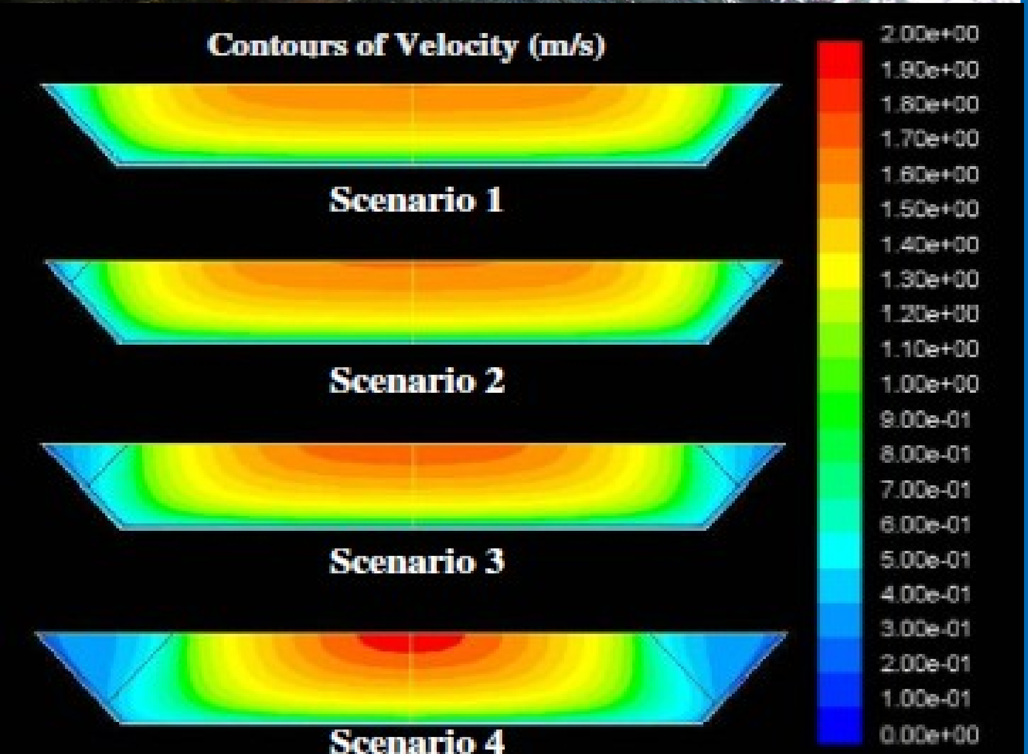

Scale-dependent Effects of Bank Vegetation on Channel Processes:

Field Data, CFD Modeling, and Restoration Design

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Outline

Background

- Context
- Objectives / hypothesis

Methods

- Field data analysis
- CFD modeling

Results

- Field / CFD

Synthesis / Implications

- Comparison of field vs. CFD
- Mechanisms of adjustment
- Stream restoration design

Bank Vegetation

Bank vegetation along streams and rivers performs important ecological and geomorphic functions

- flow hydraulics
- channel form and stability
- habitat diversity
- geotechnical stability / root reinforcement
- near-bank velocities
- hydraulic geometry
- planform characteristics
- scour pool characteristics
- stage-discharge relationships


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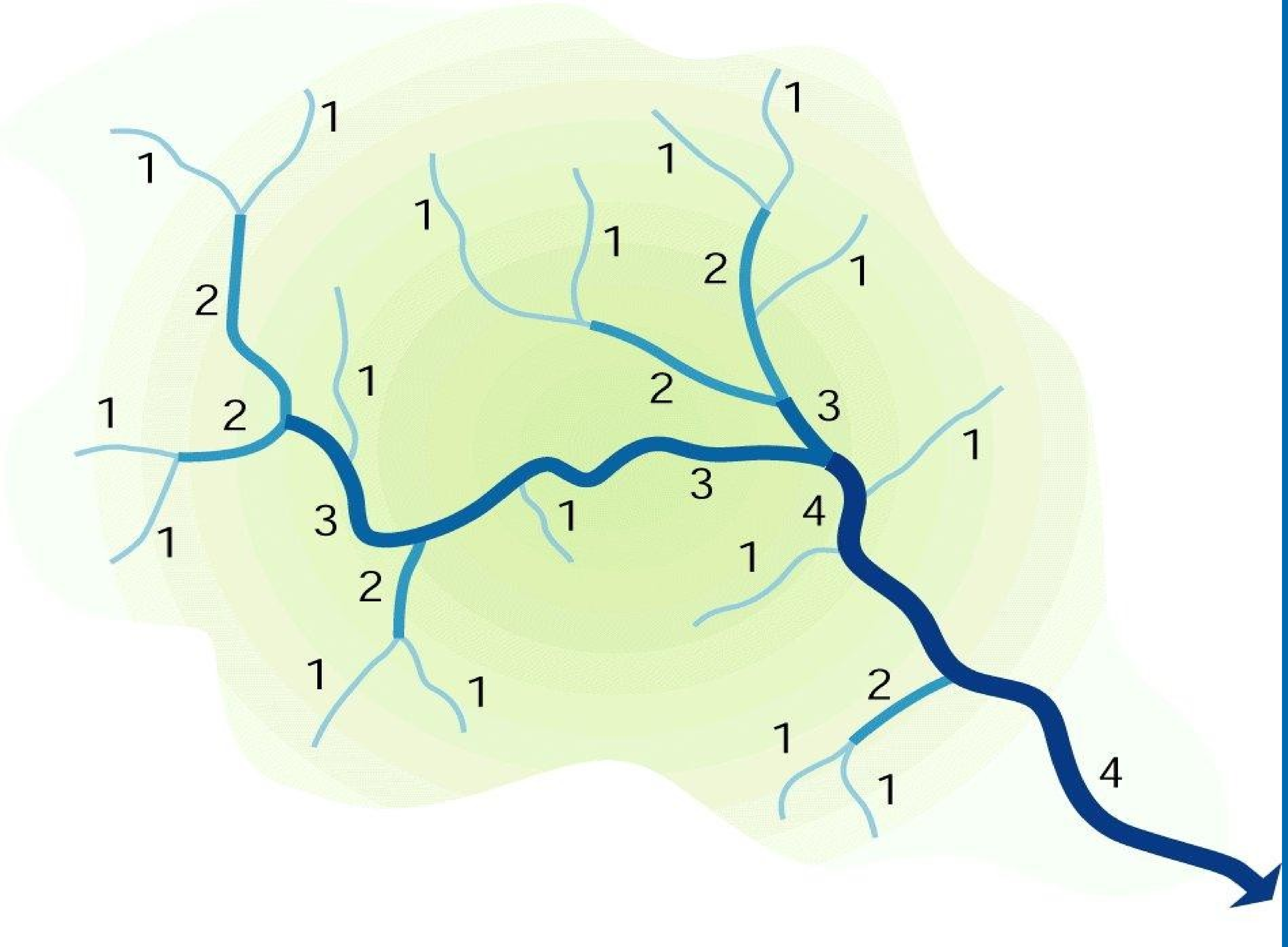
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4

