hyacinth, and from 0.16 to 0.43 for mixed vegetation with flow depth ranging from 40 to 65 cm (Shih and Rahi 1981). The Manning’s roughness is inversely calculated by using the measured flow depth and velocity in the vegetated area.

**Delft3D-FLOW Model**

The study area is simulated using Delft3D-FLOW open source program (http://oss.deltares.nl/web/delft3d/source-code). Delft3D-FLOW is capable of simulating three dimensional (3D) unsteady incompressible flow and transport phenomena resulting from tidal and/or meteorological forcing (Deltares 2011). It solves the Reynolds Averaged Navier-Stokes (RANS) equations, under shallow water (hydrostatic pressure) assumption,
on a structured staggered curvilinear grid using a finite-difference scheme (Stelling and van Kester 1994). The governing equations are solved with an Alternating Direction Implicit (ADI) technique (Stelling 1984). Delft3D-FLOW offers two different vertical grid systems: $\sigma$-grid and $Z$-grid, and four turbulence closure models: constant eddy viscosity coefficient, algebraic eddy viscosity model, $k-L$ model, and $k-\varepsilon$ model.

Delft3D-FLOW has a facility to define the bed and flow resistance on each sub-grid using a function called Trachytopes (Deltares 2011). Three classes are available in the Trachytopes function: area, line, and point class. The area class has three types: the first type is a constant coefficient for bed roughness, such as White Colebrook, Chezy, and Manning’s coefficients, the second type accounts for the form resistance resulting from sand dunes, and the third type is for the roughness coefficient in vegetated channels. In a simulation run, the roughness coefficient often remains a constant with time if choosing the first type of area class, while for the second type, it is determined by dune height, and the third by vegetation properties. The line class of Trachytopes function can be used to approximate flow resistance for elements with hedge, bridge piers, and other structures. The point class can be used to represent a set of point flow resistance elements, such as groups of individual tree or small plant.

The vegetation effects have been incorporated in Delft3D-FLOW by applying an adjusted bed roughness, such as using Klopstra et al. (1997) equation, noting that an implementation based on Klopstra et al. (1996) has been added to the Klopstra et al. (1997) equation to calculate the $C$ value for emergent vegetation (Deltares 2011) (Table B-2), or adding an artificial term to account for extra momentum loss due to vegetation using Baptist (2005) equation (Table B-2). Also, the momentum and $k-\varepsilon$ turbulent closure model
equations in Delft3D-FLOW have been modified by including the vegetation induced momentum loss as well as the influences of vegetation on turbulence generation and dissipation.

Temmerman et al. (2005) studied the impact of vegetation on flow hydrodynamic and sedimentation processes in a tidal creek within the Paulina salt marsh in the Scheldt estuary, located at the Southwest of Netherland, using the modified momentum and $k-\varepsilon$ equations in Delft3D-FLOW. The vegetation types in the marsh are *Puccinellia maritima*, *Limonium vulgare*, *Halimione portulacoides*, and *Spartina anglica*. They divided the marsh area into several subareas, and each one has a combination of four dominated vegetation types. The vegetation blockage index, $a$ value for each subarea, was calculated by measuring the density and frontal width for each vegetation type. The simulated flow velocities at a location within the vegetated area during one tidal inundation cycle showed good agreements with the observations for both flood rising and receding stages. Recently, Horstman et al. (2013) used Delft3D-FLOW for modeling the tidal dynamics in the mangrove forest in Trang Province, Thailand. The mangrove extends from a mountain cliff, and consists of a complex network of incised branching streams. *Rhizophora* trees are the dominant vegetation type throughout the mangrove. The $a$ value, was ranging from 0.320 to 3.860 m$^{-1}$. The vegetation effect was accounted for by using a constant $n$ value for the whole region, and also the equation in Baptist (2005). The modified momentum and $k-\varepsilon$ equations with 10 $\sigma$-layers in the vertical plane was also used. The simulated flow velocities, suspended sediment concentration, and the depth of deposited sediment at two locations within the mangrove, one in the main channel and the other in the forest, were compared with the observed data. Results by using a constant $n$ value for vegetation
showed higher flow velocities within the channel, and lower velocities in the forest. Both two cases are in salt water marshes where tidal flow is dominant, and vegetation types are distinct from those in fresh water marshes. None of those cases have compared the model’s performances with results using other methods not embedded in Delft3D to improve their modelling results.

The objective of this study is to evaluate the accuracy of different methods for calculating vegetation induced roughness. Those methods are not limited to those programmed in Delft3D model, but all the methods available in literature. Therefore, the first and third types of the area class of the Trachytopes function in Delft3D model are adopted for incorporating other methods for calculating vegetation-induced roughness. The orthogonal curvilinear coordinates system with the σ-grid option is adopted. The $k-\varepsilon$ turbulent closure model option is chosen to determine the coefficient of eddy viscosity. The sensitivity of modeling results to the selection of vertical grid and key parameters (e.g., $a$ value) were analyzed.

**Modeling Vegetation Impact**

This study evaluated two common approaches to approximate vegetation roughness: one used a constant $n$ value, and the other used a time-varying $n$ or Chezy’s $C$ coefficients for each sub-area. The study area was divided into several sub-areas, shown in Figure B-3, depending on the existence of channels, overbanks, and vegetation height, according to a previous study (McAlpin et al. 2008). Table B-1 summarize the $n$ values used in the first approach, in which $n_1$ and $n_2$ are the maximum values of Manning’s roughness coefficient for unvegetated and vegetated sub-areas, respectively (McAlpin et al. 2008). Two options are used in the second approach. The equations developed by
Klopstra et al. (1997) and Baptist (2005) (Table B-2), which have already been incorporated in the Delft3D-FLOW program under the Trachytopes function, are used in the first option to calculate the time varying $C$ value, in which an individual grass or vegetation is treated as a cylinder of frontal width equal to its diameter. In this study, the number and width of the leaves along with the stem diameter are used to calculate the average frontal width of an individual grass. In the second option, the rest four equations, listed in Table B-2, are programmed in the Delft3D-FLOW program under the Trachytopes function to calculate the time varying $n$ value. In this study, because of the lack of detailed vegetation distribution map, we assumed each sub-area is entirely filled with vegetation of uniform height. This assumption is justified because any measure of hydraulic resistance at the channel reach scale must, by definition, be an integrated quantity (Luhar and Nepf 2013). So, the volumetric and cross-sectional blockage factors are equal to the ratio of vegetation height to flow depth.

