Incorporating riparian vegetation roughness computation into HEC-RAS 1D model: an application of the San Joaquin River, CA

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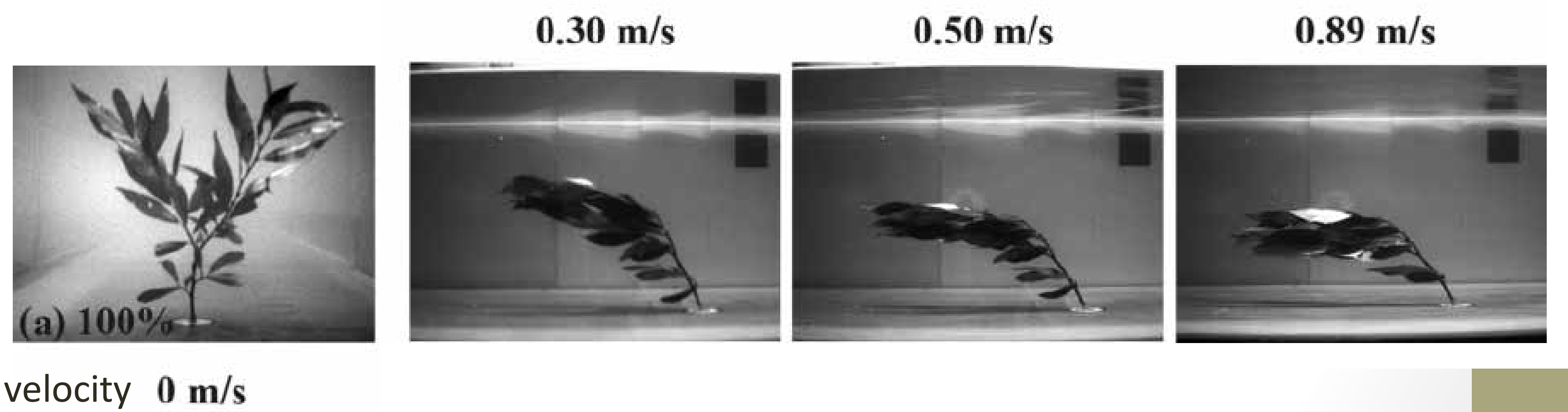
This picture is from USBR

Outline

1. Overview of existing methods for computing vegetative roughness
2. Incorporate these methods into HEC-RAS 1D model
3. An application of a reach of San Joaquin River
4. Summary

1. Existing methods used to compute vegetative roughness

- Status of vegetation in flow
  - Emergent
  - Submerged
  - Bending



Figures are from Aberle and Järvelä (2013)

1. Existing methods used to compute vegetative roughness

So vegetation roughness coefficient is determined by both vegetation properties and flow conditions.