Study Approach

Analyze field data from gravel bed streams and rivers in the US and UK with various bank vegetation characteristics

Employ three-dimensional CFD modeling in FLUENT to examine the influence of bank vegetation in gravel bed channels

Use CFD simulations to improve mechanistic understanding of patterns in the field data

Study Focus

Are the effects of bank vegetation on key hydraulic parameters used in restoration design of gravel bed streams scale-dependent?

Co-evolution of flow hydraulics, channel form, and vegetation establishment

Hypothesis

In relatively narrow channels, dense woody vegetation protruding appreciably into the bankfull flow field results in significantly higher values of bankfull dimensionless shear stress (τ^*) and slope (*S*).

Methods

Field Data Analysis

Gravel bed rivers with typed bank vegetation:

Andrews (1984) – Colorado

Charlton et al. (1978) - UK

Hey and Thorne (1986) - UK

Following Coon (1998) stratify channels with top widths > 20 m vs. < 20 m

t-tests on [illegible]* , S, R, R/D84, D84/D50

Regression: S = f(Q, D84, veg toggle)

Dimensionless Shear Stress

Ratio of erosive forces to resisting forces

Bank Veg. Types

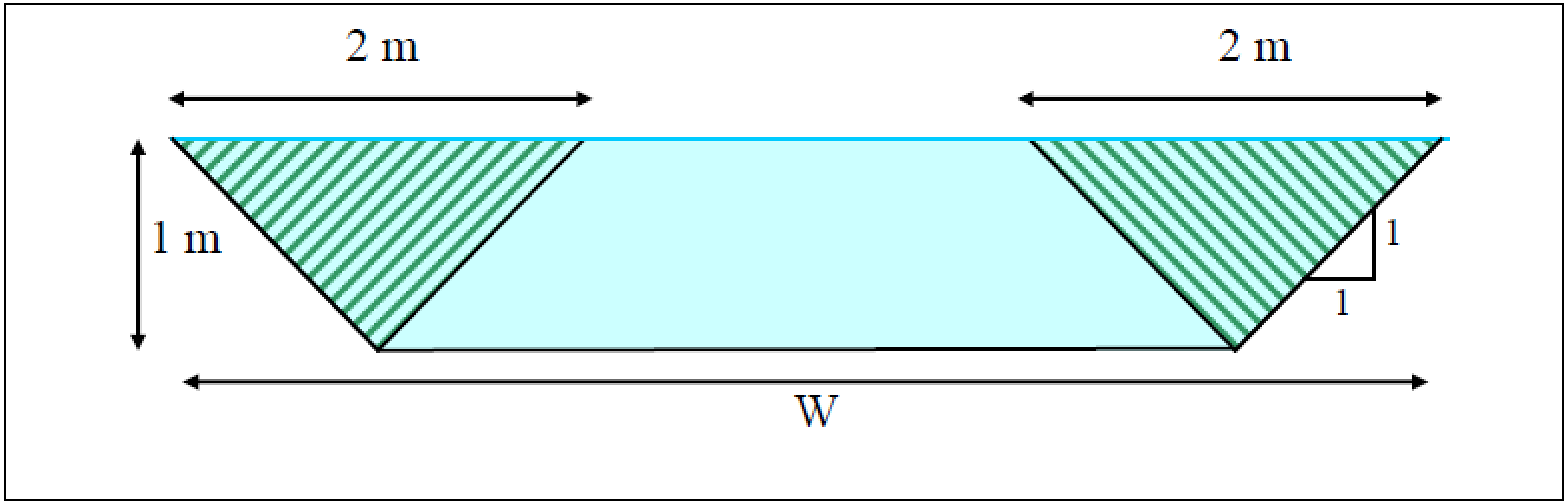
"Thin" vegetation refers to grass-covered banks, non-forested channels, or channels where tree/shrub coverage is less than 5%.

