INTERNATIONAL WORKSHOP
on *RIParian FORest*
Vegetated Channels: Hydraulic Morphological and Ecological Aspects
Trento, Italy, 20-22 February 2003

"Using vegetation properties to predict flow resistance and erosion rates"

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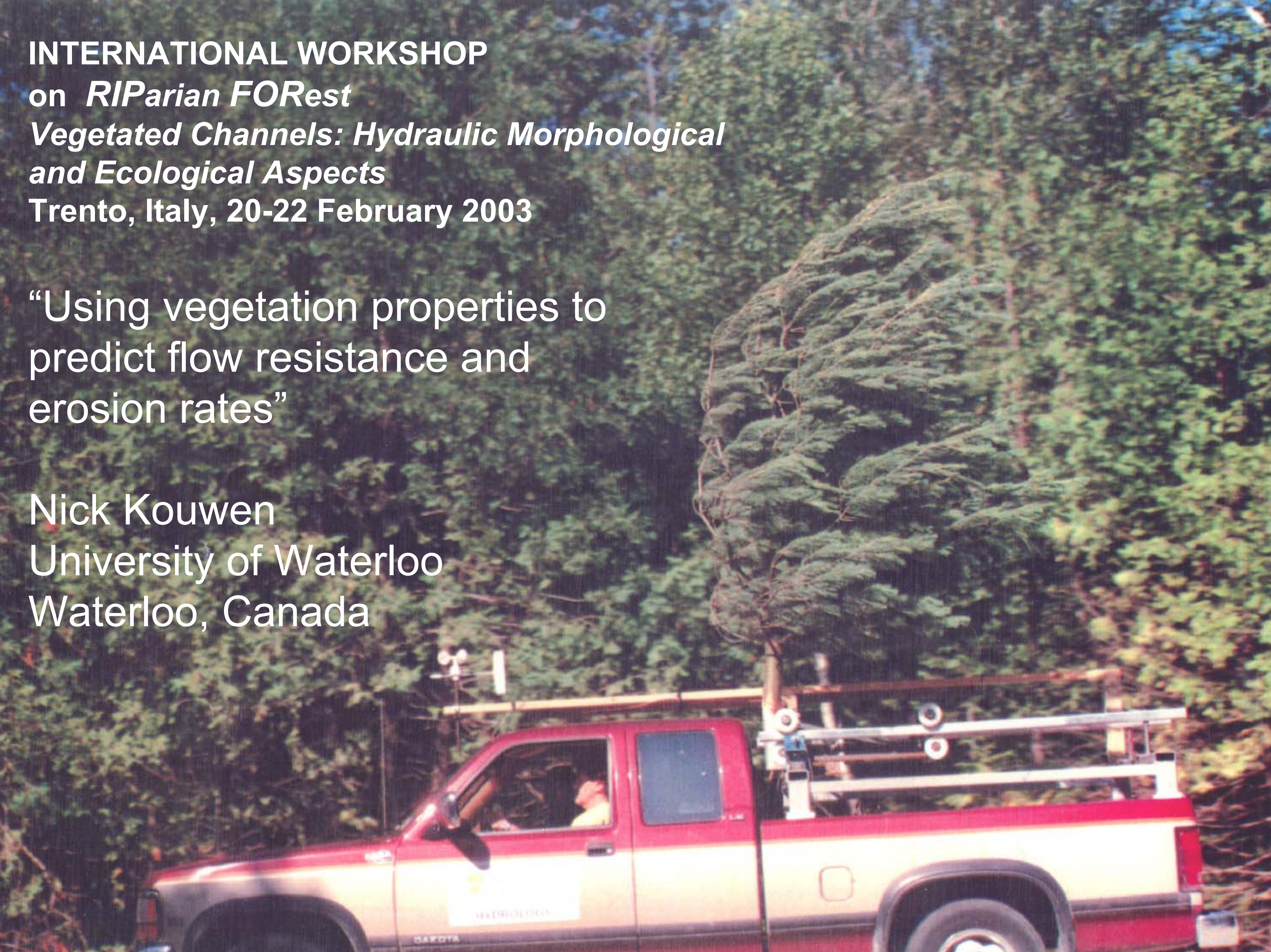
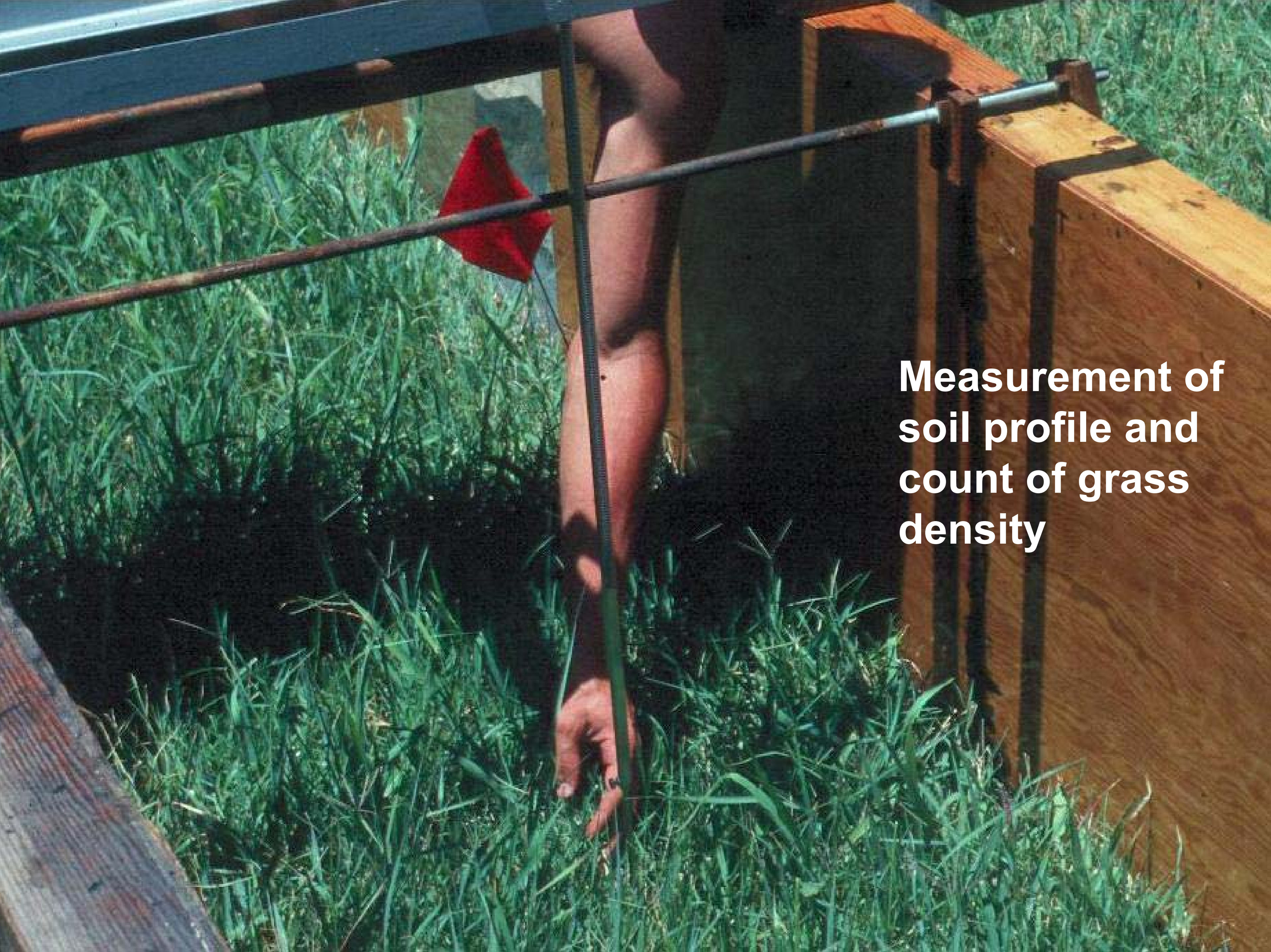
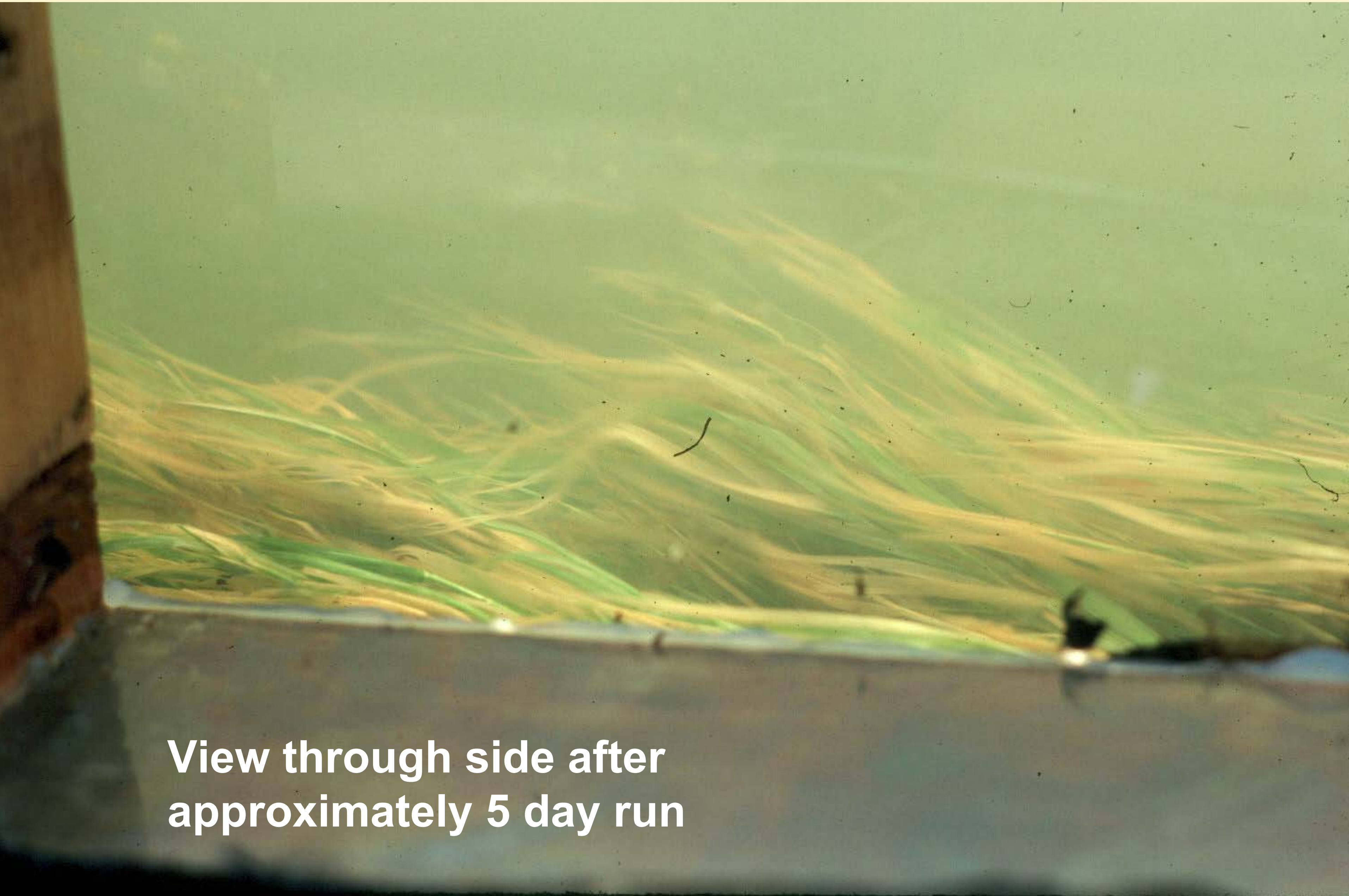


US Dept. of Agriculture, Stillwater Okla. Lab. 1985
Test channels 5% slope (This run 1.7 m^3/s 60 cfs)

