Velocity Prediction in High-Gradient Channels

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Objective

- Present methods for predicting average reach velocity and flow resistance coefficients
  - High-gradient channels: slopes > ~2%
- Will provide:
  - photo guidance for stream reaches with measured velocity and Manning's *n* values
  - an evaluation of available methods for quantitative velocity and flow resistance prediction
  - a presentation of new methods for quantatative prediction

- Average reach velocity and flow resistance coefficients are needed for:
  - hydraulic modeling
  - geomorphic / stream restoration analyses
  - ecological assessments

Average reach velocity predicted through a few approaches:

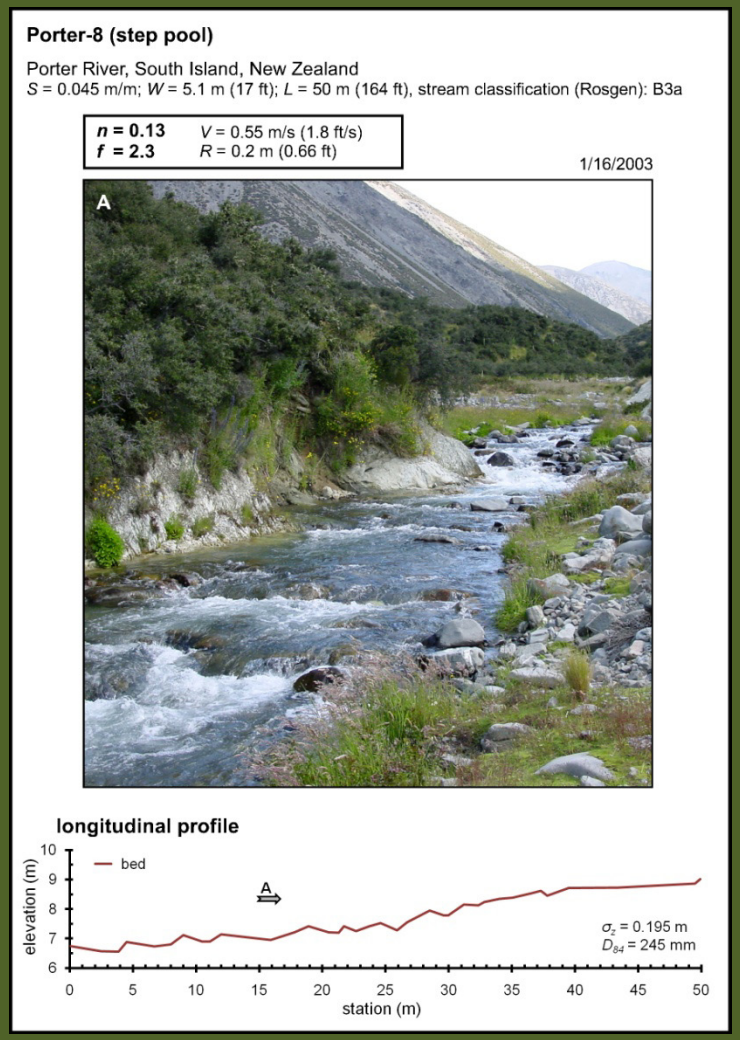
- Direct velocity prediction (regression equations)
- Indirect velocity prediction, using resistance coefficients:
  - Manning's *n*
  - Darcy-Weisbach *f*

$$V = \frac{R^{2/3} S_f^{1/2}}{n} = \sqrt{\frac{8gRS_f}{f}}$$

Resistance coefficients predicted using:

- Photographic guidance
- Regression equations
- Professional experience

$$n = 0.25\left(\frac{R}{\sigma_z}\right)^{-0.67}$$



Resistance is Oftentimes Underestimated

Ramifications:

- Overestimated reach average flow velocities
- Underestimated travel times
- Inaccurate categorization of reach-average flow regime (super v. subcritical)
- Computational instability in hydraulic models

Photo guide being developed for predicting resistance coefficients in high gradient channels

- USFS General Technical Report (GTR)
- Manning's *n*: 0.021 to 0.96
- Channels both with and without instream wood
- Channel types included in guidance:
  - Cascade
  - Step pool
  - Plane bed

Single Discharge Measurements

- 29 stream reaches
- Data Collected in:
  - Cascades of Washington State
  - Argentina
  - Chile
  - New Zealand

Examples:

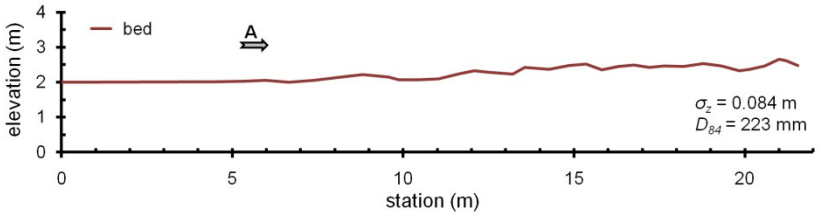
BE-A (transitional: plane bed / step pool)

Buena Esperanza, Tierra del Fuego, Argentina
S = 0.022 m/m; *W* = 4.4 m (14 ft); *L* = 22 m (71 ft), stream classification (Rosgen): B3

***n* = 0.059**	*V* = 0.77 m/s (2.5 ft/s)
***f* = 0.50**	*R* = 0.17 m (0.56 ft)

2/13/2006

longitudinal profile



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2/13/2006

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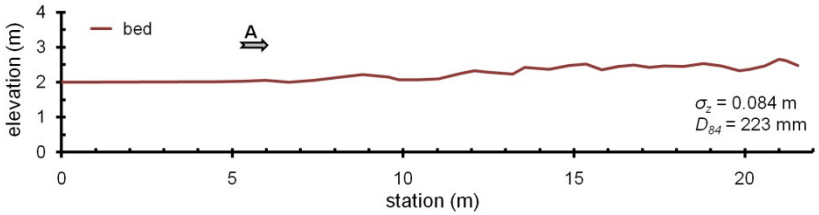


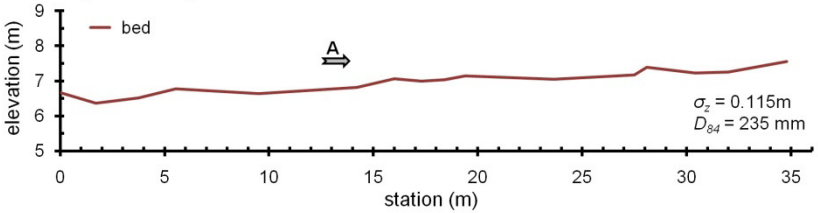
Porter-4 (transitional: plane bed / step pool)

Porter River, South Island, New Zealand
S = 0.026 m/m; *W* = 1.6 m (5.2 ft); *L* = 35 m (114 ft), stream classification (Rosgen): E3b

***n* = 0.074**
***f* = 0.74**
V = 0.74 m/s (2.4 ft/s)
R = 0.2 m (0.66 ft)

1/16/2003

longitudinal profile



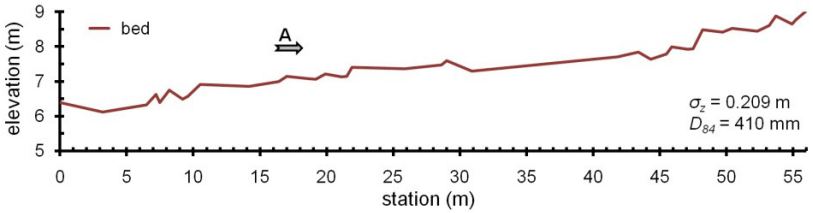
Porter-6 (step pool)

Porter River, South Island, New Zealand
S = 0.047 m/m; *W* = 3.3 m (11 ft); *L* = 56 m (183 ft), stream classification (Rosgen): B3a

***n* = 0.091**
***f* = 1.1**
V = 0.81 m/s (2.7 ft/s)
R = 0.2 m (0.66 ft)

1/16/2003

longitudinal profile



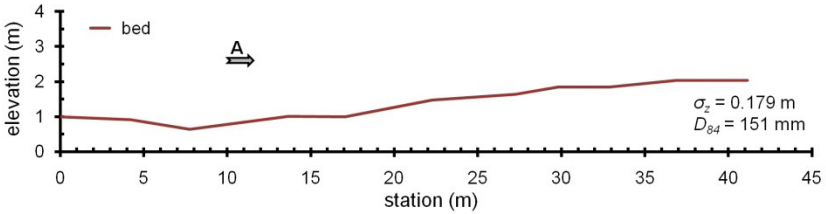
TA-15 (transitional: pool riffle / step pool)

Tres Arroyos, Malalcahuello National Preserve, Chile
S = 0.028 m/m; *W* = 3.6 m (12 ft); *L* = 41 m (135 ft), stream classification (Rosgen): B3

***n* = 0.13**
***f* = 2.7**
V = 0.31 m/s (1.0 ft/s)
R = 0.12 m (0.39 ft)

4/7/2005

longitudinal profile



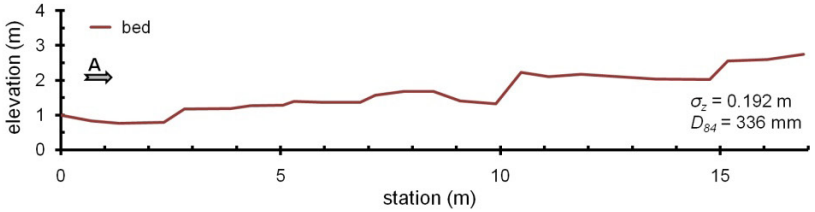
BE-G (step pool)

Buena Esperanza, Tierra del Fuego, Argentina
S = 0.10 m/m; W = 2.8 m (9.1 ft); L = 17 m (55 ft), stream classification (Rosgen): A3a+

n = 0.27	V = 0.39 m/s (1.3 ft/s)
f = 10	R = 0.19 m (0.62 ft)

3/5/2006

longitudinal profile



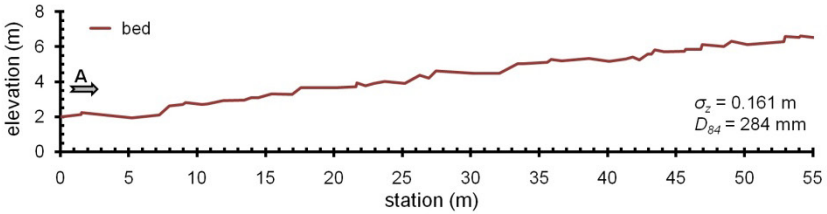
N. F. Busywild Creek (step pool)

Nisqually River Watershed, Washington State, USA
S = 0.083 m/m; W = 1.4 m (4.5 ft); L = 56 m (182 ft), stream classification (Rosgen): A3

n = 0.48	V = 0.12 m/s (0.38 ft/s)
f = 41	R = 0.085 m (0.28 ft)

7/8/1999

longitudinal profile



Multiple Discharge Measurements

- Flow resistance varies substantially by discharge
- Velocity and flow resistance guidance needed for all flow stages
- 20 stream reaches
- Data collected in:
  - Fraser Experimental Forest (Colorado)
  - Rio Cordon (Italy)

Examples:

ESL-4 (step pool)

East Saint Louis Creek, Colorado, USA

S = 0.12 m/m; W = 2.9 m (9.4 ft); L = 16 m (51 ft)

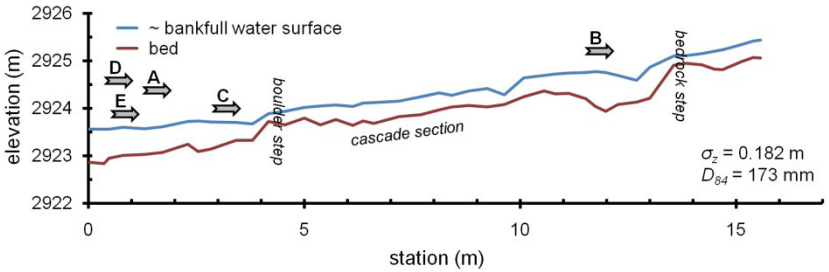
low flow

9/26/2009

Fraser Experimental Forest;
Arapaho-Roosevelt National Forest
stream classification (Rosgen): B3a

