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Effects of Vegetation on Stream Systems

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Updated on Oct. 9, 2014

Examples of Aquatic Vegetation

Willow. http://www.naturalheritage.state.pa.us

Reed canary-grass. http://www.naturalheritage.state.pa.us

Floodplain forest. http://www.nrcs.usda.gov

Floodplain forest. http://www.nature.org

Model of Wu and Wang (2004) and Wu et al. (2005)

2-D Depth-av. Flow Eqn. with Vegetation Effects

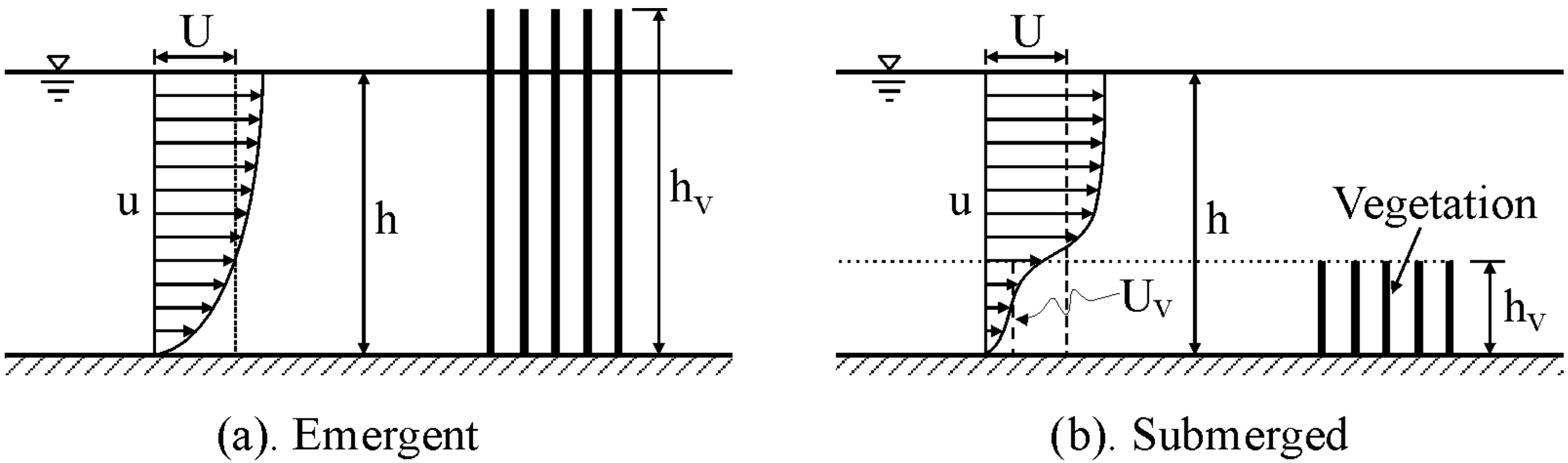
$$\frac{\partial[\rho(1-c)h]}{\partial t}+\frac{\partial[\rho(1-c)Uh]}{\partial x}+\frac{\partial[\rho(1-c)Vh]}{\partial y}=0$$

$$\frac{\partial[\rho(1-c)Uh]}{\partial t}+\frac{\partial[\rho(1-c)UUh]}{\partial x}+\frac{\partial[\rho(1-c)UVh]}{\partial y}$$
$$=-\rho g(1-c)h\frac{\partial z_s}{\partial x}+\frac{\partial(hT_{xx})}{\partial x}+\frac{\partial(hT_{xy})}{\partial y}-\tau_{bx}-f_{dx}h$$

$$\frac{\partial[\rho(1-c)Vh]}{\partial t}+\frac{\partial[\rho(1-c)UVh]}{\partial x}+\frac{\partial[\rho(1-c)VVh]}{\partial y}$$
$$=-\rho g(1-c)h\frac{\partial z_s}{\partial y}+\frac{\partial(hT_{yx})}{\partial x}+\frac{\partial(hT_{yy})}{\partial y}-\tau_{by}-f_{dy}h$$

(c = vegetation density)

Modeling of Vegetation Effects



Drag and inertia forces:

$$\vec{F} = \frac{1}{2} C_D \rho N_v A_v |U_v| \vec{U}_v + \rho C_M N_v V_v \frac{\partial \vec{U}_v}{\partial t}$$

For submerged vegetation (Stone and Shen 2002):

$$\vec{U}_v = \eta_v \vec{U} \left(\frac{h_v}{h} \right)^{1/2}$$

h_v = vegetation height, and η_v = coefficient close to 1.0

K and ε Equations

$$\frac{\partial k}{\partial t}+U\frac{\partial k}{\partial x}+V\frac{\partial k}{\partial y}=\frac{\partial}{\partial x}\left(\frac{\nu_t}{\sigma_k}\frac{\partial k}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{\nu_t}{\sigma_k}\frac{\partial k}{\partial y}\right)+P_h+P_{kb}+P_v-\varepsilon$$

$$\frac{\partial \varepsilon}{\partial t}+U\frac{\partial \varepsilon}{\partial x}+V\frac{\partial \varepsilon}{\partial y}=\frac{\partial}{\partial x}\left(\frac{\nu_t}{\sigma_\varepsilon}\frac{\partial \varepsilon}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{\nu_t}{\sigma_\varepsilon}\frac{\partial \varepsilon}{\partial y}\right)+c_{\varepsilon 1}\frac{\varepsilon}{k}\left(P_h+c_{\varepsilon 3}P_v\right)+P_{\varepsilon b}-c_{\varepsilon 2}\frac{\varepsilon^2}{k}$$

New Source Term

$$P_v=\frac{c_{vk}}{\rho(1-c)}\left(f_{dx}U+f_{dy}V\right)$$

Sediment Transport Model

Suspended-Load Transport

$$\frac{\partial\left[(1-c)hS_k\right]}{\partial t}+\frac{\partial\left[(1-c)UhS_k\right]}{\partial x}+\frac{\partial\left[(1-c)VhS_k\right]}{\partial y}$$

$$=\frac{\partial}{\partial x}\left\{\varepsilon_s h\frac{\partial\left[(1-c)S_k\right]}{\partial x}\right\}+\frac{\partial}{\partial y}\left\{\varepsilon_s h\frac{\partial\left[(1-c)S_k\right]}{\partial y}\right\}+\alpha\omega_{sk}(1-c)\left(S_{*k}-S_k\right)$$

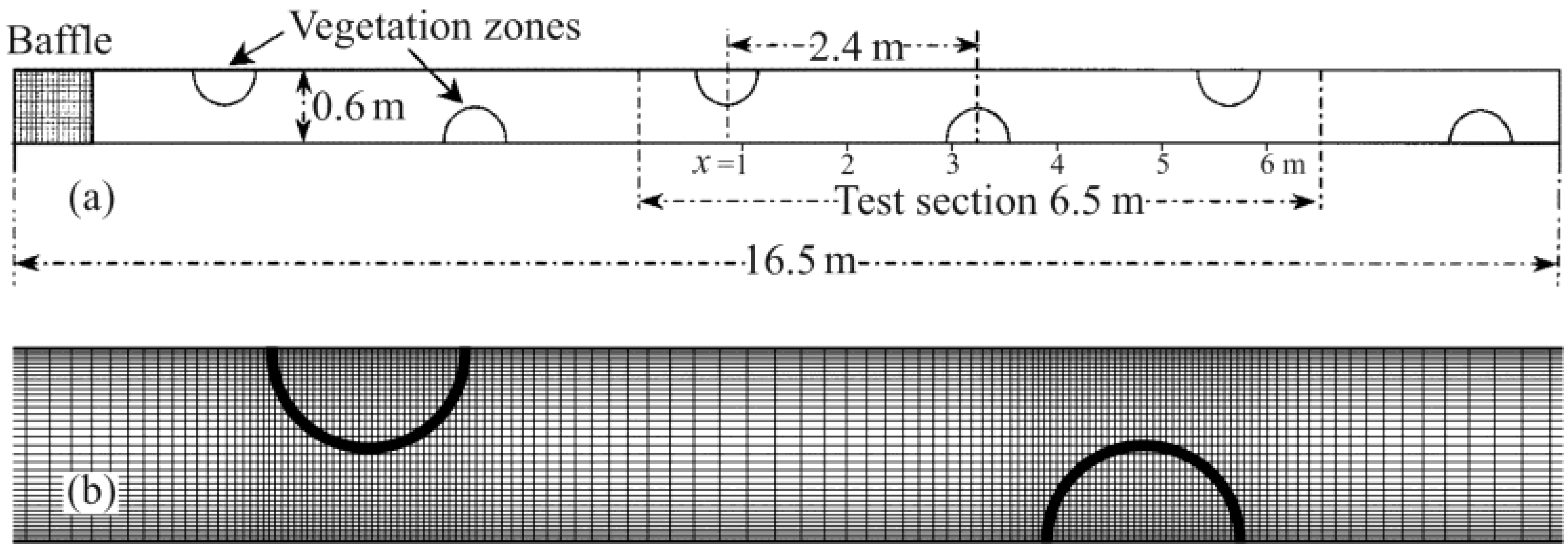
Bed-Load Transport

$$\frac{\partial\left[(1-c)\delta\bar{s}_{bk}\right]}{\partial t}+\frac{\partial\left[\alpha_{bx}(1-c)q_{bk}\right]}{\partial x}+\frac{\partial\left[\alpha_{by}(1-c)q_{bk}\right]}{\partial y}+\frac{1}{L}(1-c)\left(q_{bk}-q_{b*k}\right)=0$$

Bed Change

$$(1-p')\frac{\partial z_{bk}}{\partial t}=\alpha\omega_{sk}\left(S_k-S_{*k}\right)+\frac{1}{L}\left(q_{bk}-q_{b*k}\right)$$

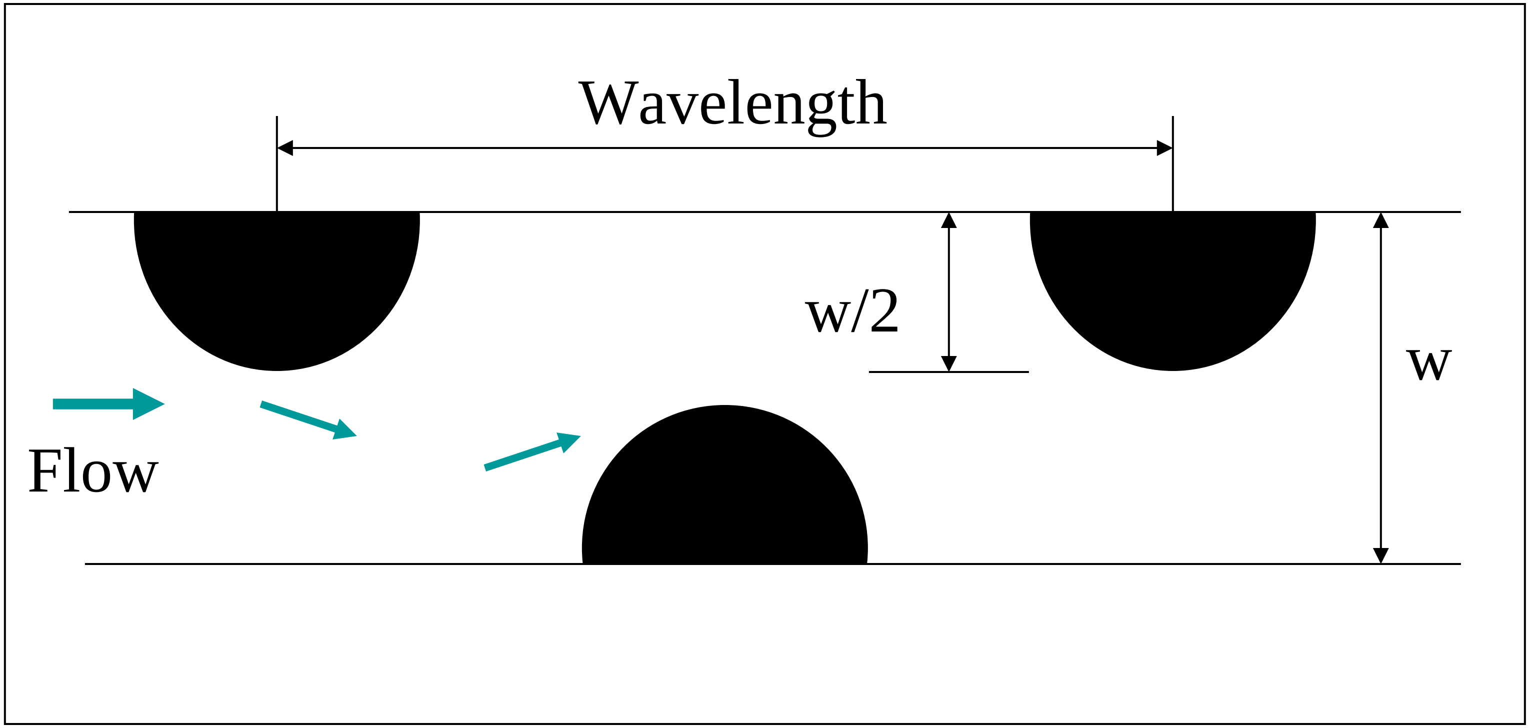
Flow around Alternate Vegetation Bars



Sketch of the flume with the simulated vegetation zones (Bennett et al., 1999)