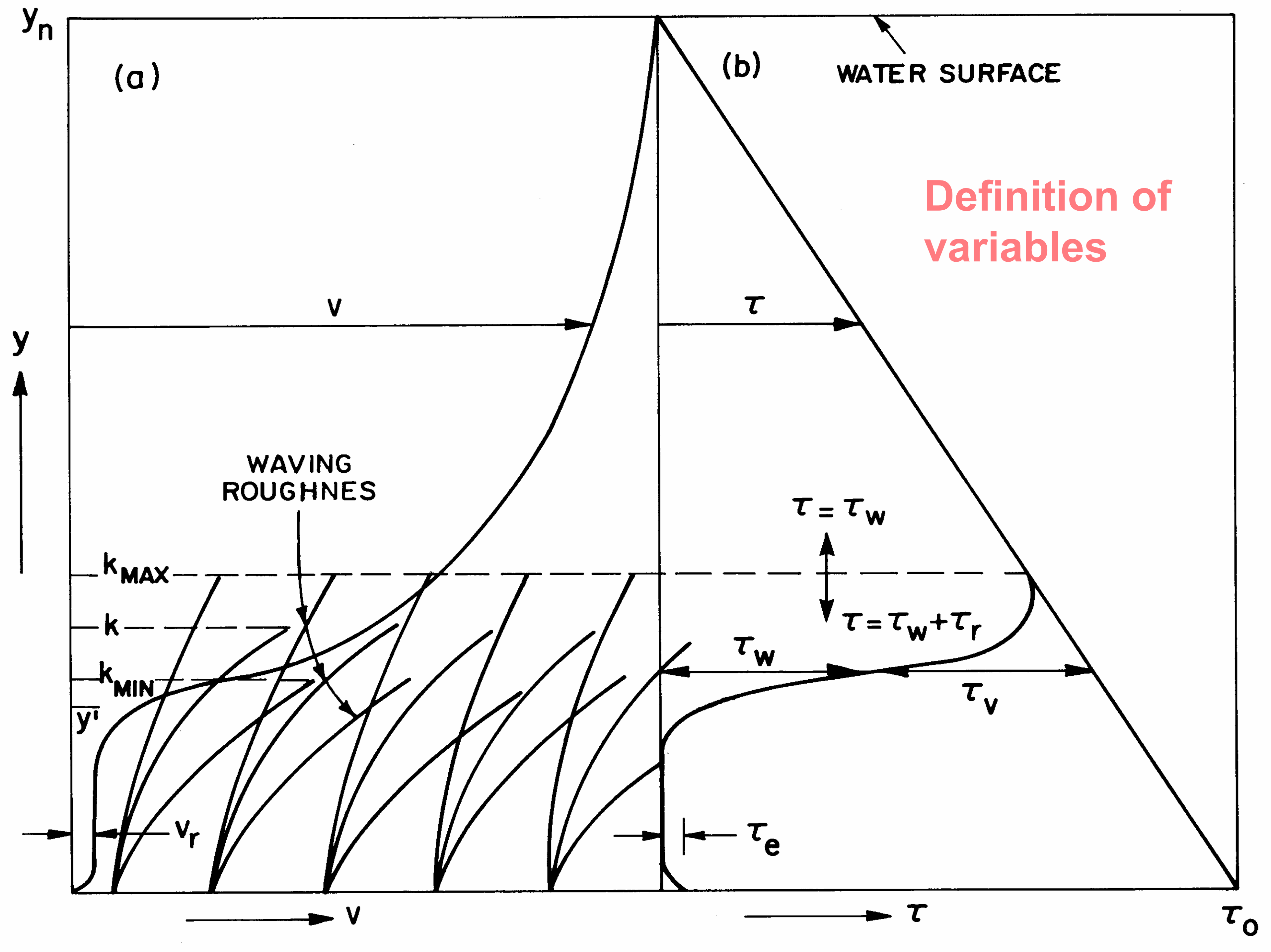

Measurement of soil profile and count of grass density



View through side after approximately 5 day run


UW Lab – plastic model of grass
Circa 1969
Use of pitot tube as reference to measure height


Click on insert to view movie


Definition of variables
y_n
(a)
(b)
WATER SURFACE
v
τ
y
WAVING
ROUGHNES
k_{MAX}
k
k_{MIN}
y'
v_r
$\tau = \tau_w$
$\tau = \tau_w + \tau_r$
τ_w
τ_v
τ_e
v
τ
τ_o

Dimensional Analysis (List of everything by Fenzl):

$$\psi\left(\rho,\mu,\sigma,h,b,J,k,\lambda,\lambda_1,\lambda_2,\ldots\lambda_n,\theta_p,\theta_s,\beta,V,y_n,g,S_f\right)=0$$

After applying the Buckingham Π theorem (by NK)

$$f=\varnothing\left\{\frac{k}{y_n},\frac{k}{h},\frac{h}{\left(\mathrm{MEI}/\tau_o\right)^{1/4}}\right\}$$

Only the most important variables are retained

M =stem density = $D^2/\lambda_1\lambda_2$

EI =vegetation stiffness

f =D - W friction factor

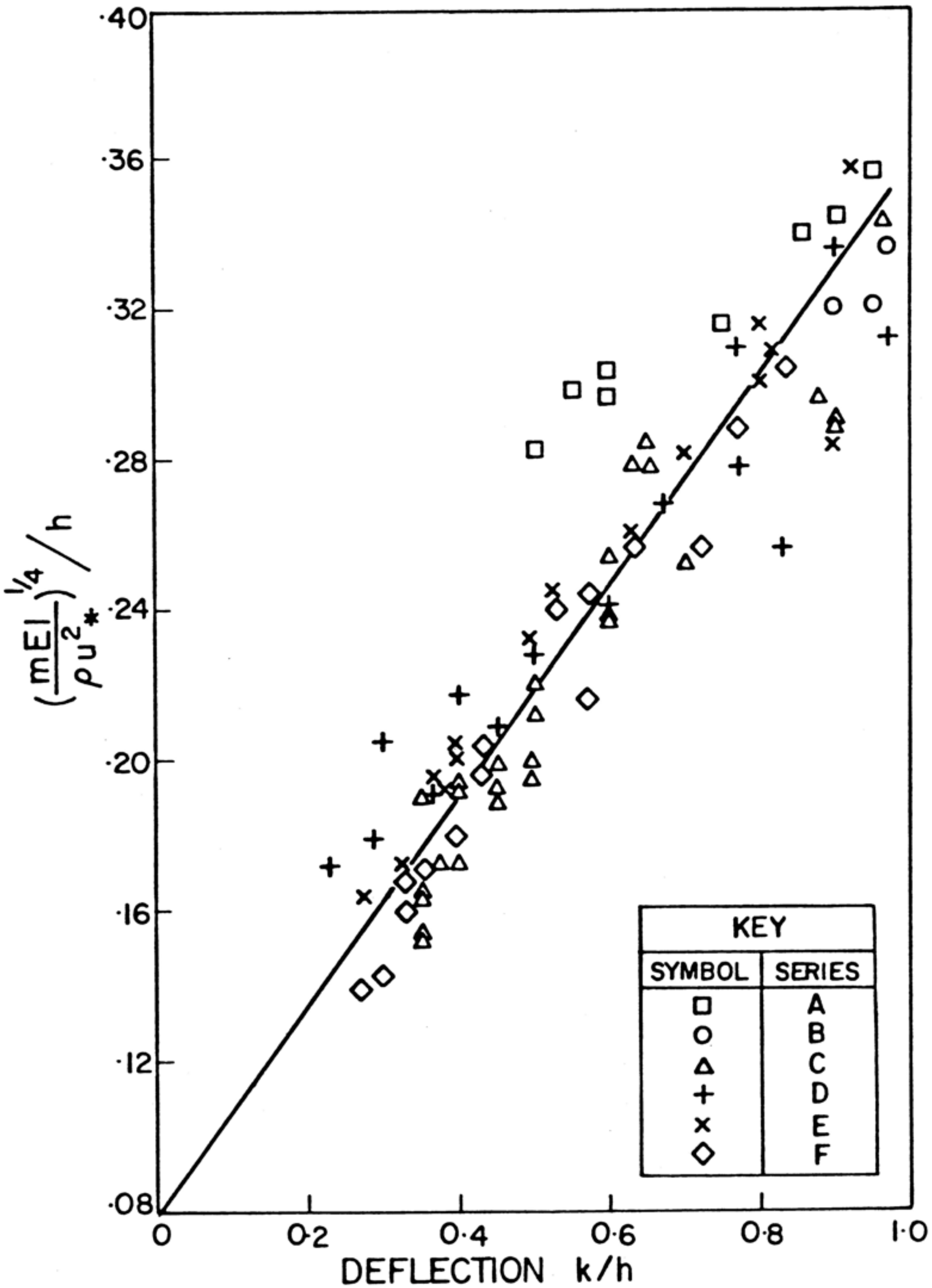
y_n =depth of flow

k =roughness height in flow

h =vegetation length

τ_o = shear stress = γALS

(NOTE: k $\leq$ h and k $\leq$ y_n)



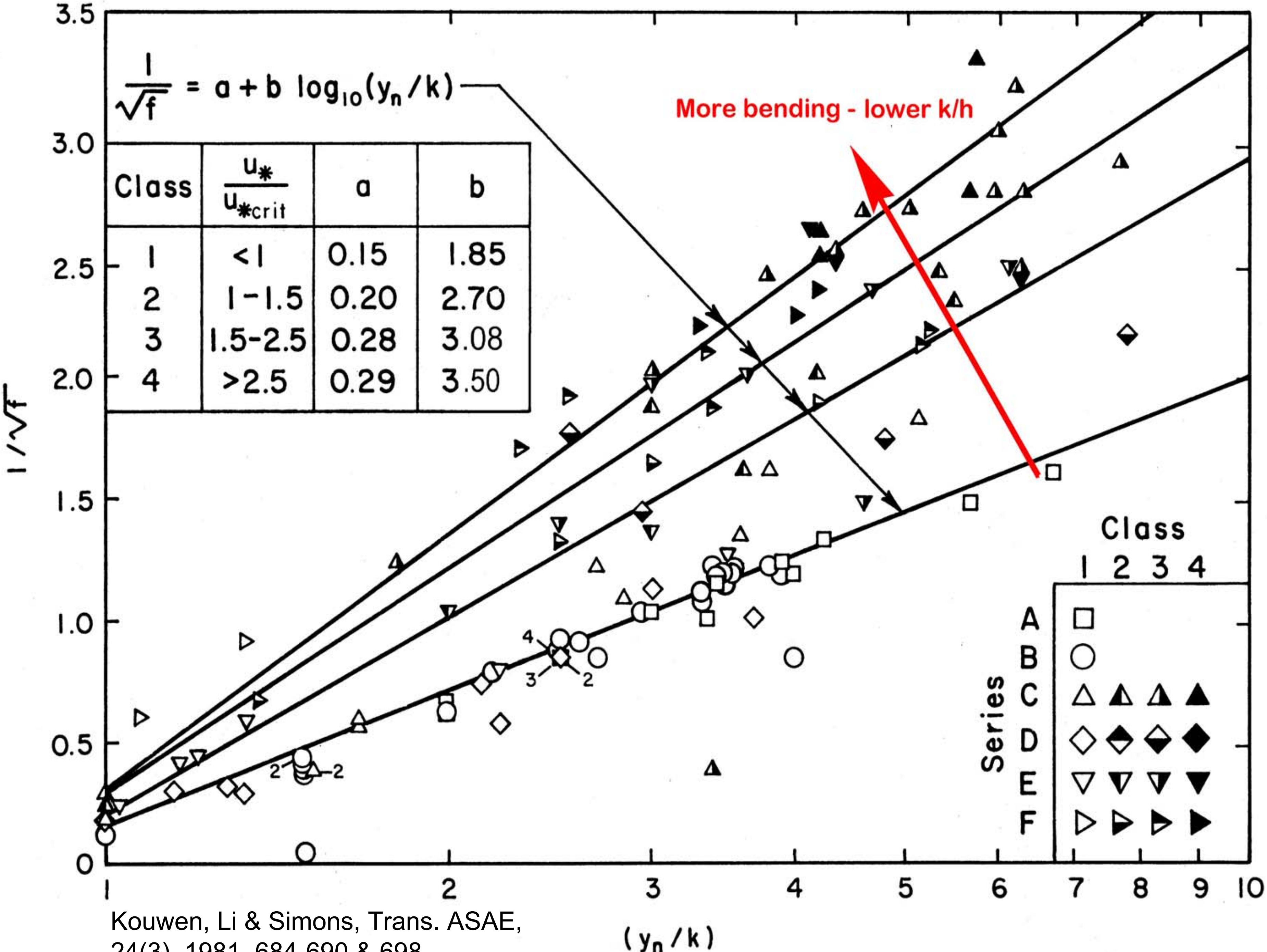
From Experiments:

