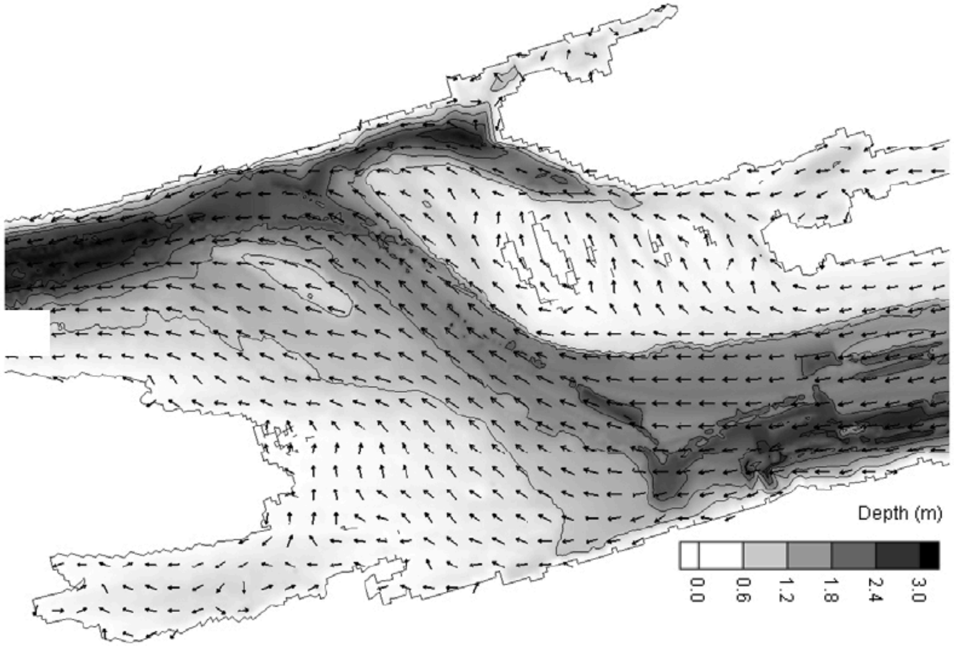
Introduction to 2D Modeling

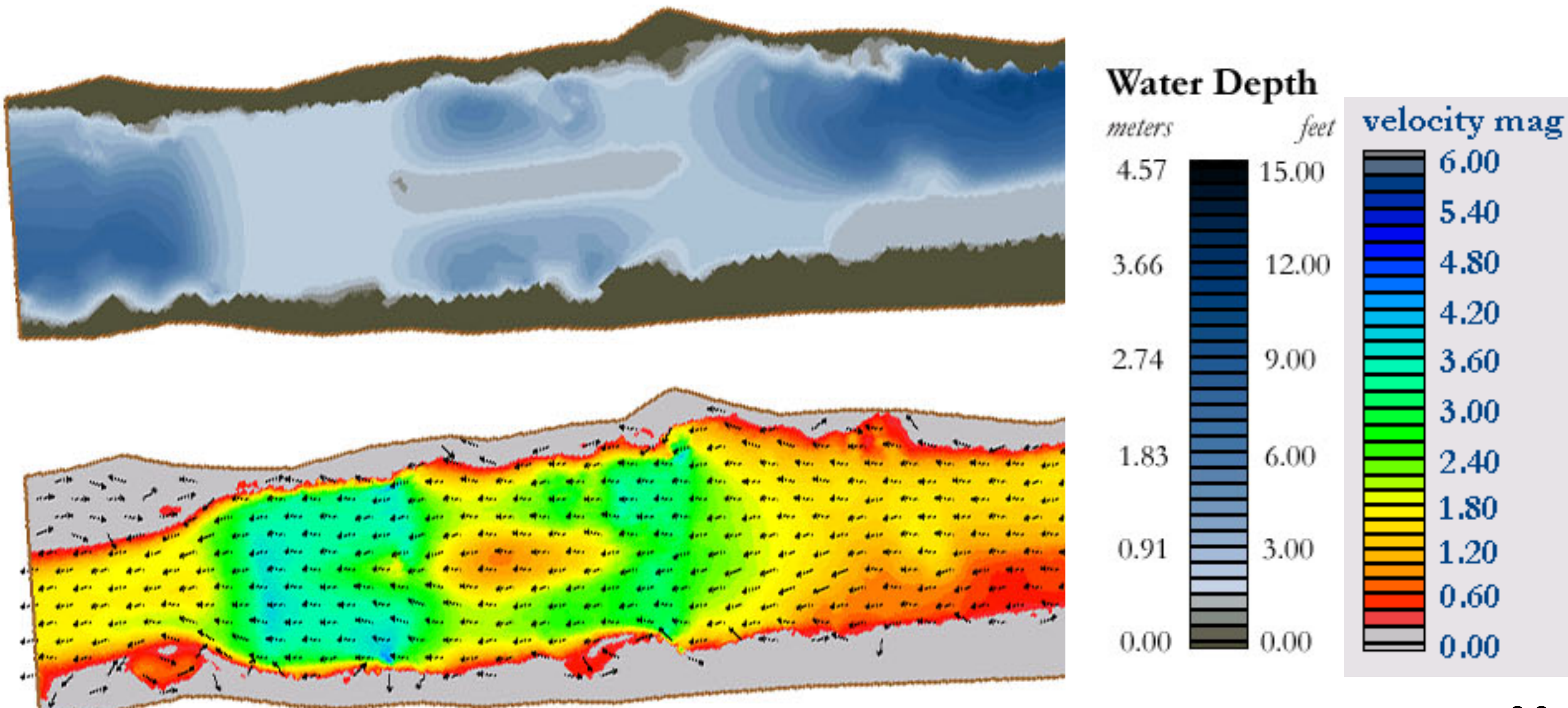
"No one believes a model, except the person who wrote it; Everyone believes data, except the person who collected it." –unknown wise scientist