ESL-4

longitudinal profile



~ bankfull flow	mid flow	low flow (facing page)
***n* = 0.23**	***n* = 0.28**	***n* = 0.32**
***f* = 6.3**	***f* = 9.7**	***f* = 14**
V = 0.63 m/s (2.1 ft/s)	V = 0.50 m/s (1.6 ft/s)	V = 0.33 m/s (1.1 ft/s)
Q = 0.61 cms (21 cfs)	Q = 0.32 cms (11 cfs)	Q = 0.12 cms (4.2 cfs)
R = 0.26 m (0.86 ft)	R = 0.26 m (0.85 ft)	R = 0.17 m (0.56 ft)
W = 2.9 m (9.4 ft)	W = 2.9 m (9.4 ft)	W = 2.3 m (7.6 ft)
Fr = 0.34	Fr = 0.27	Fr = 0.23

~ bankfull flow 6/7/2008

mid flow 7/14/2008

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ESL-4

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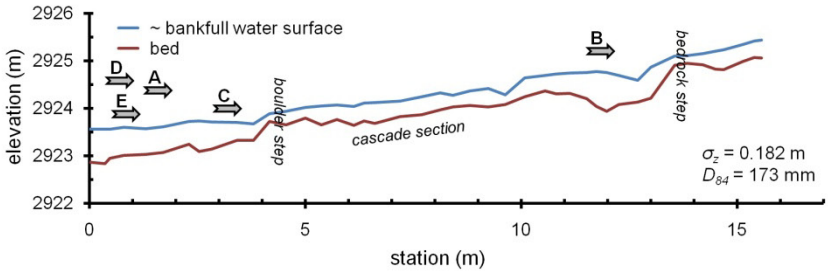

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ESL-4

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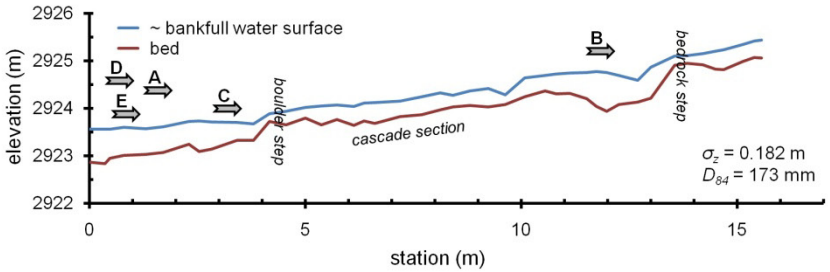

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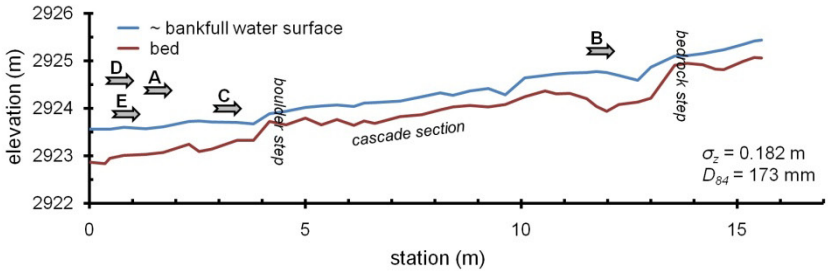

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mid flow 7/14/2008

FC-4 (step pool)

Fool Creek, Colorado, USA

S = 0.13 m/m; *W* = 1.6 m (5.2 ft); *L* = 19 m (62 ft)

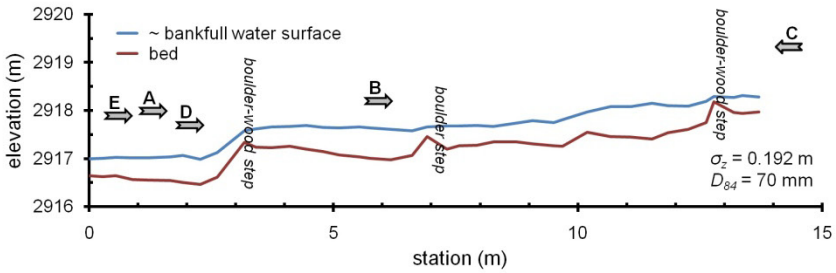
low flow

9/26/2009

Fraser Experimental Forest;
Arapaho-Roosevelt National Forest
stream classification (Rosgen): B3a

FC-4

longitudinal profile



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***n* = 0.22**	***n* = 0.31**	***n* = 0.52**
***f* = 6.3**	***f* = 16**	***f* = 47**
V = 0.59 m/s (1.9 ft/s)	*V* = 0.27 m/s (0.89 ft/s)	*V* = 0.14 m/s (0.46 ft/s)
Q = 0.22 cms (7.6 cfs)	*Q* = 0.045 cms (1.6 cfs)	*Q* = 0.014 cms (0.49 cfs)
R = 0.21 m (0.67 ft)	*R* = 0.12 m (0.38 ft)	*R* = 0.091 m (0.30 ft)
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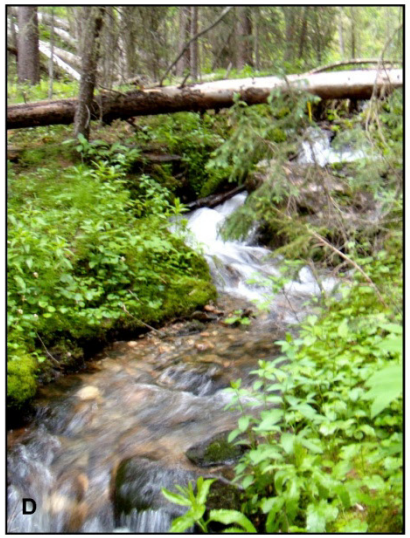

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low flow

9/26/2009

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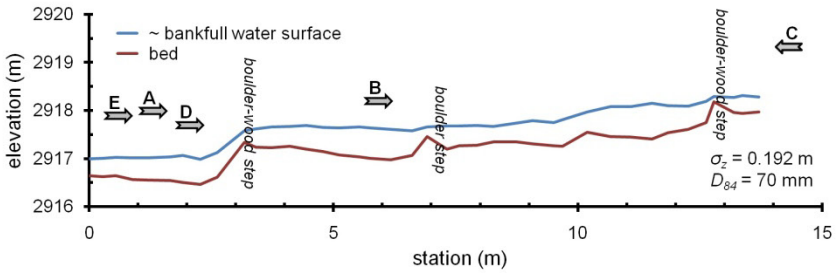
FC-4

longitudinal profile



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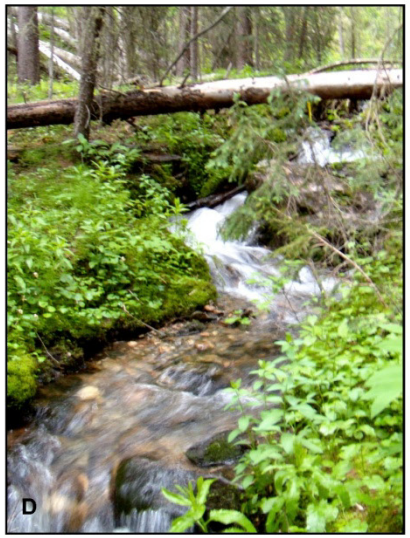

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FC-4

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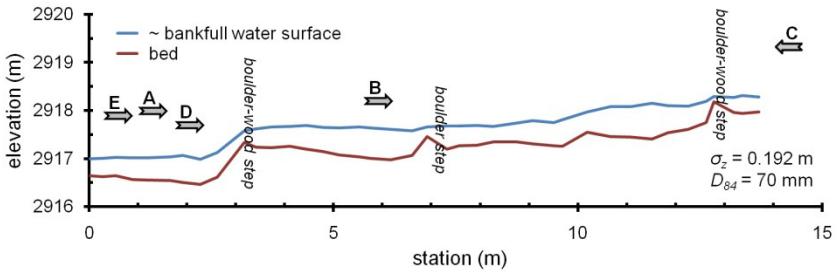

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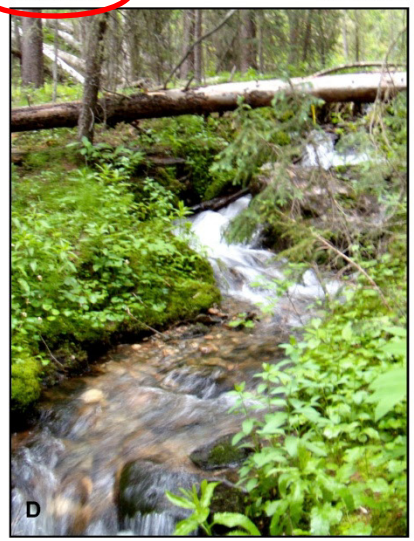

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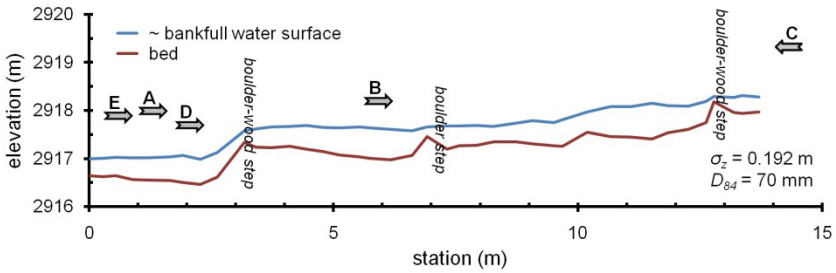

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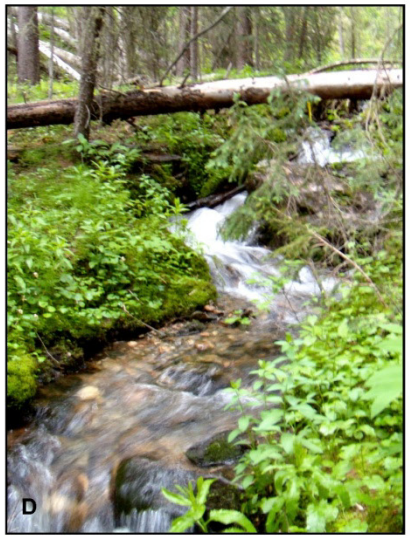
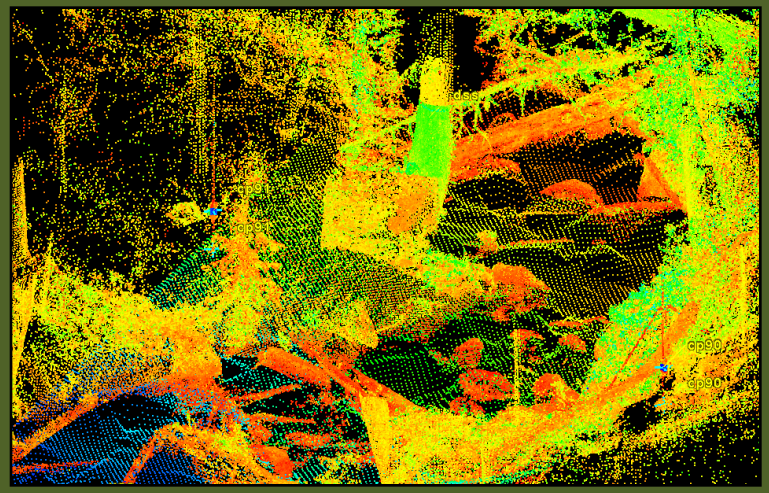
mid flow 7/21/2008