and computational mesh near vegetation zones

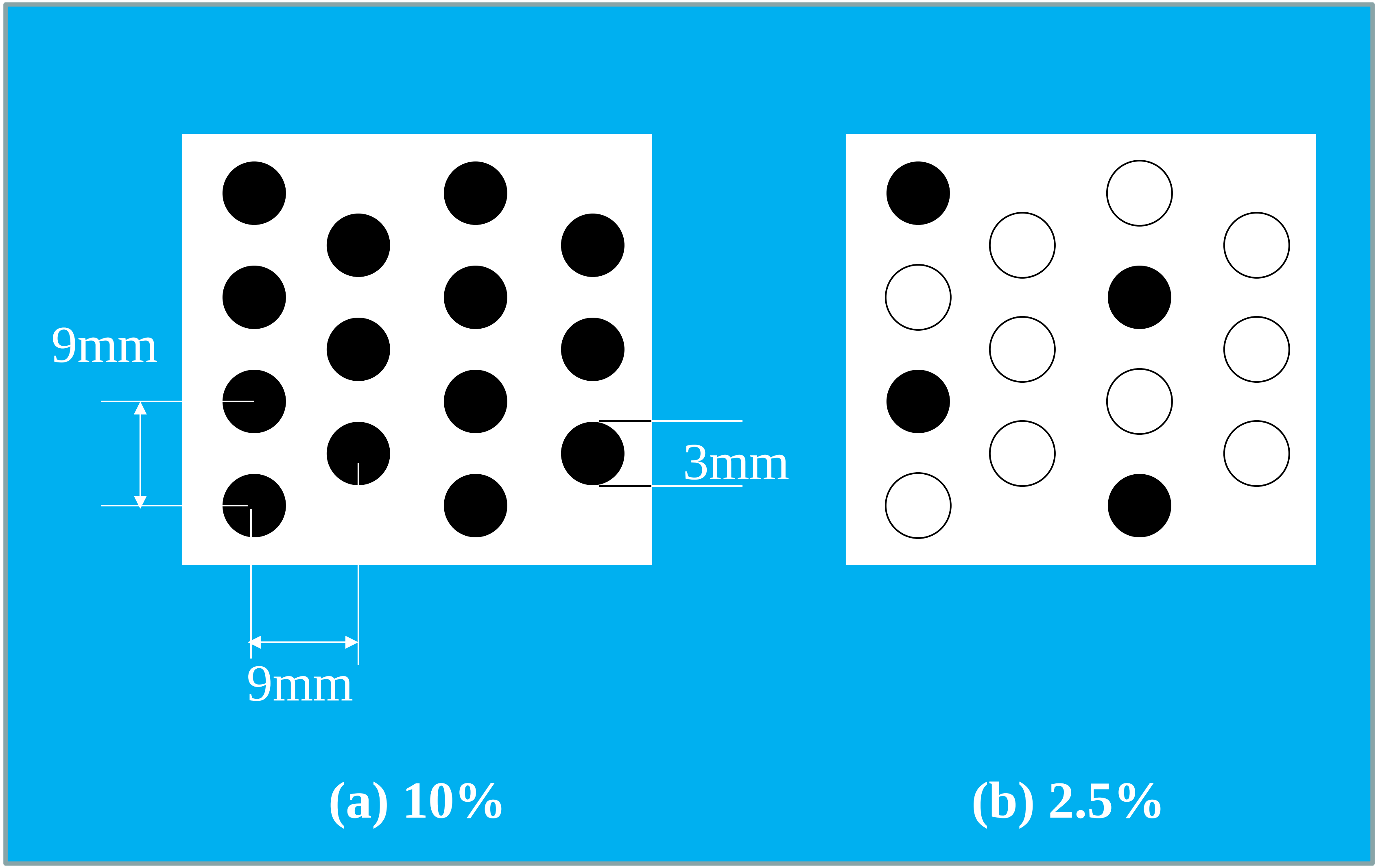
Plan view of the flume with vegetation areas



Wavelength = 4.8 m

w = 0.6 m

Close-up schematic of dowel configuration

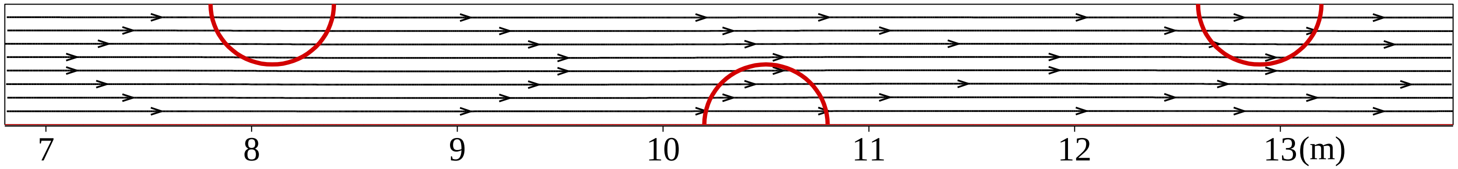


Experiment Conditions

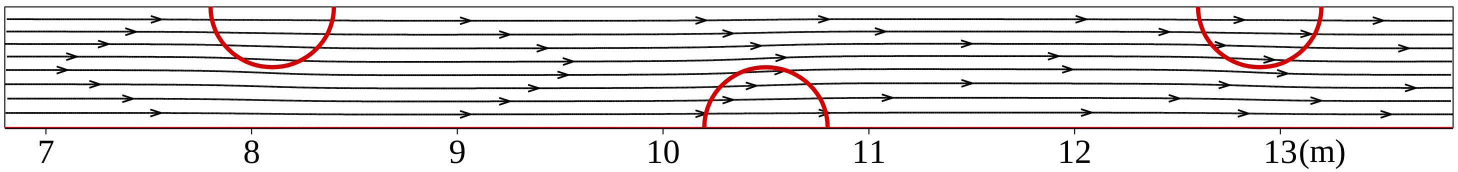
Discharge (Q)	0.0043 m3/s
Depth (d)	27 mm
Width (w)	0.6 m
Froude Number (Fr)	0.47
Vegetation Density	10% - 0.04%

Streamlines

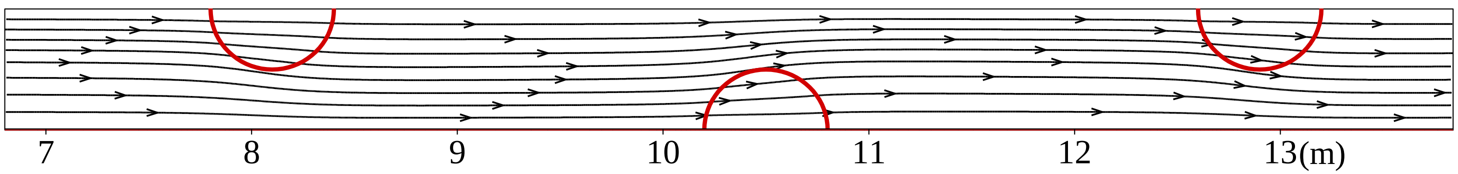
Vegetation Concentration: 0.04%



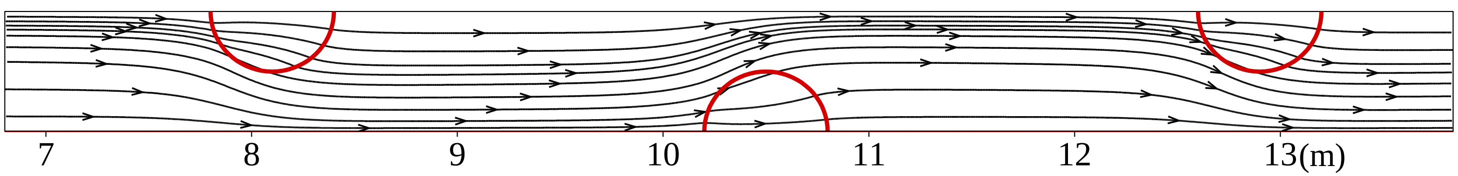
Vegetation Concentration: 0.2%



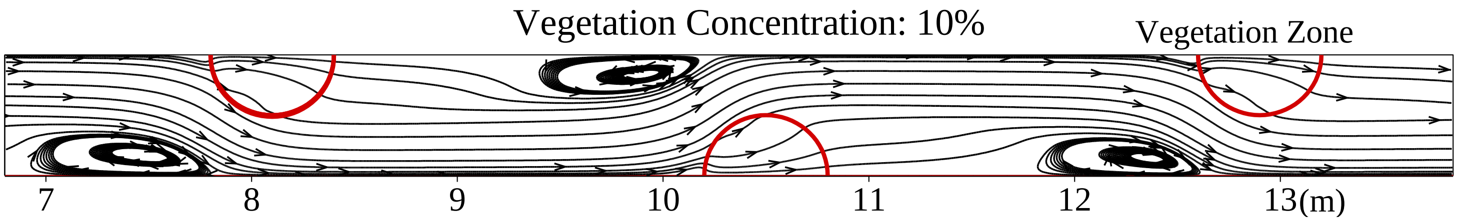
Vegetation Concentration: 0.6%



Vegetation Concentration: 2.5%



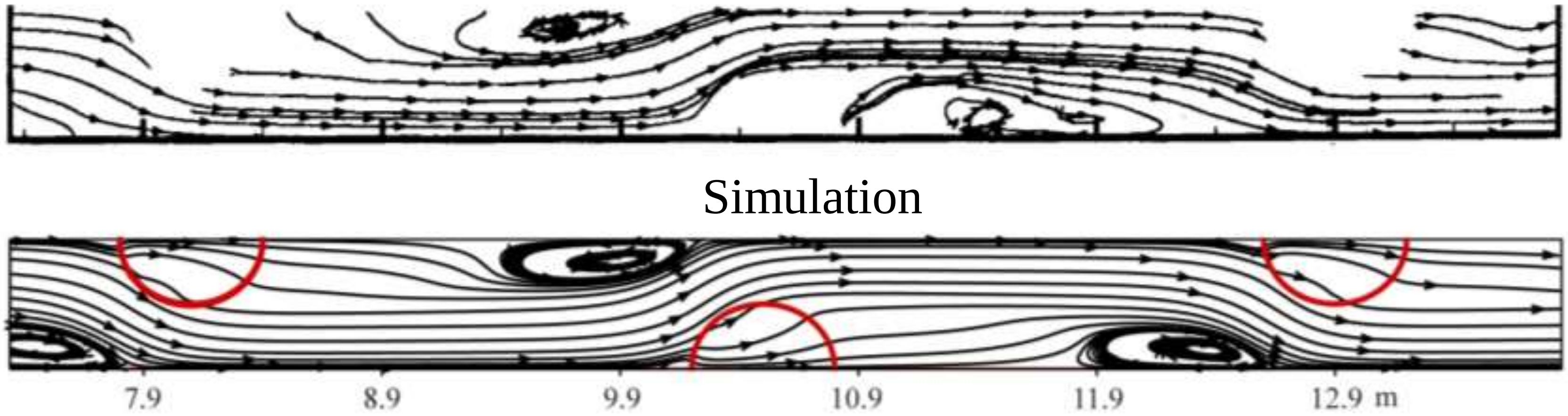
Vegetation Concentration: 10%



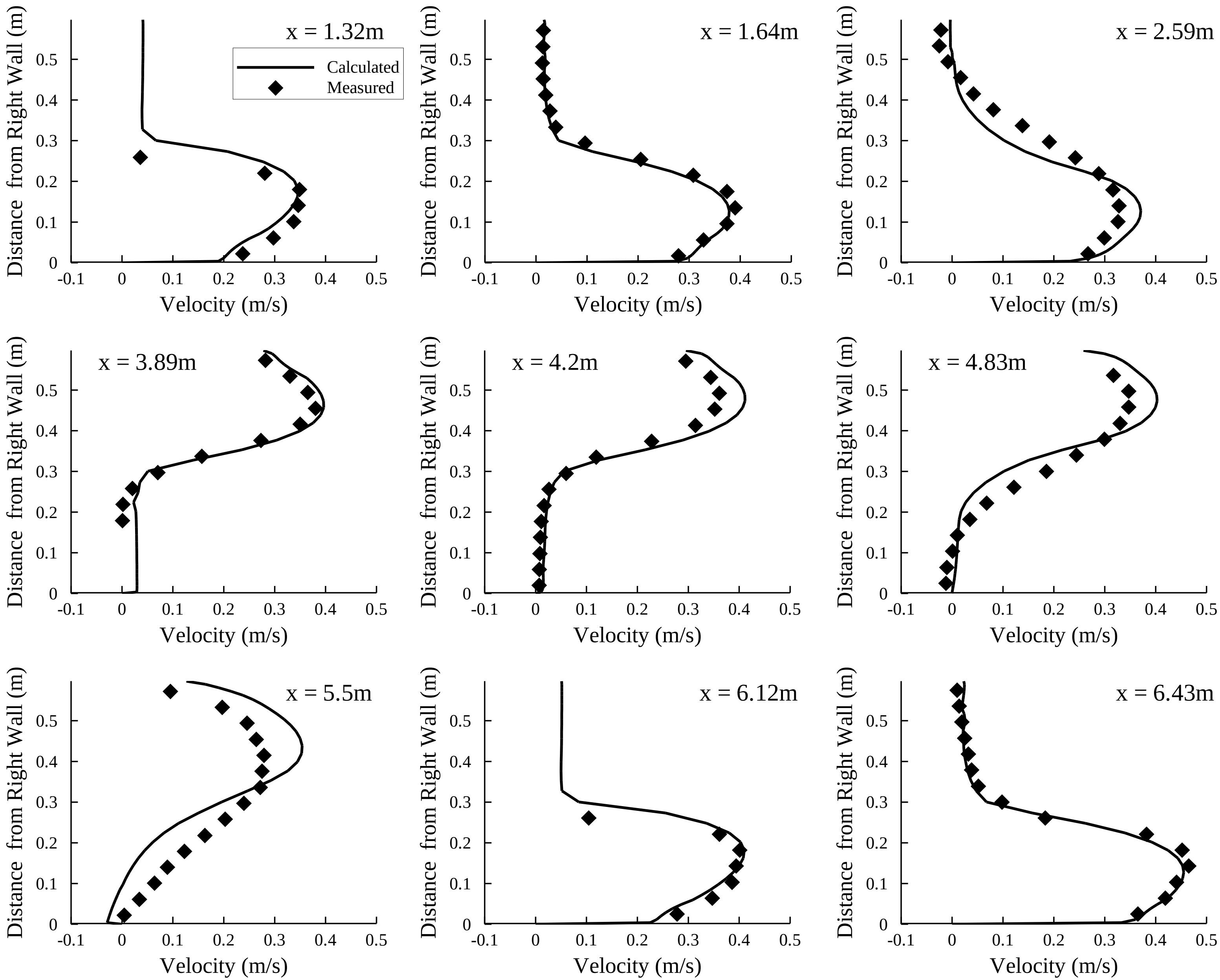
Streamlines (Vegetation Concentration c= 10%)