$$\frac{k}{h} = f_n\left[h \Big/ \left(\frac{MEI}{\tau_0}\right)^{1/4} \right]$$

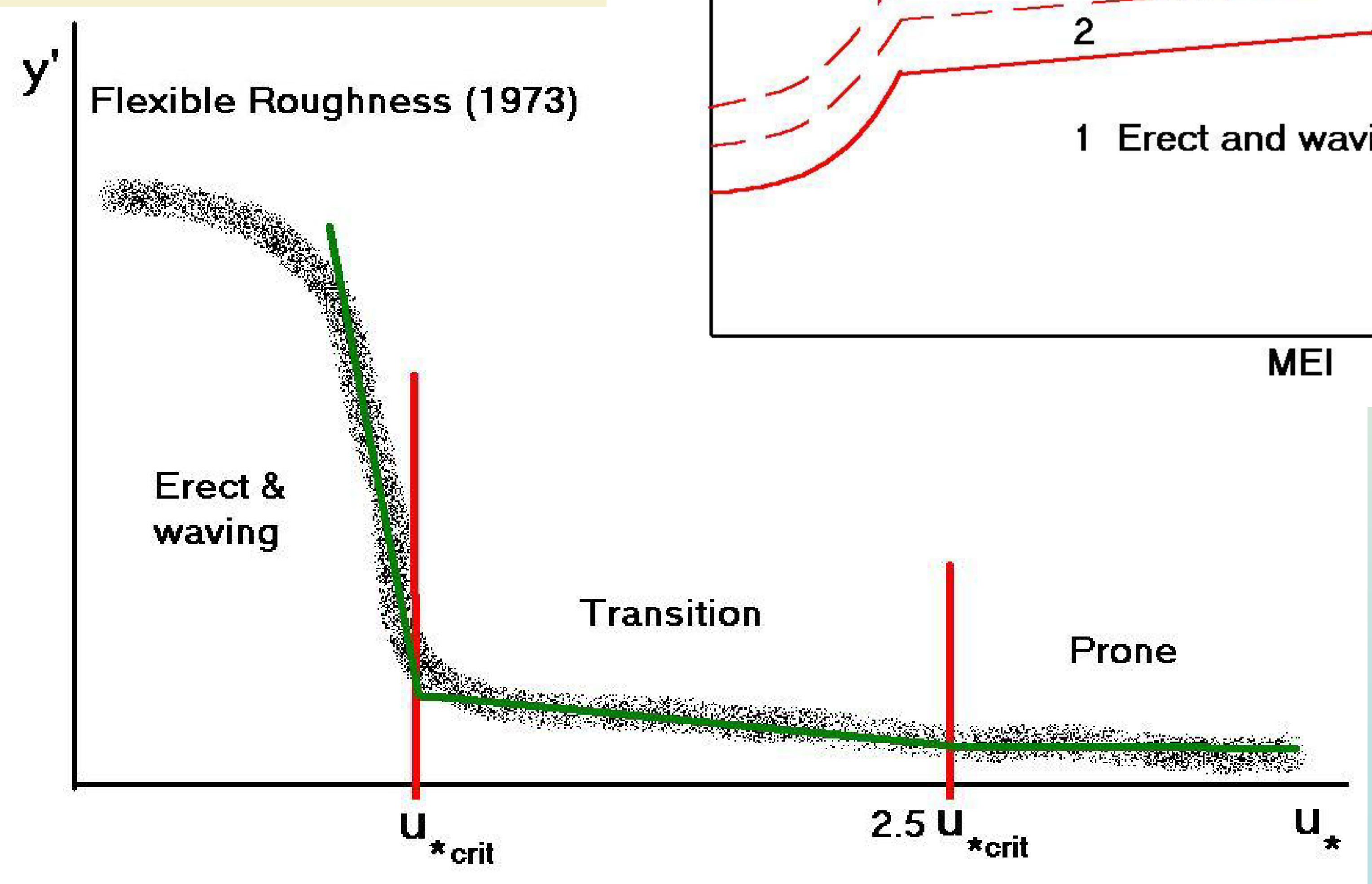
So:

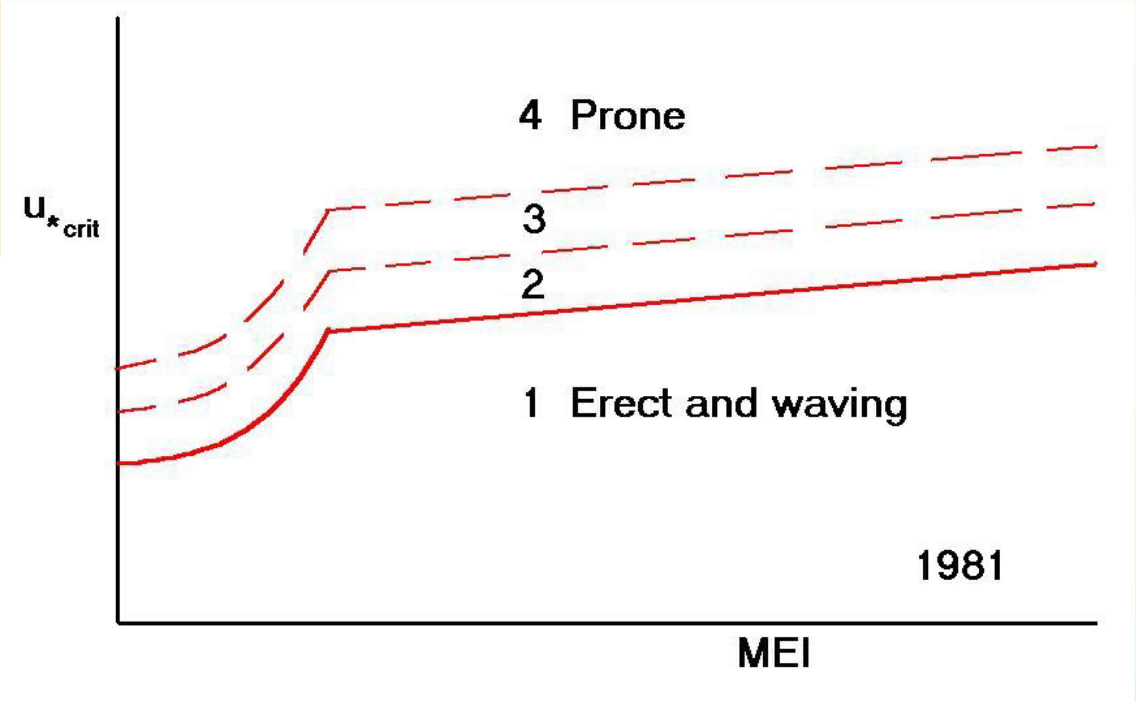
$$f = fn\left(\frac{k}{y_n}, \frac{k}{h}\right)$$

Kouwen, Unny & Hill, ASCE J. of the Hydraulics Division, May, 1973, 713-728



Kouwen, Li & Simons, Trans. ASAE, 24(3), 1981, 684-690 & 698.


y'
Flexible Roughness (1973)
Erect &
waving
Transition
Prone
u*crit
2.5 u*crit
u*


4 Prone
u*crit
3
2
1 Erect and waving
1981
MEI

i.e. f = fn (relative roughness, smoothness)

In practical terms, this means:

$$\frac{1}{\sqrt{f}} = a + b \ \log_{10}\left(\frac{y_n}{k}\right)$$

where a and b are coefficients that vary with the value of k/h - or smoothness (re: Keulegan, 1938)

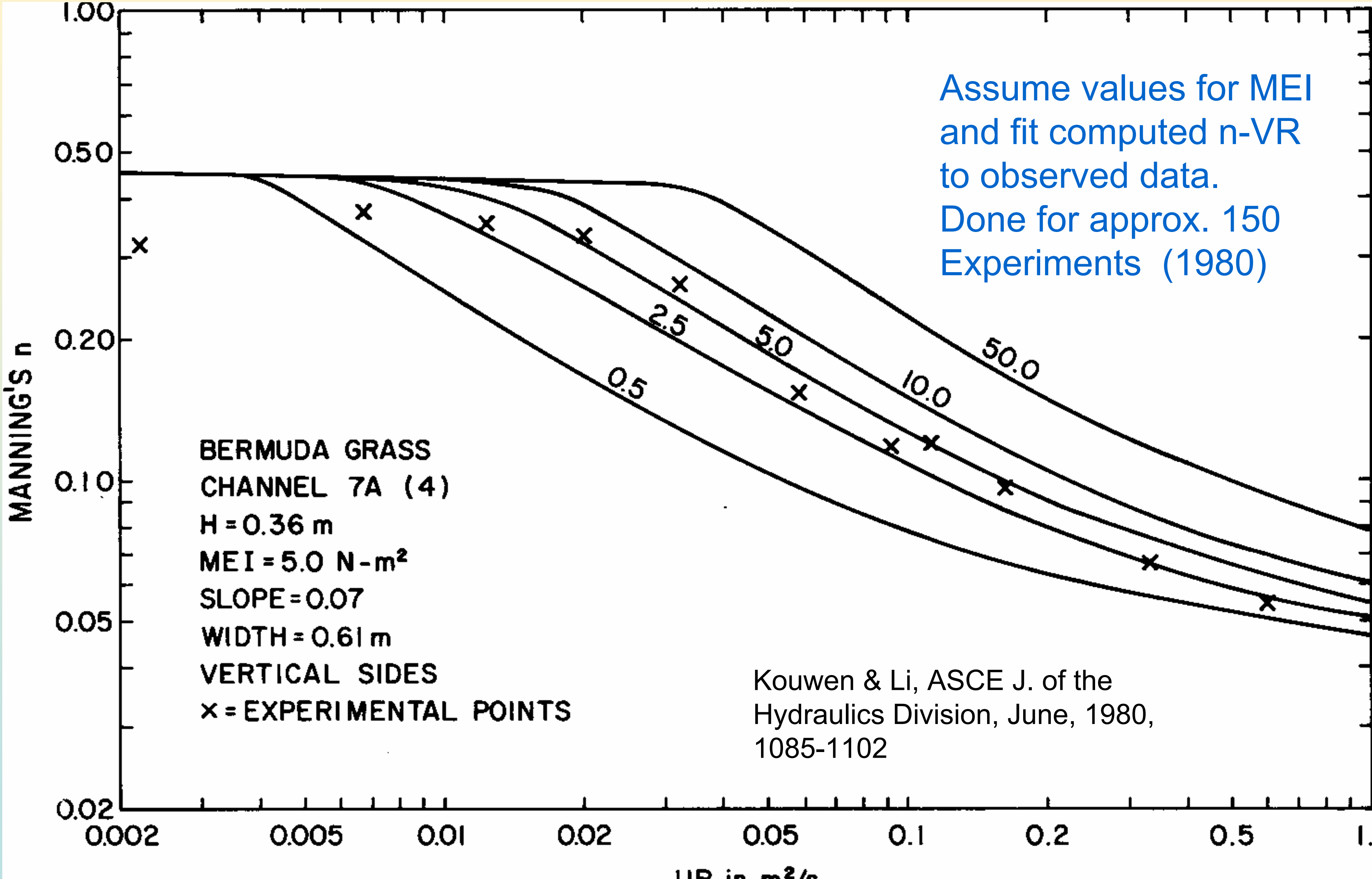
$$a = f_1\left(\frac{k}{h}\right) \qquad b = f_2\left(\frac{k}{h}\right)$$

$$V = \sqrt{\frac{8g}{f}}\sqrt{y_n S}$$

$$V = \sqrt{8g}\left[a + b\log\left\{ y_n \Big/ 0.14h\left\{\frac{\left(\frac{MEI}{\gamma y_n S}\right)^{0.25}}{h}\right\}^{1.59} \right\}\right]\sqrt{y_n S}$$