Quantitative methodologies developed…

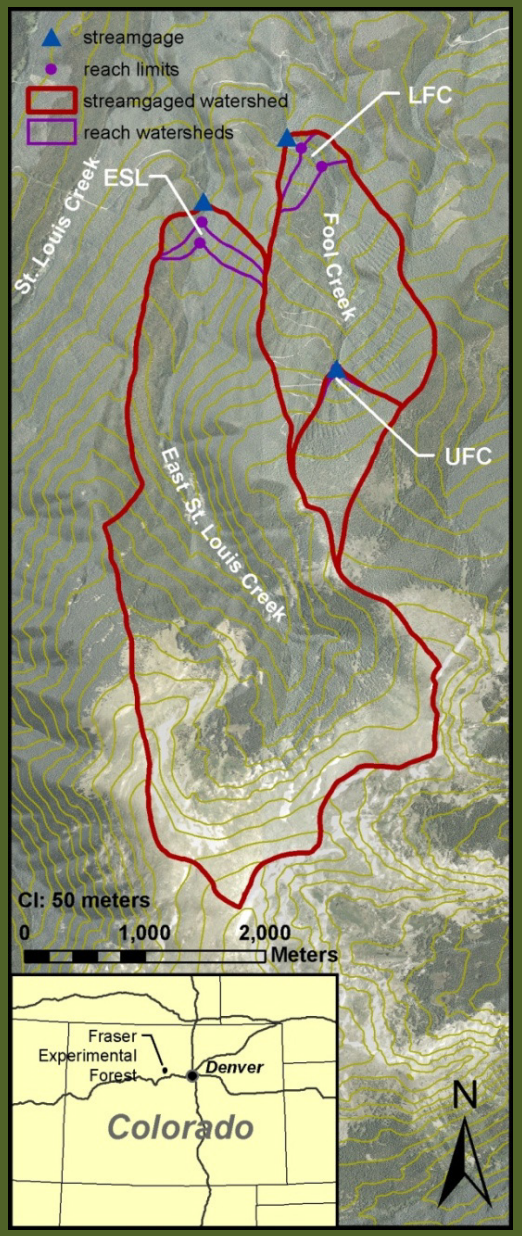
- for predicting velocity and resistance coefficients
- Channels both with and without instream wood
- Methods based on data collected in Fraser Experimental Forest, Colorado
- Supplemented with data collected in Rio Cordon, Italy, and in the Cascades

- Fraser Experimental Forest dataset developed through measurements of:
  - Average reach velocity, using Rhodamine WT tracer
  - Measurements of channel, banks and adjacent floodplain, using total station and terrestrial LiDAR
  - Water surface profiles
  - Bed material gradation

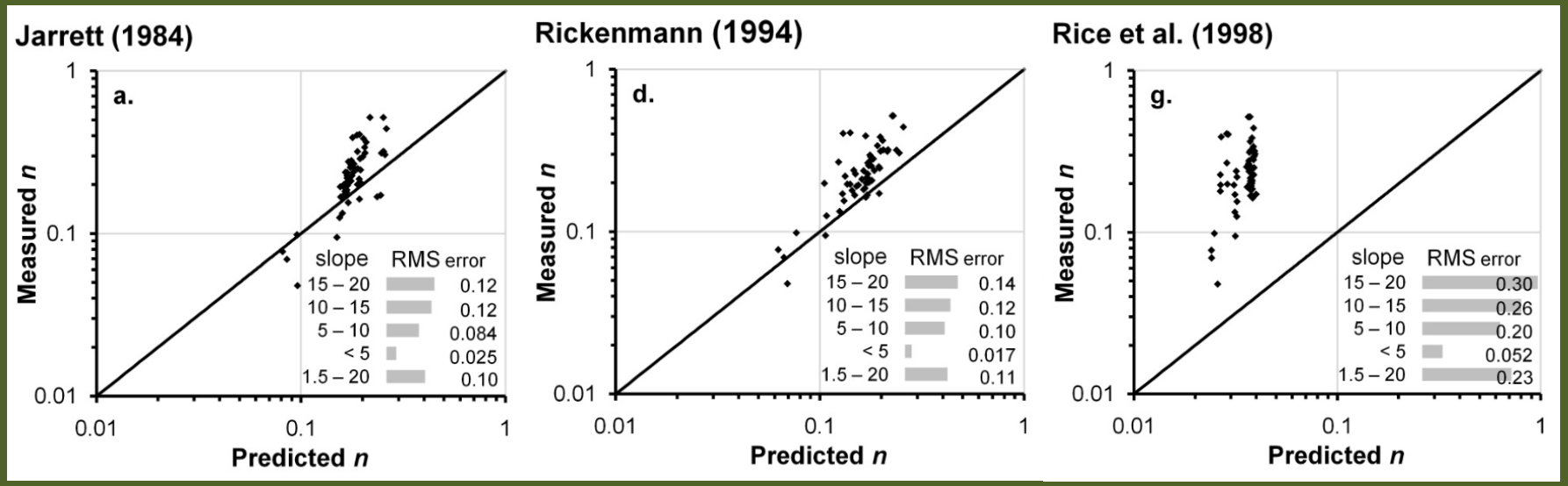


Initially, existing methods were assessed for their prediction capabilities

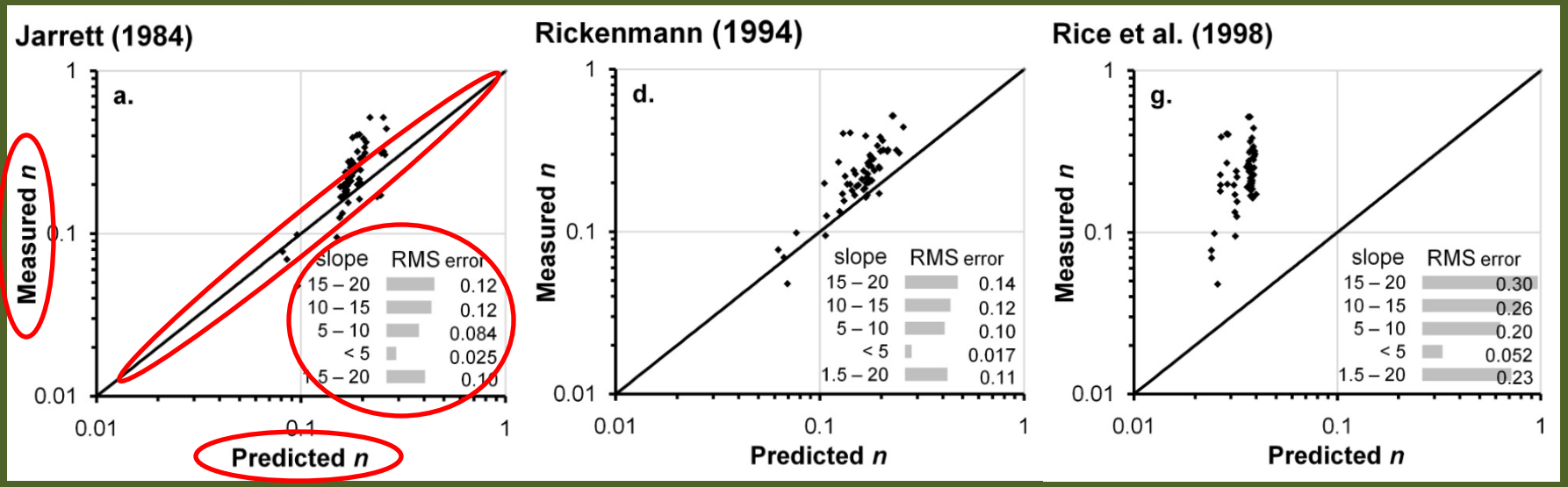
- Methods tested using Fraser dataset
  - Bankfull through low flow
  - Cascade, step pool, plane bed
  - Slope: 1.5 to 20%
  - Manning's *n*: 0.05 to 0.52
  - Velocity: 0.11 to 1.32 m/s
  - Froude number: 0.13 to 0.77



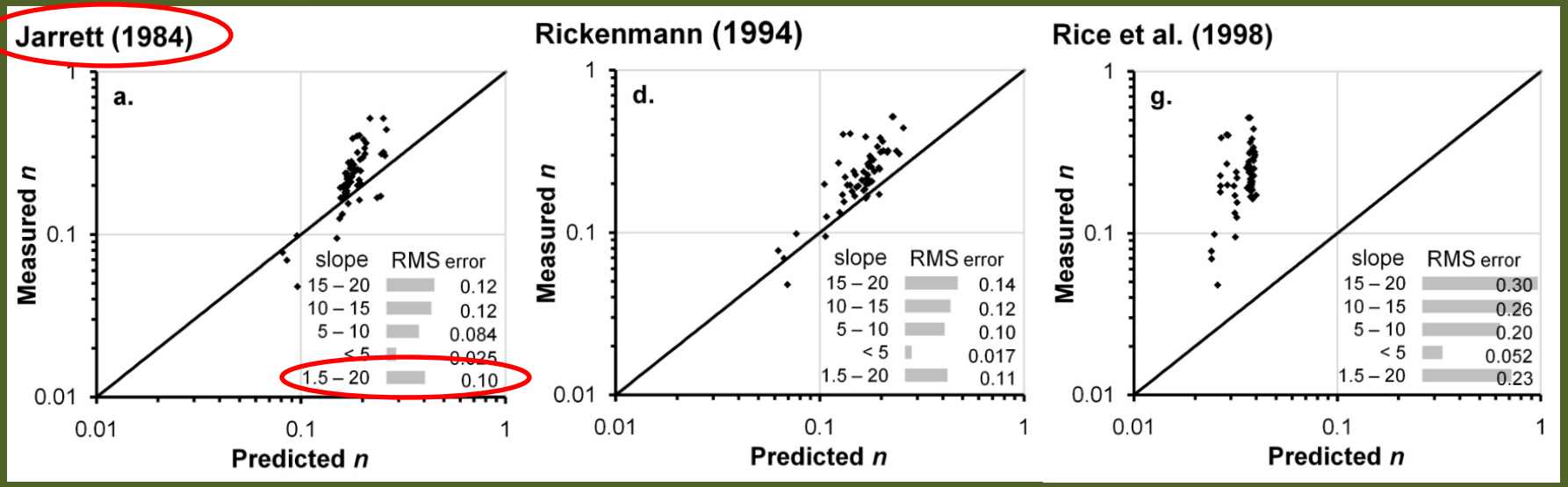
Manning's *n*


Jarrett (1984)
a.
Measured n
Predicted n
1
0.1
0.01
0.01
0.1
1
slope
RMS error
15 – 20
0.12
10 – 15
0.12
5 – 10
0.084
< 5
0.025
1.5 – 20
0.10
Rickenmann (1994)
d.
Measured n
Predicted n
slope
RMS error
15 – 20
0.14
10 – 15
0.12
5 – 10
0.10
< 5
0.017
1.5 – 20
0.11
Rice et al. (1998)
g.
Measured n
Predicted n
slope
RMS error
15 – 20
0.30
10 – 15
0.26
5 – 10
0.20
< 5
0.052
1.5 – 20
0.23

Manning's *n*


Jarrett (1984)
a.
Measured n
Predicted n
1
0.1
0.01
0.01
0.1
1
slope
RMS error
15 – 20
0.12
10 – 15
0.12
5 – 10
0.084
< 5
0.025
1.5 – 20
0.10
Rickenmann (1994)
d.
Measured n
Predicted n
slope
RMS error
15 – 20
0.14
10 – 15
0.12
5 – 10
0.10
< 5
0.017
1.5 – 20
0.11
Rice et al. (1998)
g.
Measured n
Predicted n
slope
RMS error
15 – 20
0.30
10 – 15
0.26
5 – 10
0.20
< 5
0.052
1.5 – 20
0.23

