Mapping Vegetation Properties and Flow Patterns in STAs using Wave Tests

Wasantha Lal,
Zaki Moustafa
Walter Wilcox
South Florida Water Management District

Why is the study of vegetation resistance important?

- Timing and attenuation of flood peaks in hydrologic systems and models depends on vegetation resistance
- Operation of STAs require a knowledge of hydraulic transients in vegetated wetlands
- Designing efficient treatment wetlands is primarily a hydraulic problem because of the influence of turbulence, dead flow zones, mixing and retention.

Challenges

- There is no vegetation measurements available (diameter, spacing, density, biomass)
- Access is challenging.
- Measurements of depth, slope, and flow velocity, etc. are not easy

Progress in establishing the "Science"

- ASCE J. Hydraul.

is part of the *Journal of Hydraulic Engineering*, © ASCE, ISSN 0733-9429.

- AGU/WRR Pub.


AGU PUBLICATIONS

Water Resources Research

RESEARCH ARTICLE

The use of discharge perturbations to understand in situ vegetation resistance in wetlands

A. M. Wasantha Lal[1], M. Zaki Moustafa[1], and Walter M. Wilcox[1]

- Workshop by Prof Heidi Nepf, MIT
- Contacts with Kadlec, R. H.
- 3-4 presentations at conferences

Recent Developments

Understanding of the Mechanics has changed

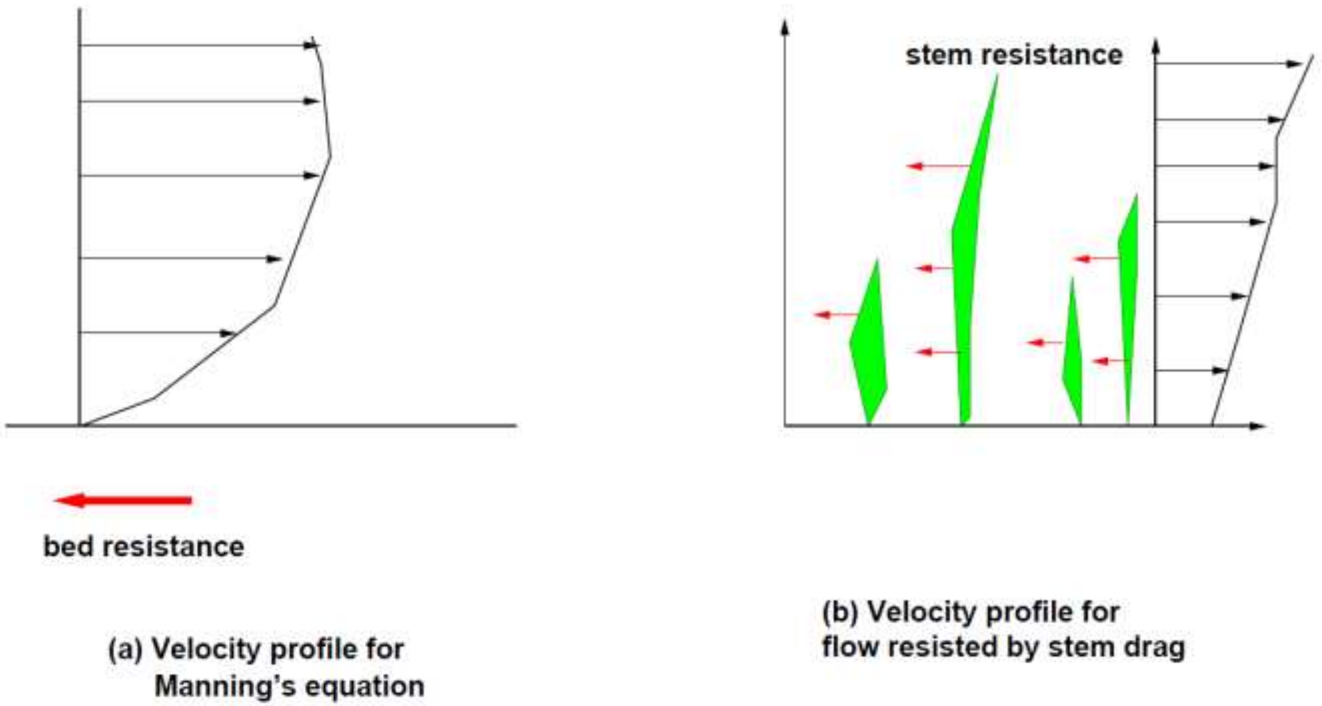


Figure 7.2: Vertical velocity profiles in open channels and vegetated wetlands

Parameterization is improving

The commonly used equation for depth-averaged force balance is

$$g s_f = \frac{1}{2} c_D a U^2 + \frac{\tau_0}{\rho H}$$

where

$$a = \frac{\text{frontal area}}{\text{volume}}$$

and ah = frontal area index.