**Model Configurations**

**Computational Mesh**

The computational grid of the study area was constructed using the available geometric and bed elevations data provided by the US Army Corps of Engineers (USACE). The computational grid is a structured grid with $M=299$, $N=53$, and $K=15$ (Figure B-4), where $M$ and $N$ are the numbers of grid points on the horizontal plane in the direction of main flow and normal to the main flow, respectively, and $K$ is the number of $\sigma$-layers in the vertical plane. A finer mesh is used in the inlet canal to capture the detailed bathymetry because of rapidly varied bed elevation in this region. The maximum grid sizes in $M$ and $N$ directions are 177.84 m and 462.5 m, respectively, and the minimum grid sizes in $M$ and
N directions are 7.13 m and 19.19 m, respectively. The grid aspect ratio (N-grid size/M-grid size) ranges from 1.0 to 20.55 (Figure B-5). The regions of high aspect ratio are located along the border of the study area, where flow is predominately along the N-direction. In the vertical plane, because the velocity gradient close to the bed is very high, the spacing of vertical layers is smallest near the bottom, and gradually increases toward the free surface (Figure B-6). The bathymetry for the entire domain shown in Figure B-7 was surveyed by the USACE based on the North American Vertical Datum of 1988 (NAVD88). Water depth has reached 6.5 m in the inlet canal, and 2.5 m in the other parts during the flood period between 1:00 pm (CDT) on November 30 to 7:00 pm (CDT) on December 3, 2003.

**Boundary Conditions**

The simulation period is from 1:00 p.m. (CDT) on November 25, 2003, to 9:00 a.m. (CDT) on January 10, 2004. The inflow data measured by U.S. Geological Survey (USGS) gauge at Highway 90, shown in Figure B-1, were used as the upstream boundary condition. The tidal heights measured at the Lake Cataouatche USGS gauge (Figure B-1) were used as the downstream boundary condition. The inflow and tidal stage hydrographs at Highway 90 and Lake Cataouatche USGS gauges, respectively, are shown in Figure B-8. Slip boundary conditions were used on the north side except for the inlet, east, and west levees. At the free surface, shear stress is zero, and at the channel bottom, flow velocity is set as zero.
Results

Eleven stream gauges are available throughout the study area, shown in Figure B-1. Figure B-9 shows the measured (observed) water surface elevation (WSE) at all gauges during the simulation period. A time step of one minute was used for both approaches to obtain numerically stable simulations.

McAlpin et al. (2008) applied the vegetation resistance equation in SED2D model, shown in Table B-2, for calculating the vegetation roughness. The parameters for vegetation induced roughness in the SED2D model equation are summarized in Table B-3 (McAlpin et al. 2008). For the Luhar and Nepf (2013), Klopstra et al. (1997) and Baptist (2005) equations, the average frontal width of an individual grass is calculated as 2.25 times the leaf width (approximately equal to 1.25 cm) plus the average stem diameter ($d = 0.4$ cm). Since the calculated frontal width for individual grass is 3.2 cm, which is equal to $8d$, this study assumes $8d$ is the vegetation frontal width. Because the $a$ value is equal to the product of the vegetation density and the frontal width. So, the larger the $a$ value, the larger the vegetation induced resistance. In a typical Panicum hemitomon grass dominated freshwater marsh in Louisiana, the vegetation density is 255 stem/m$^2$ and the average stem diameter is 0.4 cm, then the $a$-value is 8.160 m$^{-1}$. This value is within the range recommended by Luhar et al. (2008), Lightbody and Nepf (2006), and Leonard and Luther (1995), who found the $a$-value for the marsh grasses ranges from 1 to 10 m$^{-1}$. The drag coefficient, $C_d$, is taken as 1.0; and the coefficient $C_*$, the shear stress parameter at the interface between vegetated and unvegetated regions, is equal to 0.10 (Luhar and Nepf 2013). The comparison between the simulated and the corresponding observed for all gauges using two approaches are shown in Figures B-10 and B-11, respectively.
In order to identify which approach or equation gives the best match of the observed, the root mean square error (RMSE) and the Nash Sutcliffe efficiency (NSE) coefficient were used. The following equations were used to calculate RMSE and NSE:

$$\text{RMSE} = \sqrt{\frac{\sum (\text{Simulated value} - \text{Observed value})^2}{\sum \text{number of total observed points}}}$$  \hfill (1)

$$\text{NSE} = 1 - \frac{\sum (\text{Simulated value} - \text{Observed value})^2}{\sum (\text{Observed value} - \text{Observed value})^2} \quad (-\infty < \text{NSE} < 1.0)$$  \hfill (2)

The RMSE and NSE values for the two approaches were calculated for all gauges, and their ranges were shown in Figures B-12 and B-13, respectively. From these figures, one can find that the RMSEs using the equation in SED2D model and those using Luhar and Nepf (2013), Klopstra et al. (1997), and Baptist (2005) equations are relatively small. Also their NSEs are closer to 1.0, which means that the mean square errors generated by these equations are much smaller than the variance of the observed data, and the simulated results are more accurate than the results from other equations.

For the first approach, Figure B-12 showed that the range of RMSE for the simulated WSE using the constant Manning roughness coefficient for unvegetated channels \((n_1)\) is smaller than the results using the Manning’s roughness for vegetated channels \((n_2)\). The NSE value is also closer to 1.0 for the results using \(n_1\) (Figure B-13). It can be seen from Figure B-10 that the WSE results are underestimated when using the constant \(n_1\), while they are overestimated when using the constant \(n_2\). Although the results using \(n_1\) is slightly better than the ones using \(n_2\), none of them matched the results well at all the gauges. Therefore, several \(n\) values between \(n_1\) and \(n_2\) values were selected to re-run the model. However, for each value, the WSE results matched the observation data at
one gauge in one time interval but not in the others. And, the WSE results matched the observation data better at some gauges but got worse at the rest. Regardless of the $n$ value being used, there is no general improvements of modeling results. This excludes the feasibility of using a constant roughness for simulating flow hydrodynamics in a freshwater marsh.