Vegetation property

vegetation density,
stem diameter,
canopy area,
plant height,
Plant stiffness
…

Flow conditions

velocity,
water depth,
energy slope
…

1. Existing methods used to compute vegetative roughness

- A vegetation species is treated as a rigid cylinder

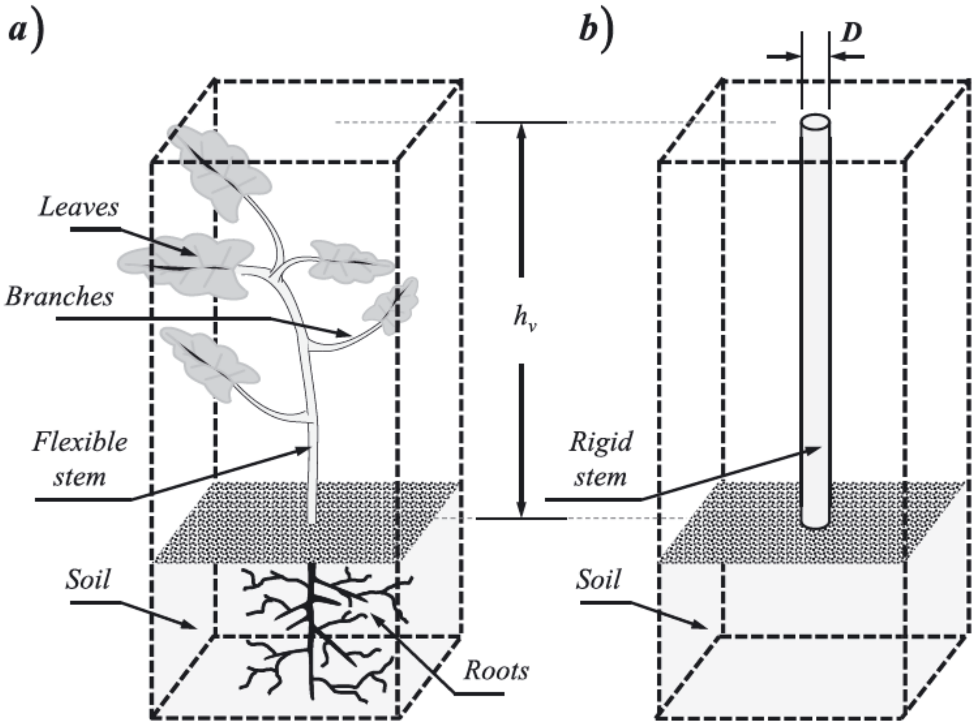


Figure 1. Scheme of the geometric properties for (a) real vegetation, and (b) rigid-cylinder analogy. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

Figure is from Andres Vargas-Luna et al. 2015

1. Existing methods used to compute vegetative roughness

- The four methods that treat vegetation species as a rigid cylinder

Baptist et al. 2007

$$n = H^{1/6}(1/C_b{}^2 + C_d mDH/2g) \qquad h_p \geq H$$

$$n = \frac{H^{1/6}}{\sqrt{\frac{1}{(1/C_b{}^2 + C_d mDh_p/2g)}} + \frac{\sqrt{g}}{\kappa}\ln(\frac{H}{h_p})} \qquad h_p < H$$

Cheng, 2011

$$C = \begin{cases} \sqrt{\frac{\pi g(1-\lambda)^3 D}{2C_d \lambda H}} & h_p \geq H \\ \sqrt{\frac{\pi g(1-\lambda)^3 D}{2C_d \lambda h_p}}\left(\frac{h_p}{H}\right)^{3/2} + 4.54\sqrt{g}\left(\frac{h_s}{D}\frac{1-\lambda}{\lambda}\right)^{1/16}\left(\frac{h_s}{H}\right)^{3/2} & h_p < H \end{cases}$$

$$\lambda = m\frac{\pi D^2}{4} \qquad n = \frac{H^{1/6}}{C}$$

Huthoff et al., 2007

$$U = \begin{cases} \sqrt{\frac{2gS}{C_d mD}}, & h_p \geq H \\ \left(\sqrt{\frac{h_p}{H}} + \frac{H-h_p}{H}\left(\frac{H-h_p}{s}\right)^{\frac{2}{3}\left(1-\left(\frac{H}{h_p}\right)^{-5}\right)}\right)\sqrt{\frac{2gS}{C_d mD}}, & h_p < H \end{cases}$$

$$s = \sqrt{\frac{1}{m}} - D \qquad n = \frac{H^{2/3}\sqrt{S}}{U}$$

Luhar and Nepf, 2013

$$n = \begin{cases} \sqrt{\frac{C_d A_d}{2g}} H^{2/3}, & H \leq h_p \\ \frac{1}{\left(\frac{2}{C}\right)^{1/2}\left(1-\frac{h_p}{H}\right)^{3/2} + \left(\frac{2}{C_d A_d h_p}\right)^{1/2}\left(\frac{h_p}{H}\right)}\frac{H^{1/6}}{\sqrt{g}}, & H > h_p \end{cases}$$

1. Existing methods used to compute vegetative roughness

- The four methods that treat vegetation species as a rigid cylinder

Methods	Vegetation factors	Hydraulic factors	Parameters	
Baptist et al. 2007	Stem density Stem diameter Plant height	Flow depth	Drag coefficient: C_d	Friction factor: C_b
Huthoff et al., 2007				
Cheng, 2011				
Luhar&Nepf, 2013				Friction factor: C

1. Existing methods used to compute vegetative roughness

- The five methods that treat vegetation species with flexibility

Freeman et al., 2000

$$n=\begin{cases}0.00003487\left(\frac{E_sA_s}{\rho A_i^* u_*^2}\right)^{0.15}\left(mA_i^*\right)^{0.166}\left(\frac{u_*R}{\upsilon}\right)^{0.622}\left(\frac{R^{2/3}S^{1/2}}{u_*}\right), & H\le 0.8h_p\\ 0.183\left(\frac{E_sA_s}{\rho A_i u_*^2}\right)^{0.183}\left(\frac{h_p}{H}\right)^{0.243}\left(mA_i\right)^{0.273}\left(\frac{\upsilon}{u_*R}\right)^{0.115}\left(\frac{R^{2/3}S^{1/2}}{u_*}\right), & H>0.8h_p\end{cases}$$