a used to define vegetation density

Computational Fluid Dynamics

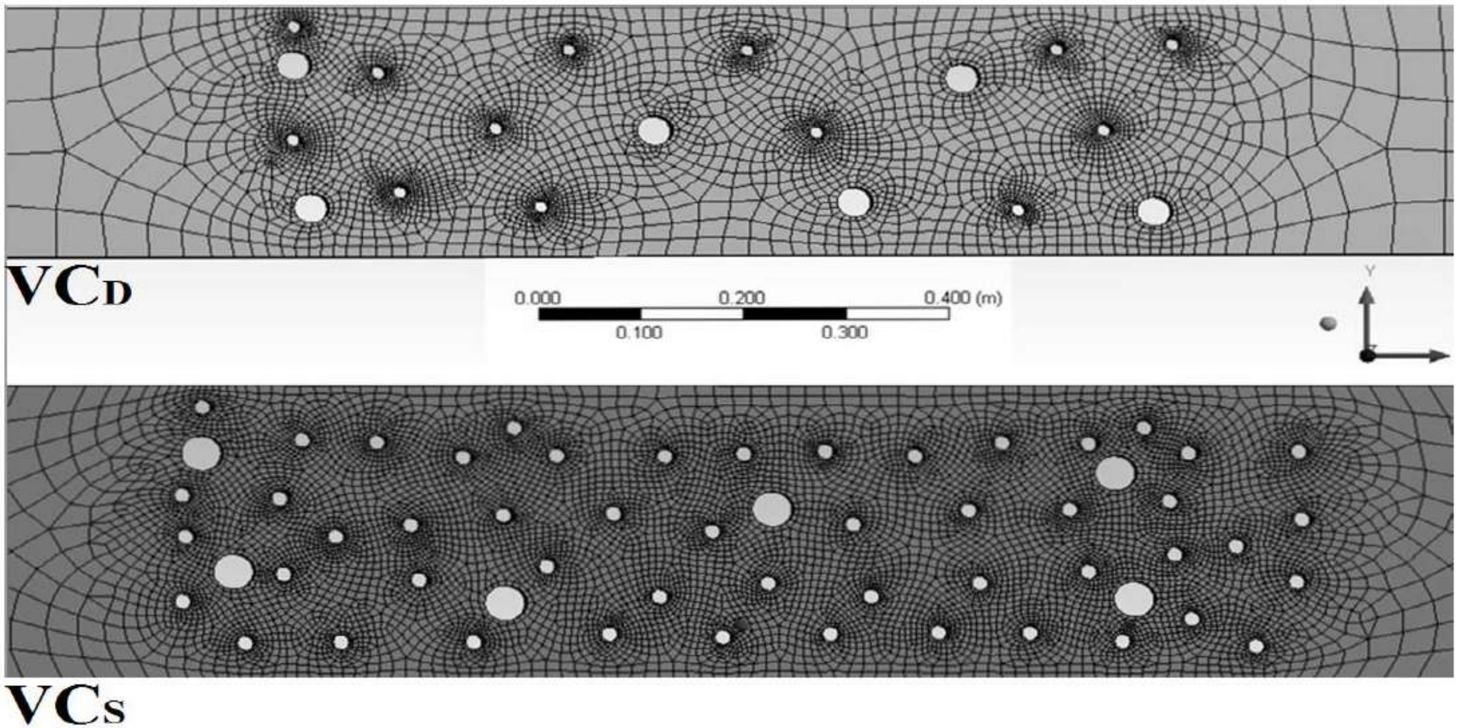


Figure-2. Plan view of the mesh for the vegetation cover (VC_D) of the deep flow region and the vegetation cover (VC_S) of the shallow flow part for the IS configurations.