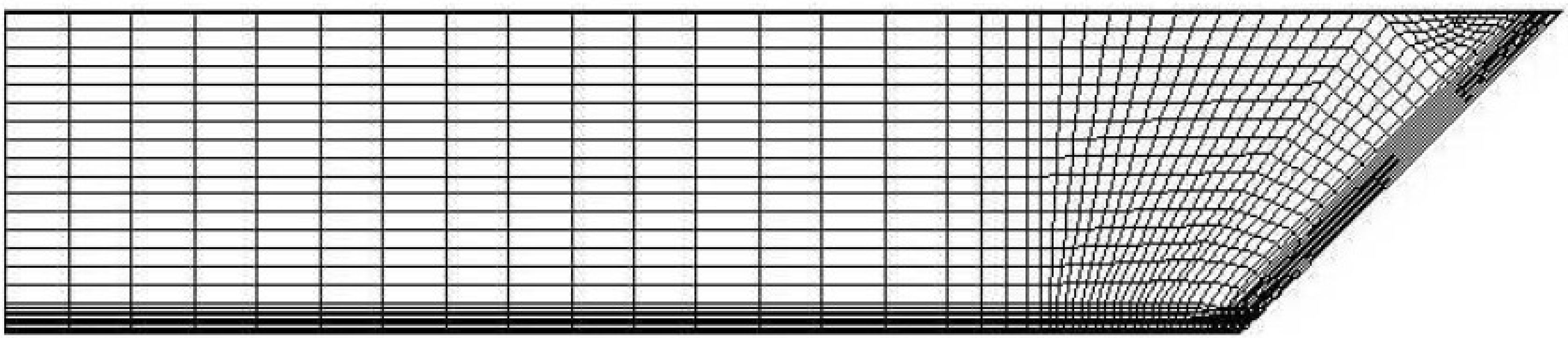
"Thick" vegetation refers to bank vegetation qualitatively described by the researchers as forested, heavy, or thick vegetated bank conditions with greater than 5% tree/shrub cover.

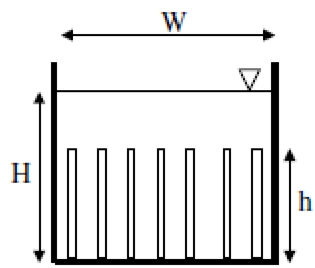
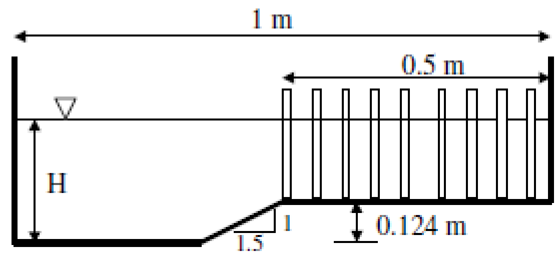
The term "thick" is best described as a qualitative index of woody vegetation dominance (density, basal area, and coverage) that is directly related to the stiffness and length scale of bank roughness elements .

CFD Approach

- Assumed turbulent diffusive terms due to vegetation are dominated by the vegetative drag term (Fischer-Antze *et al*. 2001)
- Drag force applied through the use of a porous media zone in FLUENT without modification to the turbulence models.
- Carney (2004) demonstrated that the vegetation representation used in this study could be coupled with the RNG k-e turbulence model to reasonably reproduce the laboratory velocity profiles of Tsujimoto *et al*. (1991), Dunn *et al*. (1996), and Pasche (1984).
- Conducted grid dependency tests


2 m
2 m
1 m
1
1
W



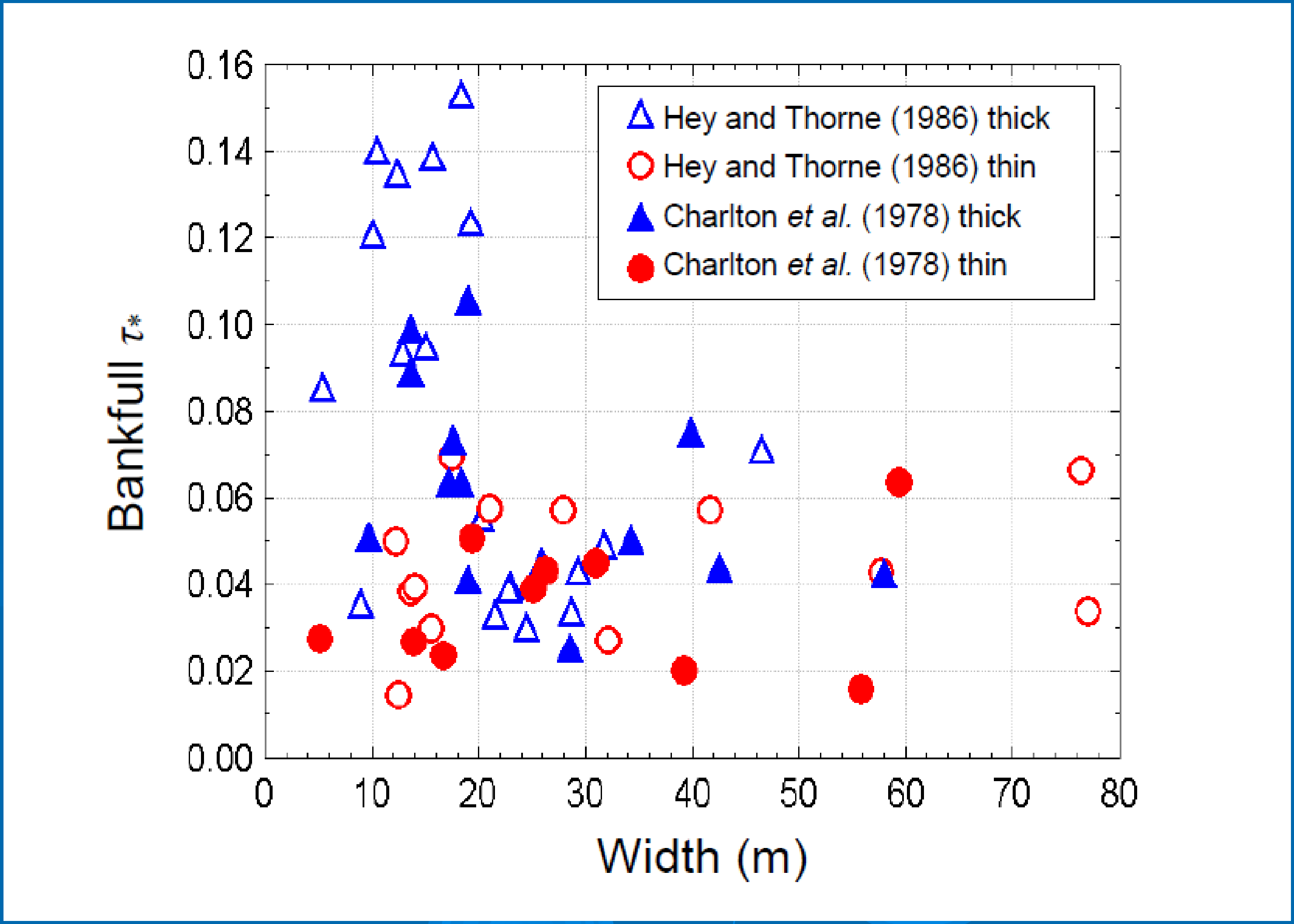
Schematic of Experiments	 				 			
Investigator	**Dunn et al. (1996)**		**Tsujimoto et al. (1991)**		**Pasche (1984)**			**Pasche and Rouve (1985)**
Experiment	1	9	R32	A31	p224	p222	p225	p1271
Width, *W* (m)	0.91	0.91	N/A*	N/A*	1	1	1	1
Slope	0.0036	0.0036	0.00213	0.0026	0.001	0.001	0.0005	0.0005
Depth, *H* (m)	0.335	0.214	0.0747	0.0936	0.2	0.2	0.2	0.225
Submerged veg. height, *h* (m)	0.12	0.12	0.041	0.046	Emergent floodplain vegetation			
Cylinder diameter (m)	0.0064	0.0064	0.001	0.0015	0.012	0.012	0.012	0.012
Vegetation density, A_v (m^{-1})	1.09	2.46	10	3.75	1.34	2.69	10.76	2.40