Manning's *n*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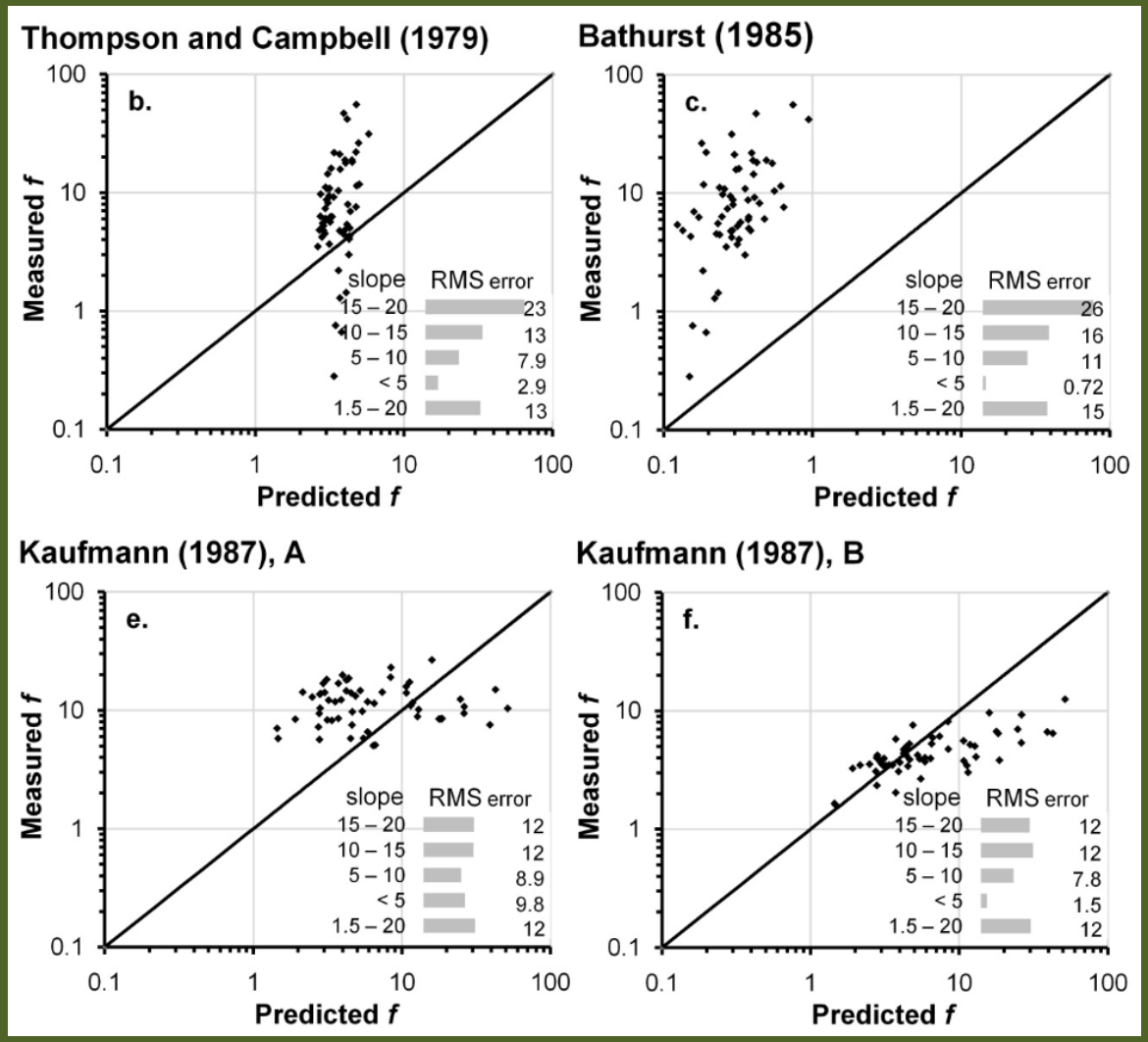
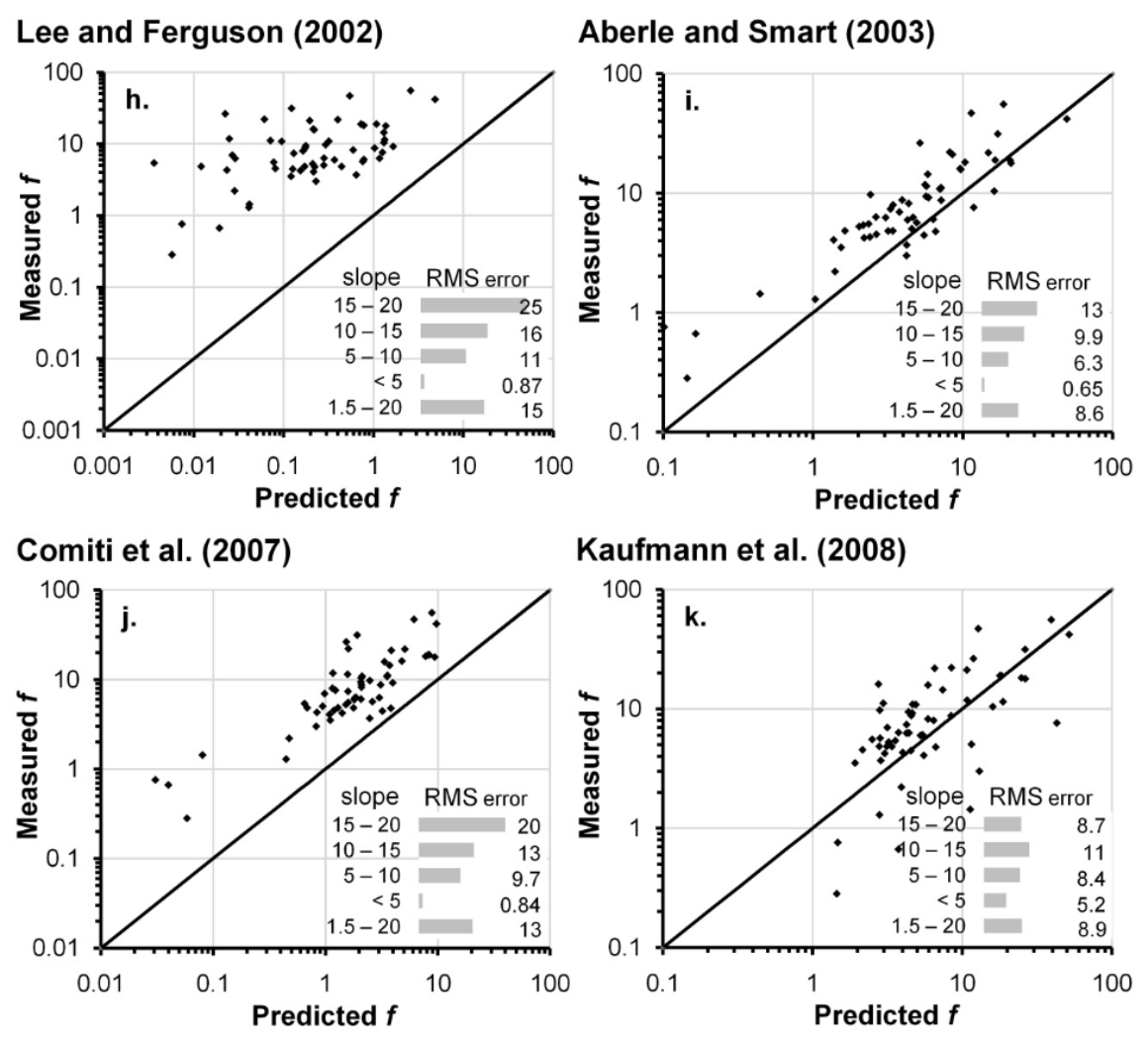
0.052
1.5 – 20
0.23