Experiment

Simulation



Velocity Comparison (c=10%)



Velocity Comparison (c=2.5%)

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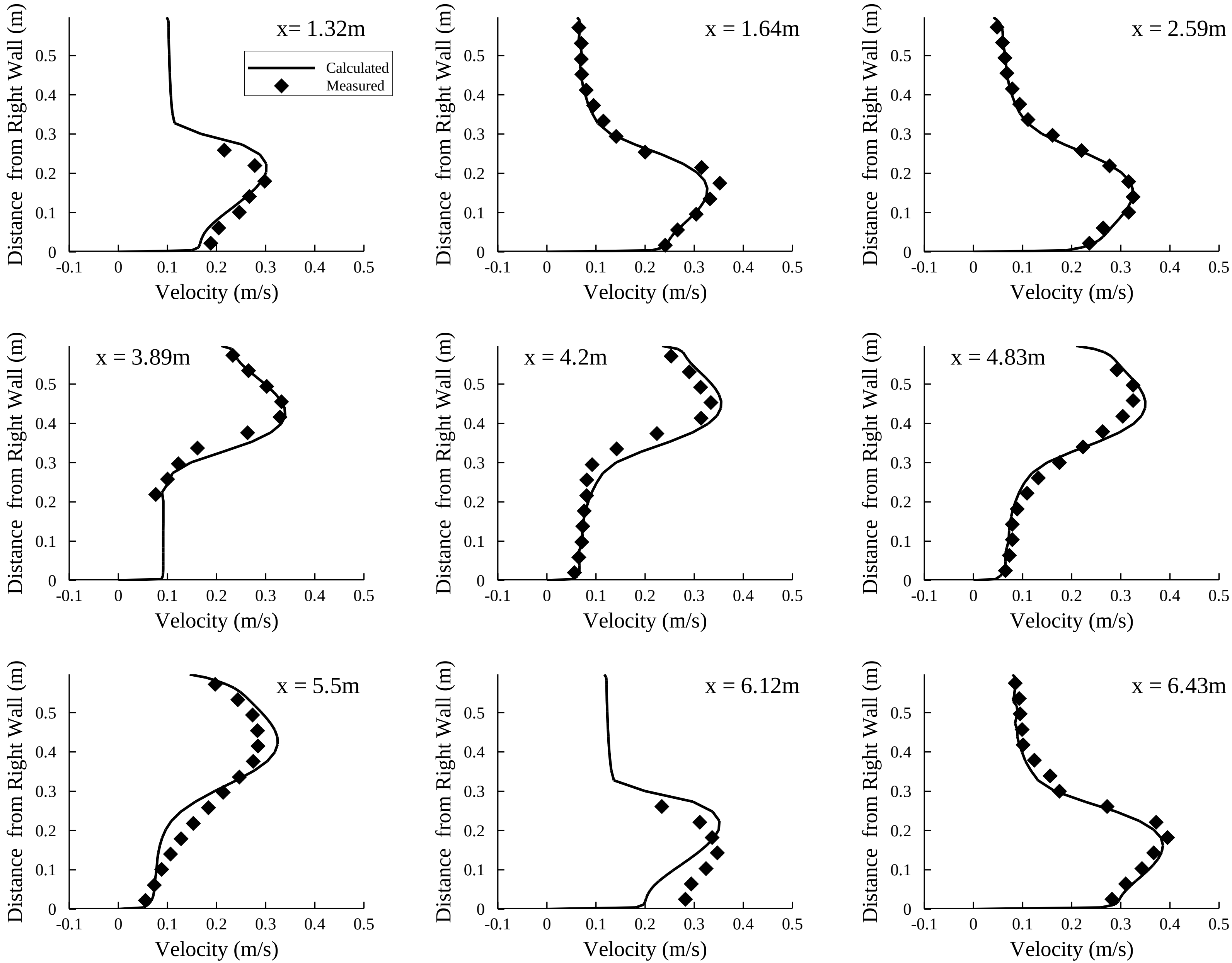
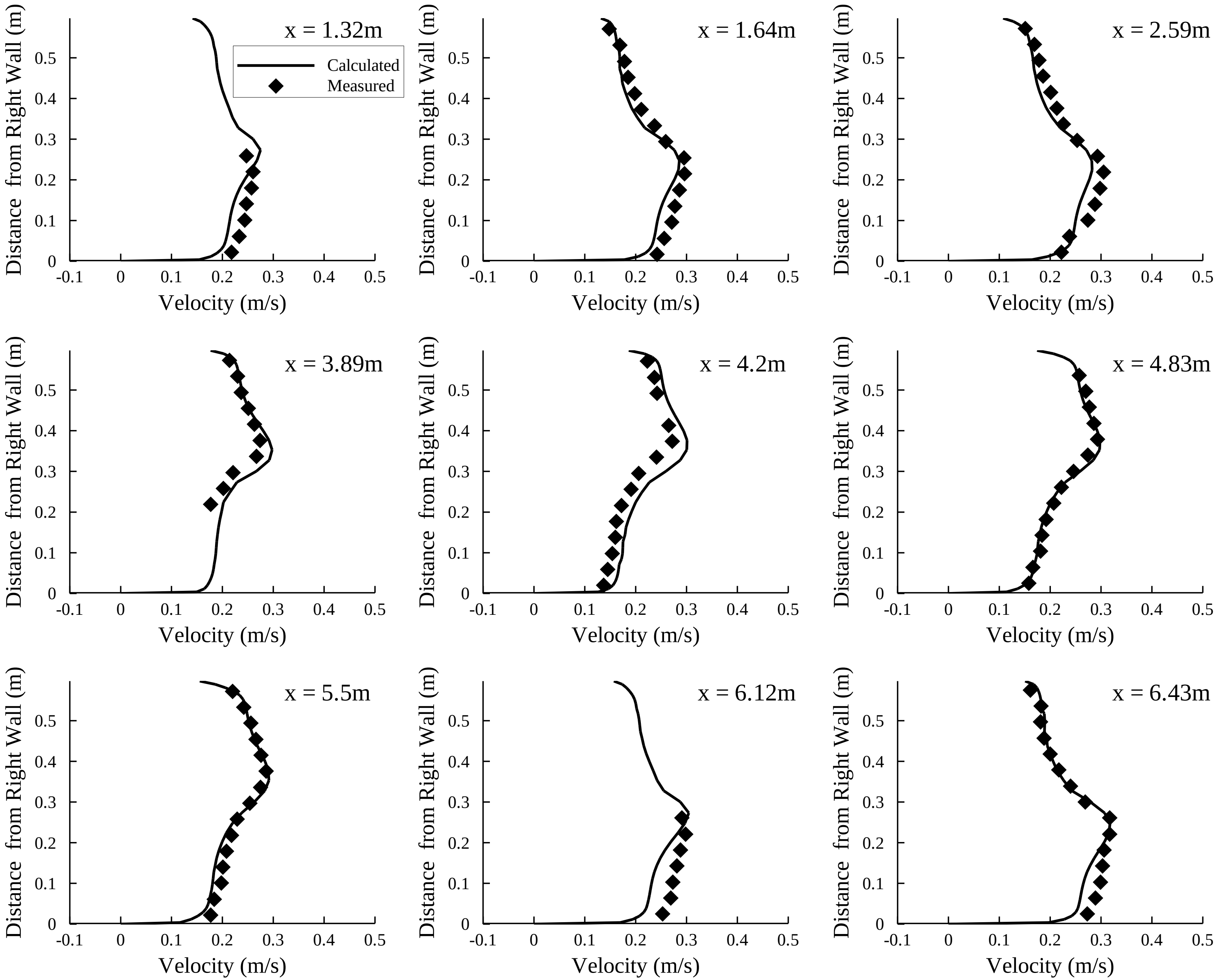
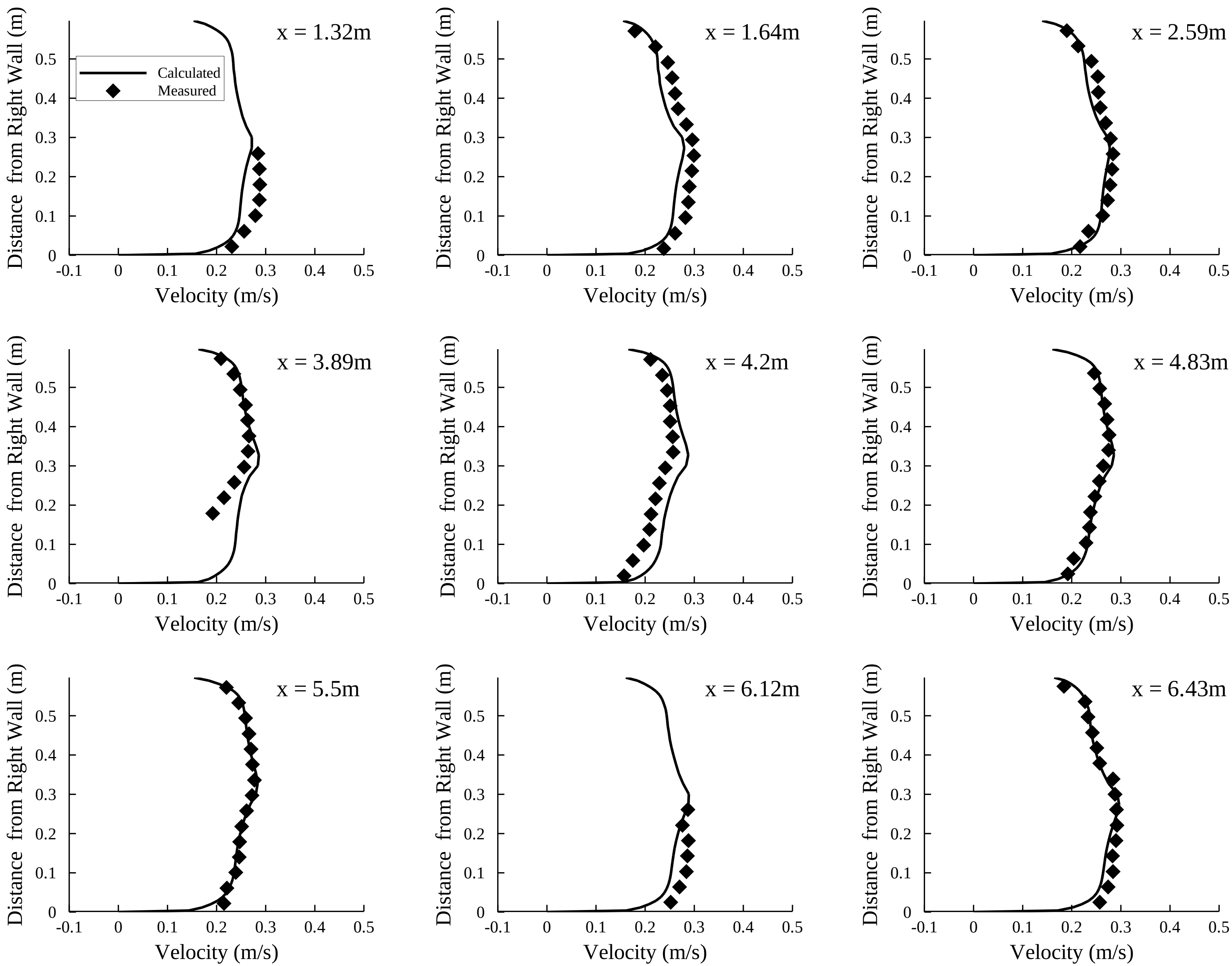


Velocity Comparison (c=0.6%)

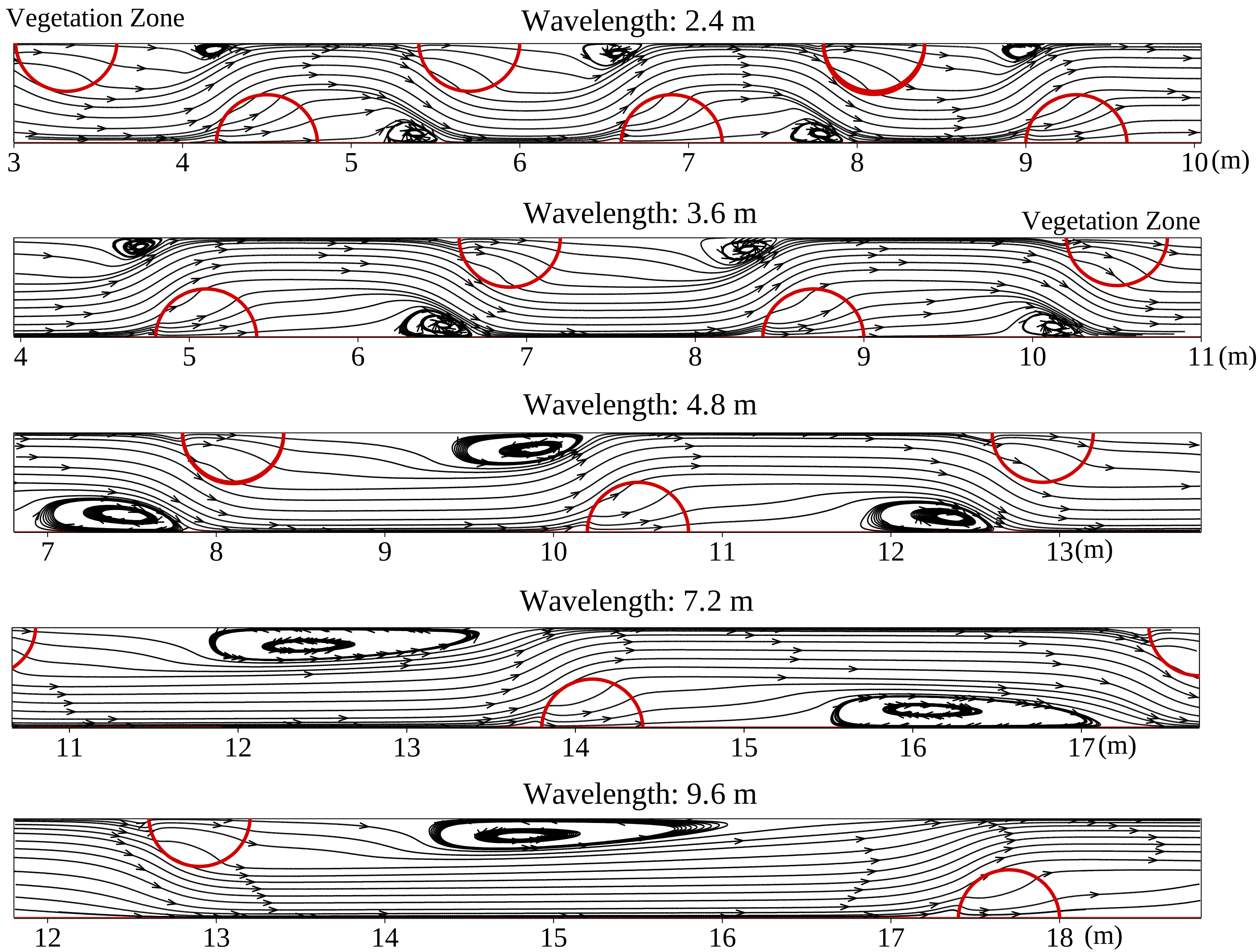


Velocity Comparison (c=0.2%)