In the absence of data,
we used wave propagation methods,
monitored wave velocity and attenuation

Basic mathematical methods used for the formulation

- Adv. Fluid Mechanics – Incompressible Flow, Panton
- Differential calculus - Hilderbrand
- Complex variables -
- Spectral analysis –
- Linear stability theory -
- Perturbation theory – Fluid mechanics, Kundu
- Transport and dispersion of solutes - Fisher

Use of depth averaged flow

2.1. Depth-Averaged Flow Equations

St. Venant's equations are used to analyze the shallow water waves generated in the wetlands. The St. Venant's equations consist of a continuity equation and a momentum equation.

$$\frac{\partial h}{\partial t}+\frac{\partial q}{\partial x}=0 \tag{1}$$

$$\frac{\partial q}{\partial t}+\frac{\partial}{\partial x}\left(\frac{q^2}{h}\right)+gh\left(s_f+\frac{\partial h}{\partial x}-s_0\right)=0 \tag{2}$$

where h = water depth; q = discharge per unit width; g = gravitational acceleration; $s_0=-\frac{\partial z}{\partial x}$ = bed slope; z = bottom elevation; $H=h+z$ = water level; s_f = friction slope. Figure 1 shows a definition sketch drawn


AGU PUBLICATIONS

Water Resources Research

RESEARCH ARTICLE

The use of discharge perturbations to understand in situ vegetation resistance in wetlands

A. M. Wasantha Lal[1], M. Zaki Moustafa[1], and Walter M. Wilcox[1]

Energy Slope s_f related to discharge $q(h, s_f)$ with a smooth function

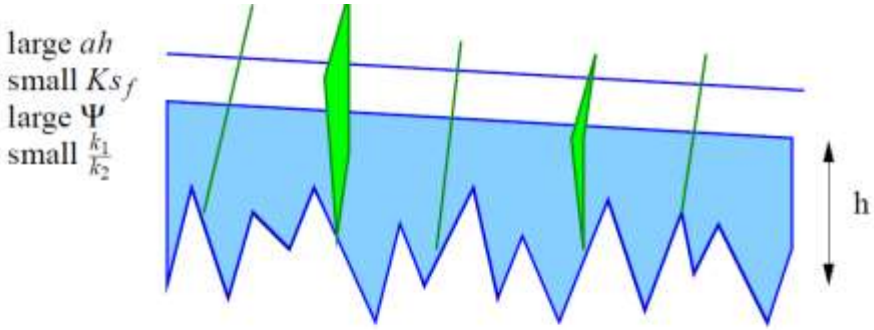
$$\Delta q = a \Delta h + K \Delta s_f$$

$$a(h, s_f) = \frac{\partial q(h, s_f)}{\partial h}, \quad \text{and} \quad K(h, s_f) = \frac{\partial q(h, s_f)}{\partial s_f}$$

a = kinematic celerity [*Chow*, 1956];

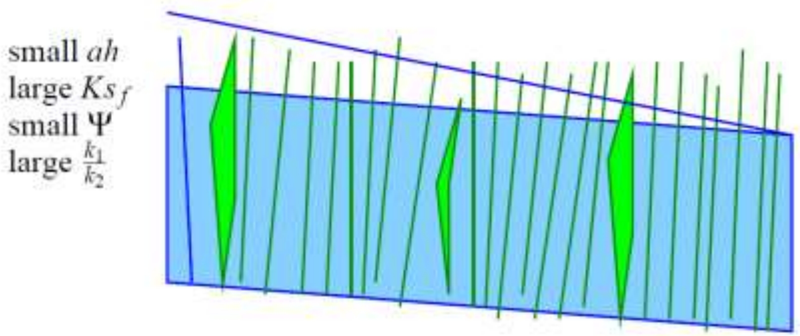
K = hydraulic diffusivity, or transmissivity

Kinematic vs Porous Media Flow



(a) Figure showing a large change in discharge with depth. Change in discharge with slope is small.

Kinematic



(b) Figure showing large change in discharge with slope. Change in discharge with depth is small.

Diffusive

For 2-D Wave Propagation in a Shallow Water Medium

Linearization of (3.1) leads to

$$\frac{\partial h}{\partial t} + a_x \frac{\partial h}{\partial x} + a_y \frac{\partial h}{\partial y} = K_x \frac{\partial^2 h}{\partial x^2} + K_y \frac{\partial^2 h}{\partial y^2} + 2K_{xy} \frac{\partial^2 h}{\partial x \partial y} \tag{3.5}$$

where

$$a_x = \frac{\partial q_x}{\partial h} = \frac{\partial T}{\partial h} s_{fx} \tag{3.6}$$

$$a_y = \frac{\partial q_y}{\partial h} = \frac{\partial T}{\partial h} s_{fy} \tag{3.7}$$