The second approach treats flow roughness as a temporal and spatial variable depending on the local flow and vegetation characteristics. The ranges of RMSE using Fisher (1992) and Reed et al. (1995) equations are larger (Figure B-12) than the results from other equations. The corresponding NSE values using those two equations are also farther from 1.0 than the rest. The range of RMSE using Luhar and Nepf (2013), Klopstra et al. (1997) and Baptist (2005) equations are the smallest, and the NSE values are also the closest to 1.0 (Figures B-12 and B-13). This attributes to the fact that Fisher (1992) and Reed et al. (1995) equations didn’t consider the degree of submergence, which differentiates the impacts of submerged and emerged vegetation. At low flow depth, the vegetation height can be comparable to flow depth, or even emergent. In this condition, vegetation induced roughness is dominant. However, as flow depth increases, vegetation becomes submerged and the influence of vegetation on flow resistance is diminishing (Nepf 2012). When the flow depth is orders of magnitude larger than the vegetation height, the vegetation induced resistance will converge to a constant (Augustijn et al. 2008). Therefore, this study recommends the use of variable Manning roughness value to account for vegetation induced roughness. The changes of the $n$ values for the runs by using Luhar and Nepf (2013), Klopstra et al. (1997) and Baptist (2005) equations at gauge 21 are shown in Figure B-14. Additionally, these three equation also incorporated the effect of vegetation
blockage index, $a$ value. The sensitivity of modeling results to the $a$ value will be discussed in the next section. Nevertheless, the simulation results indicated that these three equations are the best for simulating the spatially and temporally varied vegetation resistance.

A PC with Intel (R) Xeon (R) CPU X5550 (2 processors) and 32 GB RAM was used for the simulation. The CPU times using the first approach were 74,218.84s and 73,815.20s for the simulation using constant $n_1$ and $n_2$, respectively, whereas they are 72,790.89s and 77,252.20s using Reed et al. (1995) and Klopstra et al. (1997) equations, respectively.

**Sensitivity Analysis**

**Vegetation Blockage Index ($a$ Value)**

Luhar and Nepf (2013), Klopstra et al. (1997) and Baptist (2005) equations gave the best WSE matches of the observed data. However, the results can be sensitive to the key parameter, the $a$ value. To find the sensitivity of the results using these three equations to the variation of $a$ values, three values of $a$ were selected based on three values of the average frontal width for the individual grass, which are equal to $d$, $11d$, and $22d$. Because of the assumption of constant vegetation density (255 stem/m$^2$) and the stem diameter ($d = 0.4$ cm), the $a$ values are $1.020$ m$^{-1}$, $11.220$ m$^{-1}$, and $22.440$ m$^{-1}$, respectively.

The results of the simulated WSE using those three $a$ values were compared with the observed WSE for all gauges, and showed in Figures B-15, B-16, and B-17. When $a$ is equal to $1.020$ m$^{-1}$, the simulated WSE results were underestimated at all gauges for all three equations (Figure B-15), while they were overestimated, especially for Klopstra et al. (1997) equation, when $a$ is equal to $22.440$ m$^{-1}$ (Figure B-17). The simulated WSE results using $a = 11.220$ m$^{-1}$ approximately matched the observed WSE (Figure B-16). The
ranges and averages of the RMSE and NSE for all three equations by using different $a$ values are shown in Figures B-18 and B-19, respectively. One can find, for $a = 1.020 \text{ m}^{-1}$, the averages of RMSE are the largest, and the NSE values are the most away from 1.0, for all three equations. For $a = 11.220 \text{ m}^{-1}$, the averages of RMSE became smaller, and the NSE values got more close to 1.0. For $a = 11.220 \text{ m}^{-1}$ and $22.440 \text{ m}^{-1}$, the averages of RMSE using the Klopstra et al. (1997) equation are the largest among three equations, and the NSE values are more away from 1.0 than the other two equations. This means that this equation is high sensitive to the variation of $a$. Apparently, when $a$ is equal to $1.020 \text{ m}^{-1}$, none of the three equations gave accurate results of WSE. This means that the stem size (diameter) alone is not sufficient for calculating the frontal width for the individual grass, and the number and width of leaves must be taken into consideration. It can be seen from Figures B-12, B-13, B-18, and B-19, the smallest values of RMSE and the closest NSE values to 1.0, for the three equations, were obtained when $a$ equal to $8.160 \text{ m}^{-1}$ and $11.220 \text{ m}^{-1}$. This confirms that the best range for the average frontal width of an individual grass is between $8d$ and $11d$.

**Vertical Grid Selection**

As stated earlier, Delft3D-FLOW has two different vertical grid systems: $\sigma$-grid and $Z$-grid. The RANS equations under hydrostatic pressure assumption were solved for both $\sigma$ and $Z$-grids. An extension for solving the non-hydrostatic pressure has been added to $Z$-grid. All the computational runs conducted until now were using the $\sigma$-grid assuming hydrostatic pressure. Since the $\sigma$-grid forces the convective transport along channel bottom, it may allow false fluxes between the main channel and floodplain when their elevation difference prohibits such transport. Therefore, the sensitivity of the results to the vertical
grid selection was performed in this section using Luhar and Nepf (2013) equation. Additional computational runs are conducted using the same computational grid but 15 Z-layers in the vertical plane assuming both hydrostatic and non-hydrostatic pressure. A time step of 0.1 minute was used to obtain numerically stable solutions. The CPU times for the runs using the hydrostatic and non-hydrostatic pressure assumptions were 140,968.51s and 211,734.70s, respectively. The simulated results of WSE at all the gauges were compared with those using σ–grid and the observations in Figure B-20. The results using Z-grid with the non-hydrostatic pressure assumption is better than those using the hydrostatic pressure assumption. But, these results still deviate far away from the observations, and those using σ–grid. Figure B-21 showed the ranges of RMSE and NSE for all gauges using the σ and Z-grids, which indicated that the RMSE range using σ–grid are the least, and the NSE values are closer to 1.0 than both results using the Z-grid. The CPU time for the simulation using σ–grid is 76,613.32s, much less than those using the Z-grid. One major reason is because the σ–grid allows larger time steps (e.g., 1 min) than the Z-grid. Therefore, the Z-grid option did not yield more accurate results but more CPU times than the σ–grid. This study recommends the use of σ–grid for shallow water marsh application.