Two-dimensional (depth-averaged) hydrodynamic (2D) models have existed for decades and are increasingly used to study a variety of hydrogeomorphic processes and ecological functions as well as to aid channel design. When properly built, they provide reasonable and transparent hydraulic predictions. Like any model, they have uncertainties and are not an absolute Truth.

What a 2D Model Provides

Spatially distributed point set of water surface elevation, depth, velocity magnitude and directional components, and shear stress



Examples of 2D Model Software

Classic site-oriented channel models: FESWMS, HIVEL, RMA2

Fisheries customized channel model: RIVER2D

Floodplain/channel models: TUFLOW, TELEMAC-2D, FLO-2D, MIKE-21, MD_SWMS, and SRH-2D.

Models vary based on:

- coordinate system they use (Cartesian or curvilinear),
- exact form of the fluid-mechanics equations they solve,
- numerical solution method (finite difference, finite element, or finite volume),
- ability to handle supercritical and/or subcritical flow,
- robustness of wetting/drying algorithm,
- ability to solve steady and/or unsteady flows,
- method(s) for handling turbulence closure,
- differences in ancillary features and add-ons.

Typical 2D Model Analytical Equations (SRH-2D)

$$\frac{\partial h}{\partial t}+\frac{\partial hU}{\partial x}+\frac{\partial hV}{\partial y}=e$$

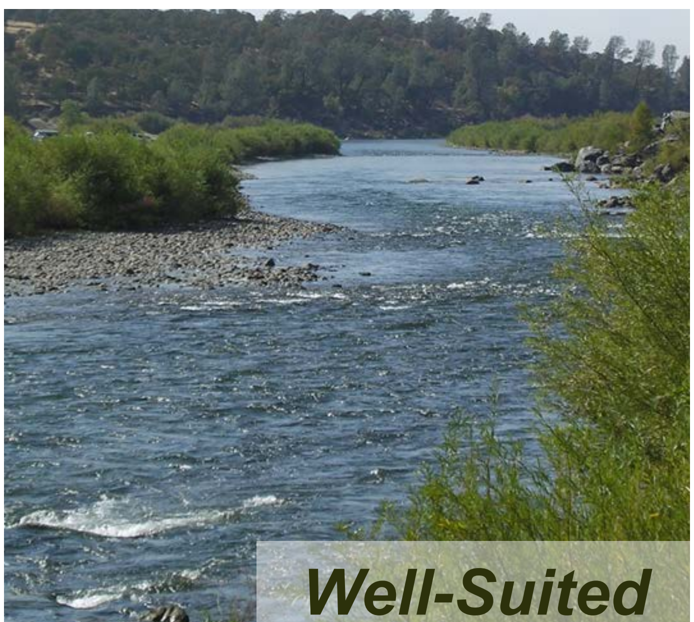
$$\frac{\partial hU}{\partial t}+\frac{\partial hUU}{\partial x}+\frac{\partial hVU}{\partial y}=\frac{\partial hT_{xx}}{\partial x}+\frac{\partial hT_{xy}}{\partial y}-gh\frac{\partial z}{\partial x}-\frac{\tau_{bx}}{\rho}+D_{xx}+D_{xy}$$