Pr

Vegetation Zones with Various Wavelength

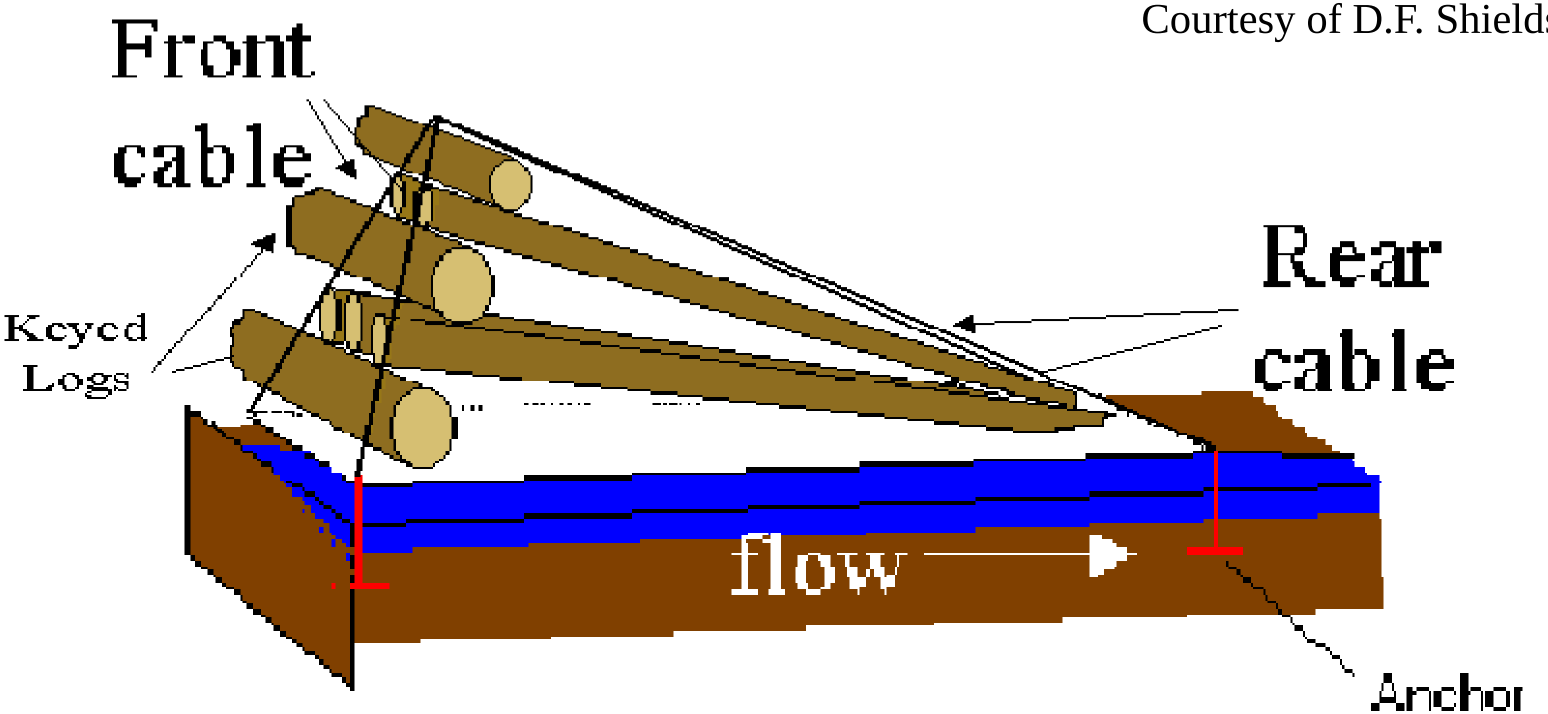


Large Woody Structures

A Deeply-incised Sharp Bend in Little Topashaw Creek within Yalobusha Watershed in North Central Mississippi. Installed large woody debris structures are marked in red lines.

Large Woody Debris Structures

Courtesy of D.F. Shields

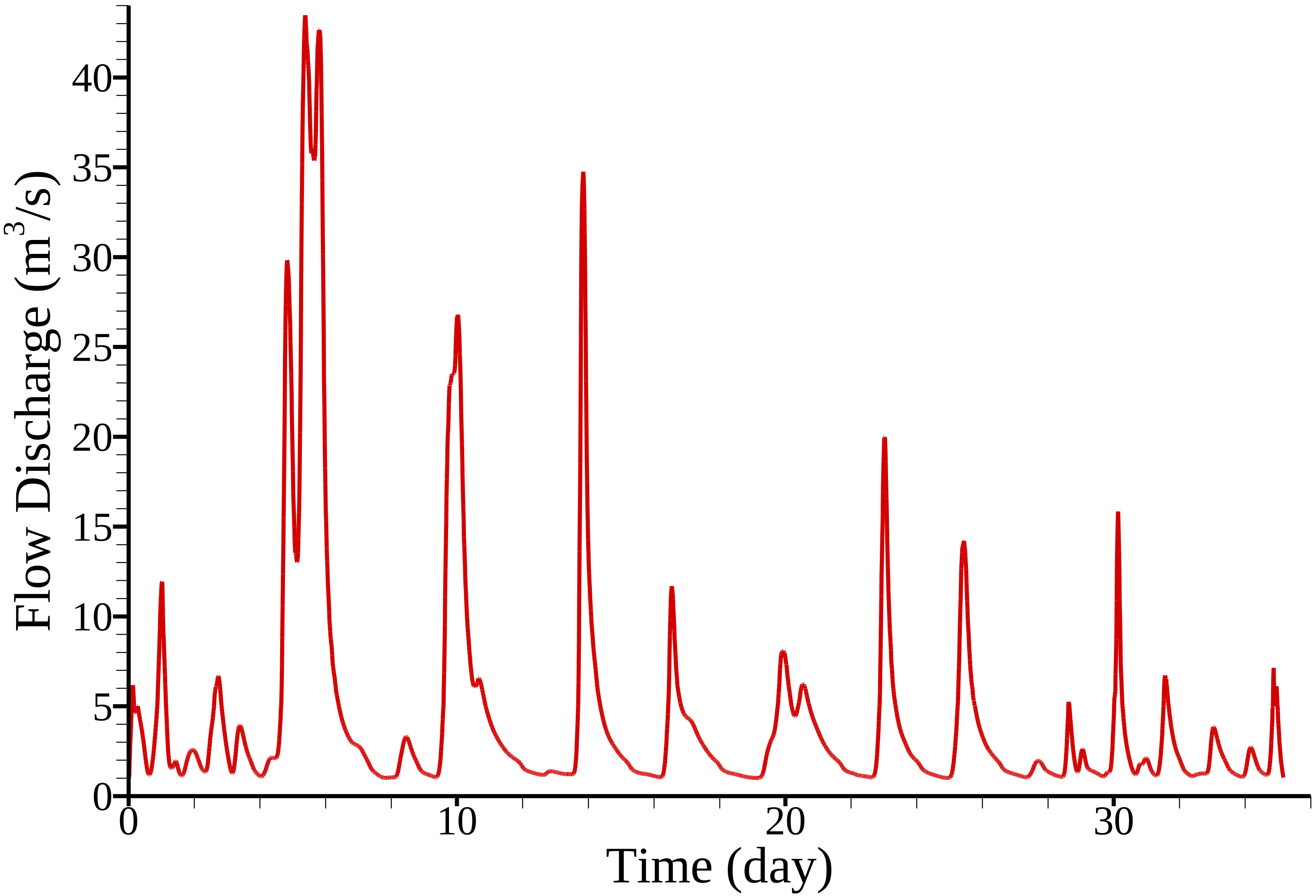


Average Diameter of Logs = 0.318 m

Average Length of Key Logs = 5.5 m

Average Length of Rack Logs = 9.2 m

Inflow Hydrograph (July 2000-June 2001)