Conclusions

This study evaluated the accuracy of various methods for calculating vegetation induced resistance in freshwater marsh. The Delft3D-FLOW model is used for simulating hydrodynamic flow field. Besides two equations embedded in Delft3D model, four other empirical equations were programmed in the original Delft3D-FLOW program. The simulated results of WSE at specific locations were compared with the corresponding observed data. Results showed that vegetation induced roughness is a spatial and temporal
variable that changes with submergence and vegetation blockage index. If treating flow roughness through each sub-area as constants, the results of WSE deviated considerably from the measurements. But, if using the equations by Luhar and Nepf (2013), Klopstra et al. (1997) and Baptist (2005), reasonable matches with the observed WSE were obtained, because they successfully incorporate the effect of the degree of submergence and the vegetation blockage index, $a$, into the roughness equation. The best results of WSE were obtained when used a constant vegetation density for the Panicum hemitomon vegetation type, and resulted in $a$ values ranging from 8.160 to 11.220 m$^{-1}$. 
Notation

The following symbols are used in this paper:

\( a \) = vegetation frontal area per unit volume (m\(^{-1}\));

\( B^V, B^X \) = volumetric and cross-sectional blockage factors, respectively (-);

\( C \) = total Chezy’s coefficient (m\(^{1/2}\)/s);

\( C_b \) = Chezy’s coefficient for the unvegetated channel (m\(^{1/2}\)/s);

\( C_D \) = drag coefficient (-);

\( C_s \) = shear stress parameter at the interface between vegetated and unvegetated flow regions (-);

\( g \) = gravity acceleration (m/s\(^2\));

\( H \) = flow depth (m);

\( h_v \) = vegetation height (m);

\( n \) = total Manning’s coefficient (s/m\(^{1/3}\));

\( n_{o_1} = n_1 \) = maximum Manning’s coefficient for unvegetated channels (s/m\(^{1/3}\));

\( n_v = n_2 \) = maximum Manning’s coefficient for vegetated channels (s/m\(^{1/3}\));

\( u_v \) = velocity within the vegetation (m/s);

\( u \) = horizontal flow velocity (m/s);

\( z_0 \) = length scale for the bed roughness of the surface layer (m);

\( \alpha \) = coefficient depends on flow depth (-);

\( \beta \) = resistance factor (s \cdot m\(^{1/6}\))

\begin{align*}
&= 0.4 \text{ (for sparse, low density vegetation } H > 0.3 \text{ m)}; \\
&= 1.6 \text{ (for moderately dense vegetation } H = 0.3 \text{ m)}; \\
&= 6.4 \text{ (for very dense vegetation } H < 0.3 \text{ m)};
\end{align*}
\( \eta \) = length scale of large scale turbulence (m);

\( K \) = von Karman constant = 0.41 (-);

\( \lambda \) = parameter representing the flow resistance due to vegetation (m\(^{-1}\)); and

\( \rho \) = water density (kg/m\(^3\)).
Tables

Table B-1. Manning’s $n$ values for each sub-area used for the first approach

<table>
<thead>
<tr>
<th>Sub-area</th>
<th>$n_1$</th>
<th>$n_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.06</td>
<td>0.10</td>
</tr>
<tr>
<td>2</td>
<td>0.06</td>
<td>0.40</td>
</tr>
<tr>
<td>3</td>
<td>0.06</td>
<td>0.40</td>
</tr>
<tr>
<td>4</td>
<td>0.12</td>
<td>0.82</td>
</tr>
<tr>
<td>5</td>
<td>0.12</td>
<td>0.82</td>
</tr>
<tr>
<td>6</td>
<td>0.06</td>
<td>0.40</td>
</tr>
<tr>
<td>7</td>
<td>0.12</td>
<td>0.82</td>
</tr>
</tbody>
</table>

Table B-2. List of the equations used to calculate $n$ and $C$ values for the second approach

<table>
<thead>
<tr>
<th>Authors/Reference</th>
<th>Equations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fisher (1992)</td>
<td>$n = n_o + 0.0239 \left( \frac{B^V}{VR} \right)$</td>
</tr>
<tr>
<td>Reed et al. (1995)</td>
<td>$n = \beta / \sqrt{H}$</td>
</tr>
<tr>
<td>SED2D Model</td>
<td>$n = \frac{n_o}{H^\alpha} (0.3048)^\nu + n_v \cdot e^{(-H/h_v)}$</td>
</tr>
</tbody>
</table>
| Luhar and Nepf (2013) | For $H/h_v \leq 1$, $n = \left( \frac{C_D a}{2} \right)^{1/2} H^{2/3} g^{-1/2}$
                         For $H/h_v > 1$, $n = \left[ \left( \frac{2}{C_s} \right)^{1/2} \left( 1 - B^x \right)^{3/2} + \left( \frac{2}{C_D a h_v} \right)^{1/2} B^x \right]^{-1} H^{1/6} g^{-1/2}$ |
For \( H/h_v \leq 1 \), 
\[
C = \frac{1}{C_D aH} + \frac{1}{2g + C_b^2}
\]

For \( H/h_v > 1 \), 
\[
C = \frac{1}{H^{3/2}} \left\{ \frac{2}{\sqrt{2A}} \left( \sqrt{C_3 e^{b\sqrt{2A}} + u_{i0}^2} - \sqrt{C_3 + u_{i0}^2} \right) + \frac{u_{i0}}{\sqrt{2A}} \ln \left( \frac{\sqrt{C_3 e^{b\sqrt{2A}} + u_{i0}^2} - \sqrt{C_3 + u_{i0}^2}}{\sqrt{C_3 e^{b\sqrt{2A}} + u_{i0}^2} + \sqrt{C_3 + u_{i0}^2}} \right) + \frac{\beta (H - (h_v - b))}{\kappa} (H - (h_v - b)) \ln \left( \frac{H - (h_v - b)}{z_0} \right) - b \ln \left( \frac{b}{z_0} \right) - (H - h_v) \right\}
\]

**Klospstra et al.** (1997)

For \( H/h_v \leq 1 \), \( C = C_b \); \( \lambda = C_D a \)

For \( H/h_v > 1 \): \( C = C_b + \frac{\sqrt{g}}{k} \ln \left( \frac{H}{h_v} \right) \sqrt{1 + \frac{C_D a h_v C_b^2}{2g}} \); \( \lambda = C_D a \frac{h_v C_b^2}{H \ C^2} \)

- For Baptist (2005) equation, a term \( -\frac{\lambda}{2}u^2 \) will be added as an extra term in the momentum equations.