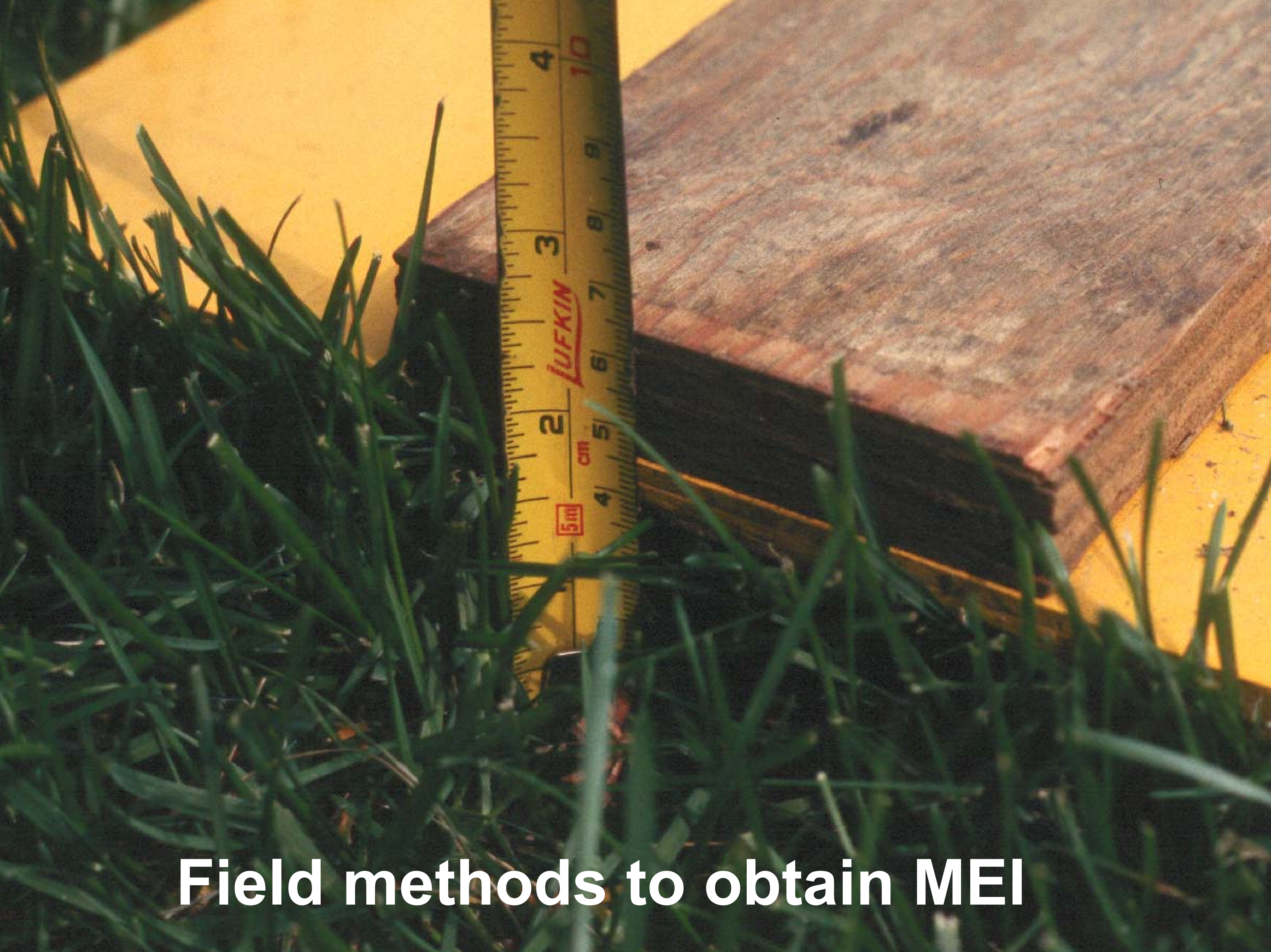
All we now need is MEI for natural vegetation

So how do we get values for MEI for natural vegetation?



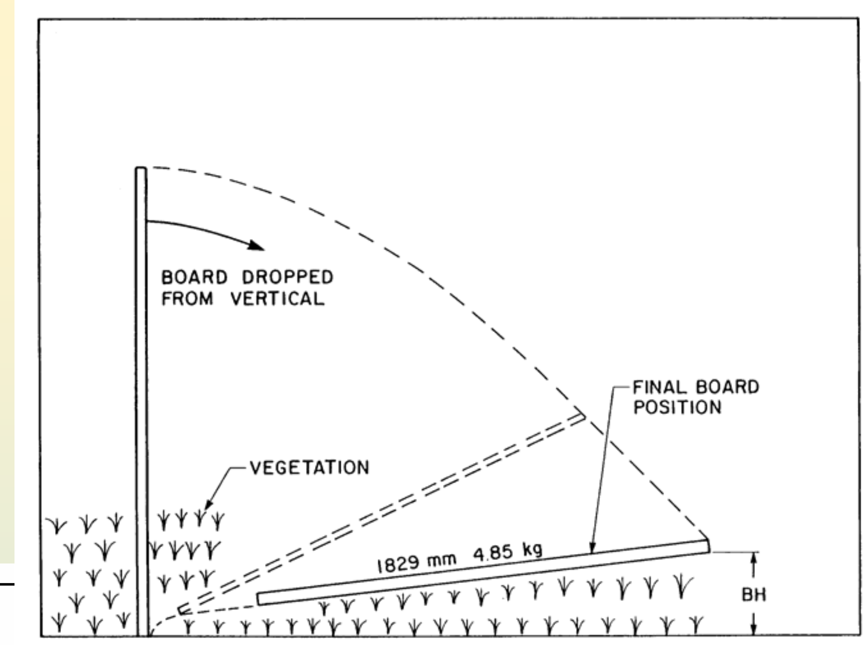
Assume values for MEI and fit computed n-VR to observed data. Done for approx. 150 Experiments (1980)

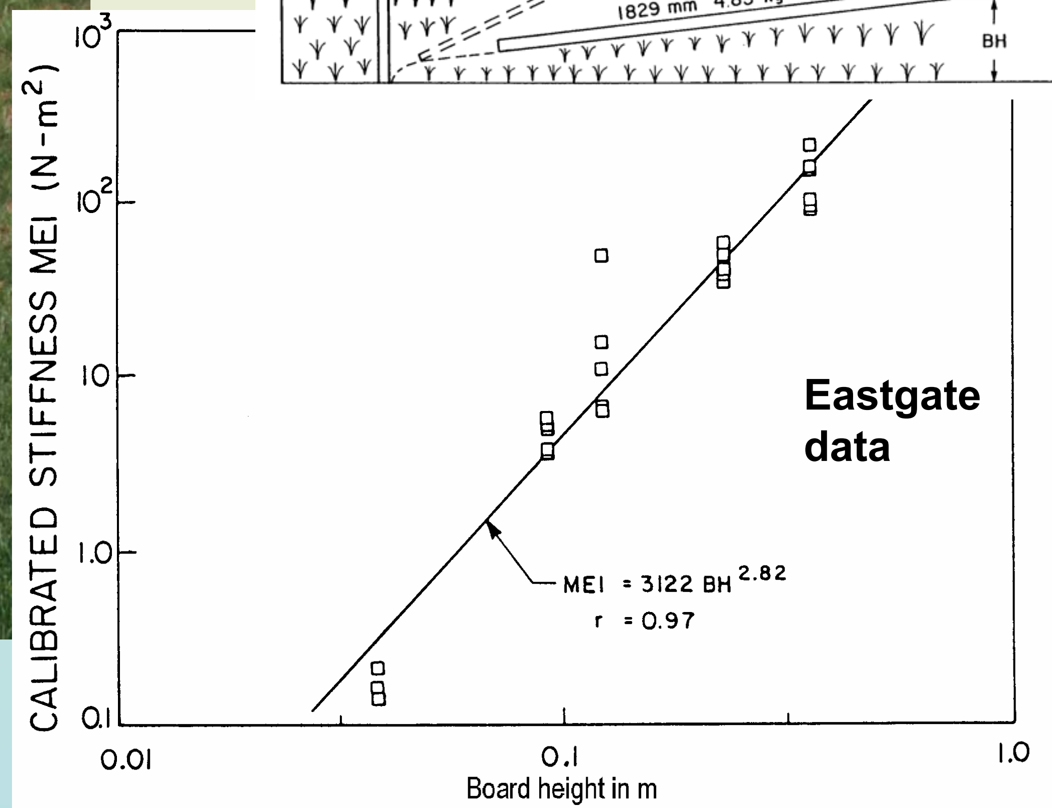
Kouwen & Li, ASCE J. of the Hydraulics Division, June, 1980, 1085-1102



Field methods to obtain MEI

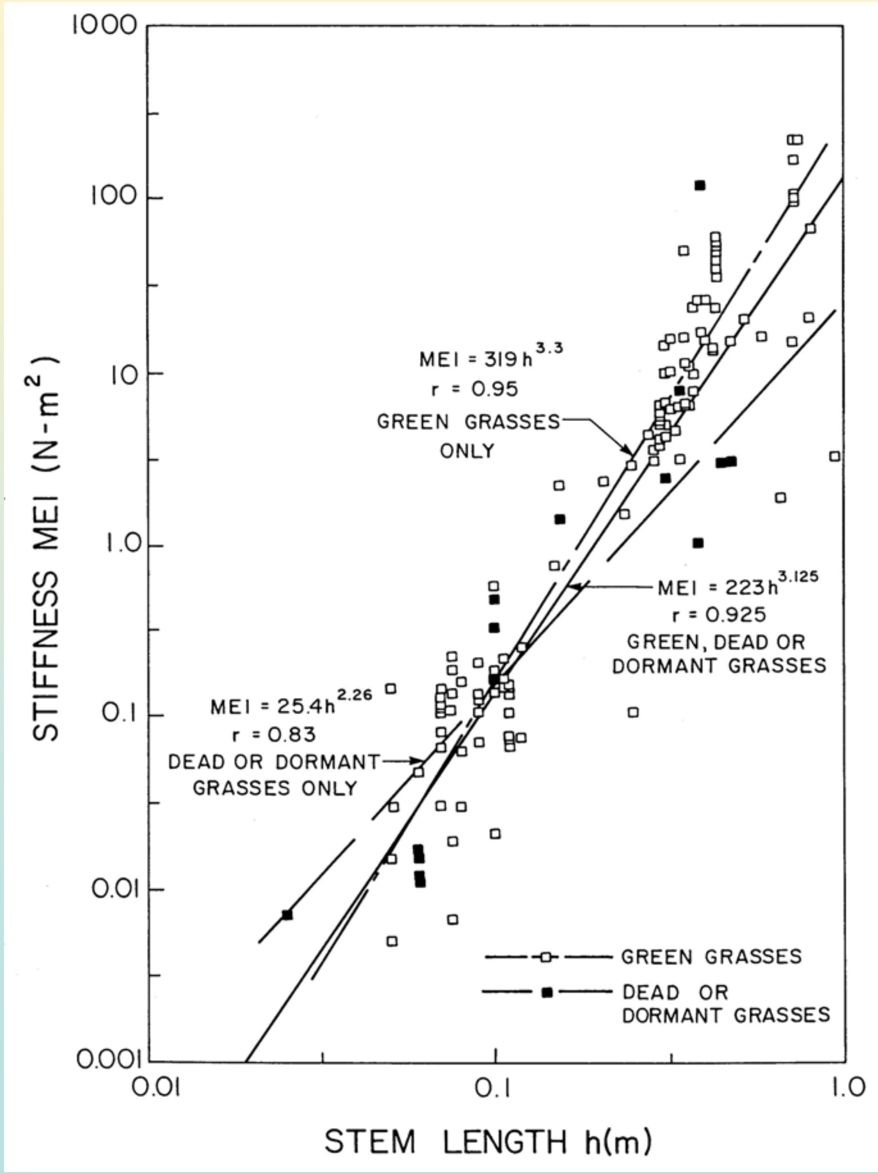
Board drop test (for MEI)
Eastgate, 1966