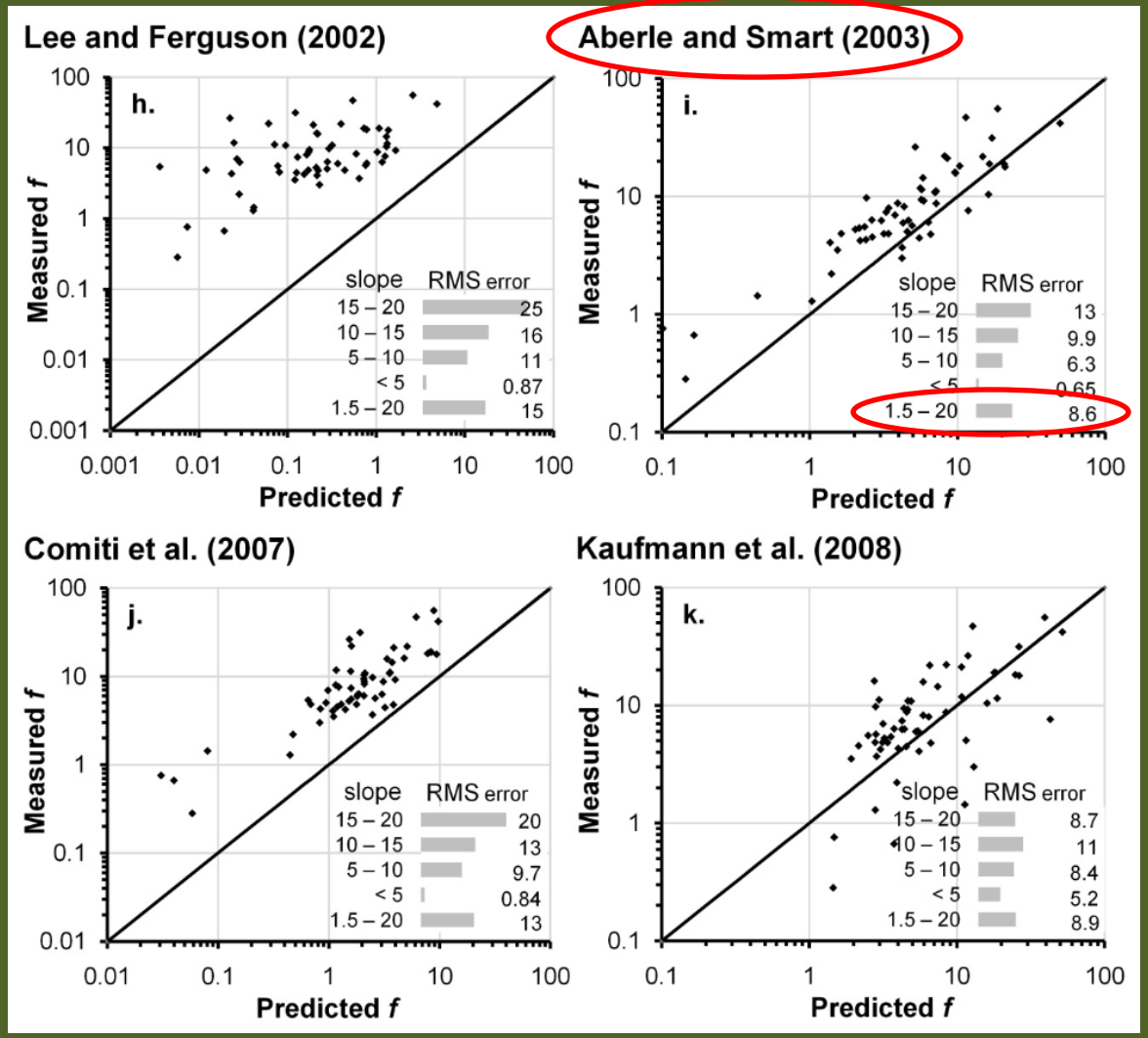
Darcy-Weisbach *f*



Darcy-Weisbach *f*



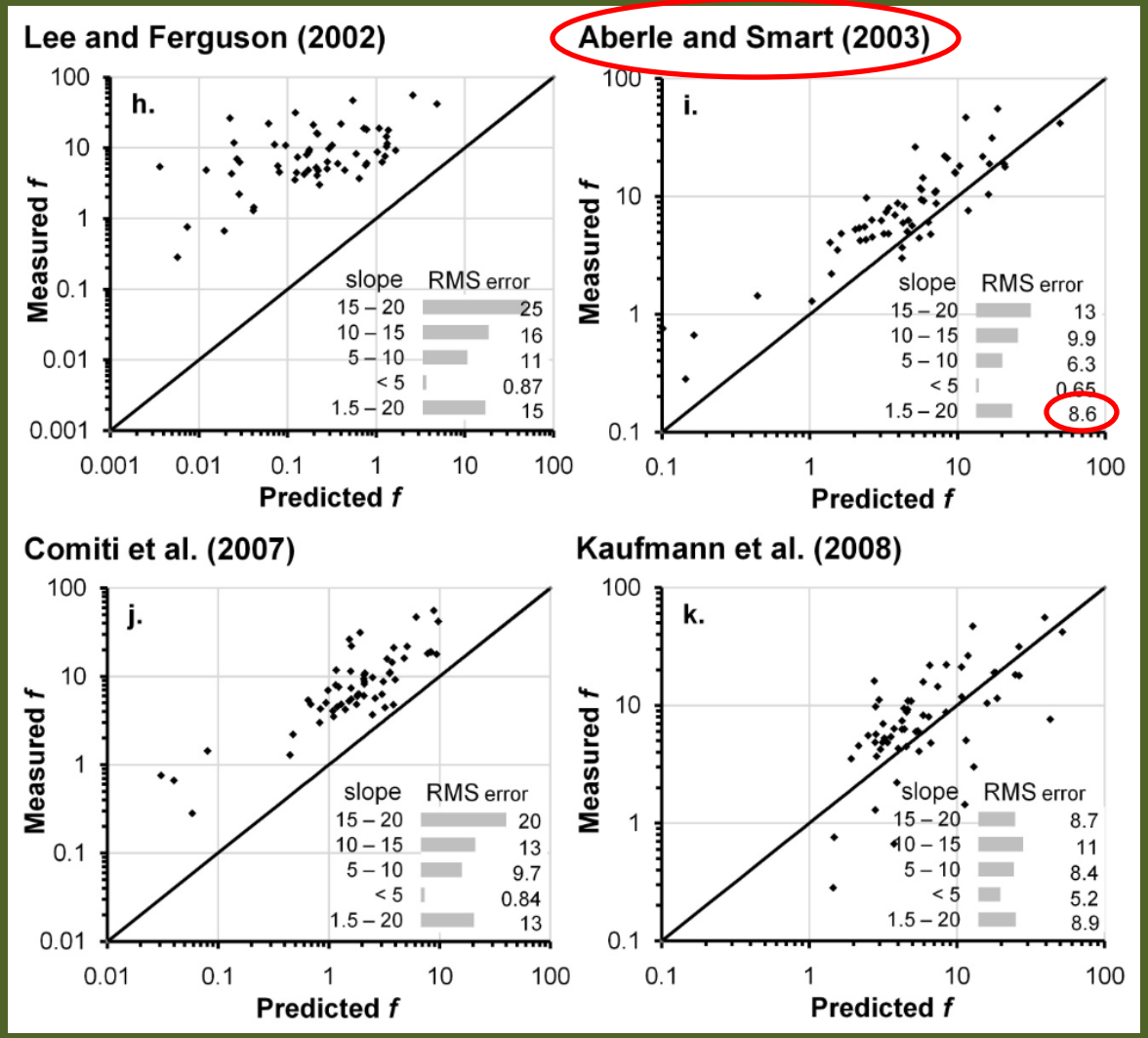
Darcy-Weisbach *f*



Resistance Coefficient Prediction

- Previously published methods typically:
  - Substantially underpredicted flow resistance
  - This results in overprediction of reach-average velocity
  - Grain size is ineffective for prediction

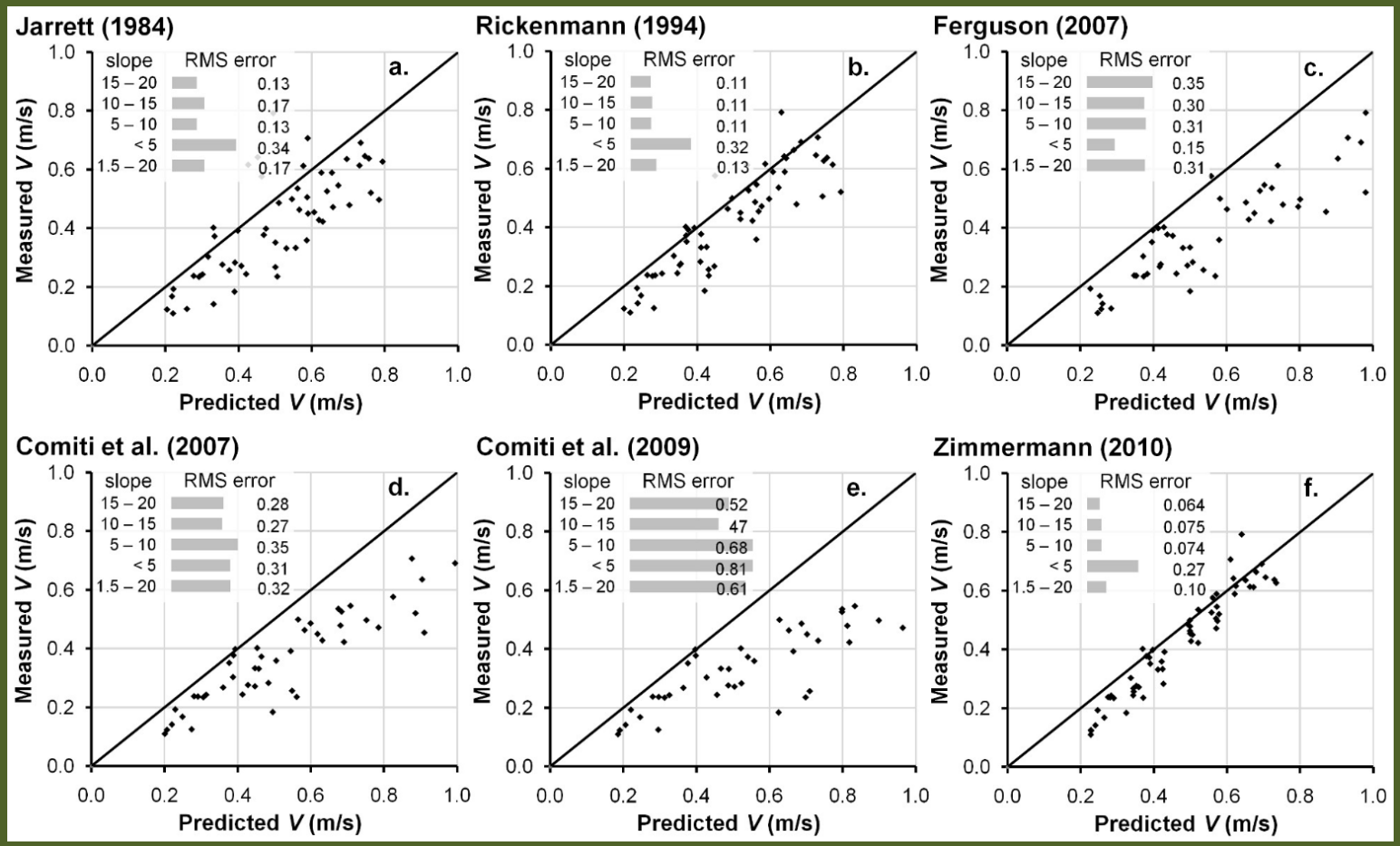
Darcy-Weisbach *f*



$$\sqrt{\frac{8}{f}} = 0.91\frac{\bar{h}}{\sigma_z}$$

- developed using flume data, with self formed grain steps

Velocity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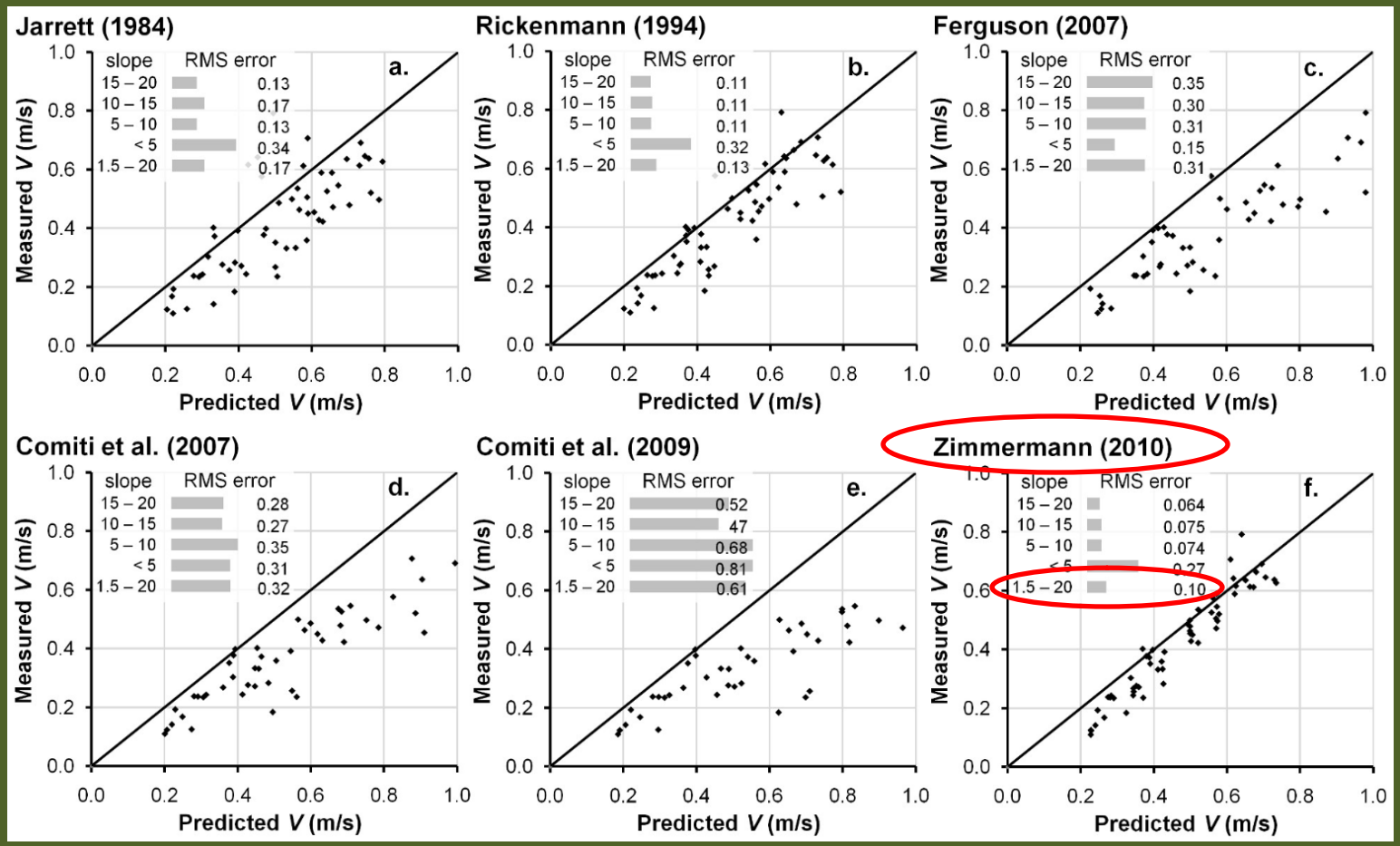
slope RMS error
15 – 20 0.13
10 – 15 0.17
5 – 10 0.13
< 5 0.34
1.5 – 20 0.17
Rickenmann (1994)
b.
slope RMS error
15 – 20 0.11
10 – 15 0.11
5 – 10 0.11
< 5 0.32
1.5 – 20 0.13
Ferguson (2007)
c.
slope RMS error
15 – 20 0.35
10 – 15 0.30
5 – 10 0.31
< 5 0.15
1.5 – 20 0.31
Comiti et al. (2007)
d.
slope RMS error
15 – 20 0.28
10 – 15 0.27
5 – 10 0.35
< 5 0.31
1.5 – 20 0.32
Comiti et al. (2009)
e.
slope RMS error
15 – 20 0.52
10 – 15 47
5 – 10 0.68
< 5 0.81
1.5 – 20 0.61
Zimmermann (2010)
f.
slope RMS error
15 – 20 0.064
10 – 15 0.075
5 – 10 0.074
< 5 0.27
1.5 – 20 0.10
Measured V (m/s)
Predicted V (m/s)
0.0 0.2 0.4 0.6 0.8 1.0