Kouwen and Fathi-Moghadam , 2000

$$n=0.228\left(\frac{U}{\sqrt{\frac{(\xi E)}{\rho}}}\right)^{-0.23}\left(\frac{H}{h_p}\right)^{0.5}\qquad H\le h_p$$

Järvelä et al., 2004

Leafy tree and shrub:

$$f=4C_{d\chi}\mathrm{LAI}\left(\frac{U}{U_\chi}\right)^{\chi}\frac{H}{h_p},\qquad H\le h_p$$

Leafless tree and shrub:

$$f=4C_d mA_{p,tot}\frac{H}{h_p},\qquad H\le h_p$$

Whittaker et al., 2015

$$n=\sqrt{\frac{C_{d0}A_{p0}mCa^{\psi/2}}{2gh_p}H^{2/3}}$$

$$Ca=\frac{\rho U^2 A_{p0}h_p^{\ 2}}{EI}$$

Fischenich, 2000

$$n=\frac{R^{1/6}}{\left(\frac{U}{u_*}\right)\sqrt{g}}\qquad \text{where}\qquad \frac{U}{u_*}=\begin{cases}\sqrt{\frac{2}{C_dA_dR}}, & H\le h_p\\ \frac{2.5}{H}(X+Y), & H>1.1h_p\end{cases}$$

$$X=1.26h_p^{\ 2}\frac{2h_p}{11C_dA_d}\left[1-e^{-5.5C_dA_d}\right]$$

$$Y=(H-0.95h_p)\left[\ln\left(\frac{H}{Kh_p}-\frac{0.95}{K}\right)-1\right]-0.05h_p\left[\ln\left(\frac{0.05}{K}-1\right)\right]$$

1. Existing methods used to compute vegetative roughness

New vegetation property introduced:

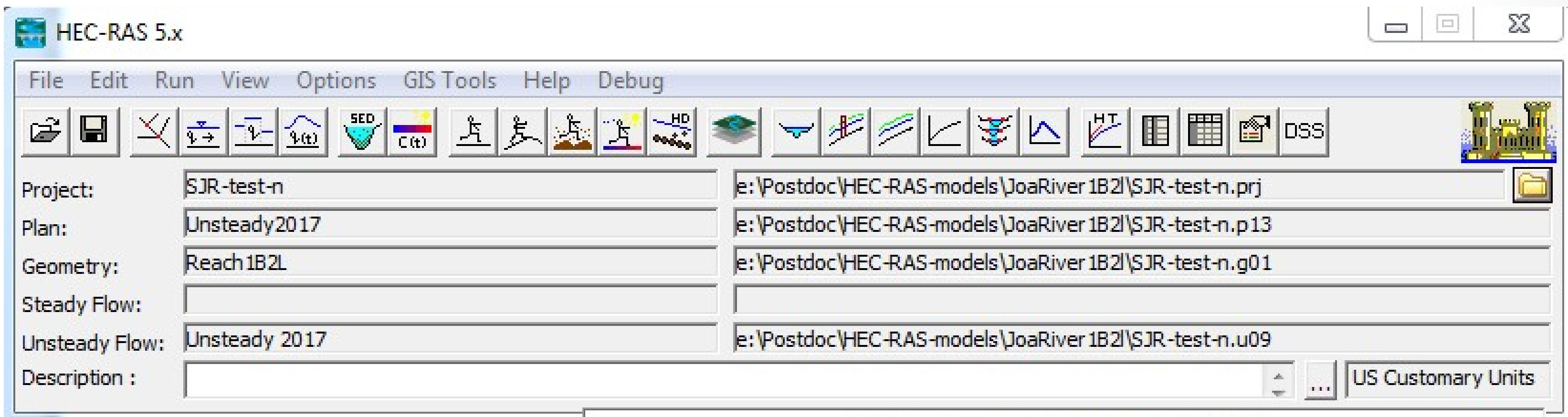
- Leaf area index (LAI), Järvelä et al., 2004
- Projected area used directly, Fischenich, 2000; Whittaker et al., 2015
- Stiffness of vegetation (E, Es, EI), Freeman et al., 2000; Kouwen and Fathi-Moghadam , 2000; Whittaker et al., 2015