$$\frac{\partial hV}{\partial t}+\frac{\partial hUV}{\partial x}+\frac{\partial hVV}{\partial y}=\frac{\partial hT_{xy}}{\partial x}+\frac{\partial hT_{yy}}{\partial y}-gh\frac{\partial z}{\partial y}-\frac{\tau_{by}}{\rho}+D_{yx}+D_{yy}$$

where t is time, x and y are horizontal Cartesian coordinates, h is water depth, U and V are depth-averaged velocity components in x and y directions, respectively, e is excess rainfall rate, g is gravitational acceleration, T_{xx}, T_{xy}, and T_{yy} are depth-averaged turbulent stresses, D_{xx}, D_{xy}, D_{yx}, and D_{yy} are dispersion terms due to depth averaging, $z = z_b + h$ is water surface elevation, z_b is bed elevation, ρ is water density, and τ_{bx}, τ_{by} are the bed shear stress components (friction).

Model Applicability

Ideal



Bed Shear Stress Equations

Shear stress components (drag force equation approach)

$$\begin{pmatrix} \tau_{bx} \\ \tau_{by} \end{pmatrix} = \rho C_f \begin{pmatrix} U \\ V \end{pmatrix} \sqrt{U^2 + V^2}; \quad \mathrm{C_f} = \frac{gn^2}{h^{1/3}}$$

where C_f is the drag coefficient, *n* is the Manning's roughness coefficient.

- Studies by Pasternack et al. (2006) and MacWilliams et al. (2006) report that 2D models overpredict bed shear stress by a factor of ~2. The recommended coefficient to reduce the model output by is 0.51.

Turbulence Closure Equations

Turbulent Stresses (T_{ij})

$$T_{xx} = 2(\upsilon + \upsilon_t)\frac{\partial U}{\partial x} - \frac{2}{3}k$$

$$T_{xy} = (\upsilon + \upsilon_t)(\frac{\partial U}{\partial y} + \frac{\partial V}{\partial x})$$

ν is kinematic viscosity of water, ν_t is turbulent eddy viscosity, and k is turbulent kinetic energy.

$$T_{yy} = 2(\upsilon + \upsilon_t)\frac{\partial V}{\partial y} - \frac{2}{3}k$$

where c_o is the minimum eddy viscosity, u^* is shear velocity, and C_t is an empirical coefficient with a wide range, but a literature average of 0.6.

$$\nu_t = c_o + C_t \cdot h \cdot u^*$$

In common usage, k=0.

$$u^* = (\tau_{bi} / \rho)^{-0.5}$$

Higher order equations using k are sometimes available.