$$K_{xx} = \frac{\partial q_x}{\partial s_{fx}} = \frac{\partial T}{\partial s_{fn}} \frac{s_{fx}^2}{s_{fn}} + T \tag{3.8}$$

$$K_{yy} = \frac{\partial q_y}{\partial s_{fy}} = \frac{\partial T}{\partial s_{fn}} \frac{s_{fy}^2}{s_{fn}} + T \tag{3.9}$$

$$K_{xy} = \frac{\partial q_x}{\partial s_{fy}} = \frac{\partial T}{\partial s_{fn}} \frac{s_{fy} s_{fx}}{s_{fn}} \tag{3.10}$$

Choose Power law equations – For Easy Mathematics

- Discharge is a function of water depth and slope:

$$q = f(depth, slope) = f(d, s)$$

Smooth function

$$q = \frac{1}{n_b} h^{1+\gamma} s^{\alpha}$$

Chosen Template

Three physical parameters to match three physical characterizations of hydraulics

- γ Gamma – gives depth variability
- α Alpha – gives level of turbulence
- n_b Manning's constant characterizes the resistance

$$q = \frac{1}{n_b} h^{1+\gamma} |s_f|^{\alpha} \operatorname{sgn}(s_f)$$

Field Test

STA3/4 Cell 2A Wave 1
Discharge 750 cfs,
Period 64 hour

STA3/4 Cell 2A

Waves generated using canal flow

Array of data loggers

Figure 2.1: Location of the data loggers and the IDs.

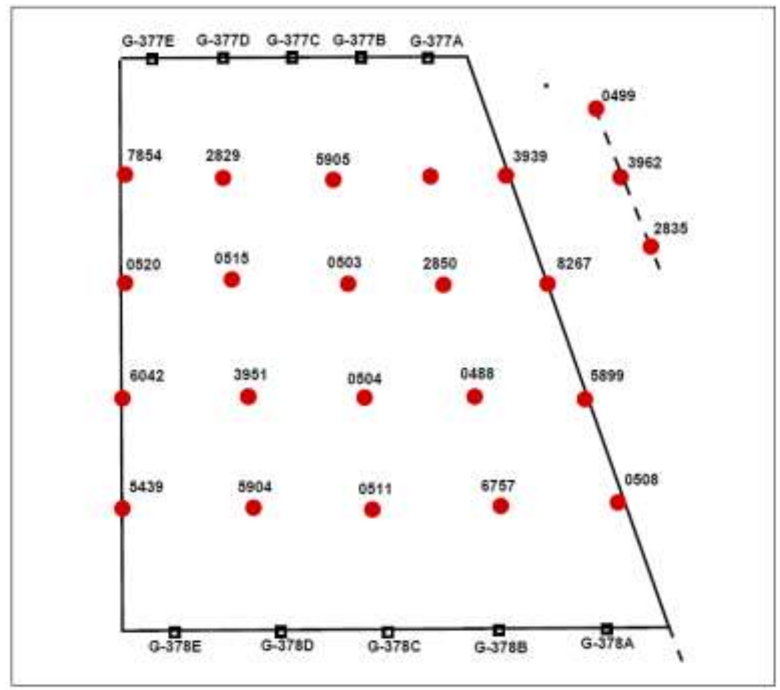


Figure 2.2: Locations of data loggers and the serial numbers. The loggers 0499, 3962 and 2835 are south of 0508 along levee