The impact of velocity on vegetation bending considered

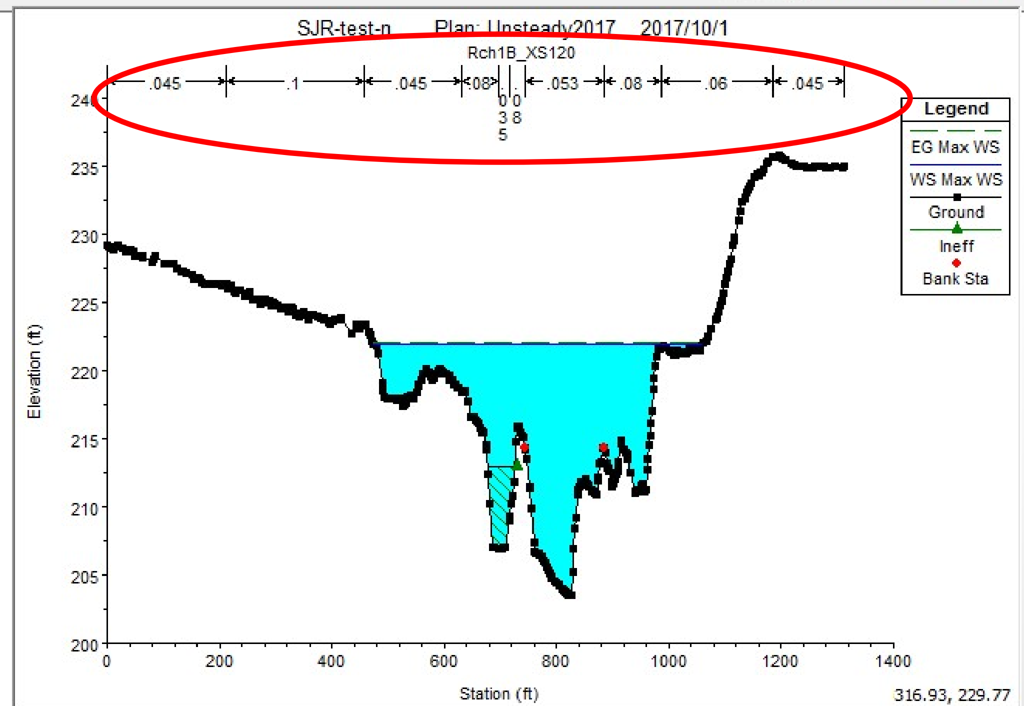
Velocity is used as a predictor in the four equations:
Freeman et al., 2000; Kouwen and Fathi-Moghadam , 2000; Järvelä et al., 2004, Whittaker et al., 2015

Are the methods that consider vegetation flexibility better than the methods that view vegetation as rigid cylinder?

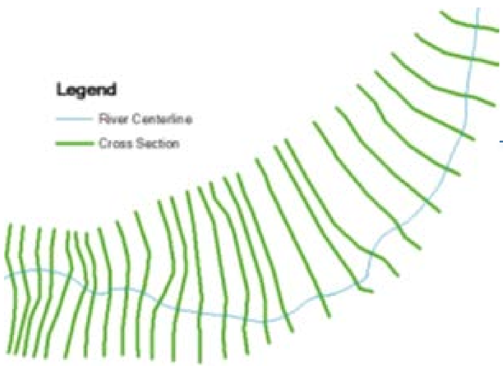
2. Incorporate these methods into HEC-RAS 1D model



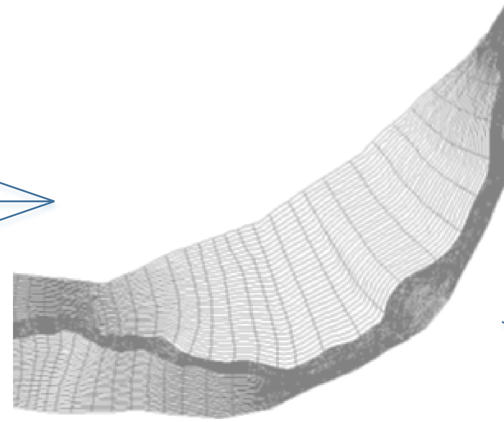
Major calibration parameter in HEC-RAS: Manning's *n* values