- For Klospstra et al. (1997) equation:

\[
A = \frac{a C_D}{2\eta} \quad C_3 = \frac{2g(H - h_v)}{\eta \sqrt{2A (e^{b\sqrt{2A}} + e^{-b\sqrt{2A}})}} \quad b = \frac{1 + \sqrt{1 + \frac{4E_i^2 \kappa^2 (H - h_v)}}}{g} \quad E_i = \frac{\sqrt{2A C_3 e^{b\sqrt{2A}}}}{2 \sqrt{C_3 e^{b\sqrt{2A}} + u_{i0}^2}} \quad z_0 = b e^{-h_v} \quad F_i = \frac{\kappa \sqrt{C_3 e^{b\sqrt{2A}} + u_{i0}^2}}{\sqrt{g(H - (h_v - b))}} \quad \eta = \max(0.001, 0.0227 h_v^{0.7}) \quad u_{i0} = \frac{h_v}{2g + C_b^2}
\]
Table B-3. Roughness parameter values for all sub-areas used in the SED2D model equation

<table>
<thead>
<tr>
<th>Sub-area</th>
<th>$n_o$</th>
<th>$h_v$ (m)</th>
<th>$n_y$</th>
<th>$\alpha$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.06</td>
<td>0.3048</td>
<td>0.10</td>
<td>0.05</td>
</tr>
<tr>
<td>2</td>
<td>0.06</td>
<td>0.381</td>
<td>0.10</td>
<td>0.20</td>
</tr>
<tr>
<td>3</td>
<td>0.06</td>
<td>0.3048</td>
<td>0.40</td>
<td>0.20</td>
</tr>
<tr>
<td>4</td>
<td>0.12</td>
<td>0.6096</td>
<td>0.82</td>
<td>0.41</td>
</tr>
<tr>
<td>5</td>
<td>0.12</td>
<td>0.762</td>
<td>0.82</td>
<td>0.41</td>
</tr>
<tr>
<td>6</td>
<td>0.06</td>
<td>0.381</td>
<td>0.40</td>
<td>0.20</td>
</tr>
<tr>
<td>7</td>
<td>0.12</td>
<td>0.6856</td>
<td>0.82</td>
<td>0.41</td>
</tr>
</tbody>
</table>
Figures

Figure B-1. Locations of the study area, Highway 90 and lake Cataouatche USGS, and the observed data gauges

Figure B-2. *Panicum hemitomon* profile (http://www.outdooralabama.com/maidencane)
Figure B-3. Sub-area divisions

Figure B-4. Study area computation grid
Figure B-5. Grid aspect ratio contour lines

Figure B-6. Distribution of vertical layers at a section passing through the inlet canal
Figure B-7. Study area bathymetry changes

Figure B-8. Boundary conditions of inflow and tidal stage hydrographs at Highway 90 and Lake Cataouatche gauges respectively
Figure B-9. WSE at all observed data gauges
Figure B-10. Observed and simulated WSE for all gauges - approach 1
Figure B-11. Observed and simulated WSE for all gauges - approach 2
Figure B-12. Ranges of RMSE for all gauges for both approaches

Figure B-13. Ranges of NSE for all gauges for both approaches
Figure B-14. Changes of the $n$ values for the runs using Luhar and Nepf (2013), Klopstra et al. (1997) and Baptist (2005) equations at gauge 21.
Figure B-15. Observed and simulated WSE for all gauges - $a = 1.020 \text{ m}^{-1}$
Figure B-16. Observed and simulated WSE for all gauges - $a = 11.220$ m$^{-1}$
Figure B-17. Observed and simulated WSE for all gauges - $a = 22.440$ m$^{-1}$
Figure B-18. Ranges and averages of RMSE for all gauges for different $a$ values using best three equations

Figure B-19. Ranges and averages of NSE for all gauges for different $a$ values using the best three equations
Figure B-20. Observed and simulated WSE for all gauges using Luhar and Nepf (2013) equation for different vertical grid selection
Figure B-21. Ranges of RMSE and NSE for all gauges using Luhar and Nepf (2013) equation for different vertical grid selection
Appendix C: (Technical Note) Three Dimensional Hydrodynamic Simulation of Tidal Flow through a Vegetated Marsh Area

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Abstract

Simulation of tidal flow in an estuarine marsh area is challenging because of resistance from spatially and temporally varied vegetation. This study simulated the tidal flow in the Davis Pond marsh area near New Orleans, Louisiana using an open source program. To quantify the time varying roughness coefficient, four empirical equations for calculating Manning’s roughness coefficient were incorporated in the program in addition to two options offered by the program to calculate the Chezy’s coefficient and one option to use the modified momentum equations and the \( k-\varepsilon \) turbulence model. Results showed that the time varying roughness coefficient equations accounting for both the degree of submergence and the vegetation frontal area gave the closest matches with the observed data.

Author keywords: Three-dimensional modeling; Vegetation; Marsh area; Tidal flow; Delft3D.

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Introduction

The resistance to flow through vegetated areas is increased by an additional drag exerted by vegetation (Zhang et al. 2010). Vegetation resistance in a channel reach is determined primarily by vegetation coverage quantified by the blockage factor (Green 2005a). This factor is defined as the fraction of channel cross-section or surface area blocked by vegetation, or the fraction of channel volume occupied by vegetation (Green 2005a). Recently, Green (2005a), Nikora et al. (2008), and Luhar and Nepf (2013) used the cross-sectional blockage factor to calculate the Manning’s $n$ value. Early researchers (Ree and Palmer 1949, Chow 1959, Petryk and Bosmaijan 1975) found the $n$ value in vegetated channels varies with flow velocity, hydraulic radius, boundary roughness, vegetation type, density, and distribution. Field data showed the Manning’s $n$ values in marsh areas varied from 0.26 to 0.55 for water hyacinth, and from 0.16 to 0.43 for mixed vegetation with flow depth ranging from 40 to 65 cm (Shih and Rahi 1981). To avoid the dependence of roughness coefficient on experimental conditions, Klopstra et al. (1997) derived an analytical model to calculate the Chezy’s coefficient, $C$, for submerged vegetation. Modifying the $n$ value for vegetated areas is a typical engineering practice, for example, the SED2D model developed by the Engineering Research and Development Center (ERDC) of the Army Corps of Engineers (COE) adopted an empirical formula to calculate $n$ value for vegetated channels (WexTech System, Inc. 2011). This study evaluated the accuracy of several formulas for calculating $n$ or $C$ values and the modified momentum and $k$-$\varepsilon$ equations through simulating flood flow in a marsh area using the Delft3D model.
Study Area Location and Characteristics

The study area is Davis Pond located on the west bank of the Mississippi River, 3.22 km (2 mi) from Luling City in the southwest of New Orleans, Louisiana (Figure C-1). The study area is enclosed by guided levees on the north, east, and west edges, and by a gabion rock weir on the south edge, along the shoreline of Lake Cataouatche. The inlet canal delivers freshwater to the study area, and then drains into Lake Cataouatche. This area is covered by typical freshwater marsh vegetation, such as *Panicum hemitomon*, *Sagittaria lancifolia*, *Eleocharis baldwinii* (Sasser et al. 2008). O’Neil (1949) found that *Panicum hemitomon* is the dominant vegetation for freshwater marshes in the Mississippi River delta. The stem height for the mature *Panicum hemitomon* is approximately 0.762 m (USDA http://plants.usda.gov), and its diameter ranges from 1 to 6 mm (Turner 1994). The leaf blade is 20-30 cm long and 1.25 cm wide (Leithead et al. 1971). For maidencane (*Panicum hemitomon*) marshes, the averaged stem density is 255 stem/m² (Turner 1994). The Davis Pond marsh is apparently a maidencane (*Panicum hemitomon*) marsh; therefore, the averaged stem density is 255 stem/m².