Decay rates and wave numbers, 750 cfs

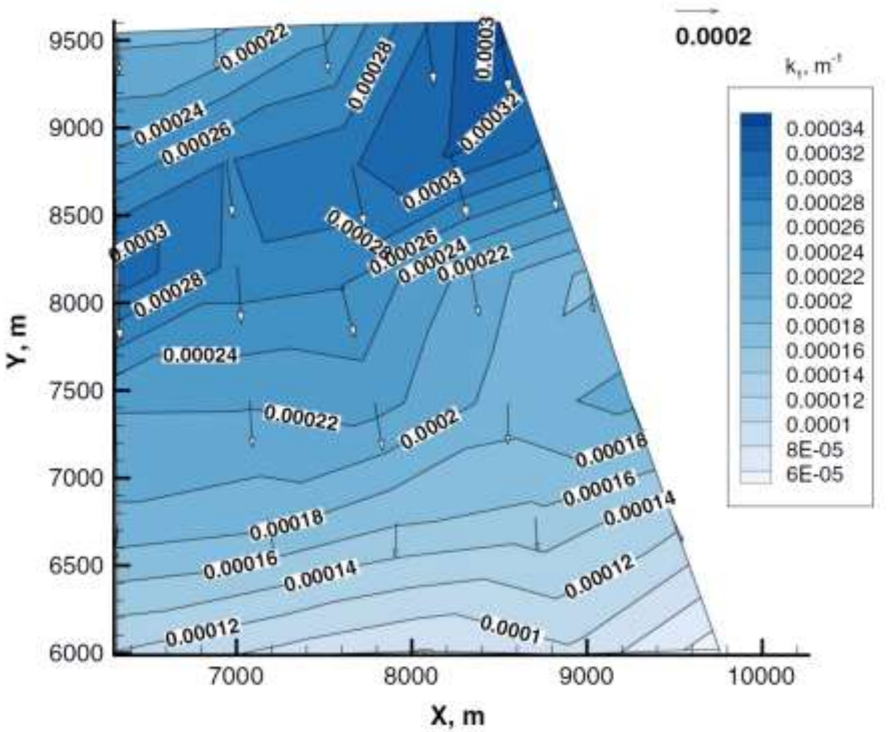


Fig. 6. Decay coefficients k_1 for STA 3/4 Cell 2A wave test with $Q = 21.2\ m^2/s$ as vectors and contours

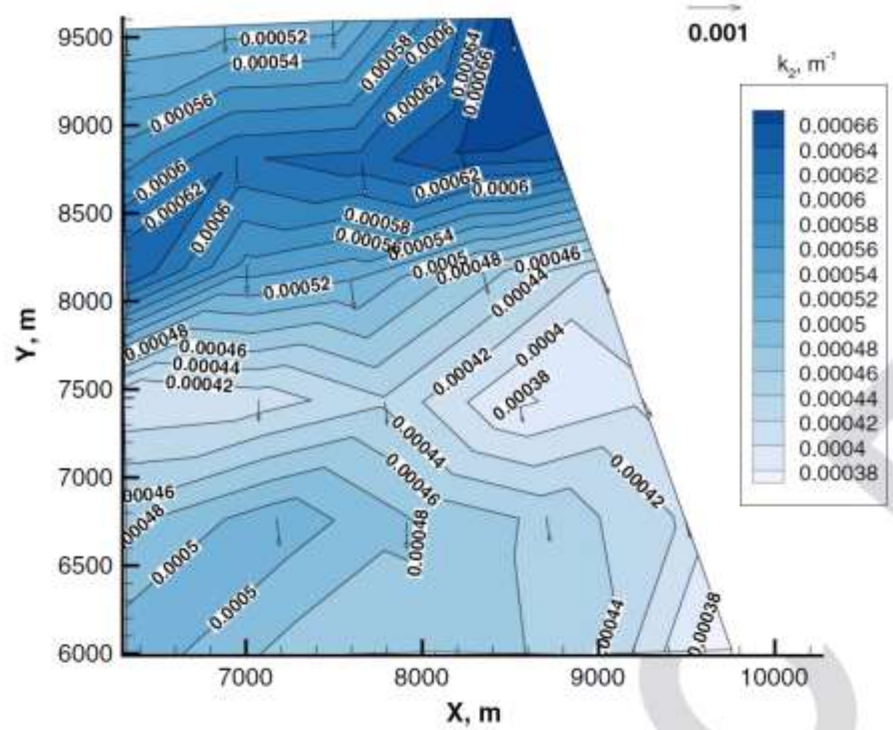


Fig. 7. Wave numbers k_2 for STA-3/4 Cell 2A wave test with $Q = 21.2\ m^2/s$ as vectors and contours