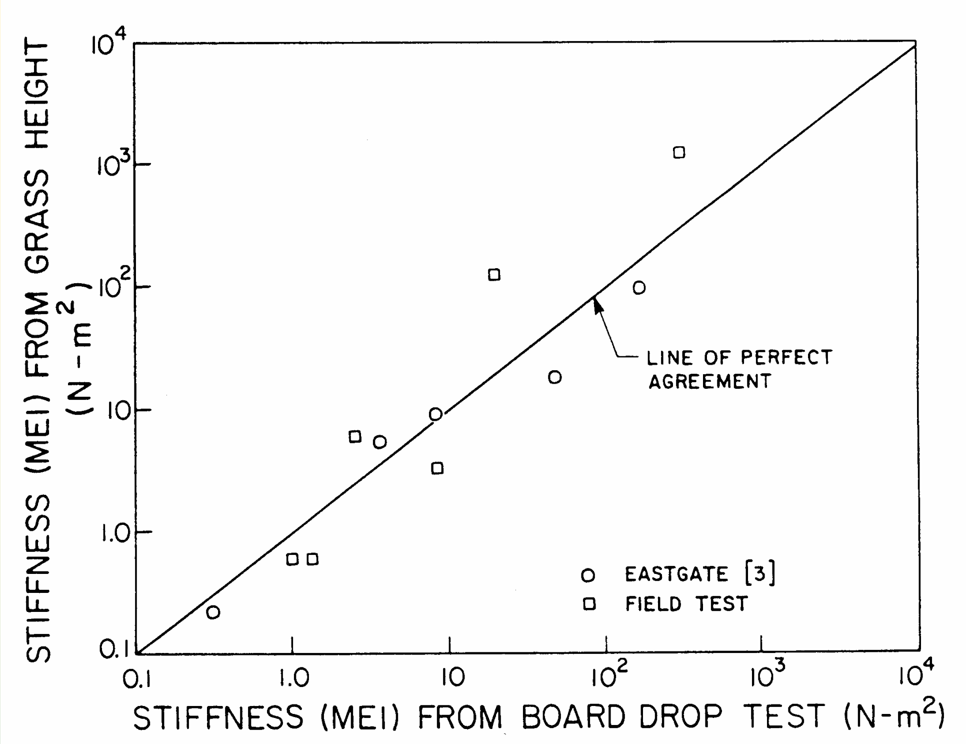




Kouwen, IAHR J. Hydraulic Research, 1988, Vol. 26, 559-568

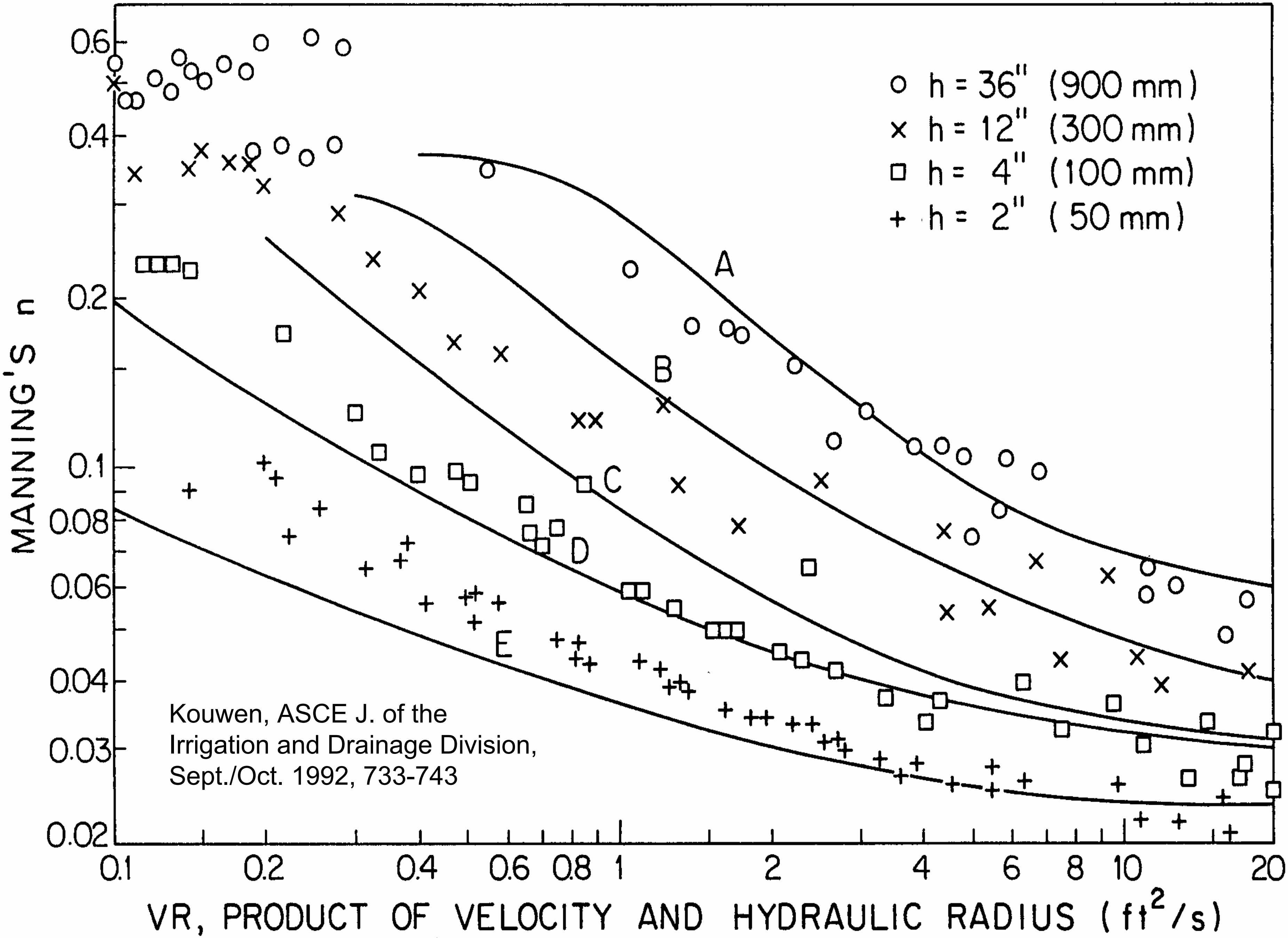
MEI can also be based on the vegetation height:





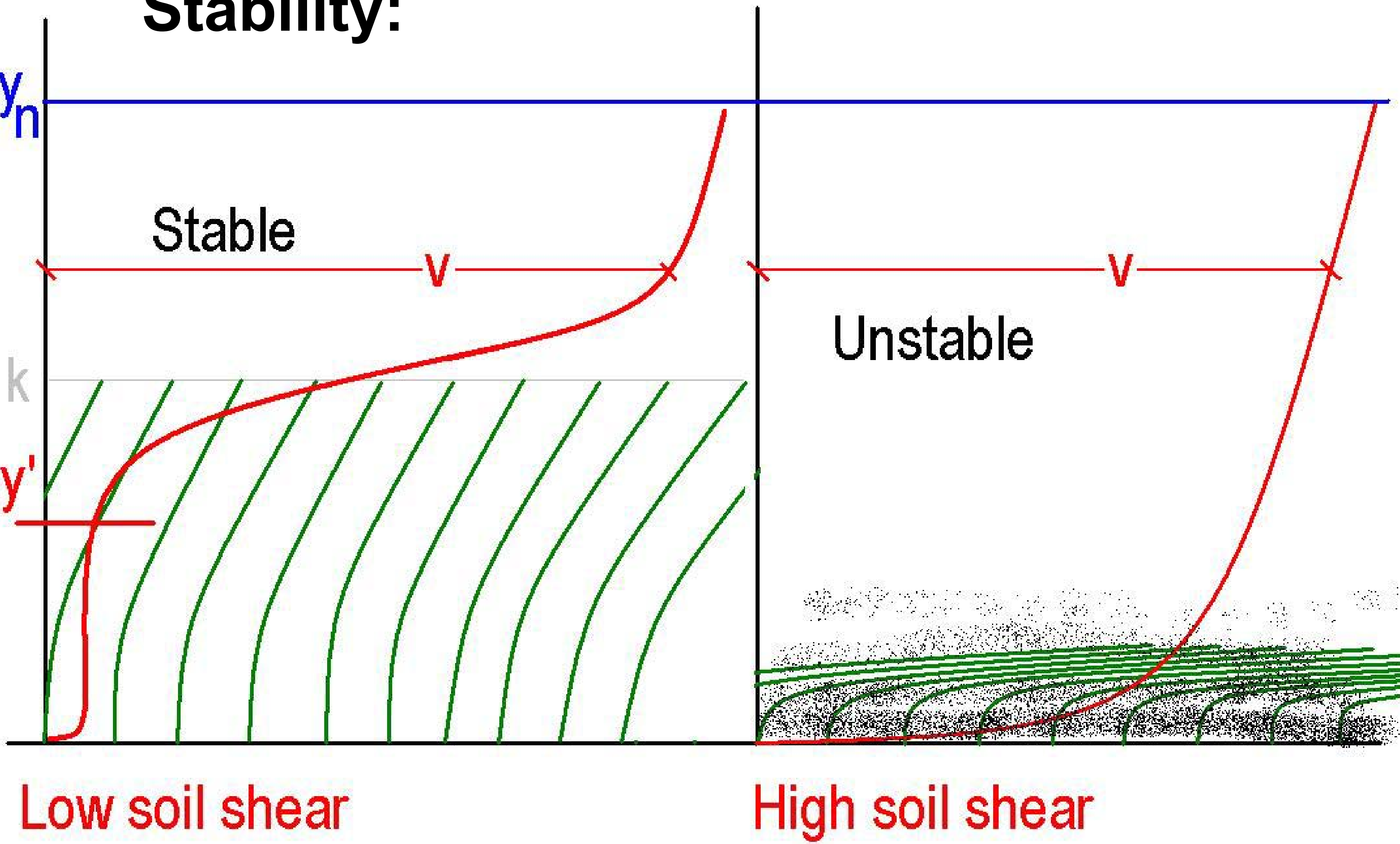
A comparison of the two methods of Estimating MEI yields similar results.