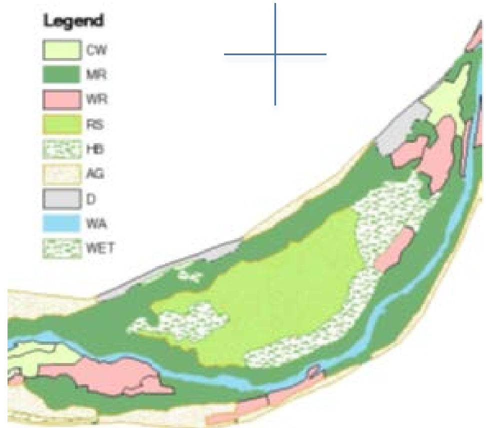
2. Incorporate these methods into HEC-RAS 1D model



HEC-RAS 1D cross section



Hydraulic polygons



Vegetation polygons

Overlay of vegetation polygons and hydraulic polygons

Vegetation type classification
Vegetation distribution data
Vegetation property information

2. Incorporate these methods into HEC-RAS 1D model

- Roughness computation in each hydraulic polygon

Compute roughness coefficient for one hydraulic polygon

- Compute roughness for each species using equations abovementioned
- Compute roughness for multiple species

$$n_v = \sqrt{\sum_{i=1}^{k} n_i^2}$$

- Compute total roughness