Transmissivity

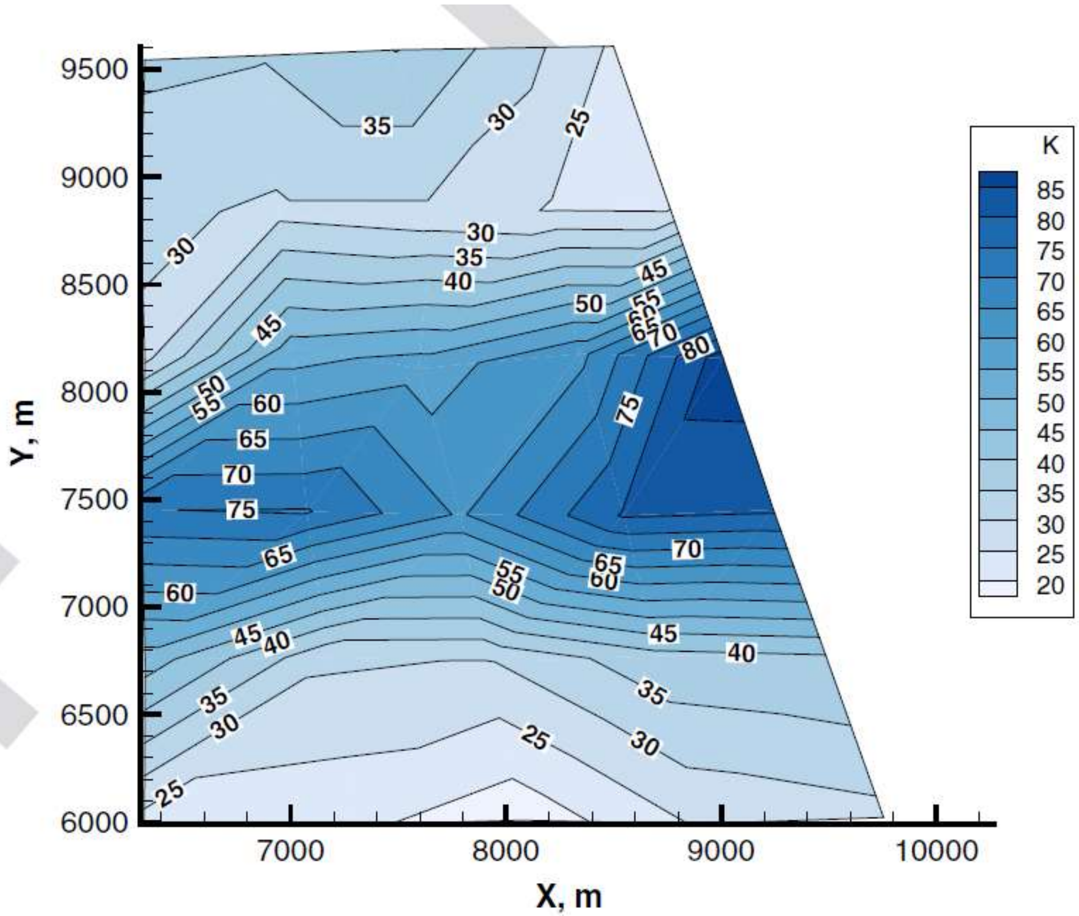


Fig. 9. Contours of transmissivity K in (m^2/s) for Cell 2A wave test with $Q = 21.2\ m^2/s$