Kouwen, IAHR J. Hydraulic Research, 1988, Vol. 26, 559-568

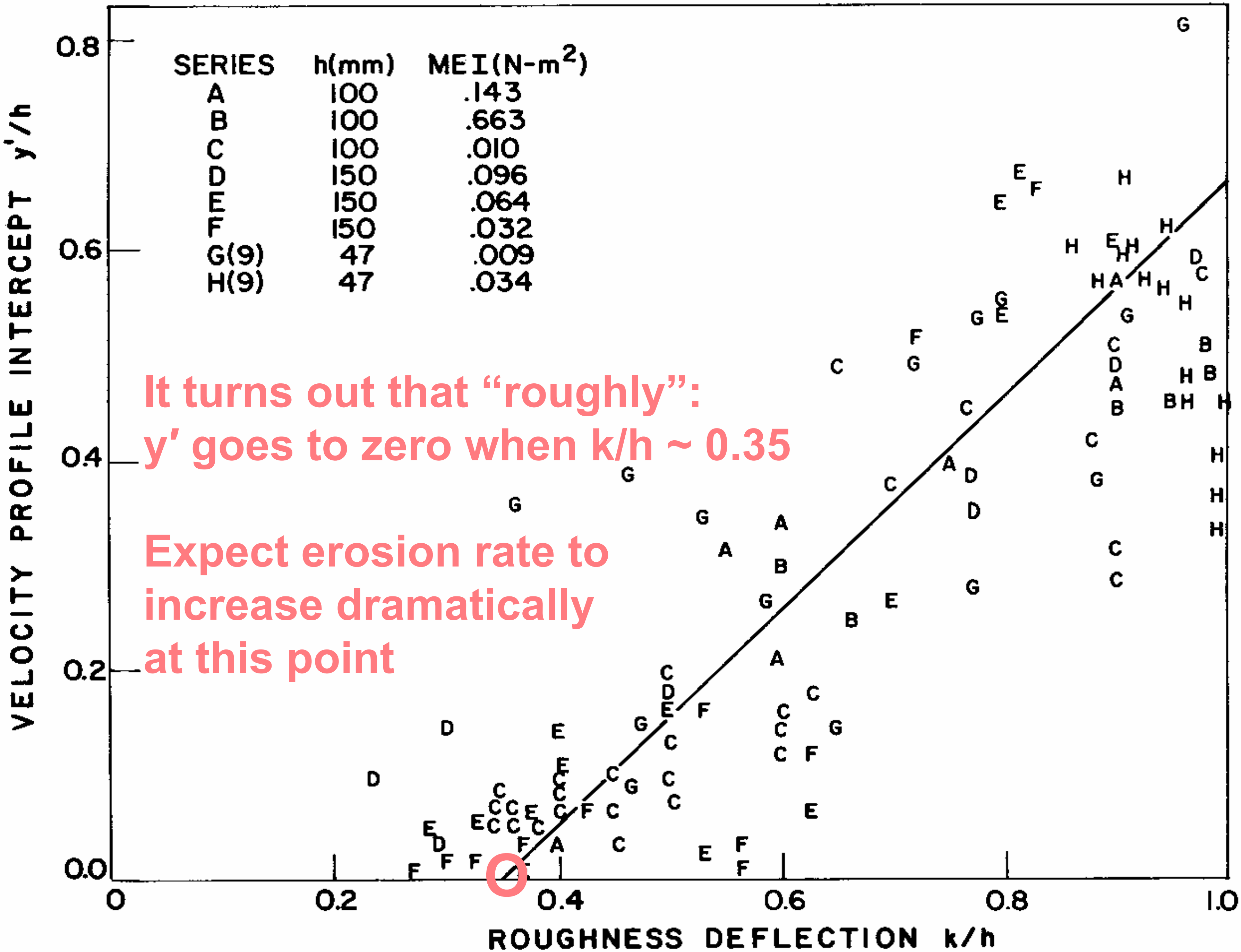


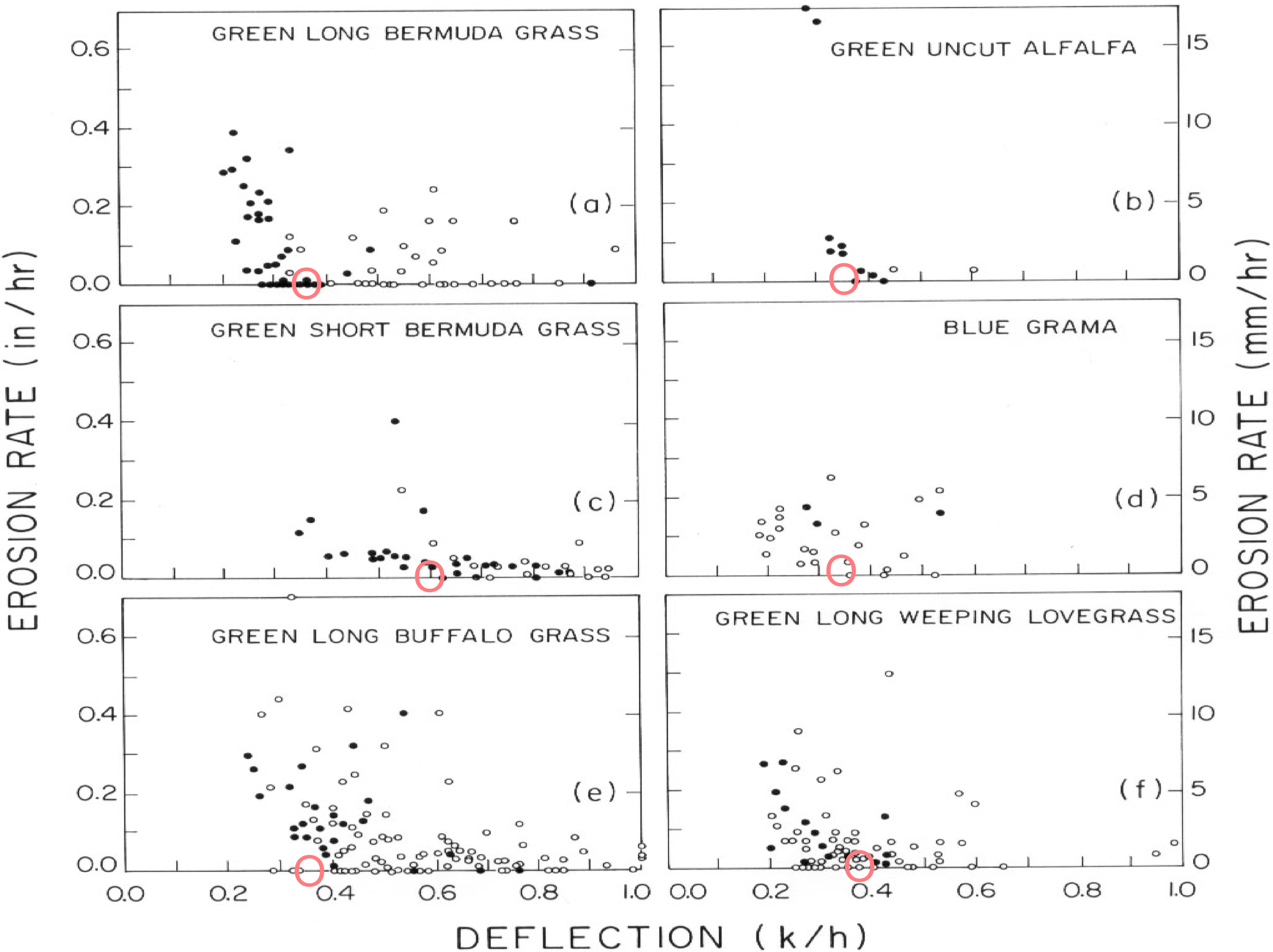
h = 36" (900 mm)
h = 12" (300 mm)
h = 4" (100 mm)
h = 2" (50 mm)
A
B
C
D
E
MANNING'S n
0.6
0.4
0.2
0.1
0.08
0.06
0.04
0.03
0.02
0.1
0.2
0.4
0.6
0.8
1
2
4
6
8
10
20
VR, PRODUCT OF VELOCITY AND HYDRAULIC RADIUS (ft^2/s)
Kouwen, ASCE J. of the Irrigation and Drainage Division, Sept./Oct. 1992, 733-743

Stability:



As long as y' has some value,
there is little shear at the bed and channel is stable


SERIES h(mm) MEI(N-m²)
A 100 .143
B 100 .663
C 100 .010
D 150 .096
E 150 .064
F 150 .032
G(9) 47 .009
H(9) 47 .034
VELOCITY PROFILE INTERCEPT y'/h
ROUGHNESS DEFLECTION k/h
0.0
0.2
0.4
0.6
0.8
0
0.2
0.4
0.6
0.8
1.0
It turns out that “roughly”:
y′ goes to zero when k/h ~ 0.35
Expect erosion rate to
increase dramatically
at this point



GREEN LONG BERMUDA GRASS
(a)
GREEN UNCUT ALFALFA
(b)
GREEN SHORT BERMUDA GRASS
(c)
BLUE GRAMA
(d)
GREEN LONG BUFFALO GRASS
(e)
GREEN LONG WEEPING LOVEGRASS
(f)
EROSION RATE (in/hr)
EROSION RATE (mm/hr)
DEFLECTION (k/h)
0.0
0.2
0.4
0.6
0.8
1.0
0
5
10
15


Scour hole developed in 250 mm long
Bermuda Grass after 5 day run
Slope 5%
Flow 1.7 m³/s
k/h for this case was ~ 0.35

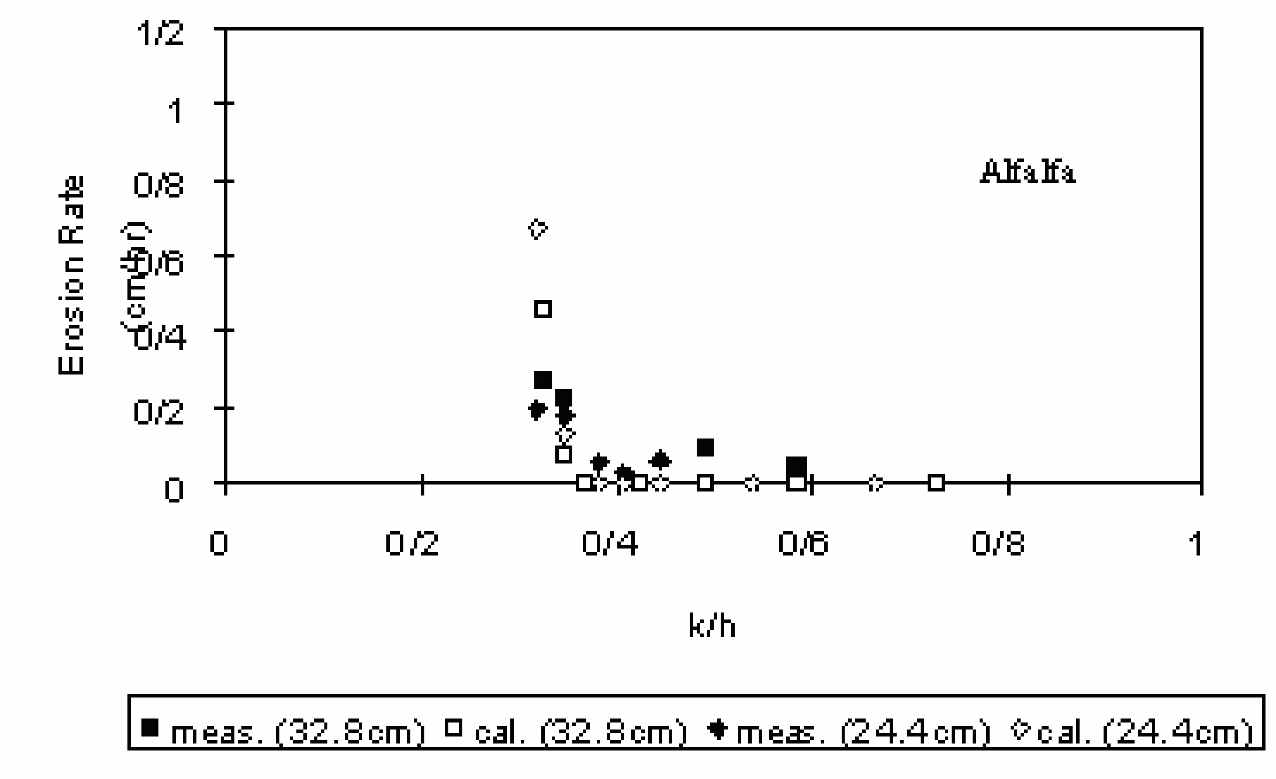
Erosion Model:

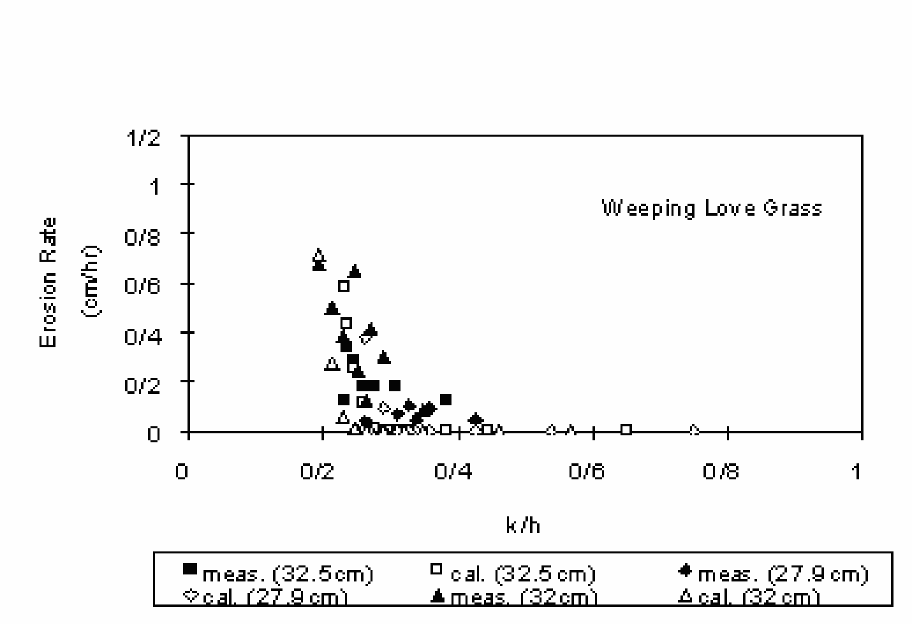
$$\tau_e = \rho g y_n S\left[(1-C_F)\left(\frac{n_s}{n}\right)^2\right]$$

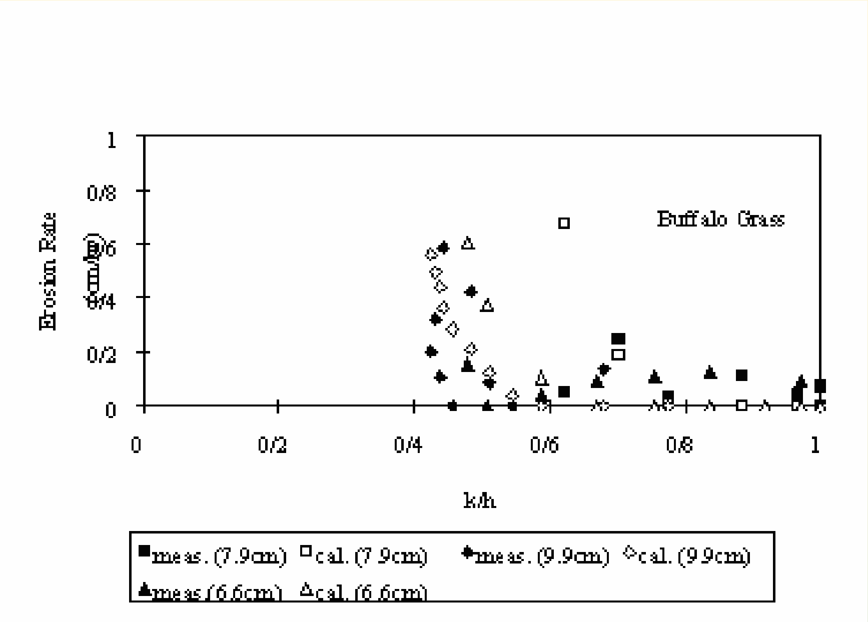
Effective shear (Temple)