Steps in 2D Modeling

1. Digital Terrain Modeling

- Visualization
- Editing
- Augmentation
- Interpolation

2. Hydrodynamic-Based Modeling

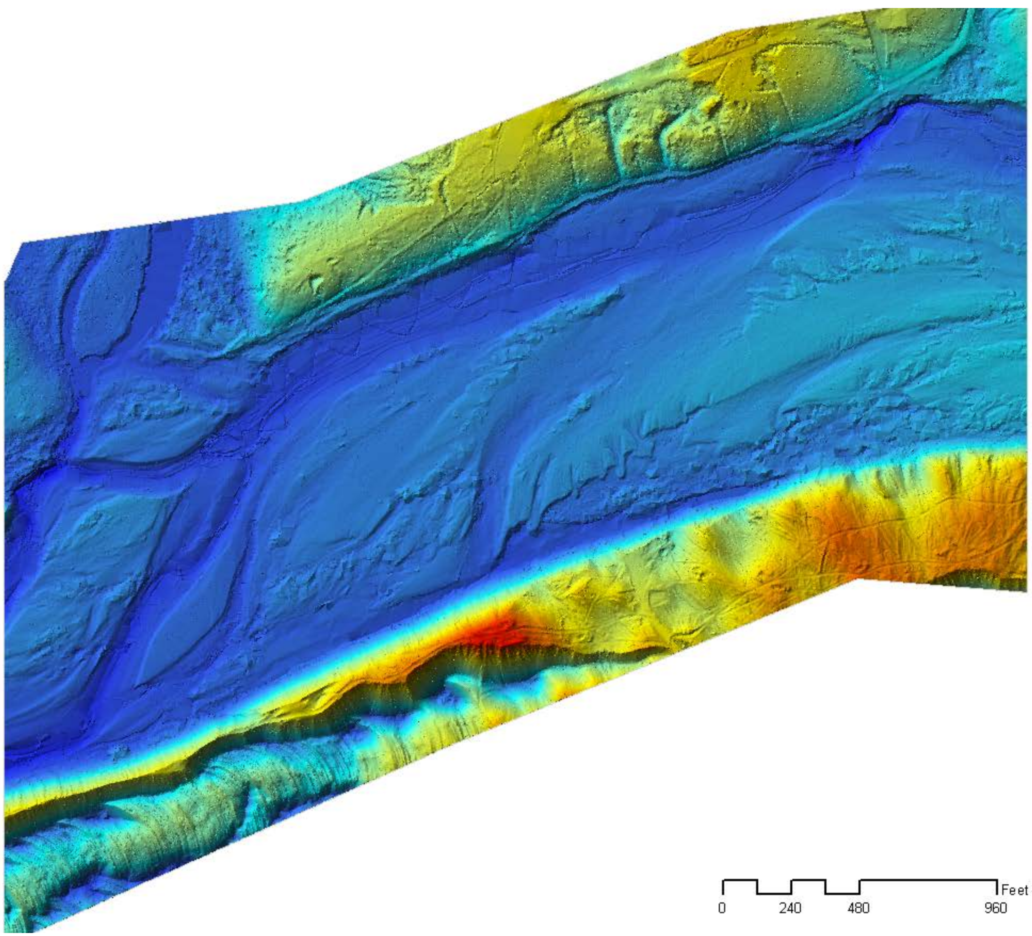
2D-Hydrodynamic Model

1. Mesh Discritization
2. Boundary Condition Definition
3. Parameterization
4. Simulation
5. Validation

- Habitat Suitability Model
- Sediment Mobility Model
- Future Models

Digital Terrain Model (DTM) (aka topographic DEM)

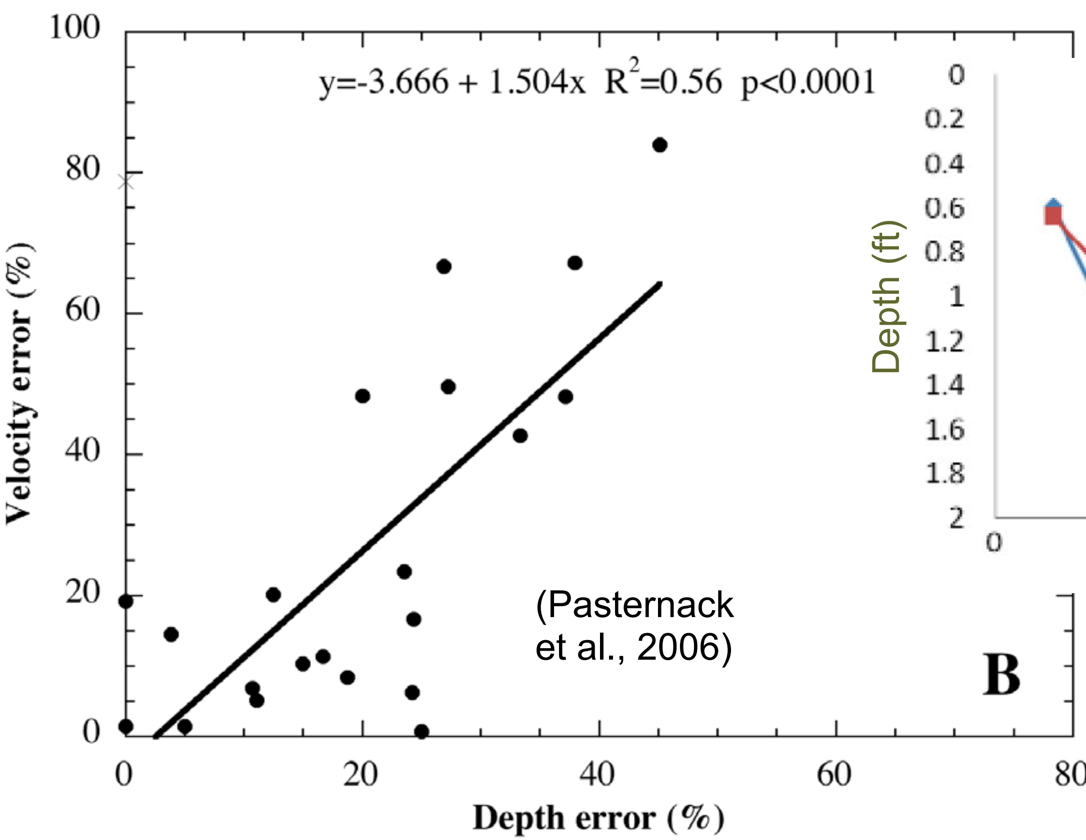
Representation of landform surface using point observations