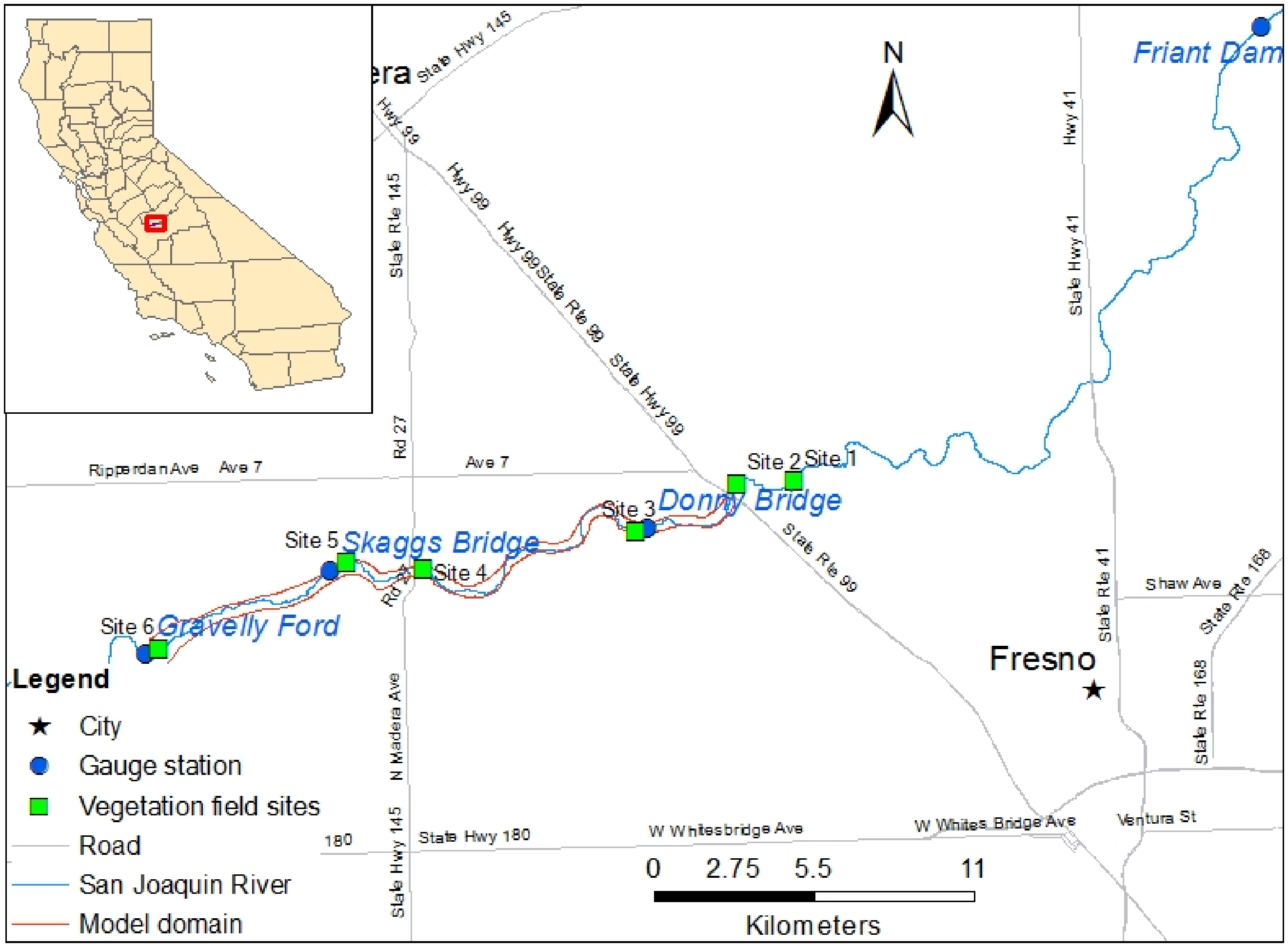
$$n = \sqrt{n_v^2 + n_b^2}$$

Compute composite roughness coefficient for a cross section

$$n_c = \left[\frac{\sum_{i=1}^{N} (P_i n_i^{1.5})}{P} \right]^{\frac{2}{3}}$$

Where P is wetted perimeter.

3. Application to a reach of San Joaquin River



Dataset

1. Vegetation mapping created in 2002
2. Vegetation field survey in 2011
3. DEM of 1m
4. River stage profile measurement under 6 flows in 2011
5. River stage time-series in 2011 and 2017 at two gauges
6. A HEC-RAS model developed by Tetra Tech (2013)

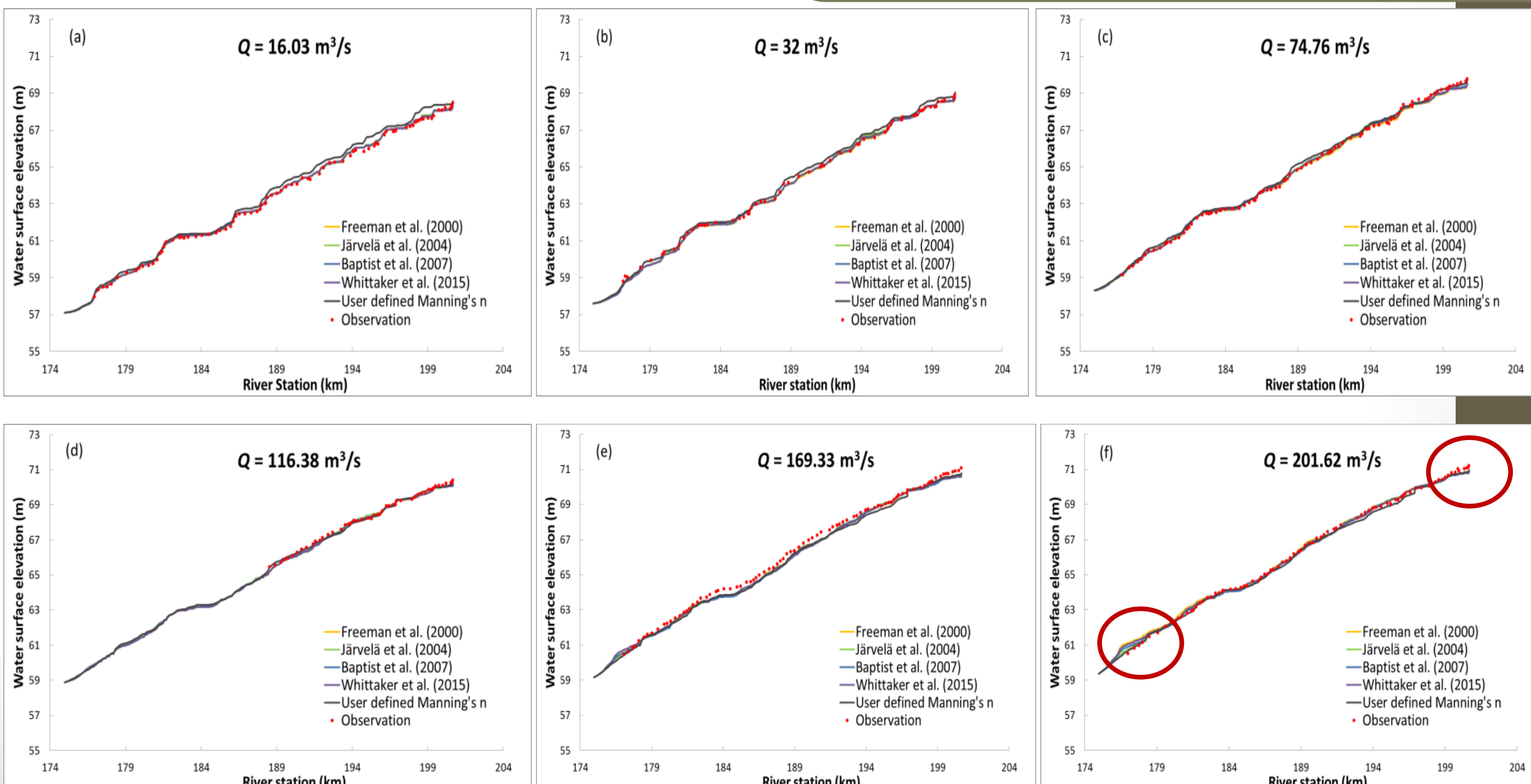
3. Application to a reach of San Joaquin River