****The Tsujimoto et al. (1991) experiments were modeled in 2D; therefore the width of the channel was not used.***

Two Types of CFD Simulations

1. Examine the spatial scale dependence of the influence of bank vegetation in channels of varying width.
2. Examine evolving hydraulics of vegetated streams due to either natural regeneration of vegetation following a disturbance event (*e.g.*, post-flood) or accelerated vegetation establishment following rehabilitation or restoration activities.

Results – Field Data



Results – Field Data

Mean values of bankfull dimensionless shear stress (τ_*) stratified by bank vegetation and channel size. Differences in τ_* by vegetation type are significant only for channels < 20 m wide.

	Channels with width < 20 m			Channels with width > 20 m		
	thin	thick	*p*-value[b]	thin	thick	*p*-value[b]
Andrews (1984)	0.034	0.058	0.0003	0.038	0.030	0.310
Charlton *et al.* (1978)	0.032	0.073	0.0040	0.038	0.047	0.397
Hey and Thorne (1986)[a]	0.045	0.094	0.0002	0.048	0.050	0.849

[a] thin = Hey and Thorne types 1 and 2, thick = Hey and Thorne types 3 and 4

[b] *p*-value = probability that τ_* for thin vegetation is less than τ_* for thick vegetation in channels < 20 m, and the probability that τ_* for thin vegetation is different than τ_* for thick vegetation in channel widths > 20 m

Results – Field Data

In all three data sets, slopes of channels < 20 m wide with thick vegetation were significantly steeper than those of channels < 20 m wide with thin vegetation ($p \leq 0.053$).

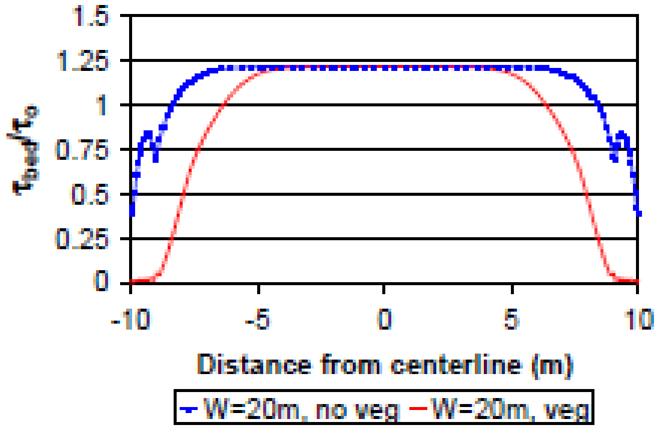
Multiple regression modeling results were very consistent for the Charlton et al. (1978) and Hey and Thorne (1986) data sets.

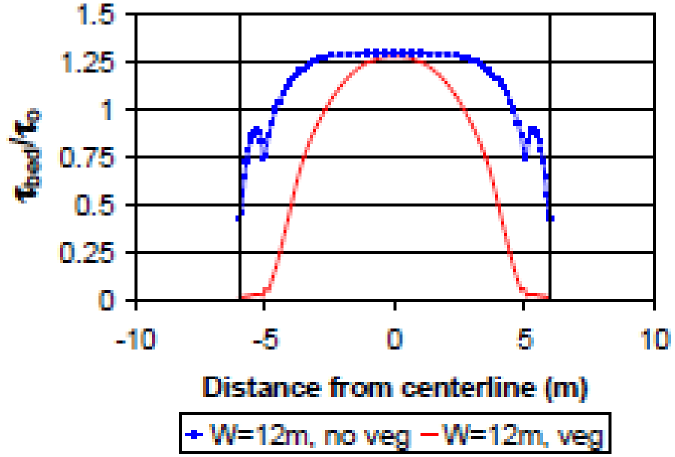
Results – Field Data

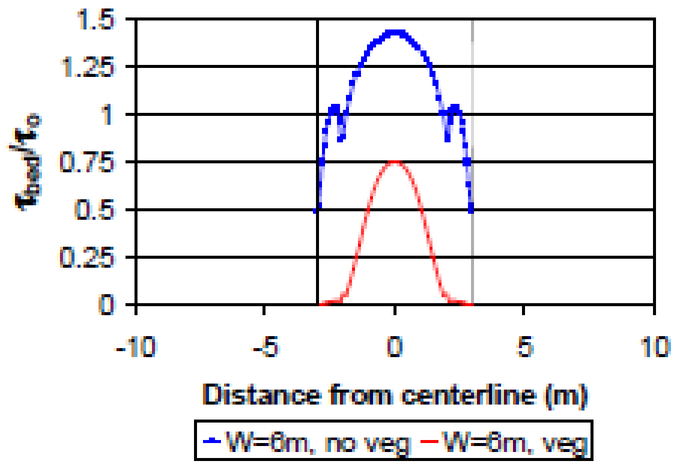
The toggle variable representing an effect of thick vegetation on channel slope solely for channels < 20 m wide was highly significant for the individual data sets ($p < 0.0012$) and both data sets combined ($p < 0.00002$).