- Point density of ~1.0 pts/m^2 is ideal target for gravel bed river.
- Best to do several passes including 1) uniform grid, 2) feature-based densification (e.g. banks, boulder clusters, streamwood, knickpoints, etc), and 3) key breaklines.
- Cannot have any data gaps in survey.

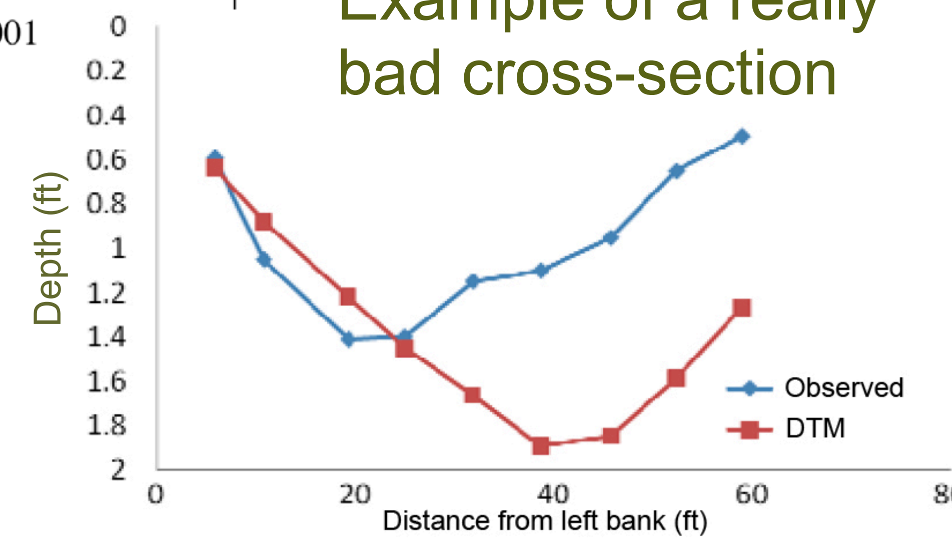
DTM Resolution and Accuracy are King!

DTM is the #1 most important determinant of the quality of the 2D model. Most controllable prediction error stems from DEM error.



(Surrogate for DEM error in this case)

Example of a really bad cross-section



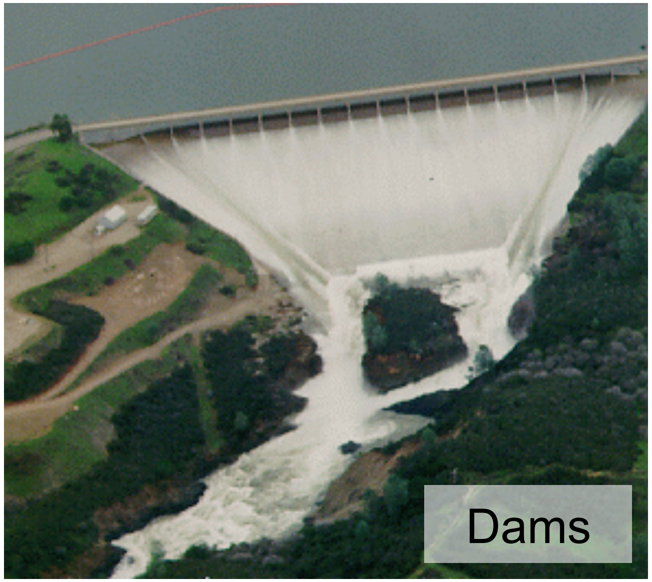
Topographic Data Sources- Extent and Resolution