1. A new HEC-RAS 1D model was developed with automatically computed Manning's *n* by 8 methods previously discussed
2. Model was calibrated with observed river stage profiles under 6 flows ---- Q = 16, 32, 75, 116, 169, 202 m^3/s
3. Model was validated by observed river stage time series at two gauges ---- Donny Bridge in 2011 and Skaggs Bridge in 2017
4. Root mean square errors between observed and modeled river stage were computed and used to estimate the performance of these roughness methods.

3. Application to a reach of San Joaquin River

- Calibration results

1. Performance of different methods is similar.
2. For low flows, model using computed *n* is better than using calibrated *n*
3. For high flow, at certain locations computed *n* is not very good.



3. Application to a reach of San Joaquin River

- Calibration results – root mean square error (unit: m)

Flow conditions (m^3/s)	16.03	32.00	74.76	116.38	169.33	201.62
Baptist et al. (2007)	**0.106**	**0.106**	**0.125**	**0.113**	**0.242**	**0.142**
Huthoff et al. (2007)	**0.106**	**0.106**	**0.125**	**0.112**	**0.241**	**0.141**
Cheng (2011)	**0.106**	**0.106**	**0.125**	**0.112**	**0.237**	**0.139**
Luhar and Nepf (2013)	**0.106**	**0.106**	**0.125**	**0.112**	**0.239**	**0.139**
Freeman et al. (2000)	0.100	0.111	0.132	0.123	0.212	0.174
Järvelä et al. (2004) leafy	0.121	0.106	0.137	0.121	0.225	0.126
Whittaker et al. (2015)	0.113	0.110	0.126	0.121	0.231	0.148
User defined Manning's n	0.322	0.199	0.164	0.094	0.251	0.207

Vegetation is viewed as rigid cylinder: errors are almost the same.

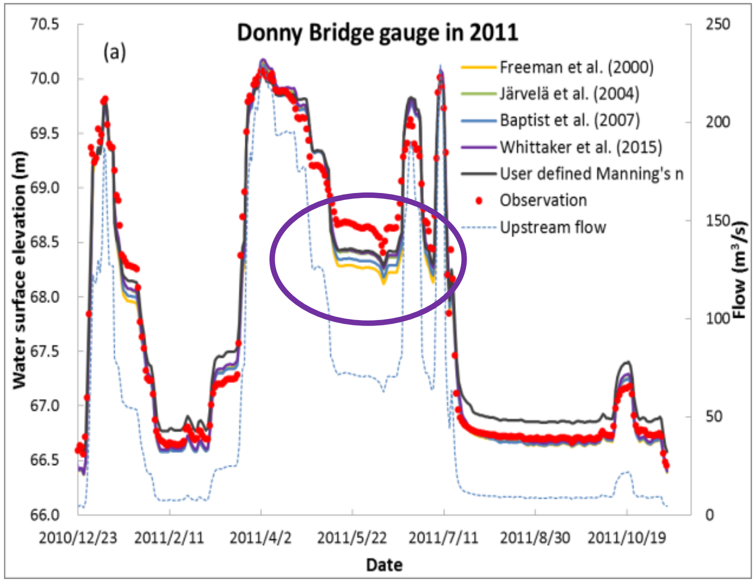
Vegetation flexibility is considered, the errors vary.