Slopes of channels < 20 m wide with thick vegetation were on average 60% and 105% steeper for a given combination of *Q* and *D*84 in the Hey and Thorne (1986) and Charlton et al. (1978) data sets, respectively.

Results - CFD

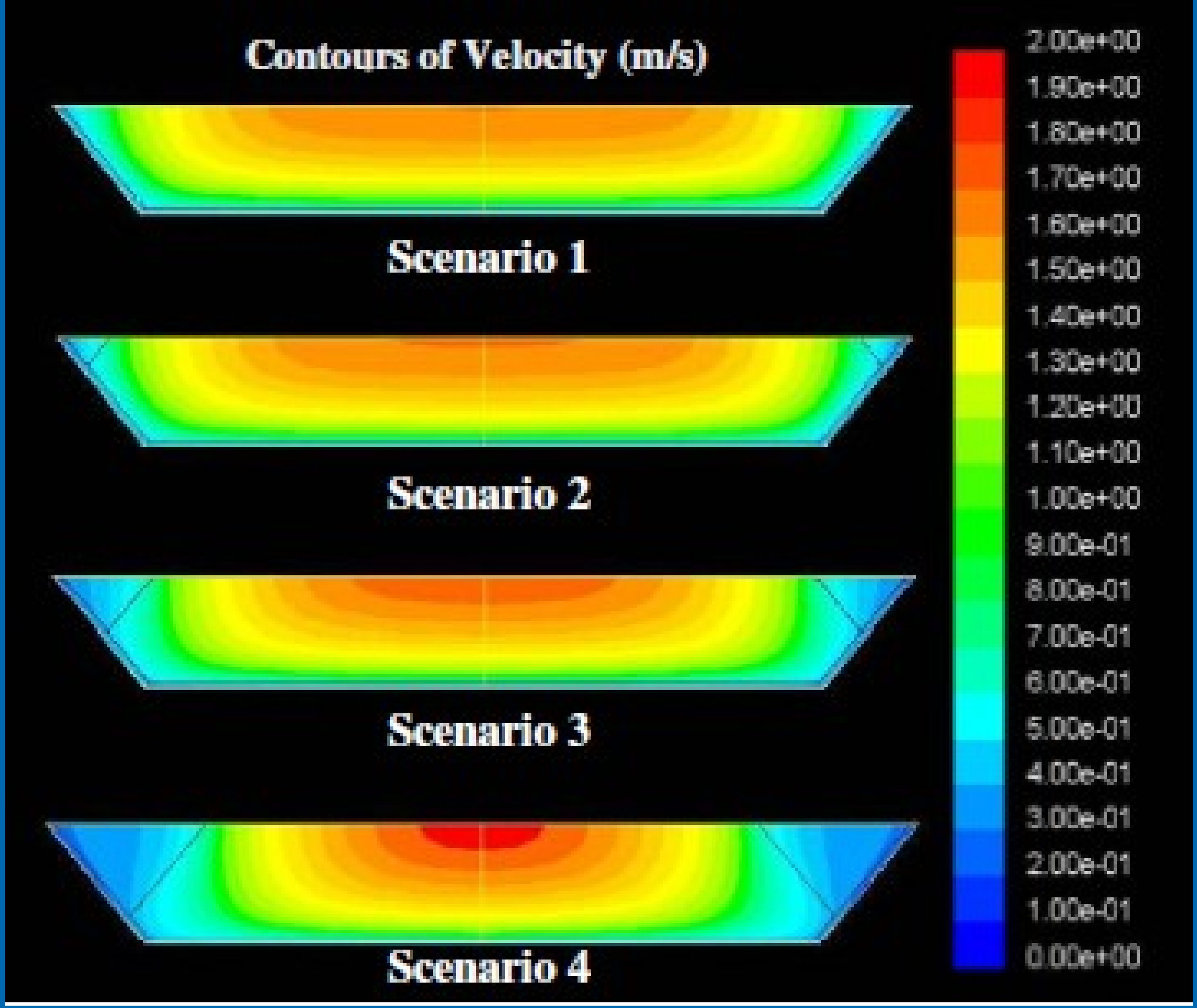

1.5
1.25
1
0.75
0.5
0.25
0
-10
-5
0
5
10
τ_{bed}/τ_o
Distance from centerline (m)
W=20m, no veg
W=20m, veg