Velocity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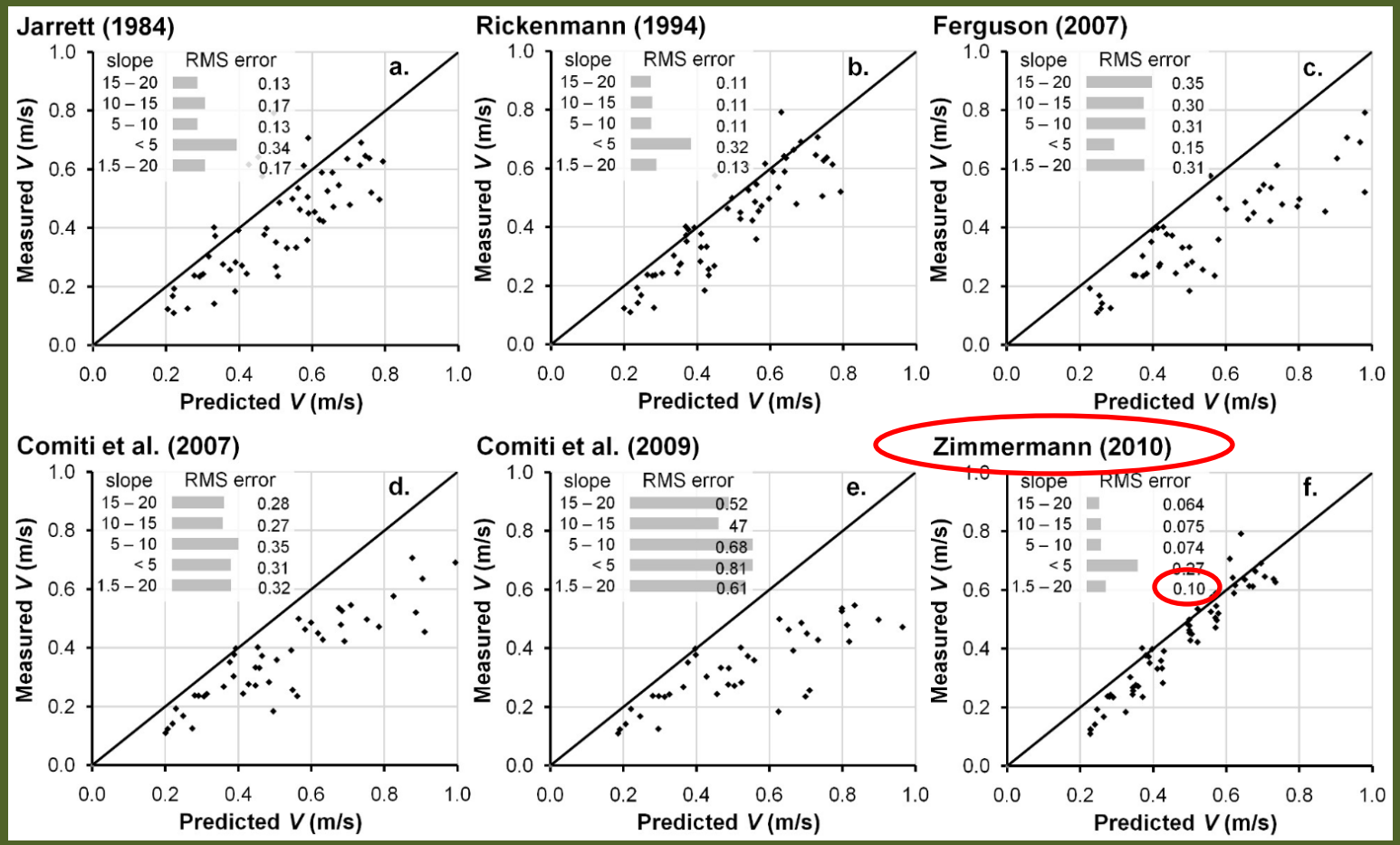
Velocity Prediction

- Previously published methods typically:
  - Overpredict reach-average velocity
  - Grain size is ineffective for prediction

Velocity



$$V^* = 0.58 q^{*0.39}$$

$$V^* = \frac{V}{\sqrt{gD_c}}$$

$$q^* = \frac{q}{\sqrt{gD_c^3}}$$

$$D_c = \sigma_z$$

- Flume data, in self formed cascade channels
- Developed using dimensionless velocity and unit discharge

Methods that predicted best (compared to field data):

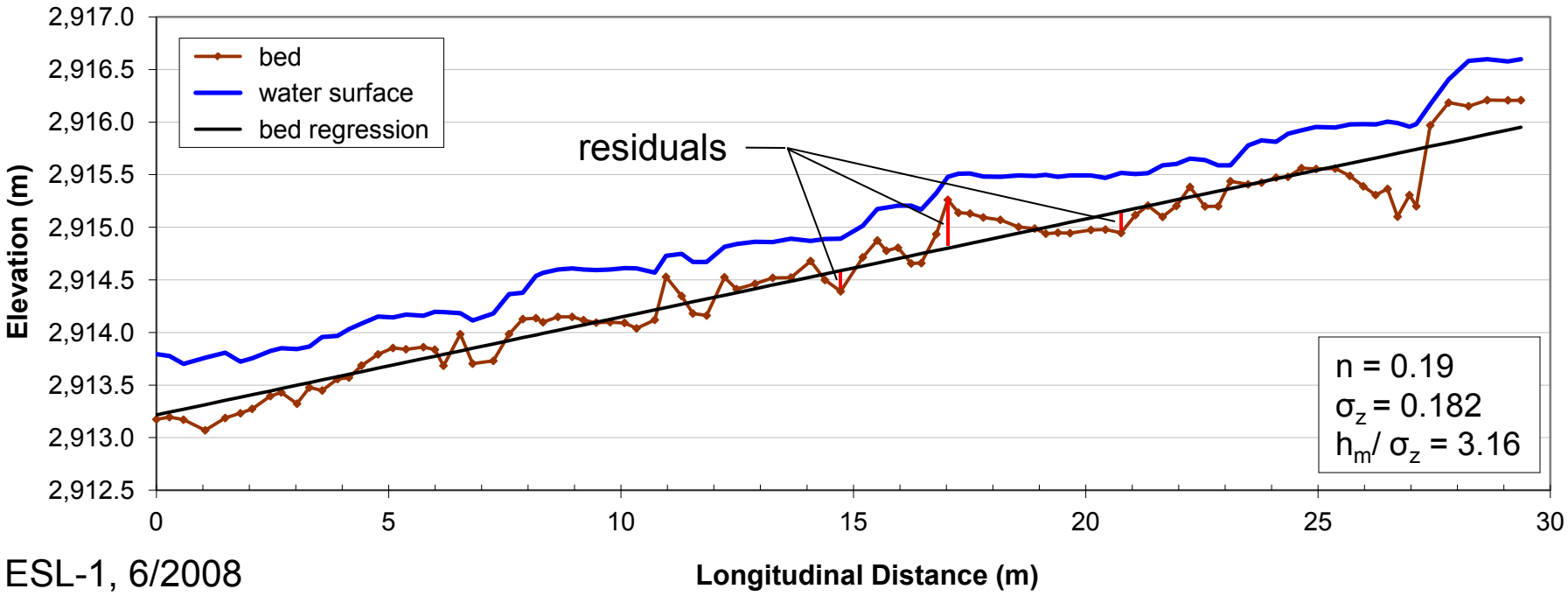
- Most effective existing prediction methods use:
  - relative submergence *(n* and *f)* -- h/σ_z
  - dimensionless method *(V)* -- $D_c = \sigma_z$

$$V^* = \frac{V}{\sqrt{gD_c}} \qquad q^* = \frac{q}{\sqrt{gD_c^3}}$$

  - D_c: roughness parameter
  - Methods developed using flume data
  - Desirable to have prediction tools based on field data