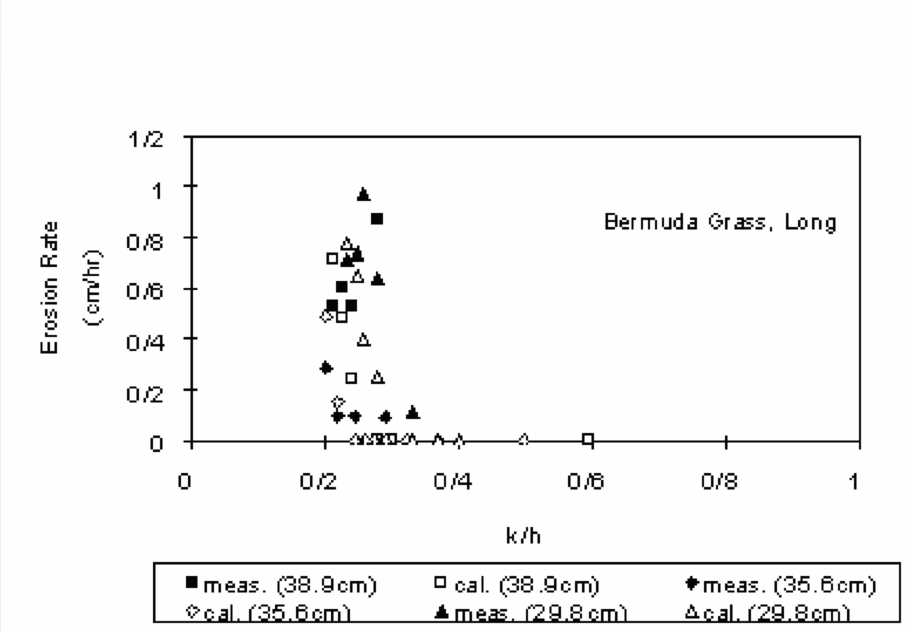
$$Er = kk(\tau_e - \tau_c)^{a'}$$

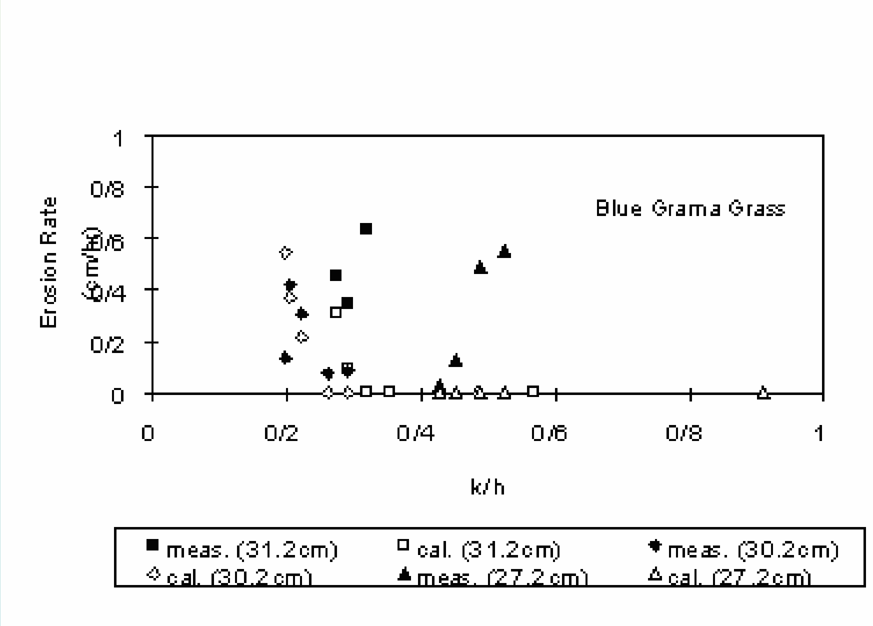
Duboys sediment transport equation to estimate detachment

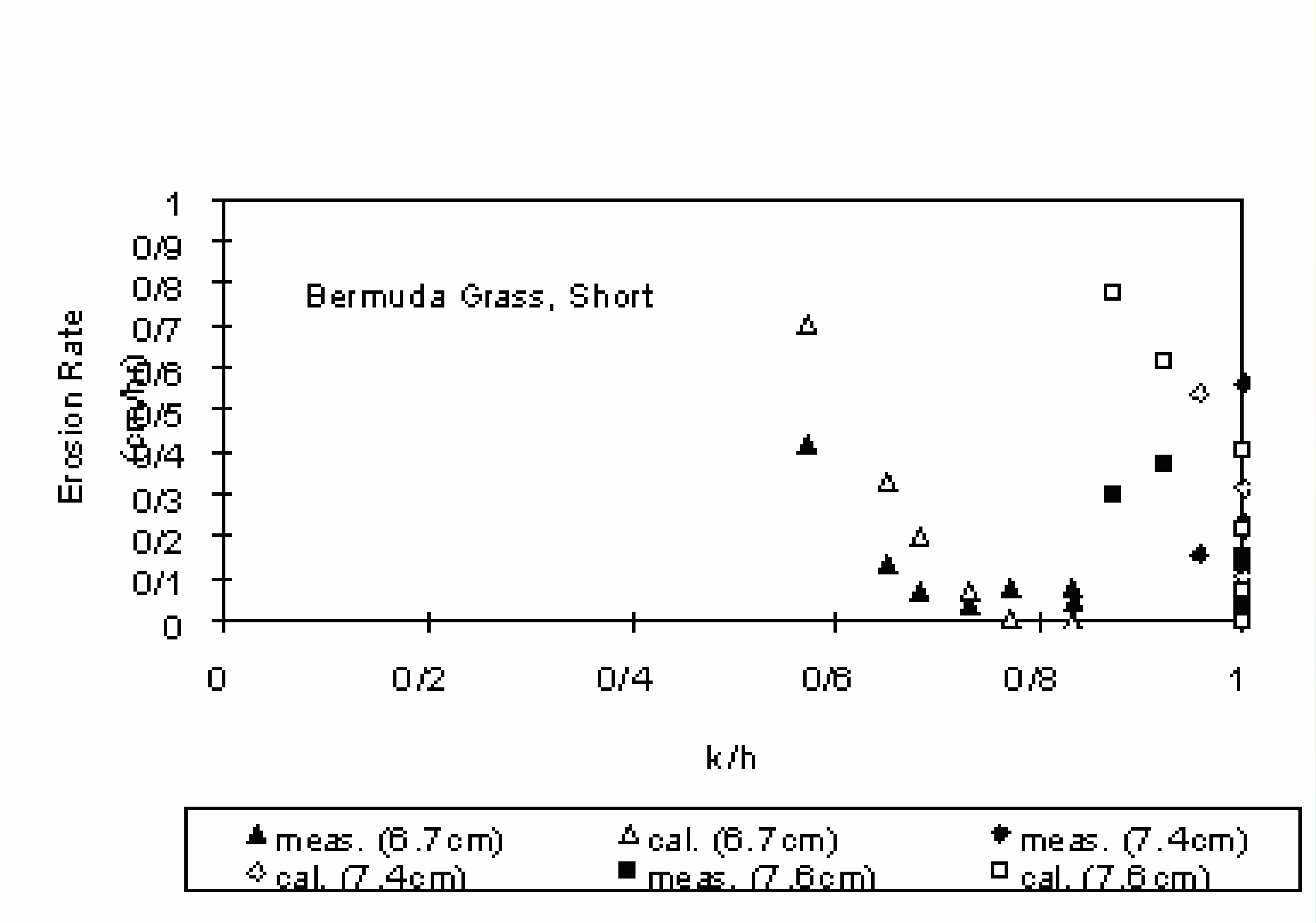



Weeping Love Grass
Erosion Rate (cm/hr)
k/h
meas. (32.5cm)
cal. (32.5cm)
meas. (27.9cm)
cal. (27.9cm)
meas. (32cm)
cal. (32cm)


Buffalo Grass
Erosion Rate (cm/hr)
k/h
meas. (7.9cm)
cal. (7.9cm)
meas. (9.9cm)
cal. (9.9cm)
meas (6.6cm)
cal. (6.6cm)


Bermuda Grass, Long
Erosion Rate (cm/hr)
k/h
meas. (38.9cm)
cal. (38.9cm)
meas. (35.6cm)
cal. (35.6cm)
meas. (29.8cm)
cal. (29.8cm)


Blue Grama Grass
Erosion Rate (cm/hr)
k/h
meas. (31.2cm)
cal. (31.2cm)
meas. (30.2cm)
cal. (30.2cm)
meas. (27.2cm)
cal. (27.2cm)



Conclude:

Onset of instability can be predicted by Temple-Duboys model

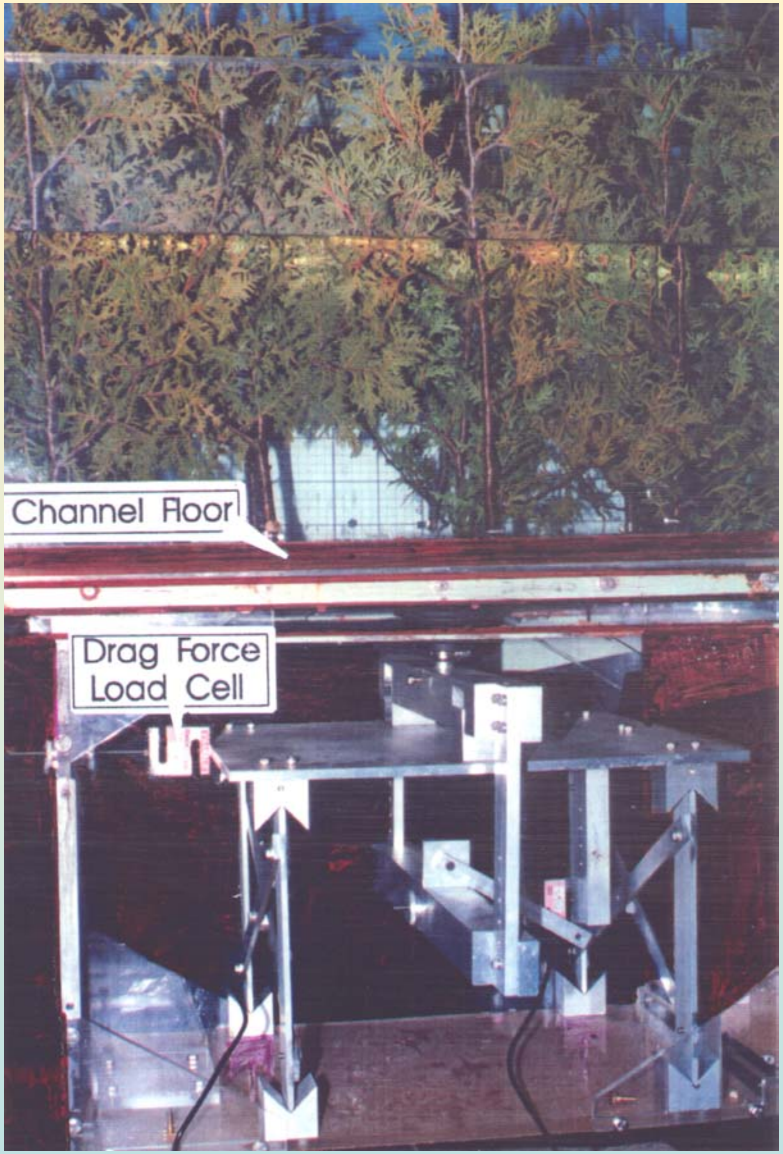
kk and **a** in Duboys eqn. the same for all plots

Only the Cover Factor C_f adjusted

Details: Samani & Kouwen. ASCE J. Hyd. Eng. Jan. 2002

Drag on trees


•Straight, level road with no cross-wind
•10 – 80 km/hr in 10 km/hr increments
•Cedar, Spruce, Austrian and White pine trees
•Up to 3.5 m in height. Freshly cut.
(please note: in Canada we normally drive on the right)



Dense cedar saplings in a flume
with one tree in the force balance

Saplings of cedar, spruce and two species of Pine were tested in water and air.

Drag was measured and recorded for a period of time using force balance tables and a load cell.

In water, the additive principle was tested. Different patterns were used.

Fathi-Moghadam & Kouwen
ASCE J. Hydraulic Eng.
Jan. 1997 pp. 51-57


In water:
In air:

$$C_d = fn_1\left(A_o, V, \rho, y_n, J, g, \mu, h, \xi\ , \phi, \omega, l_1 \ldots, l_n\right)$$

$$fn_2\left(C_d, \xi, \phi, \frac{A_\circ}{y_n{}^2}, \frac{l_1}{y_n}, \frac{l_2}{y_n}, \frac{h}{y_n}, \frac{\rho V^2 y_n{}^4}{J}, \frac{\rho V y_n}{\mu}, \frac{V^2}{g y_n}, \frac{\omega y_n}{V}\right) = 0$$

$$fn_3\left(C_d(\frac{A}{\forall})h, \frac{\rho V^2 h^4}{\xi J}, \frac{\rho V y_n}{\mu}, \frac{V^2}{g y_n}, \frac{\omega y_n}{V}\right) = 0$$

$$C_d\left(\frac{A}{\forall}\right)h = fn_4\left(\frac{\rho V^2 h^4}{\xi J}\right)$$

$$f = 4C_d\left(\frac{A}{a}\right) \qquad f = \alpha\left(\frac{V}{\sqrt{\frac{\xi E}{\rho}}}\right)^\beta \qquad \xi E = N f_1{}^2\left(\frac{m_s}{h}\right)$$

$$f = 4C_d\left(\frac{A}{a}\right)$$

A = Momentum Absorbing Area

a = horizontal area of canopy

$$f = \alpha\left(\frac{V}{\sqrt{\frac{\xi E}{\rho}}}\right)^{\beta}$$

ξ = parameter to account for plant deformation due to flow velocity

ξE = vegetation index

$$\xi E = Nf_1^2\left(\frac{m_s}{h}\right)$$

(Nickas & Moon, 1988)