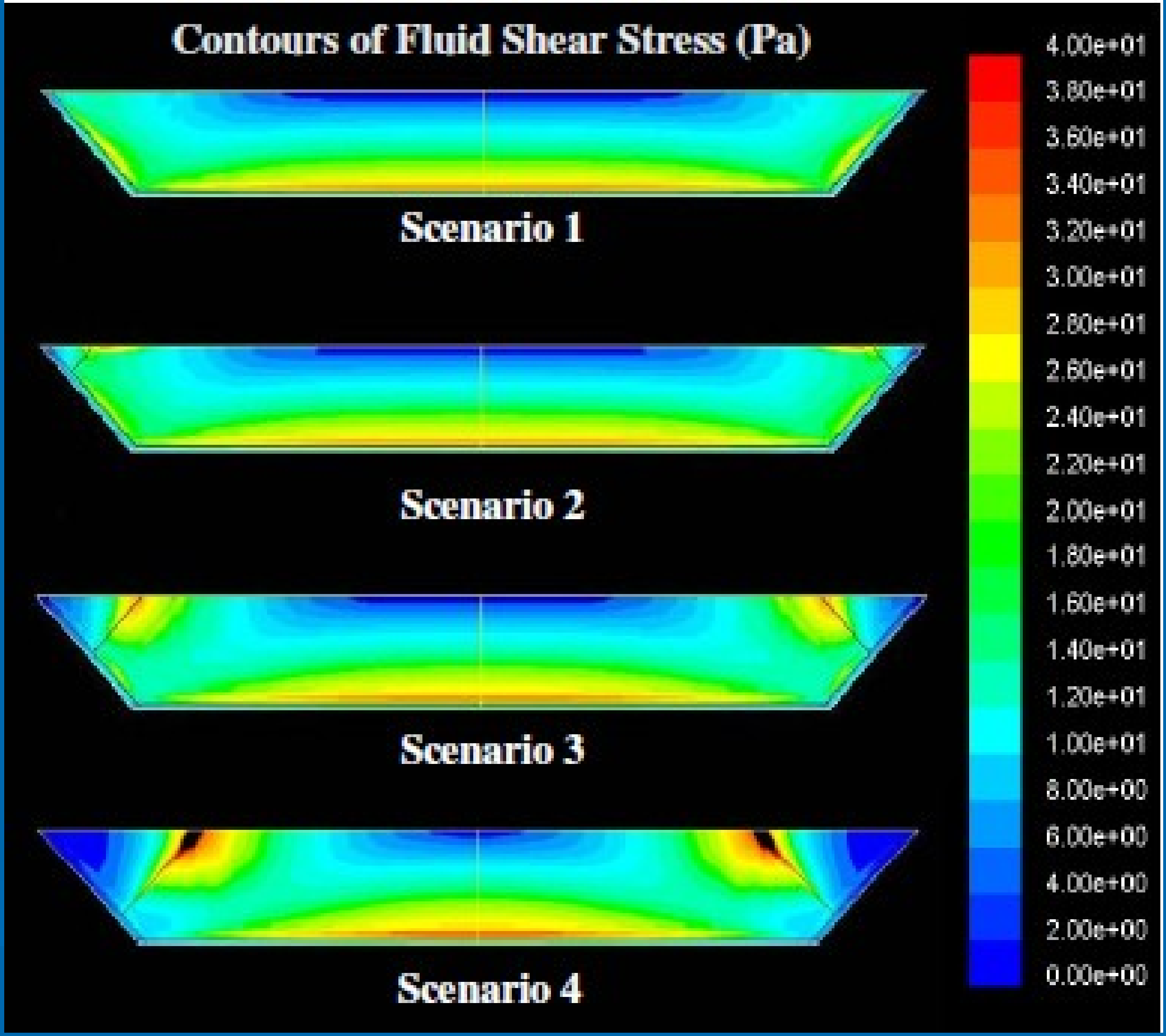

1.5
1.25
1
0.75
0.5
0.25
0
-10
-5
0
5
10
τ_{bed}/τ_o
Distance from centerline (m)
W=12m, no veg
W=12m, veg