σ_z : Standard Deviation of Bed Elevations

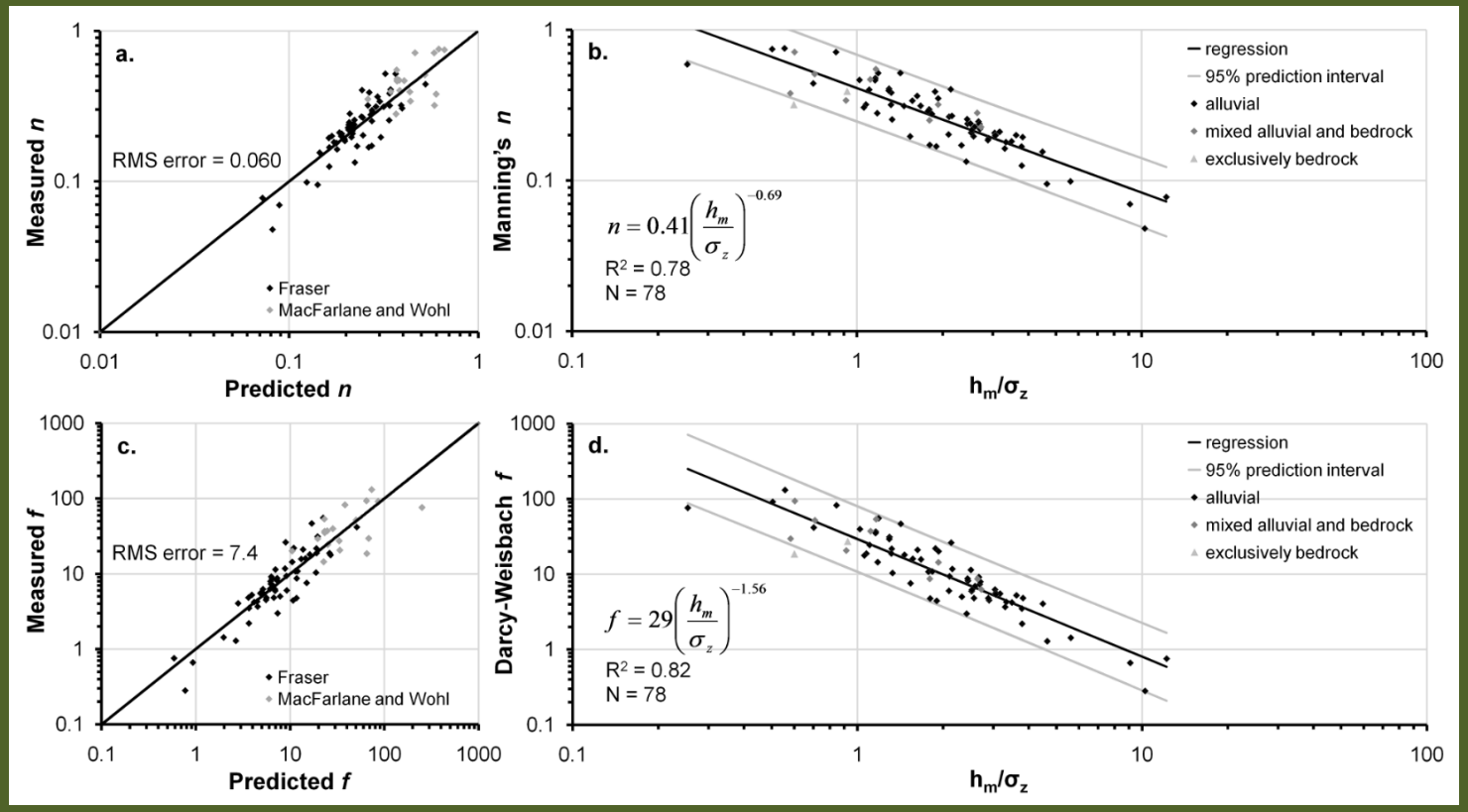
- Detrended variation in bed elevations



ESL-1, 6/2008

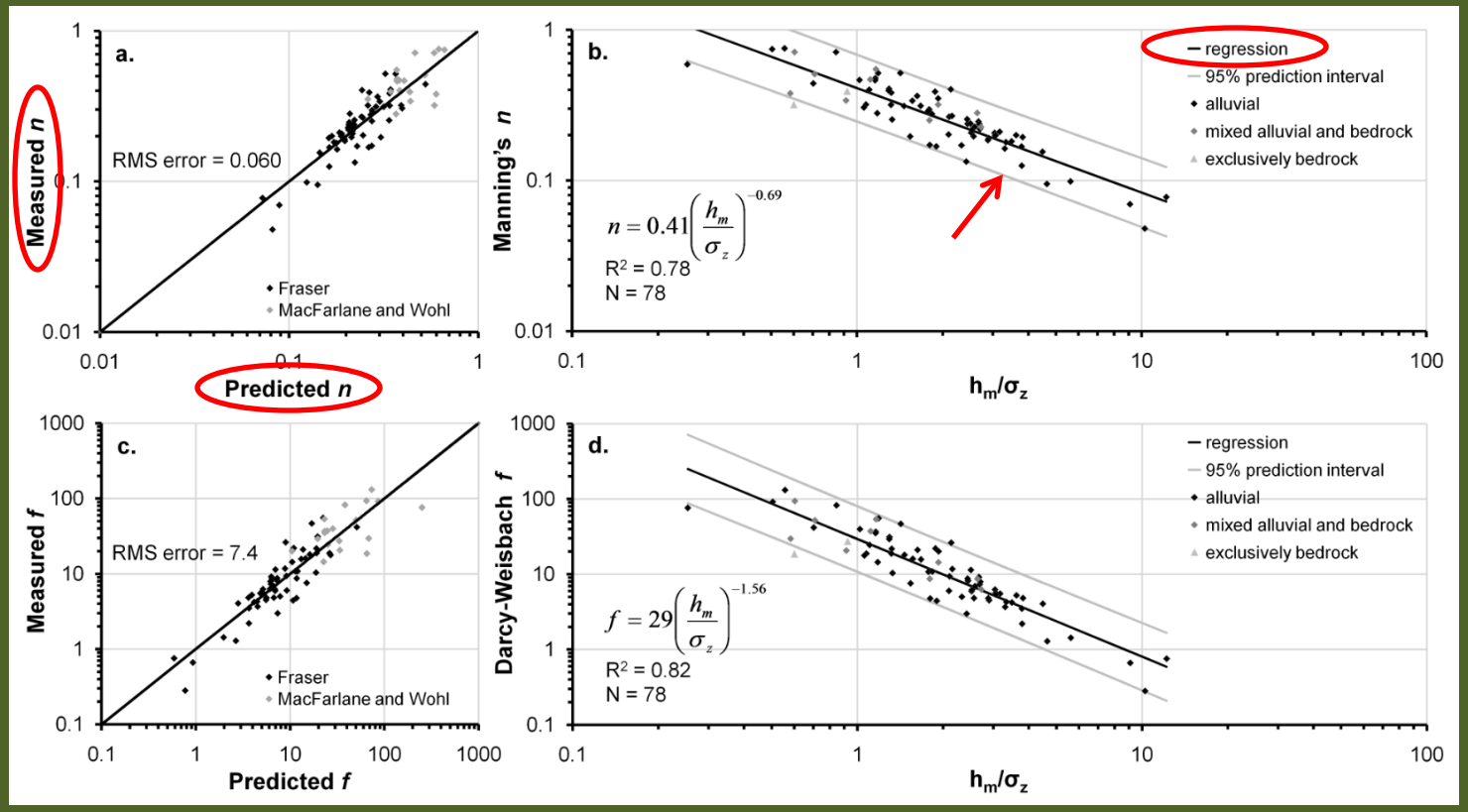
Resistance Coefficient Prediction

- Fraser, and MacFarlane and Wohl (2003) datasets
- Relative bedform submergence (h/σ_z)



Resistance Coefficient Prediction

- Fraser, and MacFarlane and Wohl (2003) datasets
- Relative bedform submergence (h/σ_z)



Resistance Coefficient Prediction

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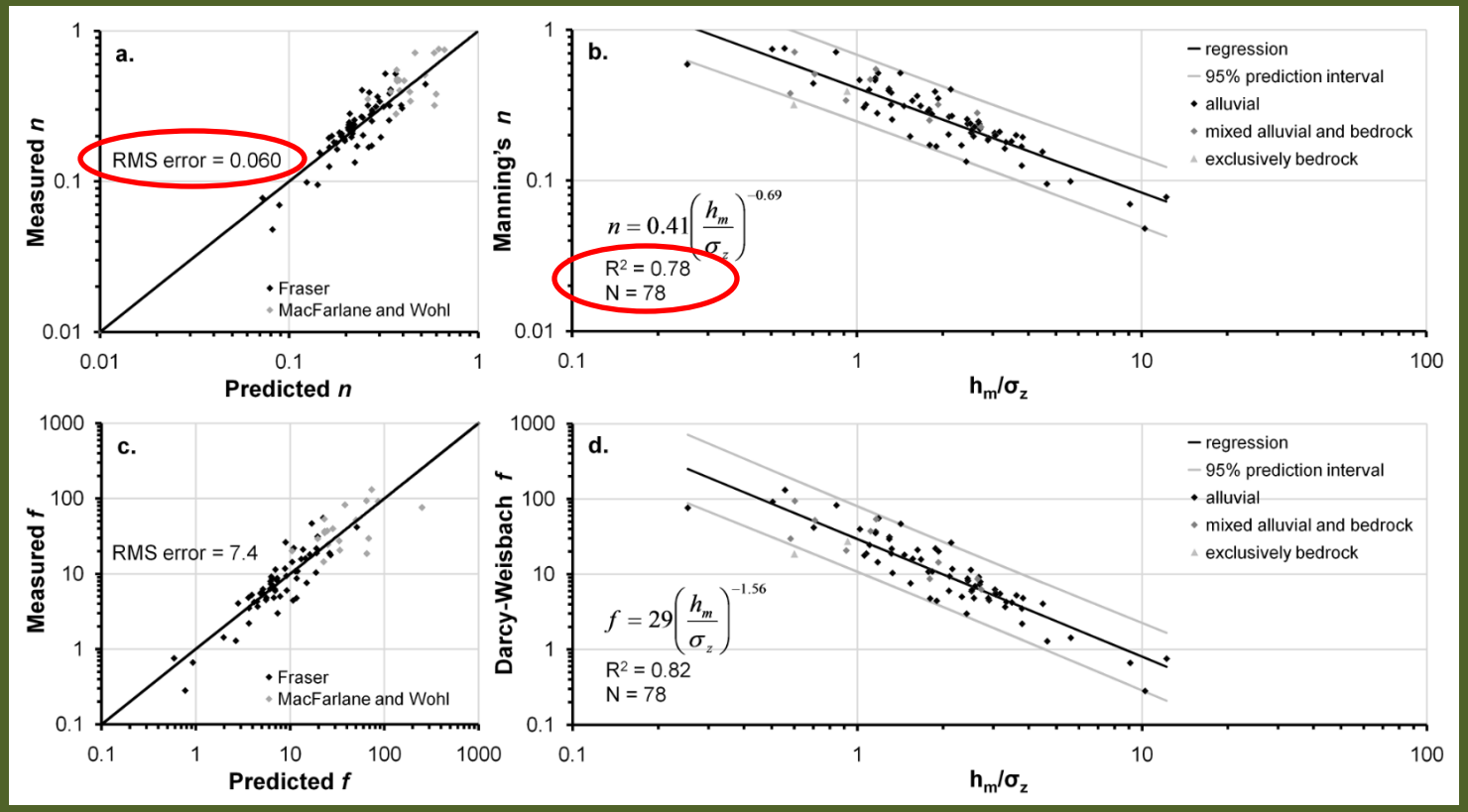
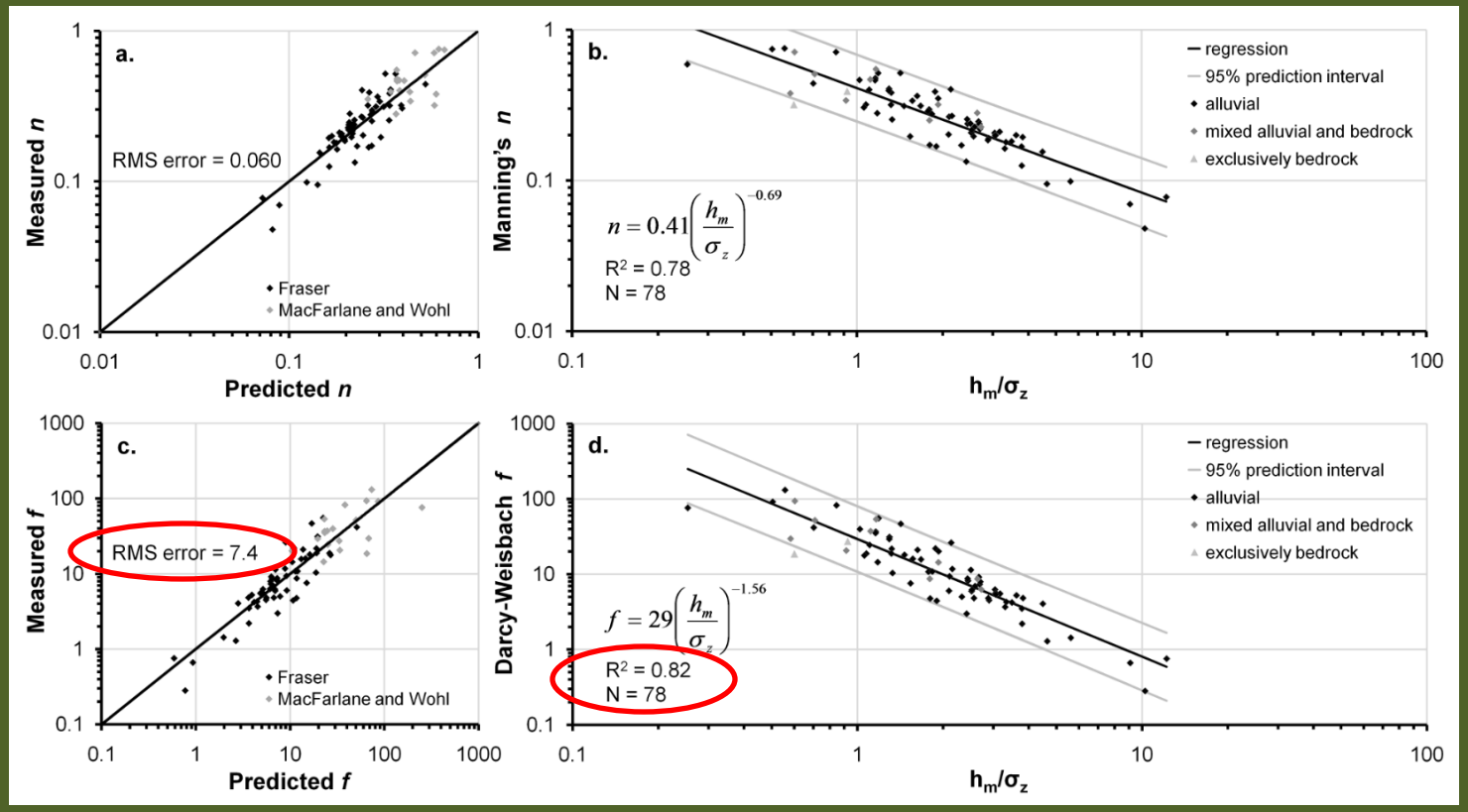
- Relative bedform submergence (h/σ_z)