Contours of $1 + \gamma$

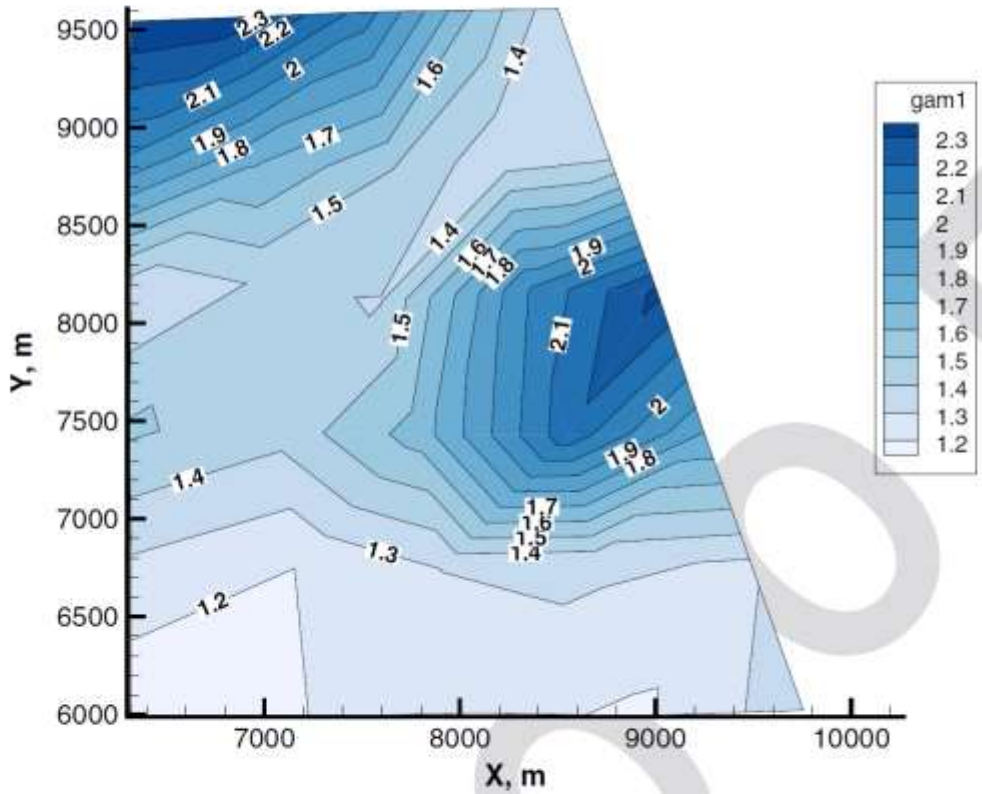


Fig. 12. Contours of $1 + \gamma$ for Cell 2A wave test with $Q = 21.2\ m^2/s$; values much larger than 1 indicate possible short-circuiting

$$\Psi = \frac{\text{Discharge through the kinematic mechanism}}{\text{Discharge through the diffusion mechanism}}$$