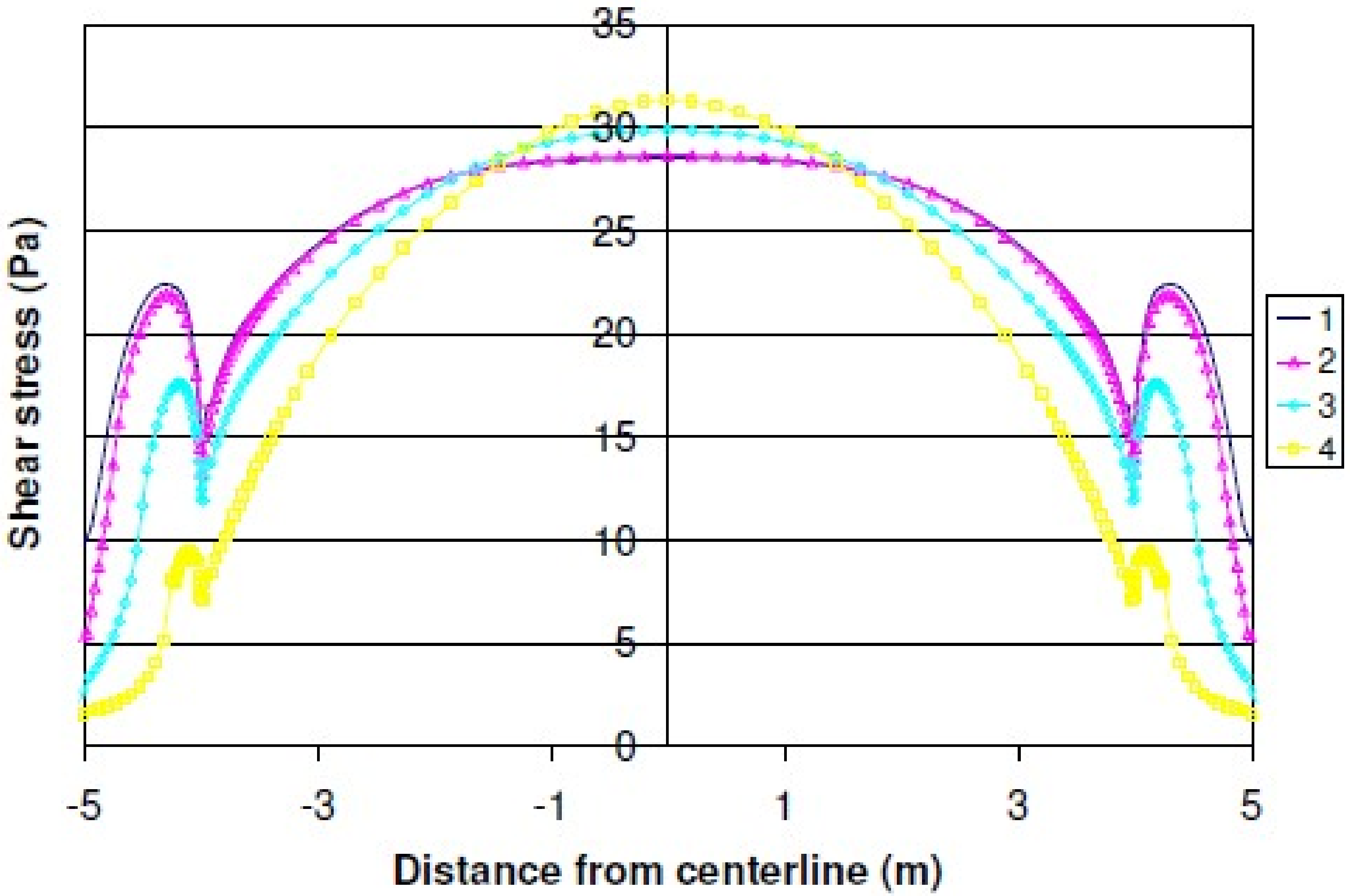

1.5
1.25
1
0.75
0.5
0.25
0
-10
-5
0
5
10
τ_{bed}/τ_o
Distance from centerline (m)
W=6m, no veg
W=6m, veg

Comparison of $\tau_{bed,avg}/\tau_o$ and the portion of shear stress consumed by the vegetation for channels of different widths. In this case, for consistency of comparison between computed shear stresses, τ_o is computed as the average shear stress over the entire boundary in an unvegetated channel according to Equations (5) and (6).

Top width (m)	Bed shear stress fraction $\tau_{bed,avg} / \tau_o$	Vegetation shear stress fraction $1 - \tau_{bed,avg} / \tau_o$
6	0.37	0.63
12	0.74	0.26
20	0.86	0.14
30	0.91	0.09


Contours of Velocity (m/s)
Scenario 1
Scenario 2
Scenario 3
Scenario 4
2.00e+00
1.90e+00
1.80e+00
1.70e+00
1.60e+00
1.50e+00
1.40e+00
1.30e+00
1.20e+00
1.10e+00
1.00e+00
9.00e-01
8.00e-01
7.00e-01
6.00e-01
5.00e-01
4.00e-01
3.00e-01
2.00e-01
1.00e-01
0.00e+00


Contours of Fluid Shear Stress (Pa)
Scenario 1
Scenario 2
Scenario 3
Scenario 4
4.00e+01
3.80e+01
3.60e+01
3.40e+01
3.20e+01
3.00e+01
2.80e+01
2.60e+01
2.40e+01
2.20e+01
2.00e+01
1.80e+01
1.60e+01
1.40e+01
1.20e+01
1.00e+01
8.00e+00
6.00e+00
4.00e+00
2.00e+00
0.00e+00



Shear stress (Pa)
35
30
25
20
15
10
5
0
-5
-3
-1
1
3
5
Distance from centerline (m)
1
2
3
4

Some Implications

If Qs ~τ*1.5*w*, then the fact that widths of the small, thick channels average 60% of their thin counterparts would require τ* to increase ca. 40-45% for equivalent capacity

The *ca*. 20-25% decrease in bed shear predicted in the CFD simulations combined with *w* reduction ☾60-70% increase in τ* to achieve a comparable sediment transport capacity.

Some Implications

Veg. influence in natural channels appears to be greater than in our CFD simulations:

- No topographic complexity
- No veg. heterogeneity
- Flow blockage effects not represented

Field data suggest slope increase may be the predominant mode of adjustment in small, thickly vegetated channels

- depth and grain size account for <20% of the observed twofold increase in bankfull τ^*.

Stream Restoration
General design approaches

Analogy
- Reference reach(es)
- Regional curves
- Hydraulic geometry
- "Natural Channel Design"

Analytical
- Tractive force
- Live bed
  - System of equations
  - Sediment continuity