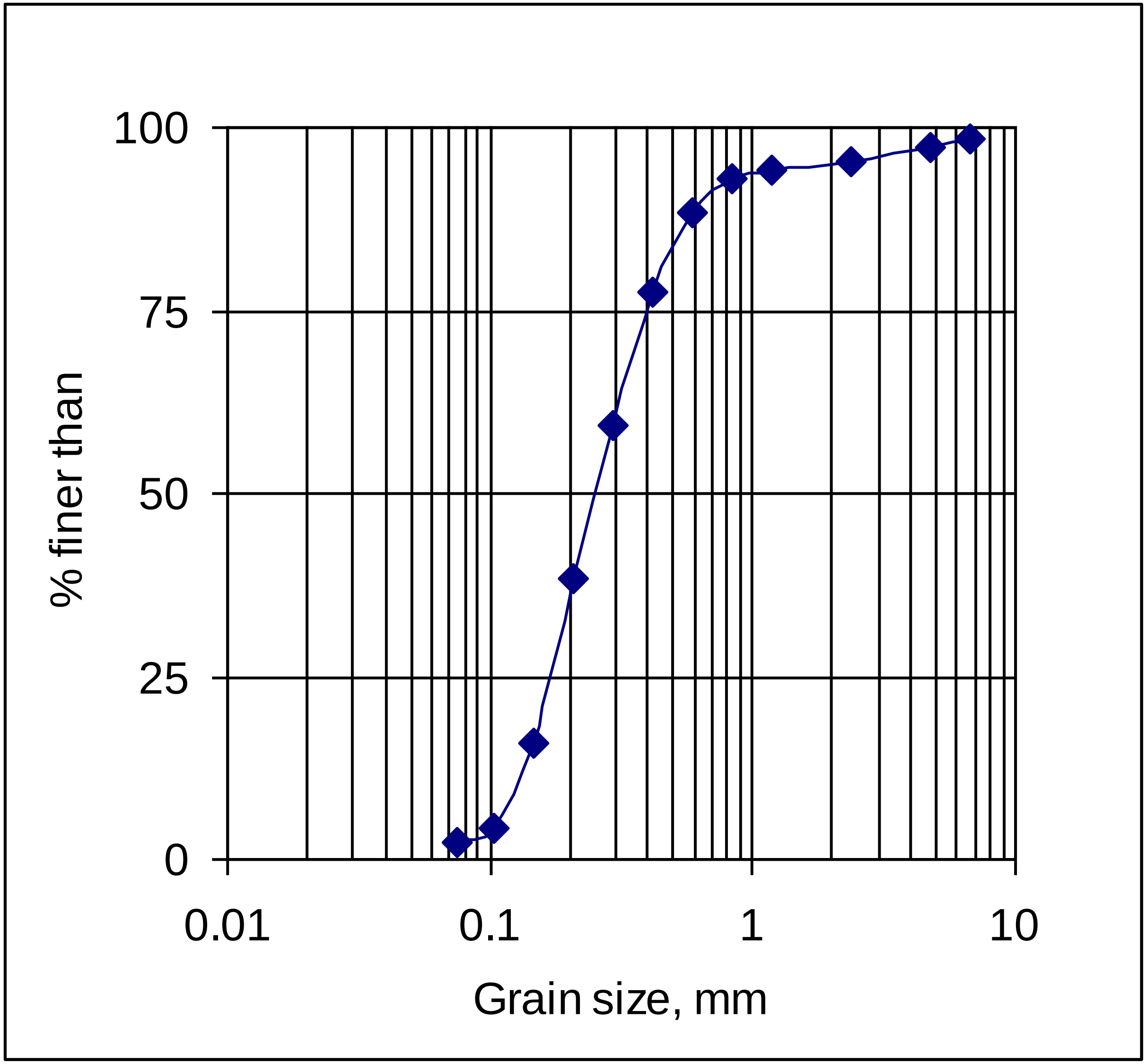


Bed Material

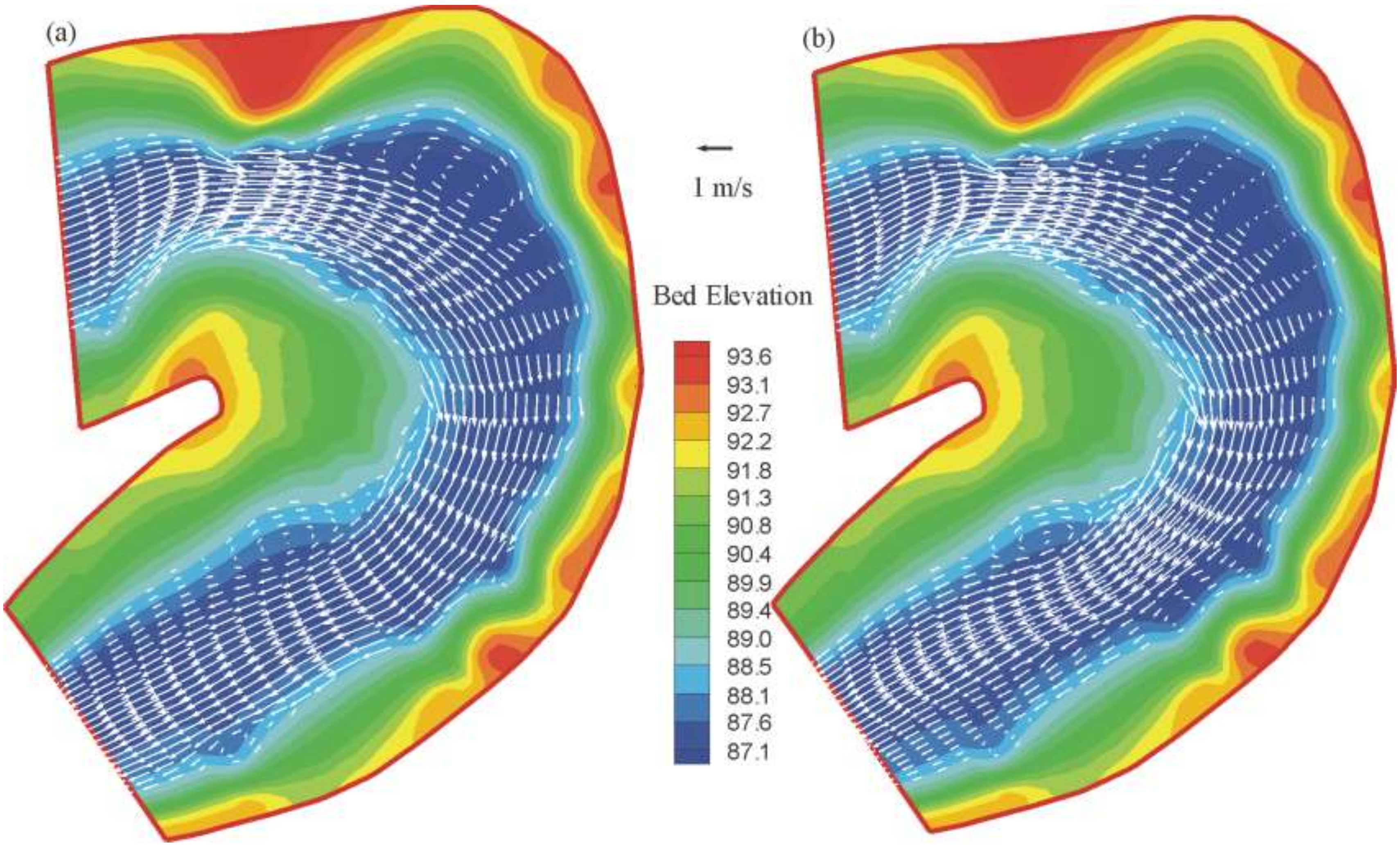
D_{84}=0.52mm

D_{50}=0.26 mm

D_{16}=0.15mm

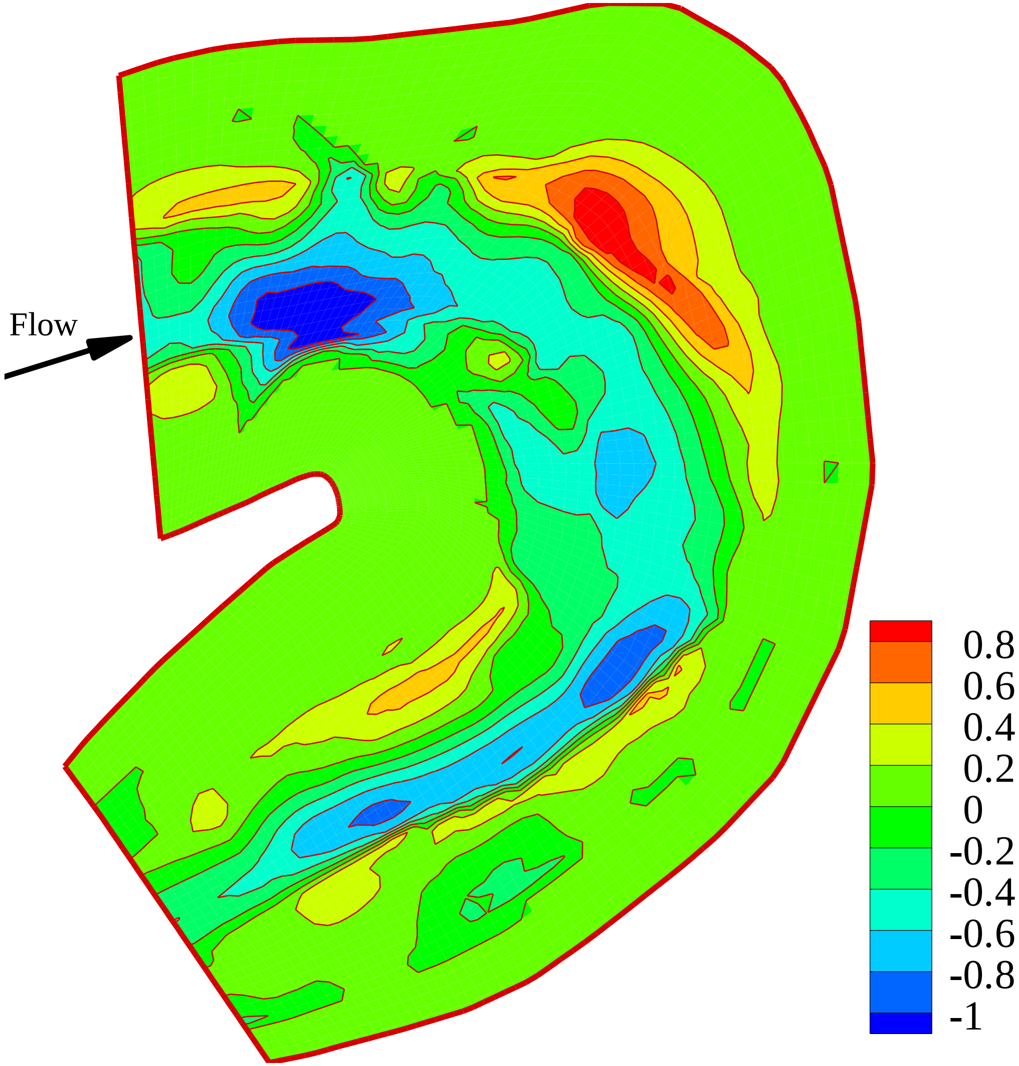


Simulated Flows in Little Topashaw Creek

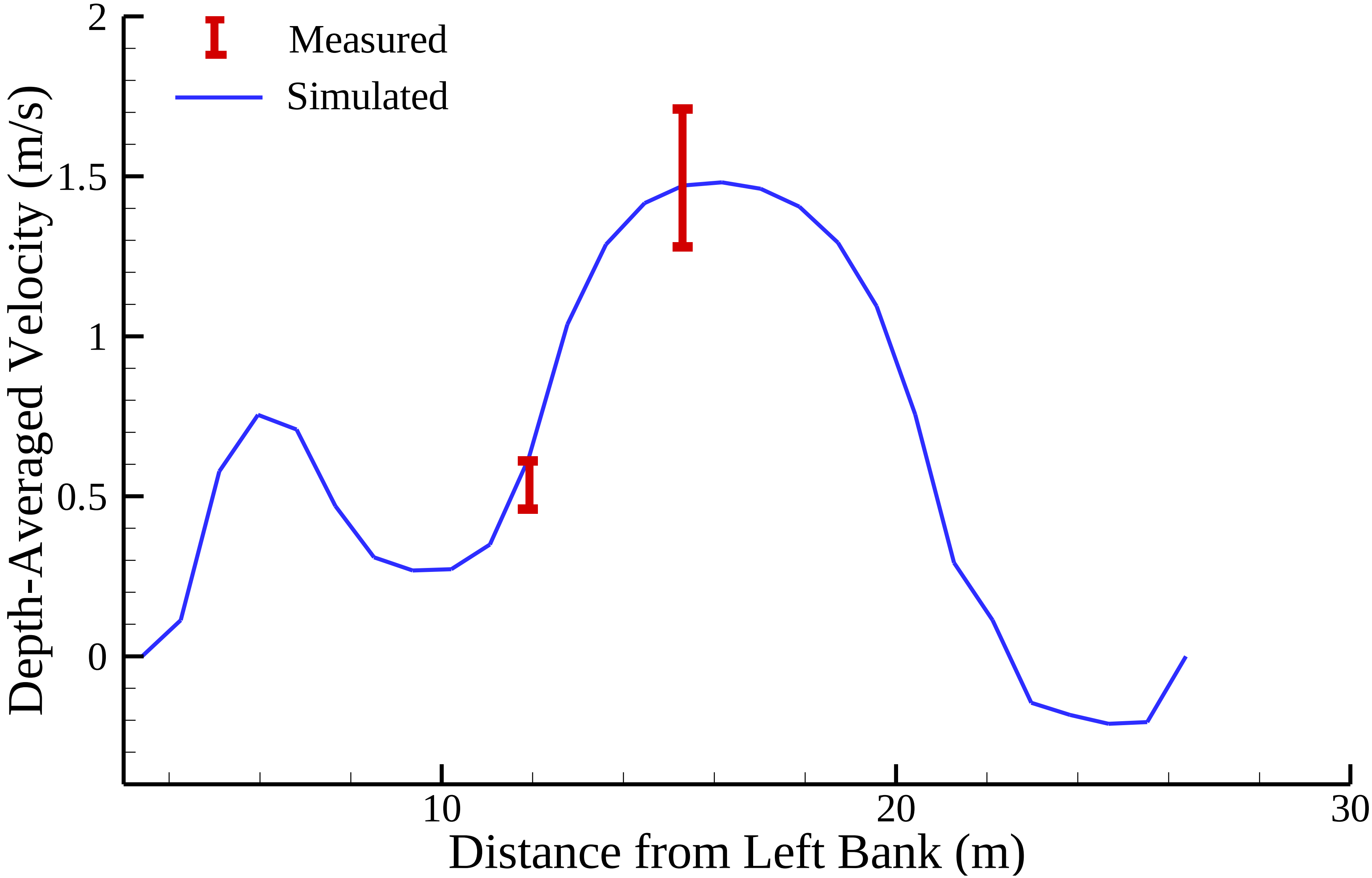


(a) without and (b) with Large Woody Structures

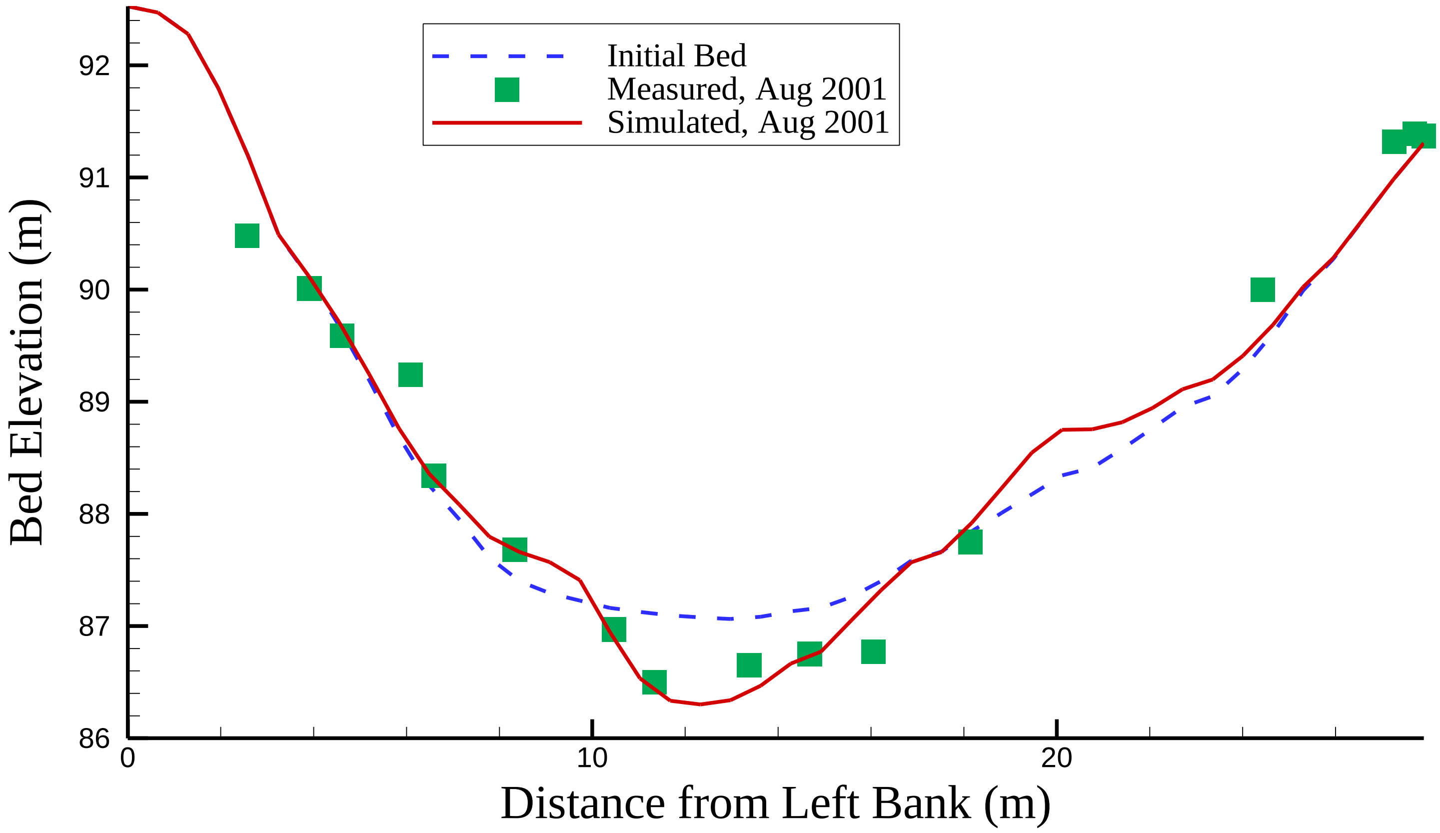
Simulated Bed Change after 1 Year



Flow Velocity at Cross Section LTH2



Bed Changes after 1 Year in Cross Section LTH2



Fish Species Considered

Blacktail Shiner (*Cyprinella venusta*)

It is usually most abundant in areas with swift current and riffles with silt, gravel, and bedrock substrates.