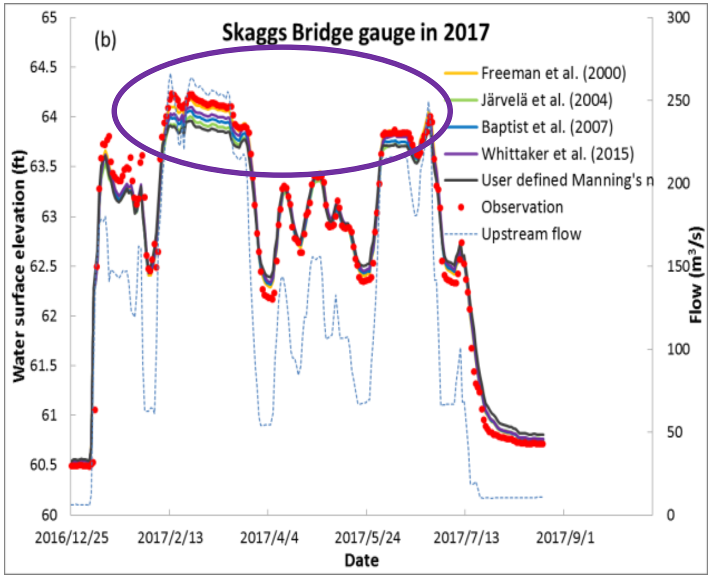
For most flow conditions, the model with computed Manning's n had smaller errors, expect for flow *Q* = 116.38. However, this flow only has fewer observations.

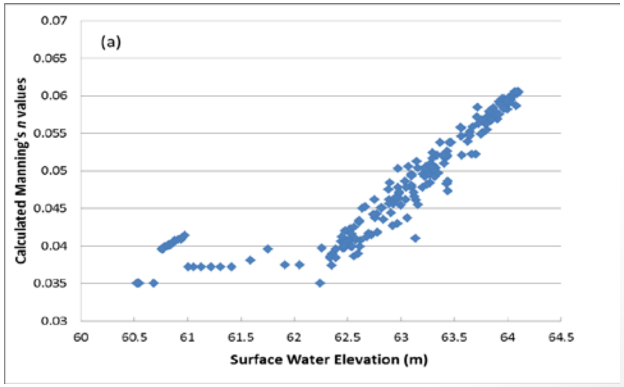
3. Application to a reach of San Joaquin River

- Validation results

The model using computed *n* performed better than the model using pre-defined *n* for the flow larger than maximum calibration flow.



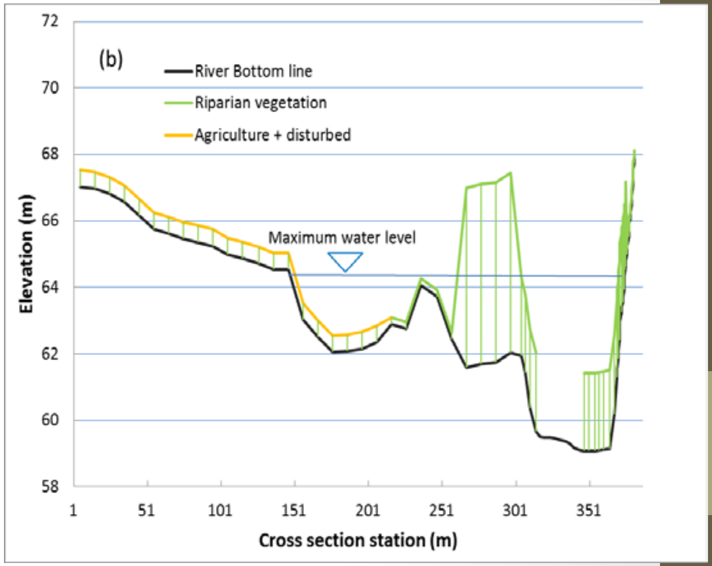




Dynamic Manning's *n* changed with flow and water depth

3. Application to a reach of San Joaquin River

- Whittaker et al. (2015) have the least validation error. Root mean square error for 2011 is 0.17 m and for 2017 is 0.19m.
- The error difference is not so obvious when different roughness methods were used to compute Manning's n. Probably because most vegetation was not completely submerged even under the largest flow.
- A much larger flood event is needed to further evaluate the performance of these methods.



4. Summary

- For San Joaquin River case study, the best method for calibration is Järvelä et al. (2004) and the best method for validation is Whittaker et al. (2015). Both methods take account of vegetation flexibility and include velocity in roughness coefficient computation. However, the two methods are not obviously better than the other methods.
- The methods that view vegetation as rigid cylinder such as Baptist et al. (2007) also produced reasonably good results. Therefore, when flow is not large enough to fully submerge most vegetation, it is acceptable to simplify riparian vegetation as rigid cylinder.
- These methods need to be further tested by larger flood and more field surveyed vegetation data.

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Questions?