Computational Model

The study area is simulated using Delft3D-FLOW open source program, version 4.00.02.557M (http://oss.deltares.nl/web/delft3d/source-code). Delft3D-FLOW is capable of simulating three dimensional (3D) unsteady incompressible flow and transport phenomena resulting from tidal and/or meteorological forcing. It solves the Reynolds Averaged Navier Stokes equations on a structured staggered curvilinear grid using a finite-difference scheme (Stelling and van Kester 1994). The governing equations are solved by using the Alternating Direction Implicit (ADI) technique (Stelling 1984). In this study,
flow field is simulated using the 3D unsteady flow with the \( k-\varepsilon \) turbulent closure model option. The orthogonal curvilinear coordinates system with the \( \sigma \)-grid option was adopted.

The computational grid is a structural grid with \( 596 \times 155 \) grid points on the horizontal plane in the main flow and normal to the main flow directions, hereafter called the M and N directions, respectively, and 15 layers in the vertical plane (Figure C-2). The maximum grid sizes in M and N directions are 90.06 m and 156.61 m, respectively, and the minimum grid sizes in M and N directions are 3.44 m and 6.16 m, respectively. In the vertical plane, because the velocity gradient is very high near the bed surface, the spacing of vertical layers is the smallest near the bottom, and it gradually increases toward the free surface (Figure C-3). The bathymetry of the entire domain was surveyed based on the North American Vertical Datum of 1988 (NAVD88).

The simulation period is from 1:00 pm on November 25, 2003, to 9:00 am on January 10, 2004. The observed water surface elevations (WSE) measured by the U.S. Geological Survey (USGS) gauge at Highway 90 (Figure C-1) were used as the upstream boundary condition. The tidal heights measured at the Lake Cataouatche USGS gauge (Figure C-1) were used as the downstream boundary condition. The WSE and tidal height at Highway 90 and Lake Cataouatche USGS gauges, respectively, are shown in Figure C-4. At the water surface, shear stress is set as zero.

Six equations, listed in Table B-2, were used to calculate the time-varying \( n \) or \( C \) coefficients. The first four equations were programmed in the Delft3D-FLOW program, and the rest, by Klopstra et al. (1997) and Baptist (2005), respectively, are available in Delft3D-FLOW program (Deltares 2011). In this study, the time-varying \( n \) or \( C \) coefficients were treated similarly in both flow directions, and a depth averaged velocity
was used in Fisher (1992) equation. The volumetric and cross-sectional blockage factors were assumed equal to the ratio of averaged vegetation height \((h_v)\) to flow depth \((H)\), provided that vegetation is distributed approximately uniformly throughout the entire channel area. This assumption is justified because any measure of hydraulic resistance at the channel reach scale must, by definition, be an integrated quantity (Luhar and Nepf 2013).

In addition, Delft3D-FLOW has an option to incorporate the effects of vegetation by modifying the momentum equations and the \(k-\varepsilon\) turbulent closure model (Deltares 2014). The influence of vegetation on the momentum equations is accounted by adding the vegetation drag force \(F = \left(\frac{1}{2}\right) \rho C_D a u^2\), where \(\rho\) is the density of water \((\text{kg/m}^3)\); \(C_D\) is the drag coefficient; \(a\) is the vegetation frontal area per unit volume, and \(u\) is the horizontal flow velocity. Vegetation also affects the vertical mixing, which is reflected in the extra source terms, \(T\) and \(T \tau^{-1}\), in the \(k\) and \(\varepsilon\) equation, respectively, where \(T\) is the work spent on the fluid per unit time \((\text{W})\); and \(\tau\) is the minimum of the dissipation time scale of free turbulence and the dissipation time scale of eddies between the vegetation. This approach is adapted as the seventh method for quantifying vegetation impacts.

A PC with Intel Xeon X5550 (2 processors) and 32 GB RAM was used for the simulation. To achieve stable numerical solutions, the time step is 1 min when using the formula in Klopstra et al. (1997) and the modified momentum and \(k-\varepsilon\) equations embedded in Delft3D, and 0.5 min for the remaining equations listed in Table B-2. The CPU time for the run using Klopstra et al. (1997) is 235,072.4 s; and using the modified momentum and \(k-\varepsilon\) equations, it is 268,841.92 s. The CPU times for the other runs are between 502,118.4 s.
to 547,267.6s, which are the CPU times using the Baptist (2005) and SED2D model equations, respectively.

**Results**

The study area was divided into several sub-areas (Figure C-1), depending on the existence of channels, overbanks, and vegetation height, according to a previous study (McAlpin et al. 2008). Among several stream gauges installed throughout the study area, the measurements of WSE at gauges 22 and 27 and the inflow at Highway 90 gauge were selected for model verification. McAlpin et al. (2008) simulated the study area using the RMA2 model, a depth-averaged two-dimensional model developed by ERDC-COE, and also applied the vegetation resistance equation in SED2D model (shown in Table B-2) for calculating the vegetation roughness. The parameters for vegetation-induced roughness in the SED2D model are summarized in Table B-3.

For the equations in Luhar and Nepf (2013), Klopstra et al. (1997), Baptist (2005), and the modified momentum and $k$-$\varepsilon$ equations, $a$ is determined by multiplying the vegetation density and the average frontal width of individual vegetation. The average frontal width for the *Panicum hemitomon* is approximately 2.25 times its leaf width, approximately 1.25 cm (Leithead et al. 1971), plus the average stem diameter of 0.4 cm (Turner 1994). Then, the calculated frontal width for individual *Panicum hemitomon* is 3.2 cm. The density of *Panicum hemitomon* is 255 stem/m$^2$, then the $a$ value is found to be 8.16 m$^{-1}$. The $a$ value is within the range recommended by Luhar et al. (2008) and Lightbody and Nepf (2006), who found the $a$ value for the marsh grasses ranges between 1 and 10 m$^{-1}$. The drag coefficient, $C_D$, is taken as 1.0; and the coefficient $C_\tau$, the shear
stress parameter at the interface between vegetated and unvegetated regions, is equal to 0.10 (Luhar and Nepf 2013).