Largemouth Bass (*Micropterus salmoides*)

It is a top predator in the studied aquatic ecosystem

Habitat Suitability Index Model

Weighted Usable Area

$$WUA = \sum_{i}^{M} CSI_i \cdot \Delta A_i$$

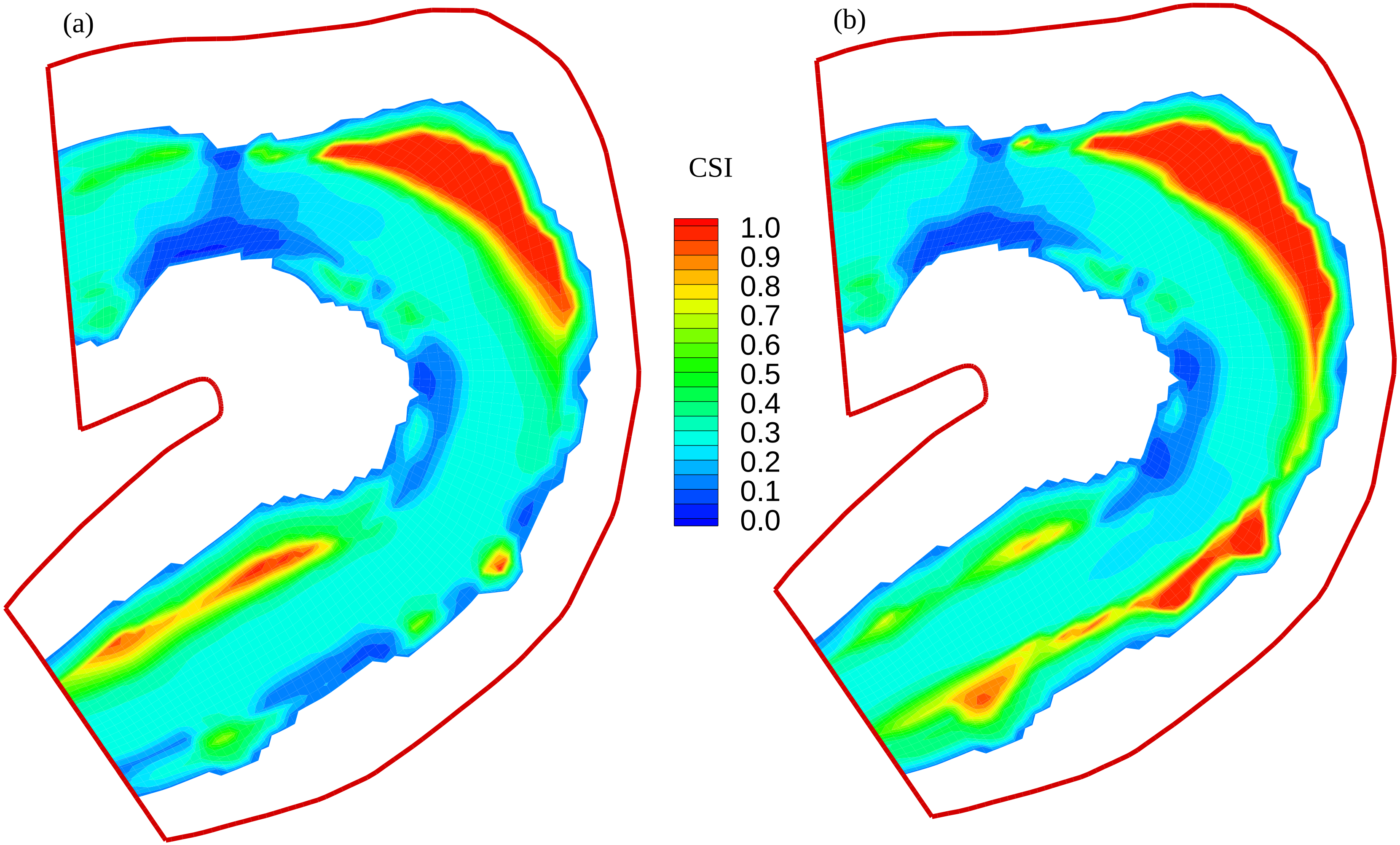
Overall Suitability Index

$$OSI = \sum_{i}^{M} CSI_i \cdot \Delta A_i \Big/ \sum_{i}^{M} \Delta A_i$$

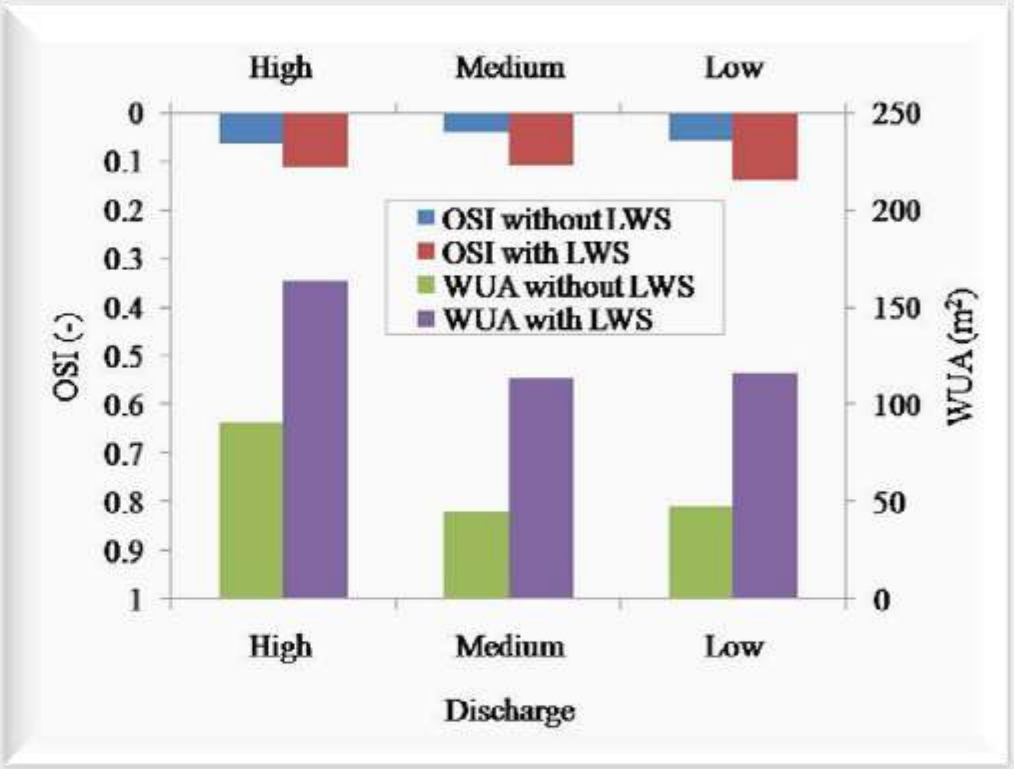
$$CSI_i = \text{Combined suitability index}$$

$$\Delta A_i = \text{Area of each wetted cell}$$

Combined Habitat Suitability Index



HSI Evaluation



The maximum increase of WUA for Blacktail Shiner was **22%**, while the maximum increase for Largemouth Bass was **155%**.

Comparison with Observations

Discharge (m^3/s)		Blacktail Shiner: Weight Usable Area (m^2)		Largemouth Bass: Weight Usable Area (m^2)	
		Without LWS	With LWS	Without LWS	With LWS
High	15.5	300.42	341.66	90.85	164.12
Medium	5.0	150.71	184.88	44.53	113.97
Low	1.5	112.97	138.35	47.26	116.15

Table 4 Summary of electrofishing catch (mean values) before and after LWS construction (Shields et al., 2006)

Quantity	Upstream	Treated reach	Downstream
	Before/After	Before/After	Before/After
Total no. of fish species	13/22	19/25	17/27
Fish catch biomass, g/150 m	262/337	150/407	168/397
Mean no. of fish per sample	74/143	129/177	141/186
Mean no. of species per sample	6.8/11.4	6.8/12.8	6.3/13.1
No. of Blacktail Shiner (*Cyprinella venusta*)	64/230	368/778	410/753
No. of Largemouth Bass (*Micropterus salmoides*)	0/7	0/9	3/3
Length of largest individual in each sample, cm	13/16	9/14	10/12

- ✓**The number of Blacktail Shiners doubled in the treated reach.**
- ✓**Largemouth Bass were captured in the treated reach following LWS construction but not before.**

Model of Wu and Marsooli (2012) and Wu (2013)

2-D Depth-Averaged Flow Equations

$$\frac{\partial(\rho h)}{\partial t}+\frac{\partial(\rho hu)}{\partial x}+\frac{\partial(\rho hv)}{\partial y}+\rho_b\frac{\partial z_b}{\partial t}=(\rho_s-\rho_w)\left[\frac{\partial}{\partial x}\left(\varepsilon_s h\frac{\partial C_t}{\partial x}\right)+\frac{\partial}{\partial y}\left(\varepsilon_s h\frac{\partial C_t}{\partial y}\right)\right]$$

$$\frac{\partial}{\partial t}(\rho uh)+\frac{\partial}{\partial x}(\rho u^2h)+\frac{\partial}{\partial y}(\rho uvh)$$
$$=\frac{\partial}{\partial x}\left(\mu_t h\frac{\partial u}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu_t h\frac{\partial u}{\partial y}\right)-F_x-\rho gh\frac{\partial z_s}{\partial x}-\frac{1}{2}gh^2\frac{\partial \rho}{\partial x}-\rho g\frac{n^2m_bUu}{h^{1/3}}$$

$$\frac{\partial}{\partial t}(\rho vh)+\frac{\partial}{\partial x}(\rho uvh)+\frac{\partial}{\partial y}(\rho v^2h)$$
$$=\frac{\partial}{\partial x}\left(\mu_t h\frac{\partial v}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu_t h\frac{\partial v}{\partial y}\right)-F_y-\rho gh\frac{\partial z_s}{\partial y}-\frac{1}{2}gh^2\frac{\partial \rho}{\partial y}-\rho g\frac{n^2m_bUv}{h^{1/3}}$$

Sediment Transport Model

Sediment Transport

$$\frac{\partial(hC_t)}{\partial t}+\frac{\partial(huC_t)}{\partial x}+\frac{\partial(hvC_t)}{\partial y}=\frac{\partial}{\partial x}\left(\varepsilon_s h\frac{\partial C_t}{\partial x}\right)+\frac{\partial}{\partial y}\left(\varepsilon_s h\frac{\partial C_t}{\partial y}\right)-\frac{1}{L}(UhC_t-m_b q_{t*})$$

Bed Change

$$(1-p'_m)\frac{\partial z_b}{\partial t}=\frac{1}{L}(\bar{U}hC_t-m_b q_{t*})+\frac{\partial}{\partial x}\left[D_s\bar{U}hr_bC_t\frac{\partial z_b}{\partial x}\right]+\frac{\partial}{\partial y}\left[D_s\bar{U}hr_bC_t\frac{\partial z_b}{\partial y}\right]$$

Sediment Transport Capacity q_{t*}

by Wu et al. (2000) Formula

Other Parameters

Eddy viscosity:

$$\nu_t = \sqrt{\left(\alpha_0 U_* h\right)^2 + \left(l_h^2 \left|\bar{S}\right|\right)^2}$$

Sediment adaptation length:

$$L = \max\left\{L_b, \frac{\bar{U}h}{\alpha\omega_s}\right\}$$

Numerical Methods

Finite volume method

Explicit algorithm – Euler scheme in time

HLL Riemann Solver for streamwise intercell fluxes and HLPA scheme for lateral fluxes

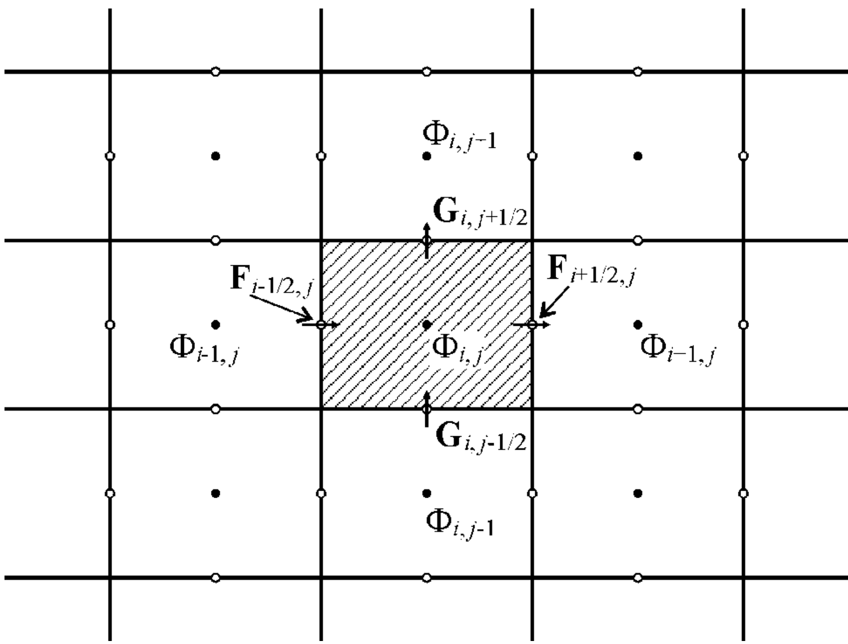
MUSCL piecewise linear reconstruction for second-order accuracy in space