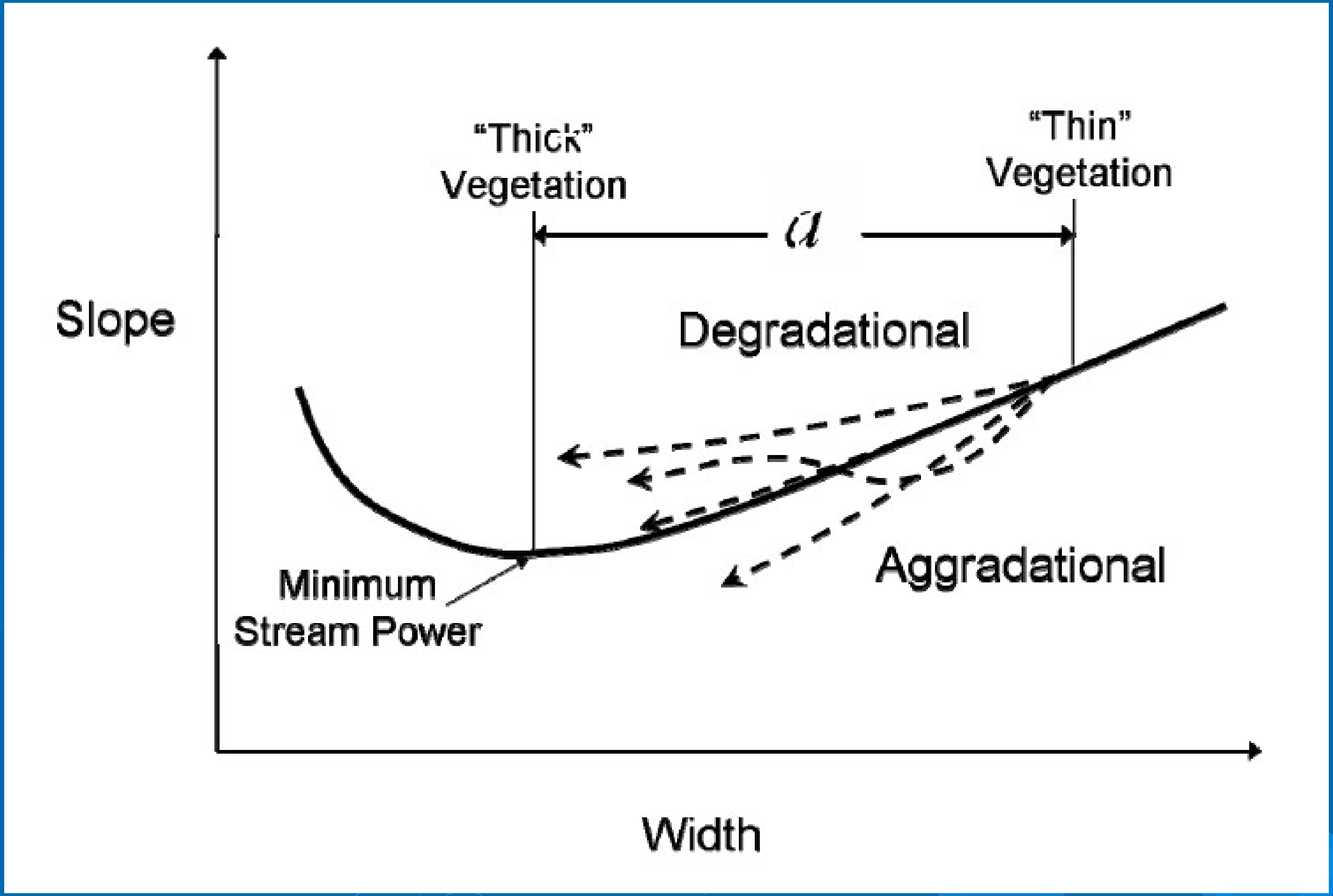
Some Implications

Careful with τ^*

Streams and vegetation co-evolve

Analogy approaches should account for the scale-dependent effect of bank vegetation on τ^*, slope, and width.

Some Implications - Analytical



Conclusions

The lateral dimension of channel size relative to the length scale of vegetative roughness is a key missing parameter in understanding shear stress (and sediment transport) in small streams.
The field data and CFD simulations indicate a significant scale-dependent effect of bank vegetation that has not been previously accounted for in downstream hydraulic geometry relationships, regime slope models, and shear stress partitioning schemes.

Conclusions

The scale-dependent influence of bank vegetation also has important implications for stream restoration designs based on tractive force, regime, and analytical approaches.


First Type of CFD Simulation

Channel bank angle, slope, depth, grain size distribution, and vegetation characteristics (shape extending into the channel and inertial loss coefficient) were all held constant for each run. The porous zone representing vegetation was given a *CDAv* value of 11.5 m-1 reported for natural channels by Fischenich (1996) , where *CD* is a drag coefficient and *Av* is a measure of vegetation density (L-1).

Second Type of CFD Simulation

Simulated vegetative succession in a channel of fixed characteristics (width, side slope, bed roughness, and channel slope) with four vegetation treatments.

Veg. protrusion is increased in each scenario by lowering the minimum elevation of vegetation on the bank.

Inertial loss coefficient is increased to simulate increasing flow resistance as vegetation matures and becomes denser and stiffer.

$$\frac{F_{D,total}(z)}{V_{total}} = c_b \frac{\frac{\rho}{2} C_D \frac{\pi}{4} D_{my} D_{mz} u(z)^2}{\frac{\pi}{6} D_{mx} D_{my} D_{mz}} = \frac{3}{4} \rho \frac{c_b C_D}{D_{84x}} u(z)^2$$

$$\frac{F_{D,i}}{V_{fluid}} = \frac{1}{2} \rho C_D A_v u_{mag} u_i$$

$$A_v = nD_s = \frac{D_s}{\lambda^2}$$

$$\tau_{ij} = (\mu + \mu_e)\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)$$

$$\tau_{bed,avg} = \frac{\sum (\tau_{ij} d)_w}{W}$$

Channel characteristics for scenarios simulating establishment of bank vegetation. Bottom width = 4 m; Side slopes = 1:1; $S_o = 0.003$; $D_{84} = 50$ mm; $Q = 5.75$ m³/s. Depth is measured from the top of the D_{84} grains. $\bar{u}$ and u_{max} are the average and maximum downstream velocities for the cross section. $\tau_{bed,avg}$ and $\tau_{bed,max}$ are the average and maximum bed shear stress respectively, computed using equations (5) and (6) at the D_{84} grain height across the channel boundary.

Scenario	1 (no vegetation)	2	3	4 (full vegetation)
Distance from bed vegetation begins (m)	-	0.75	0.5	0.25
$C_d A_v$ (m^{-1})	-	0.4	0.8	1.2
Depth, z above the D_{84} grain height (m)	1	1.005	1.057	1.166
$\bar{u}$ (m/s)	1.277	1.269	1.201	1.074
u_{max} (m/s)	1.801	1.807	1.865	1.948
τ_o (Pa) =	24.4	24.5	25.6	27.8
$\tau_{bed,\ avg}$ (Pa) =	25.6	25.6	25.3	23.7
$\tau_{bed,\ max}$ (Pa) =	28.5	28.7	29.9	31.4

Some Implications - Analytical

Careful with τ^*

Hey (1997) – channel slope is not influenced by bank vegetation ☾a 'problem' for extremal hypotheses such as minimum stream power. This study - slope is significantly influenced by bank vegetation in channels < 20 m wide

Inferences regarding the realism of extremal hypotheses are spurious in the absence of stream power and shear stress partitioning schemes that account for scale-dependent vegetation effects.

CFD Approach

Straight, prismatic, trapezoidal channels

Drag force representation of vegetation (*e.g.*, Fischer-Antze *et al*., 2001)

Porous treatment of bed roughness described in Carney *et al*. (2006) to investigate the influence of bank vegetation on flow hydraulics in trapezoidal channels.

Conducted grid dependency tests

Examine:

- scale-dependency of vegetation influence in channels with similar characteristics but different widths, and
- changes in flow hydraulics following a succession of vegetation establishment along a channel.