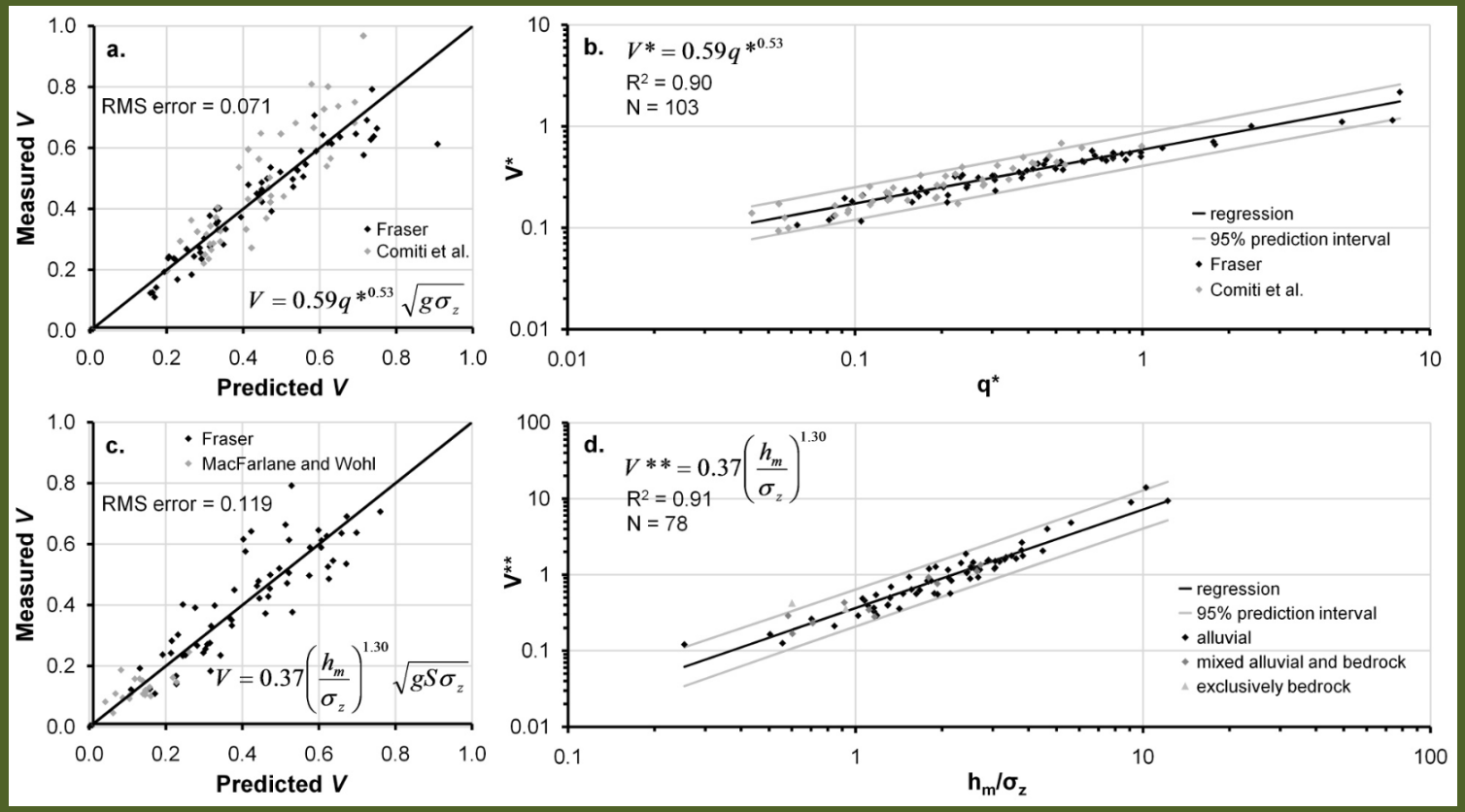
Resistance Coefficient Prediction

- Fraser, and MacFarlane and Wohl (2003) datasets
- Relative bedform submergence (h/σ_z)



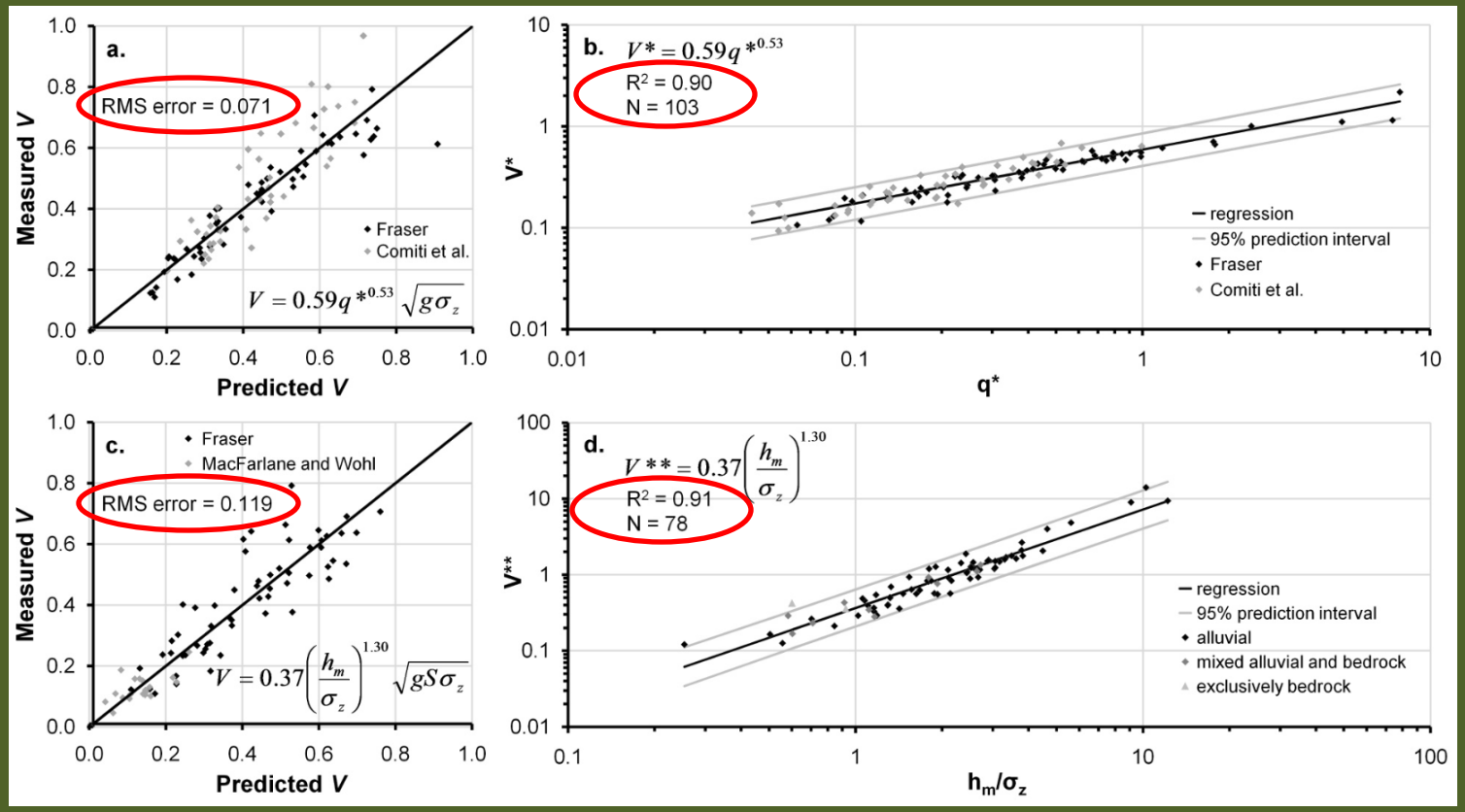
Velocity Prediction

- Using dimensionless velocity/unit discharge (V*/q*) or relative bedform submergence (h/σ_z)
- Fraser, Comiti et al. (2007), MacFarlane and Wohl (2003)



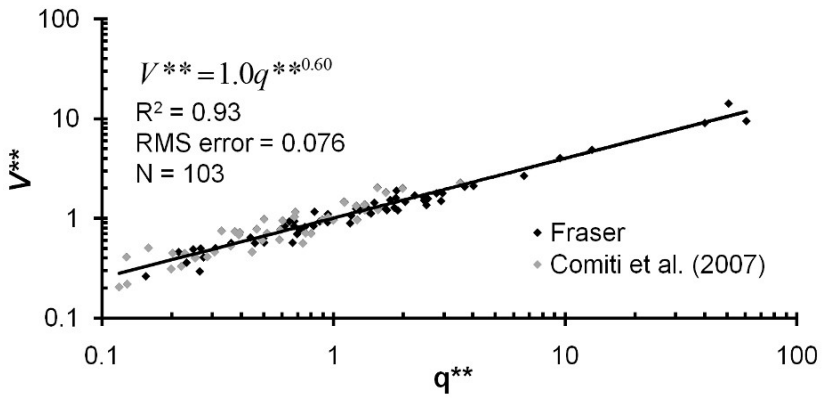
Velocity Prediction

- Dimensionless velocity/unit discharge (V*/q*) and relative bedform submergence (h/σ_z)
- Fraser, Comiti et al. (2007), MacFarlane and Wohl (2003)



Velocity Prediction

- Results of analysis using these field data indicate that:



$$\frac{V}{u^*} = \frac{h}{\sigma_z} = \sqrt{\frac{8}{f}} = \frac{h}{D_c}$$

shear velocity = $u^* = \sqrt{ghS_f}$

More information:

- “Velocity prediction in high-gradient channels”
  - Journal of Hydrology
  - Yochum, Bledsoe, David, Wohl (in press)
  - doi:10.1016/j.jhydrol.2011.12.031
- “Photographic guidance for flow resistance coefficients in high-gradient channels”
  - USFS General Technical Report (GTR)
  - Yochum, Comiti, Wohl, David, Cho, Curran, MacFarlane (in development)

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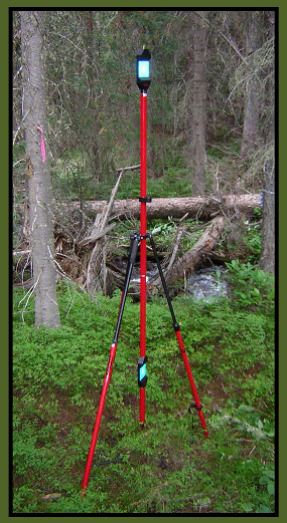
- Additional researchers: Francesco Comiti, Luca Mao, Janet Curran, William MacFarlane
- National Science Foundation (grant number EAR0608918)
- US Forest Service (photo guide funding)



Questions?

NRCS

Colorado State University