$$\Psi = \frac{a(h)h}{K(h)s_f}$$

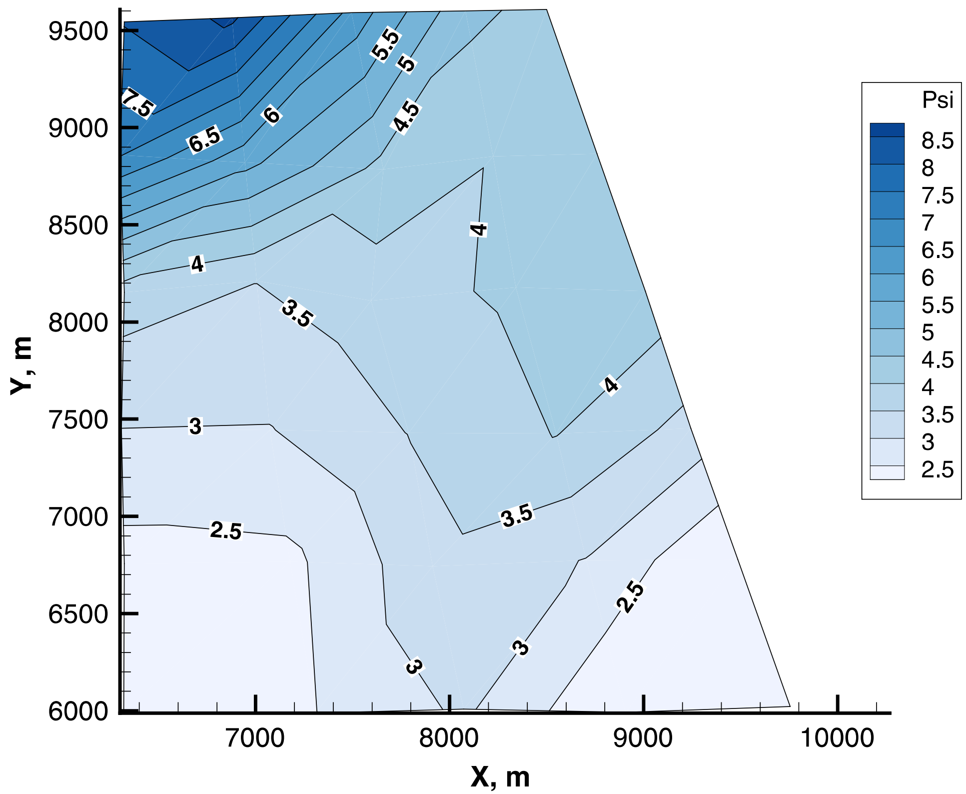


Fig. 14. Contours of Ψ for Cell 2A wave test with $Q = 21.2\ \mathrm{m^2/s}$

Function q(h,s_f) on log-log axes

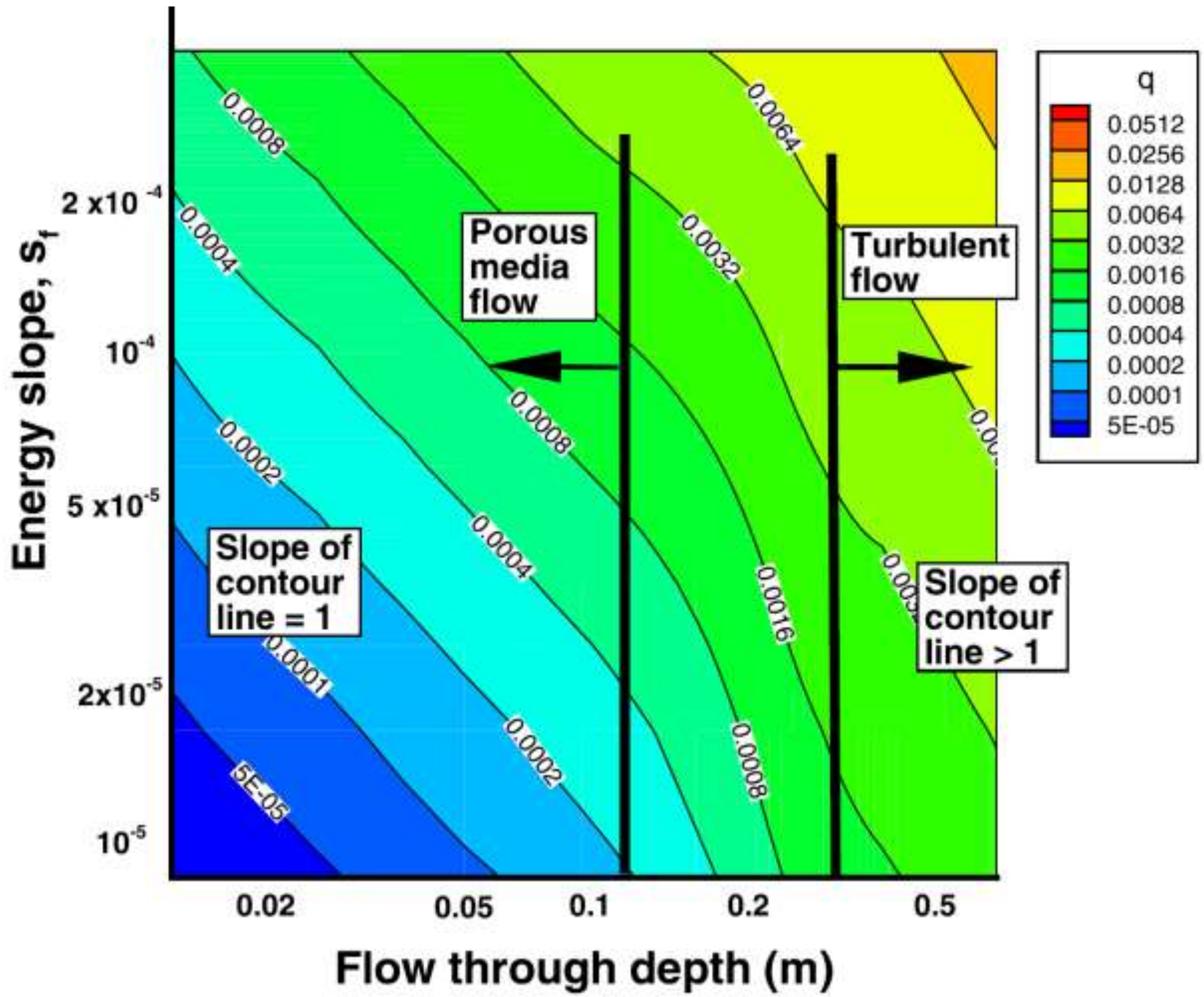


Figure 7. Contours of average discharge per unit width q (m^2/s) obtained using power law equations. The plots are made on log-log axes.

K, transmissivity regimes

- K < 20 m^2/s – dense cattail – excellent
- 20 < K < 60 m^2/s – cattail with open spaces
- 60 < K m^2/s – watch for short circuiting (k > 100 m/
- 1000 < K – shallow overland flow
- 4000 < K – deep hole

- 0.001-0.01 m/s hyd cond - sand

Velocity nonuniformity $(1+\gamma)$

- $(1+\gamma)$ = 1 uniformly distributed over depth
- Between 1 and 3 - normal
- Over 3 – Velocity non-uniformity

- 1.67 – Overland flow

Summary

- Maps for wave decay, wave speed, and resistance.
- In-situ bulk resistance functions, were graphical plots of q(slope, depth), and power-law equations.
- Dimensionless numbers to detect kinematic and diffusive flow conditions or laminar/turbulent conditions in STAs.