The results of inflow at the Highway 90 gauge and WSE at gauges 22 and 27 were compared with the observed data in Figure C-5. To determine which method gives the best match of the observed inflow and WSE, the root-mean square error (RMSE) and the Nash Sutcliffe efficiency (NSE) coefficient were calculated. The following equations were used to calculate RMSE and NSE:

\[
RMSE = \sqrt{\frac{\sum (\text{Simulated value} - \text{Observed value})^2}{\sum \text{number of total observed points}}}
\]

\[
NSE = 1 - \frac{\sum (\text{Simulated value} - \text{Observed value})^2}{\sum (\text{Observed value} - \text{Observed value})^2}
\leq \frac{1}{\infty} < \text{NSE} < 1.0
\]

The RMSE and NSE values for all methods were summarized in Table C-1. From this table, the RMSE values for the equations in Luhar and Nepf (2013), Klopstra et al. (1997), and Baptist (2005) are smaller than those for the rest of methods. Also the NSE values for these equations (Luhar and Nepf 2013; Klopstra et al. 1997; Baptist 2005) are closer to 1.0 than those from the rest of methods, which means that the mean square error generated by using each equation is much smaller than the variance of observed data. Essentially, the closer the NSE values are to 1, the more accurate the modeling result.

The RMSE values for Fisher (1992) and Reed et al. (1995) equations are larger than three methods discussed in the previous paragraph, and the NSE values are farther from 1.0, because both of them do not consider the degree of submergence that differentiates the impacts of submerged and emerged vegetation. The Fisher (1992) equation does not account for the nonlinear nature of the \( n-VR \) relationships, where \( V \) and \( R \) are the depth-
averaged velocity and hydraulic radius, respectively (Green 2005b). The RMSE values for the roughness equation in SED2D model and the modified momentum and $k-\varepsilon$ equations are approximately close to one another, but they are greater than those from using the equations in Luhar and Nepf (2013), Klopstra et al. (1997), and Baptist (2005). The NSE values from those two methods are slightly further from 1.0 than those from the Luhar and Nepf (2013), Klopstra et al. (1997), and Baptist (2005) equations. Therefore, the equations from Luhar and Nepf (2013), Klopstra et al. (1997), and Baptist (2005) performed better for simulating the spatially and temporally varied vegetation. This is because these equations account for both the degree of submergence and the frontal area of individual vegetation per unit volume ($a$ value).

Figure C-6 showed the effect of degree of submergence on the $n$ value for subarea 1, by using the equations in Luhar and Nepf (2013), Klopstra et al. (1997), and Baptist (2005). A constant $a$ value ($a = 8.16 \text{ m}^{-1}$) was used for all the equations in Figure C-6. The values of $n$ from the equations in Luhar and Nepf (2013), and Klopstra et al. (1997) have the same trend and are approximately close to one another but deviate from the equation in Baptist (2005). This is because the equations in Luhar and Nepf (2013) and Klopstra et al. (1997) calculate the vegetation roughness by using the updated degree of submergence value, whereas the equation in Baptist (2005) calculates the vegetation roughness by using the same degree of submergence value and also adds an extra term, $-\left[\frac{2}{3}\lambda u^2\right]$, to the momentum equation, in which $\lambda$ is the parameter representing the flow resistance due to vegetation. In the case of emerged vegetation, as the degree of submergence is increased, the $n$ values calculated by the equations in Luhar and Nepf (2013) and Klopstra et al. (1997) are increased owing to the increase of vegetation frontal area, whereas it is a constant ($n_o$).
in Baptist (2005) equation, where \( n_0 \) is the maximum \( n \) value for an unvegetated channel. In the case of submerged vegetation, the \( n \) value decreases with the increasing degree of submergence until reaching a constant value. This attributes to two factors: (1) the reduction of relative roughness from vegetation to flow \( (h_v/H) \); and (2) the bending of nonrigid plants. As flow depth in the flow layer increases, the influence of vegetation is minimizing as a result of the reduced relative roughness, \( h_v/H \), in the vegetation layer. In the meantime, if the vegetation is nonrigid, the shear layer above the vegetation layer makes the submerged vegetation more prone to bending than the emerged ones. When vegetation bends, vegetation frontal area will decrease so that the resistance to flow will decrease. This relationship is qualitatively represented by the \( n-VR \)’s curve in Ree (1949). At very large degrees of submergence, the vegetation resistance to flow becomes independent from the degree of submergence, as soon as the vegetation layer acts as a rough surface, and the resistance to flow becomes a constant (Augustijn et al. 2008). Consequently, the roughness can be approximated by a constant \( n \) value at large degrees of submergence.

The simulated results of inflow at Highway 90 gauge and WSE at gauges 22 and 27 (Figure C-5) were calculated without taking the effect of vegetation bending. Because these results showed good matches with the measurements, especially for the equations in Luhar and Nepf (2013), Klopstra et al. (1997), and Baptist (2005), for this simulation case, the vegetation bending has a minor effect on vegetation resistance.

The time variations of \( n \) and Reynolds number (\( R \)) from the simulations using the equations in Luhar and Nepf (2013), Klopstra et al. (1997), and Baptist (2005) at all three gauges were shown in Figure C-7. At Highway 90 gauge (Figure C-7 (a)), located in
subarea 1, the $n$ values are small and approximately constant for all equations, indicating vegetation was submerged during the simulation period with a high degree of submergence.

For gauge 22 (Figure C-7 (c)), located in subarea 6, the $n$ values are bigger than that observed in Highway 90 gauge. The $n$ values from the Baptist (2005) equation are not constant and less than the unvegetated value ($n_o$). This indicated that the vegetation was submerged during the simulation period. For gauge 27 (Figure C-7 (e)), located in subarea 4, the $n$ values were larger than those in other gauges. The $n$ values from the Baptist (2005) equation were sometimes equal to a constant, $n_o$, and at the other times less than $n_o$, implying vegetation in this location is sometimes emerged and at the other time submerged depending on flow conditions. The time variation of $R$ at Highway 90 gauge is shown in Figure C-7 (b). The $R$ values from the Baptist (2005) equation were somehow higher than those from the other equations especially during the time period from 64 to 420 hr. The $R$ value ranges from 177,571.4 to 4,220,428.2, and Froude number ($F$) from 0.004 to 0.08 because the simulated inflows from this equation were high (Figure C-5). At gauges 22 and 27 (Figures C-7 (d and f)), the $R$ values were approximately the same from all the equations except for the peak flow period from 50 to 100 hr, where the Baptist (2005) equation gave higher values of $R$, ranging from 36,469.6 to 78,866.3. The Froude number ranges from 0.014 to 0.02.