Nf_1 = natural frequency of the tree

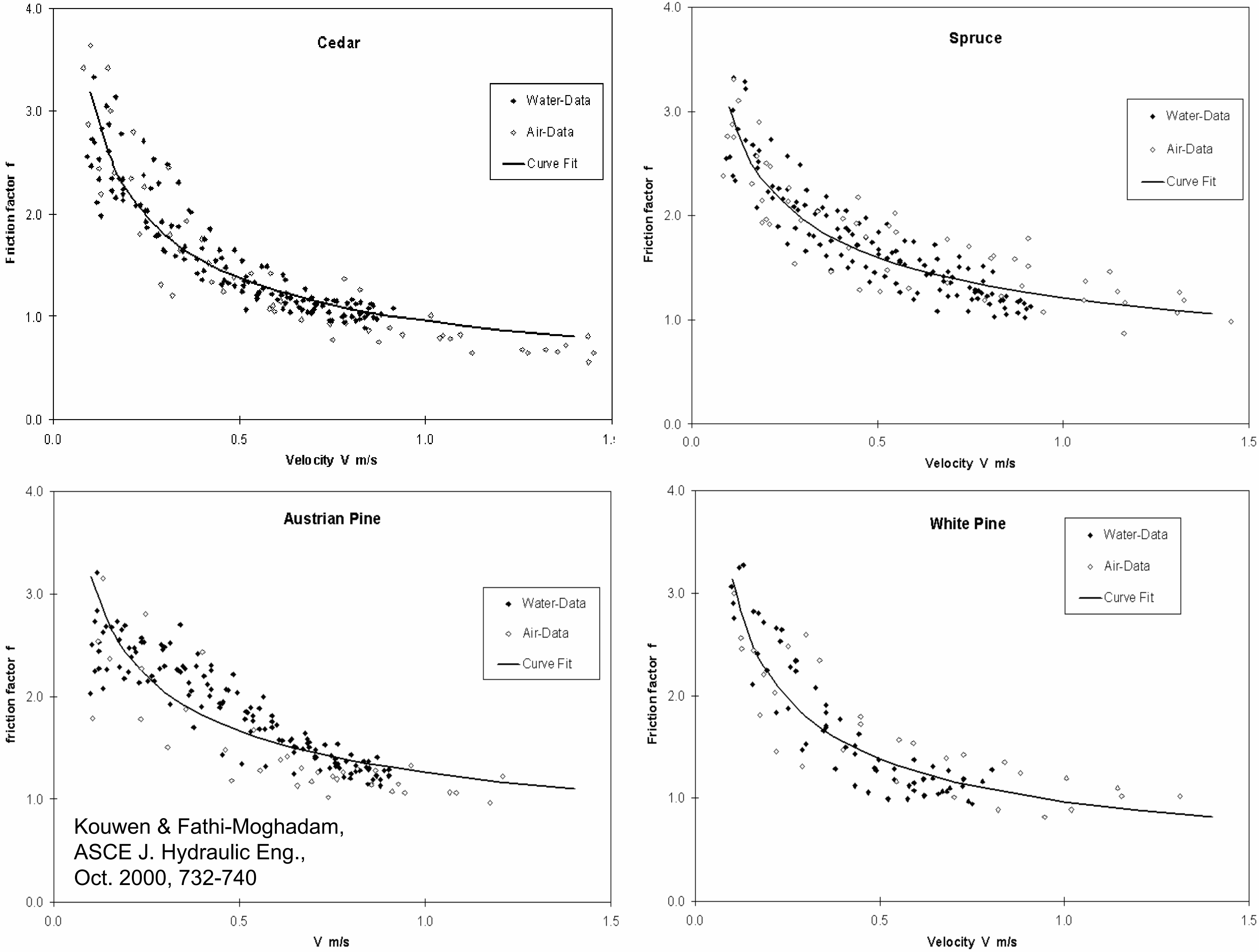
m_s = total tree mass

h = height of the tree (or canopy)

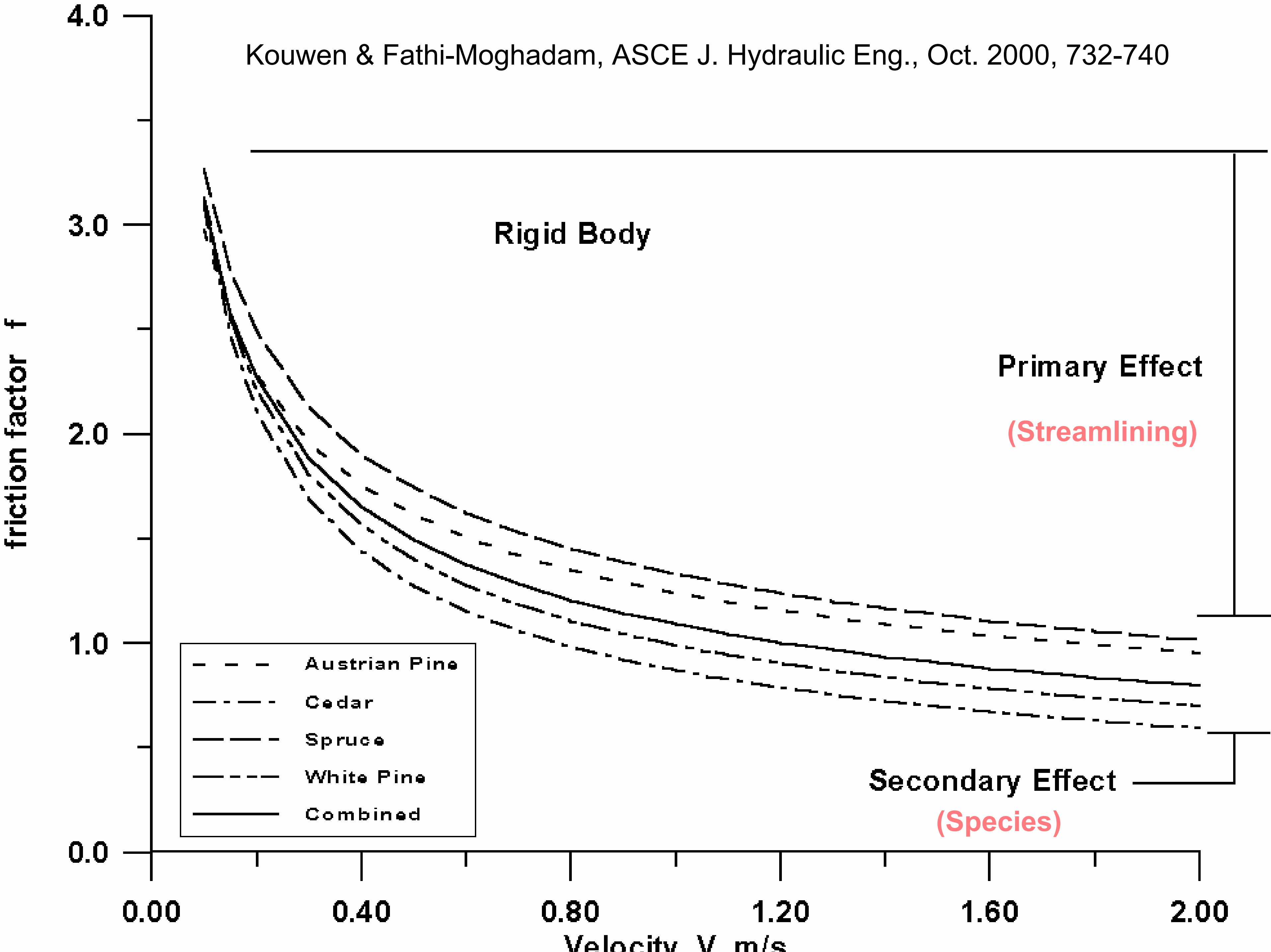
Kouwen & Fathi-Moghadam, ASCE J. Hydraulic Eng., Oct. 2000, 732-740

Trolley and load cell to measure
Force on a tree
Accelerometer to obtain Natural
Frequency

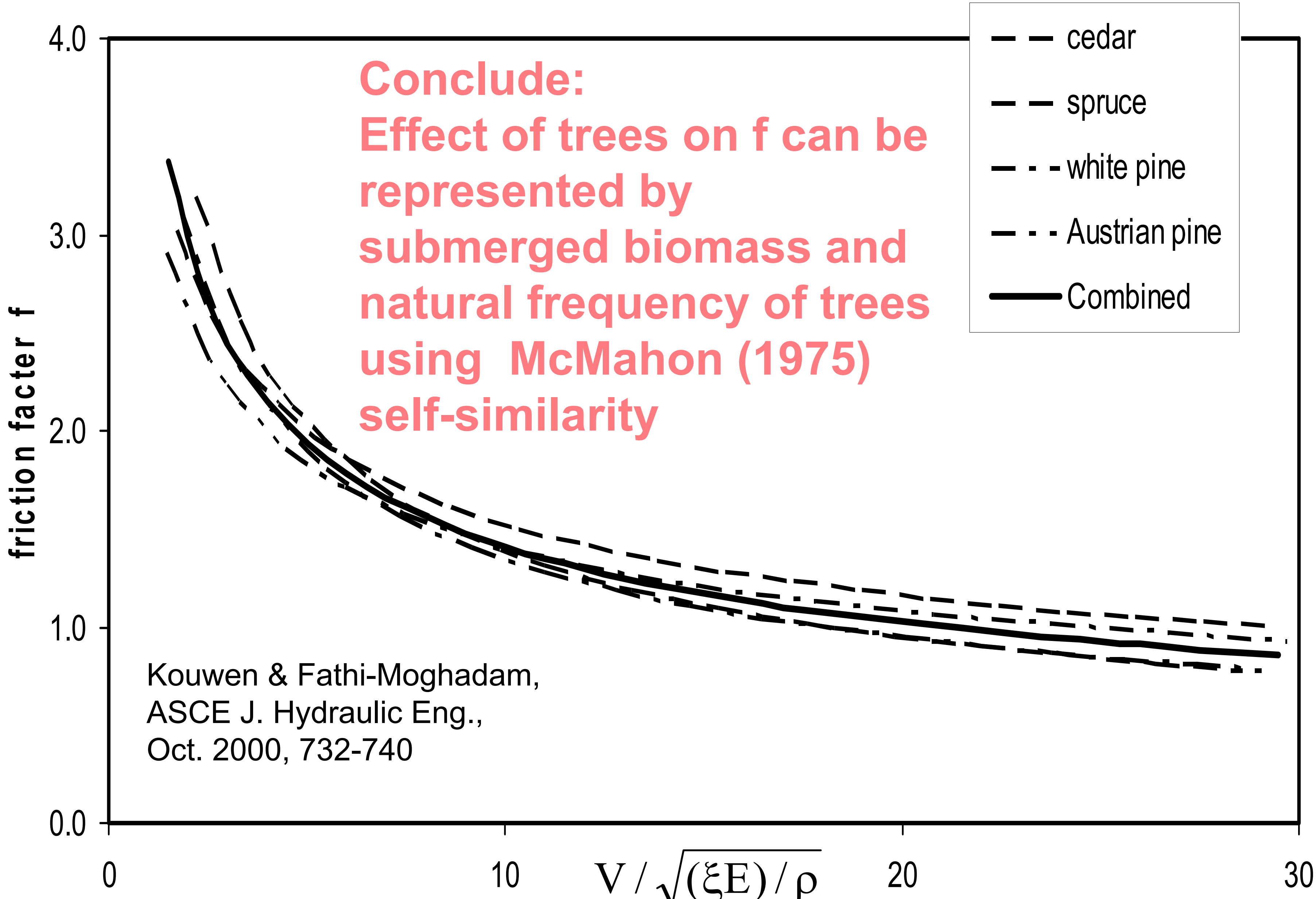
Shaker table and spectrum analyzer to
Obtain natural frequency of the tree.



Cedar
Water-Data
Air-Data
Curve Fit
Friction factor f
Velocity V m/s
Spruce
Water-Data
Air-Data
Curve Fit
Friction factor f
Velocity V m/s
Austrian Pine
Water-Data
Air-Data
Curve Fit
friction factor f
V m/s
Kouwen & Fathi-Moghadam,
ASCE J. Hydraulic Eng.,
Oct. 2000, 732-740
White Pine
Water-Data
Air-Data
Curve Fit
Friction factor f
Velocity V m/s
0.0
0.5
1.0
1.5
2.0
3.0
4.0


Kouwen & Fathi-Moghadam, ASCE J. Hydraulic Eng., Oct. 2000, 732-740
Rigid Body
Primary Effect
(Streamlining)
Secondary Effect
(Species)
Austrian Pine
Cedar
Spruce
White Pine
Combined
friction factor f
4.0
3.0
2.0
1.0
0.0
0.00
0.40
0.80
1.20
1.60
2.00

Air and Water Tests



Conclude:
Effect of trees on f can be represented by submerged biomass and natural frequency of trees using McMahon (1975) self-similarity

Kouwen & Fathi-Moghadam,
ASCE J. Hydraulic Eng.,
Oct. 2000, 732-740

Summary

- Dimensional analysis provides a unified approach to flow resistance due to vegetation.
- The flexural characteristics of vegetation have a major effect on resistance.
- The biomechanical properties of grass as they affect flow resistance are in essence an “equivalent to plastic stiffness”.

Thank you

Presentation at http://www.watflood.ca