Finite-Volume Discretization

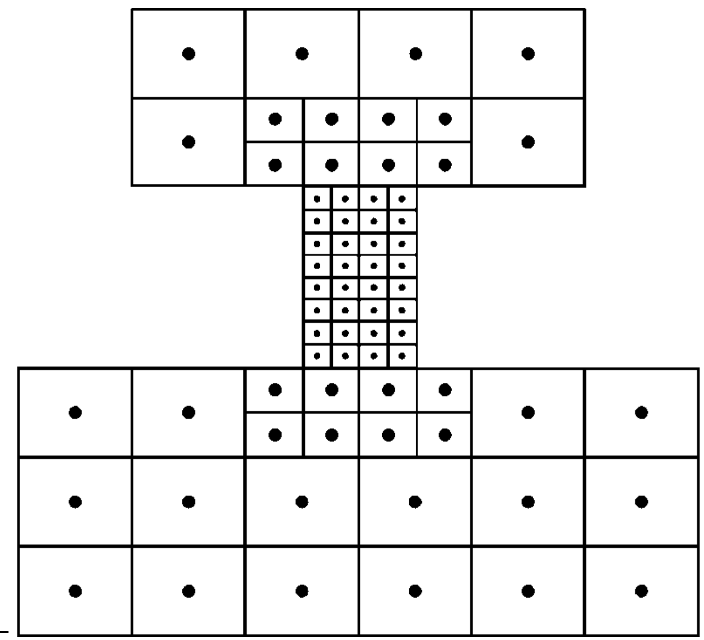
$$\frac{\partial \mathbf{\Phi}}{\partial t} + \frac{\partial \mathbf{F}(\mathbf{\Phi})}{\partial x} + \frac{\partial \mathbf{G}(\mathbf{\Phi})}{\partial y} = \mathbf{S}(\mathbf{\Phi})$$

$$\mathbf{\Phi}_{i,j}^{n+1} = \mathbf{\Phi}_{i,j}^{n} - \frac{\Delta t}{\Delta x_{i,j}}\left(\mathbf{F}_{i+1/2,j}^{n} - \mathbf{F}_{i-1/2,j}^{n}\right) - \frac{\Delta t}{\Delta y_{i,j}}\left(\mathbf{G}_{i,j+1/2}^{n} - \mathbf{G}_{i,j-1/2}^{n}\right) + \Delta t\,\mathbf{S}_{i,j}$$

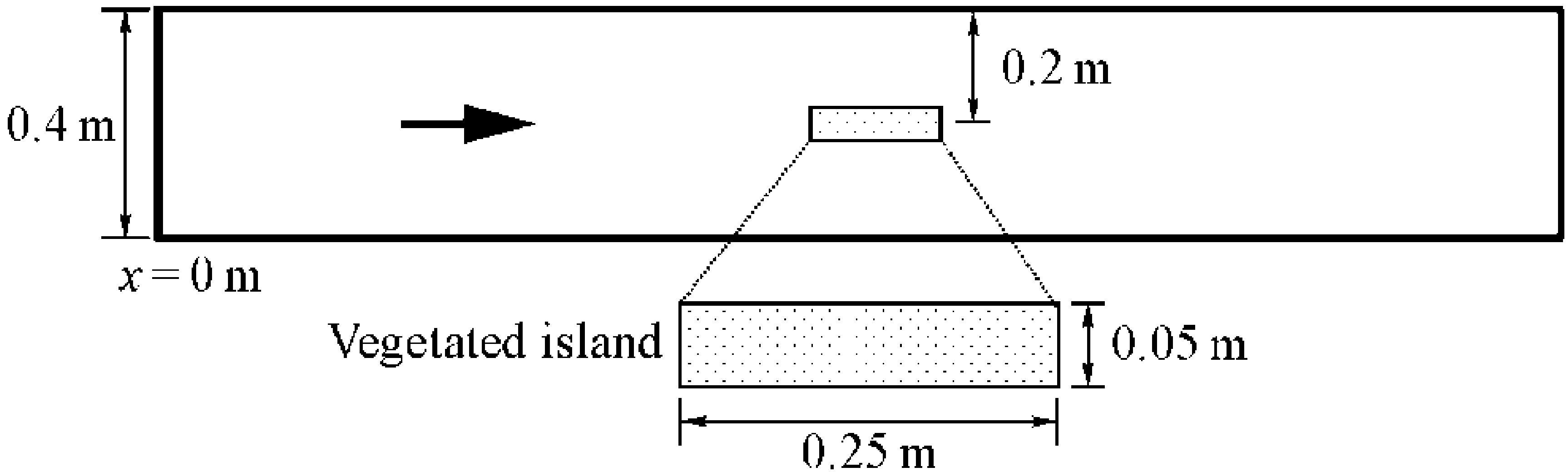
Rectangular mesh



Quadtree



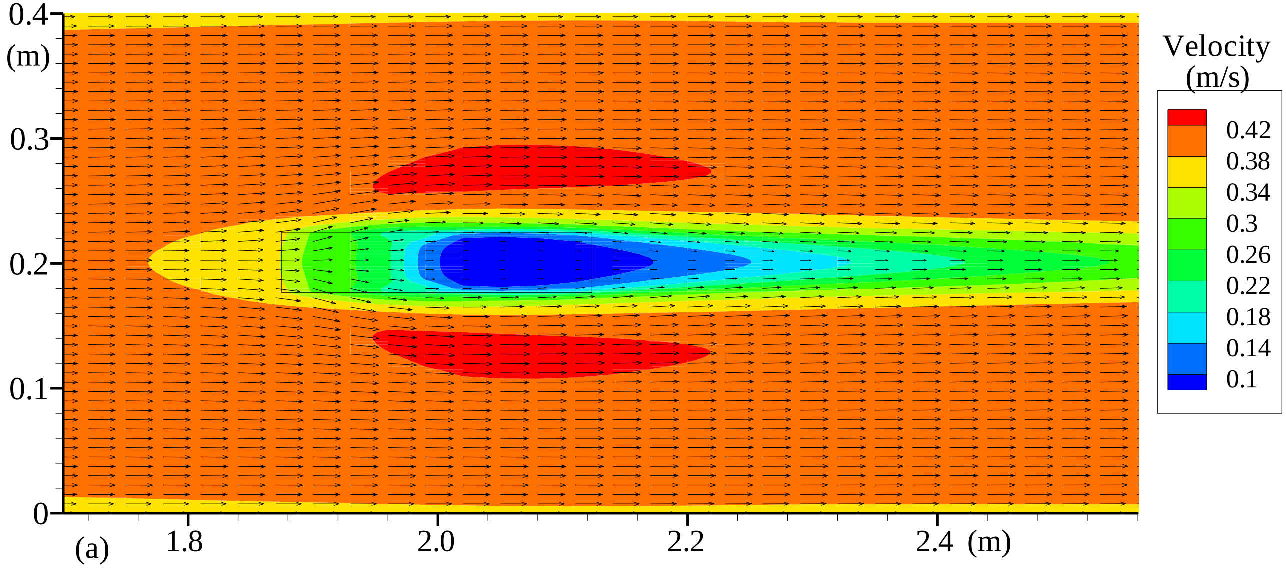
Bed Changes around Vegetated Island



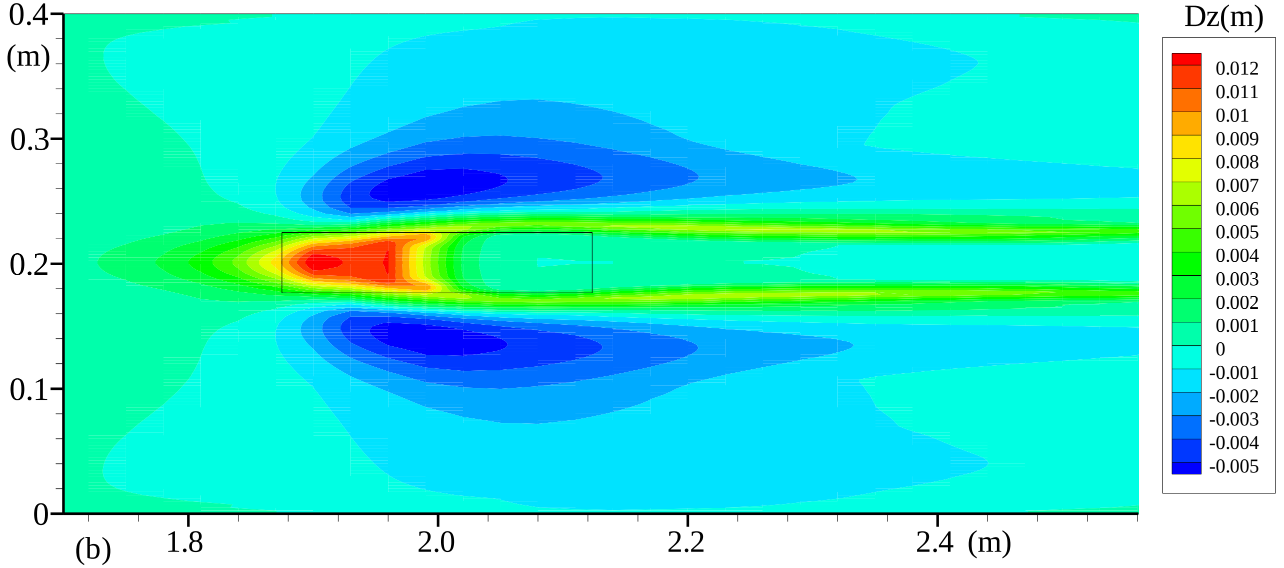
Plan view of Tsujimoto's (1998) experiments

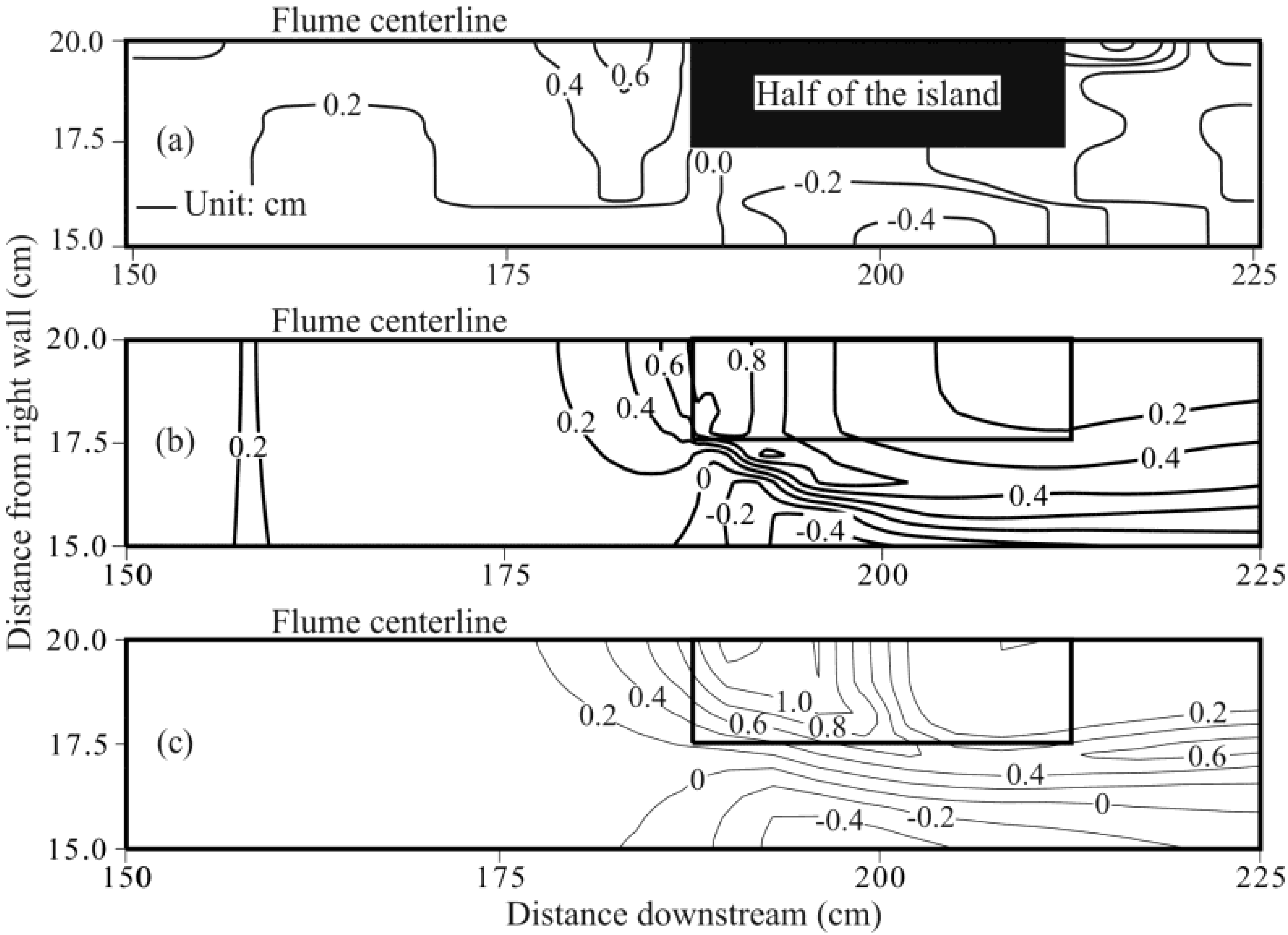
Simulation Results (Wu, 2013)

Velocity



Bed change

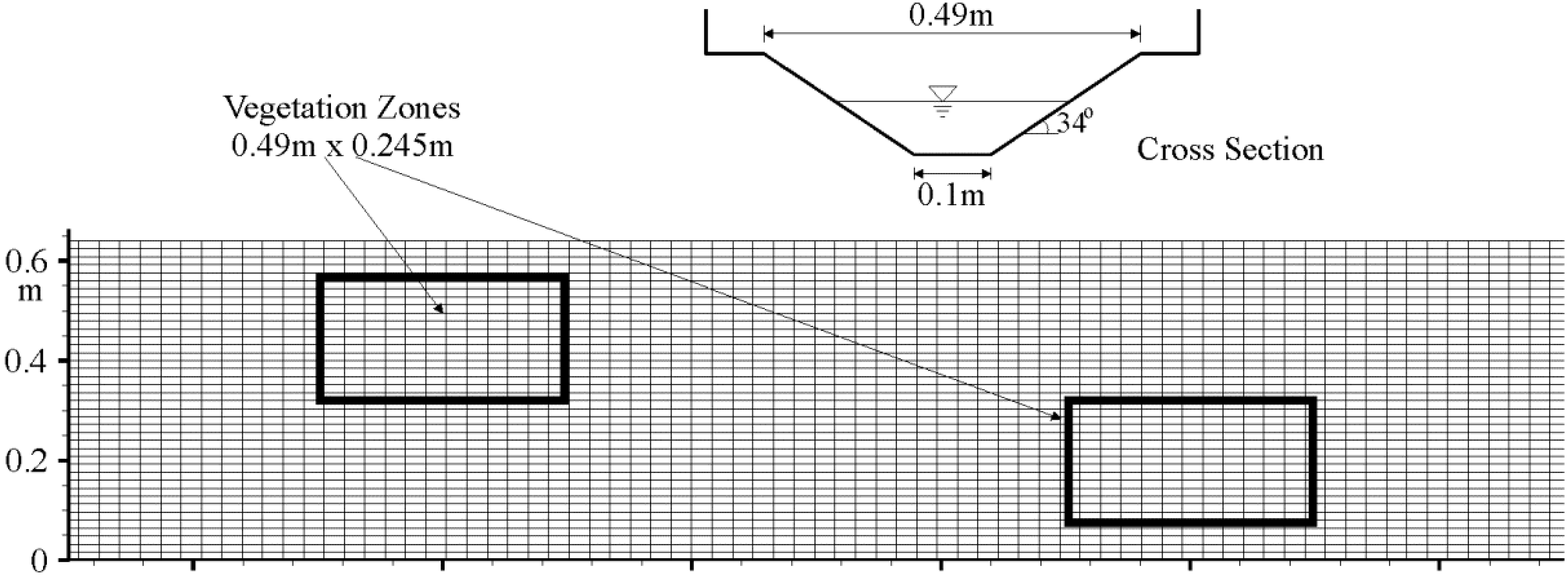




Bed changes around vegetated island: (a) Measured by Tsujimoto (1998); (b) Calculated by Wu and Wang (2004); and (c) calculated by Wu (2013) (contour unit: cm).