**Grid Sensitivity Analysis**

A new computational grid was adopted to test the sensitivity of modeling results to grid selection. The new grid was coarser than the previous one with $M=299$, $N=53$, and 15 layers in the vertical plane. The maximum grid sizes in the $M$ and $N$ directions are
177.84 m and 462.5 m, respectively, and the minimum grid sizes in the M and N directions are 7.13 m and 19.19 m, respectively. New runs were conducted using the best three equations (Luhar and Nepf 2013; Klopstra et al. 1997; Baptist 2005). The time step of 1 min. was used for all equations to obtain stable numerical solutions. The CPU times for all three runs are 63,453.47 s, 80,452.05 s, and 81,176.72 s by using the equations in Klopstra et al. (1997), Luhar and Nepf (2013), and Baptist (2005), respectively. The results of simulated inflow at gauge Highway 90, and WSE at gauges 22 and 27 using both grids, but only the Klopstra et al. (1997) equation, as an example, were plotted in Figure C-8, which shows that the simulated results using both grids are close to one another (except at the time period from 100 to 450 hr, where the simulated results using the fine mesh are closer to the observations). The same results were observed using the other two equations. Because the CPU times for the runs using the coarse mesh are much less than that for the runs using the fine mesh, the adoption of coarse mesh gives reasonable simulation results with less CPU time.

Conclusions

A 3D hydrodynamic simulation of flood flow through Davis Pond marsh area was conducted by using the Delft3D-FLOW open source program. The study area is covered with freshwater marsh, and the vegetation roughness is approximated by the time-varying Manning’s $n$ and Chezy’s $C$ coefficients and the modified momentum and $k$-$\varepsilon$ equations. The simulation results of inflow and WSE at several gauges have reasonably matched the observed data when using the time-varying roughness coefficient equations (Luhar and Nepf 2013; Klopstra et al. 1997; Baptist 2005) among the other equations or methods used, because they successfully incorporated the effects of both the degree of submergence and
the vegetation frontal area per unit volume. Also using these equations, the simulation results agreed very well with the observations for both fine- and coarse-grid meshes. The maximum vegetation resistance was reached when vegetation just changed from the emerged to the submerged state, and the vegetation effect becomes a constant at high degrees of submergence. For this case study, the vegetation bending has a minor effect on vegetation resistance.
Notation

The following symbols are used in this paper:

\( a \) = vegetation frontal area per unit volume \( (m^{-1}) \);

\( B^V, B^K \) = volumetric and cross-sectional blockage factors, respectively \((-)\);

\( C \) = total Chezy’s coefficient \( (m^{1/2}/s) \);

\( C_b \) = Chezy’s coefficient for the unvegetated channel \( (m^{1/2}/s) \);

\( C_D \) = drag coefficient \((-)\);

\( C_s \) = shear stress parameter at the interface between vegetated and unvegetated flow regions \((-)\);

\( F \) = vegetation drag force \( (N) \);

\( F \) = Froude number \((-)\);

\( g \) = gravity acceleration \( (m/s^2) \);

\( H \) = flow depth \( (m) \);

\( h_v \) = vegetation height \( (m) \);

\( n \) = total Manning’s coefficient \( (s/m^{1/3}) \);

\( n_o, n_v \) = maximum Manning’s coefficients for unvegetated and vegetated channels, respectively \( (s/m^{1/3}) \);

\( R \) = hydraulic radius \( (m) \);

\( R \) = Reynolds number \((-)\);

\( T \) = work spent on the fluid per unit time \( (W) \);

\( u \) = horizontal flow velocity \( (m/s) \);

\( u_v \) = velocity within the vegetation \( (m/s) \);

\( V \) = depth averaged velocity \( (m/s) \);
\( z_0 \) = length scale for the bed roughness of the surface layer (m);

\( \alpha \) = coefficient depends on flow depth (-);

\( \beta \) = resistance factor \((s \cdot m^{1/6})\)

\[ \beta = \begin{cases} 
0.4 & \text{(for sparse, low density vegetation } H > 0.3 \text{ m)}; \\
1.6 & \text{(for moderately dense vegetation } H = 0.3 \text{ m)}; \\
6.4 & \text{(for very dense vegetation } H < 0.3 \text{ m)}; 
\end{cases} \]

\( \eta \) = length scale of large scale turbulence (m);

\( K \) = von Karman constant = 0.41 (-);

\( \lambda \) = parameter representing the flow resistance due to vegetation \((m^{-1})\); and

\( \rho \) = water density \((kg/m^3)\).
Tables

Table C-1. RMSE and NSE values for simulated results compared with observations

<table>
<thead>
<tr>
<th>Gauge</th>
<th>RMSE/</th>
<th>NSE</th>
<th>RMSE/</th>
<th>NSE</th>
<th>RMSE/</th>
<th>NSE</th>
<th>RMSE/</th>
<th>NSE</th>
<th>RMSE/</th>
<th>NSE</th>
<th>RMSE/</th>
<th>NSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Highway 90</td>
<td>49.99/0.44</td>
<td>43.19/0.70</td>
<td>26.18/0.88</td>
<td>17.87/0.95</td>
<td>17.80/0.96</td>
<td>19.69/0.95</td>
<td>33.93/0.85</td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>22</td>
<td>0.149/0.67</td>
<td>0.112/0.81</td>
<td>0.061/0.94</td>
<td>0.025/0.99</td>
<td>0.026/0.99</td>
<td>0.021/0.99</td>
<td>0.057/0.95</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>0.161/0.65</td>
<td>0.13/0.78</td>
<td>0.069/0.94</td>
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<td>0.034/0.98</td>
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<td></td>
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</tr>
</tbody>
</table>
Figures

Figure C-1. Study area, locations of the USGS and observed data gauges, and subarea divisions
Figure C-2. Study area computation grid
Figure C-3. Distribution of vertical layers at a section passing through the inlet canal

Figure C-4. Boundary conditions of WSE and tidal height at the Highway 90 and Lake Cataouatche gauges, respectively
Figure C-5. Observed and simulated inflow and WSE
Figure C-6. $n$ value versus degree of submergence for the three (best) equations
Figure C-7. Time variations of $n$ and $R$ from the best three equations: (a and b) Highway 90 Gauge; (c and d) Gauge 22; (e and f) Gauge 27.
Figure C-8. Observed and simulated inflow and WSE using fine and coarse meshes.
REFERENCES


consultants, Lelystad, Netherlands. Commissioned by Rijkswaterstaat/RIZA, Netherlands.