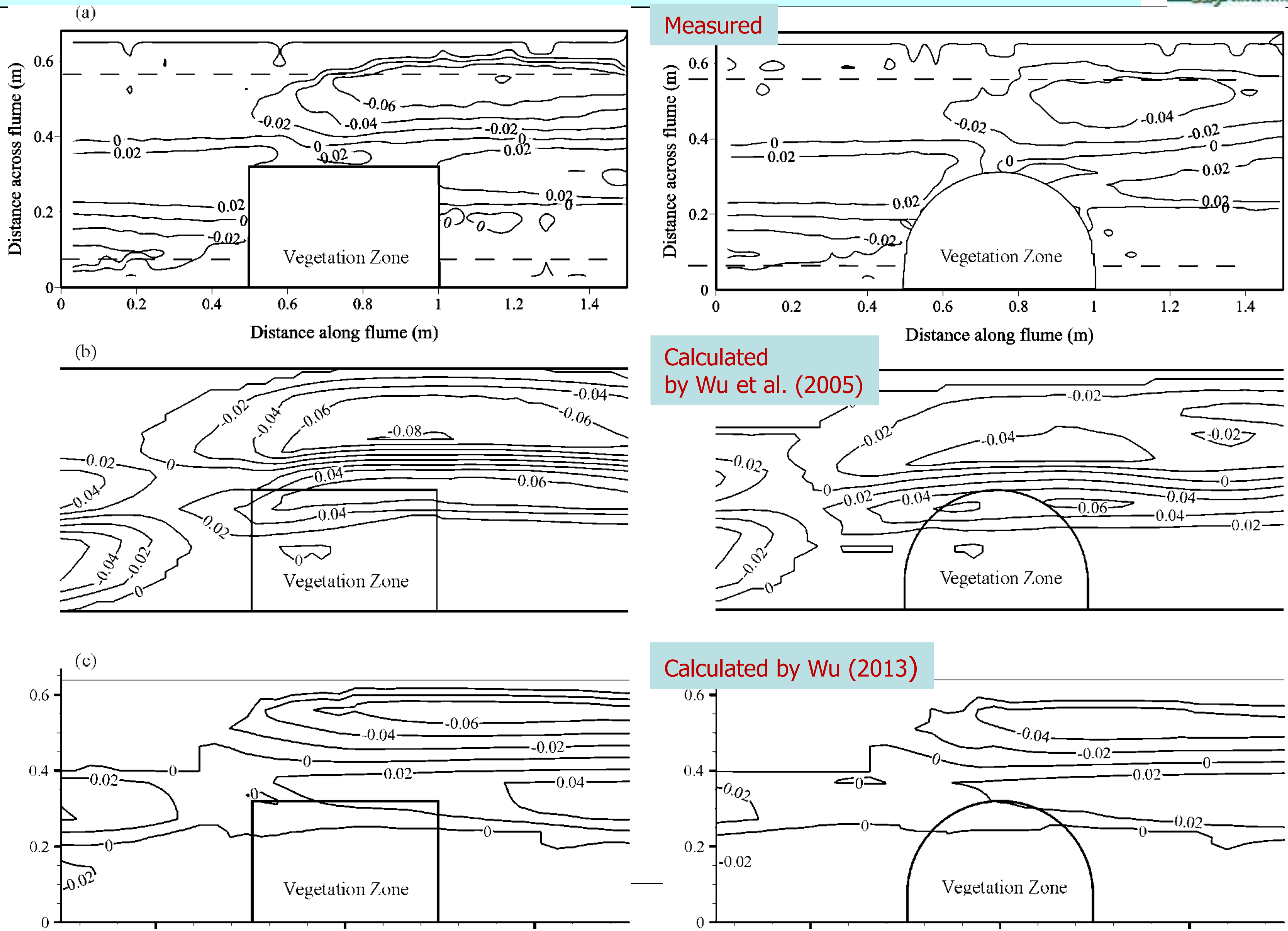
Bed Change around Alternate Veg. Bars

Setup of experiments of Bennett and Alonso (2003)

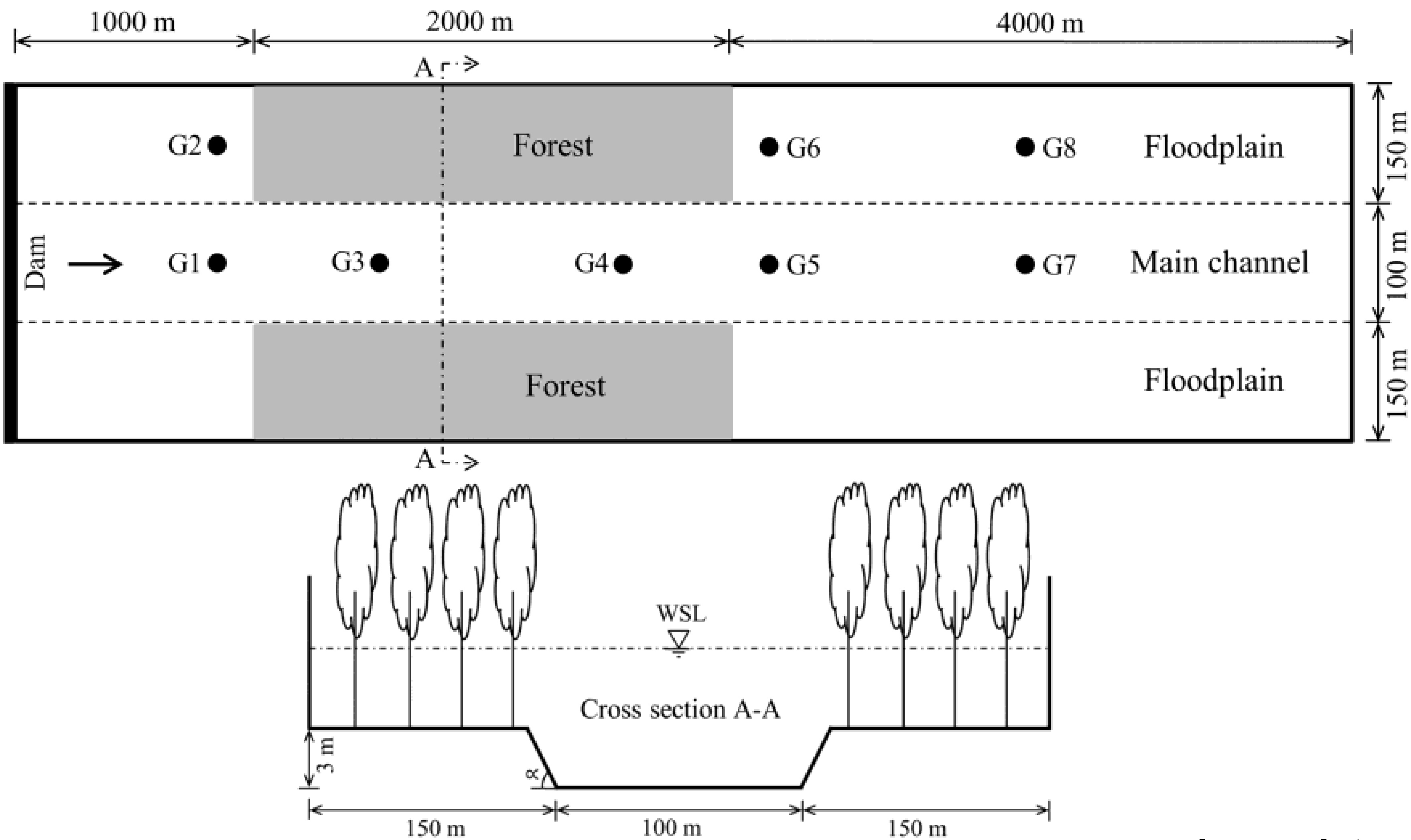


Mesh and sketch of the experiments of Bennett and Alonso (2003)

Calculated vs. Measured Bed Changes

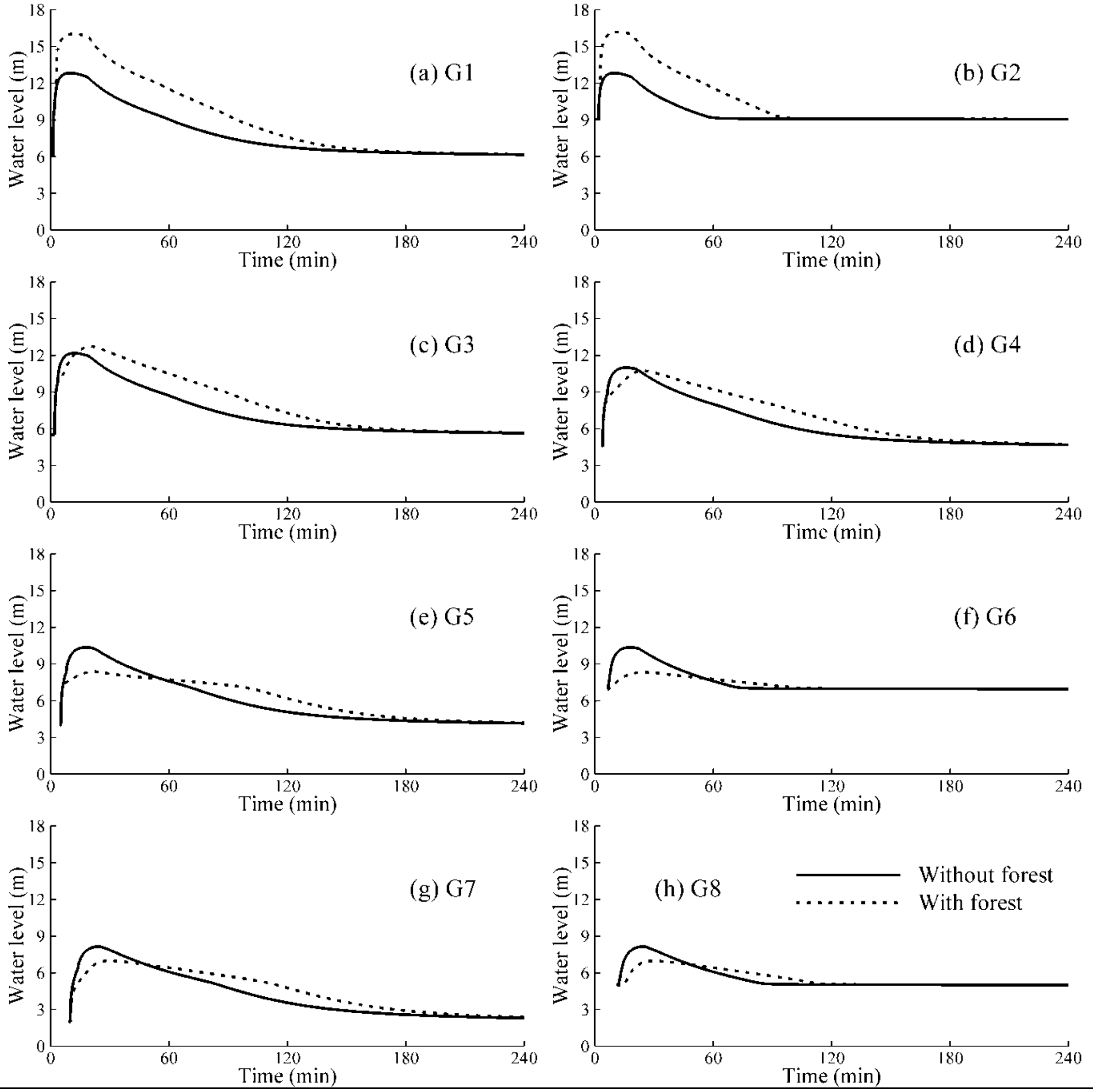


Dam-Break Flow over Vegetated Channel



Wu and Marsooli (2012)

Dam-Break Flow over Vegetated Channel



Publications Related

W. Wu and S. S.Y. Wang (2004). "Depth-averaged numerical modeling of flow and sediment transport in open channels with vegetation," Riparian Vegetation and Fluvial Geomorphology, edited by S. J. Bennett and A. Simon, AGU, pp. 253–265.

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W. Wu (2013). "An explicit finite-volume depth-averaged 2-D model of morphodynamic processes near marsh edges and vegetation patches." Proc. 12th International Symposium on River Sedimentation, Kyoto, Japan, Sept. 1-5.