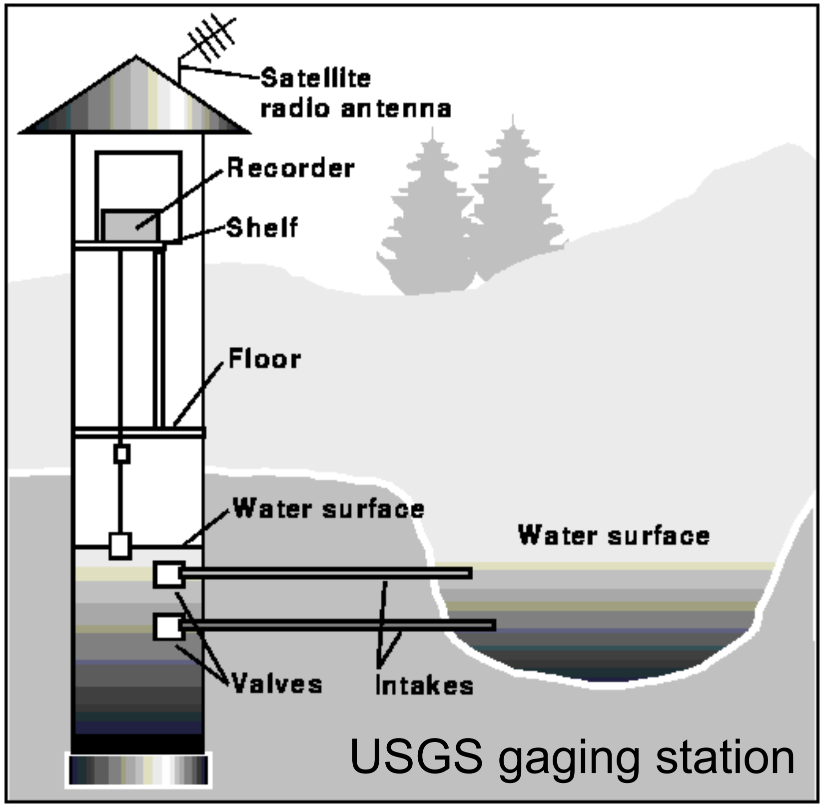
TECHNOLOGY	**EXTENT** (Reach Lengths)	**RESOLUTION** (pt./m^2)
Airborne LiDaR	10's – 100's km	1-8
Bathymetric LiDaR	10's – 100's km	0.5 – 4
Aerial Photogrammetry	10's – 100's km	0.1 – 1
Total Station Surveying	100 – 5,000 m	0.1 – 4
rtkGPS Surveying	100 – 5,000 m	0.1 - 4
Terrestrial Laser Scanning (aka ground-based LiDaR)	100 – 5,000 m	10 – 10,000
Multi-beam Sonar	1 – 25 km?	10- 100 (per m linear)
Single-beam Sonar	5 – 100 km?	0.05 – 5

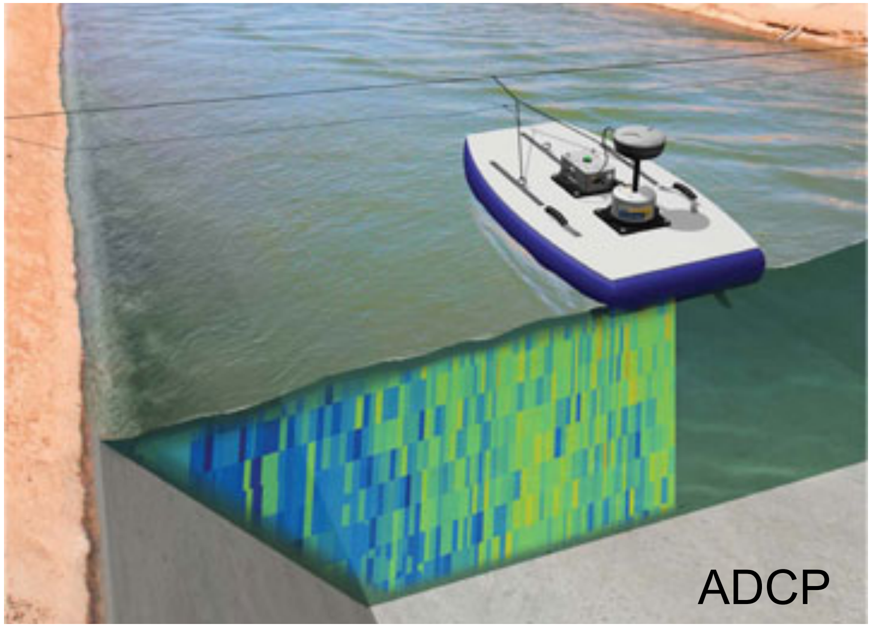
Courtesy of J. Wheaton

Hydrological Data Needs
Flow Inputs

Must know the discharges at all inlets to the model domain.

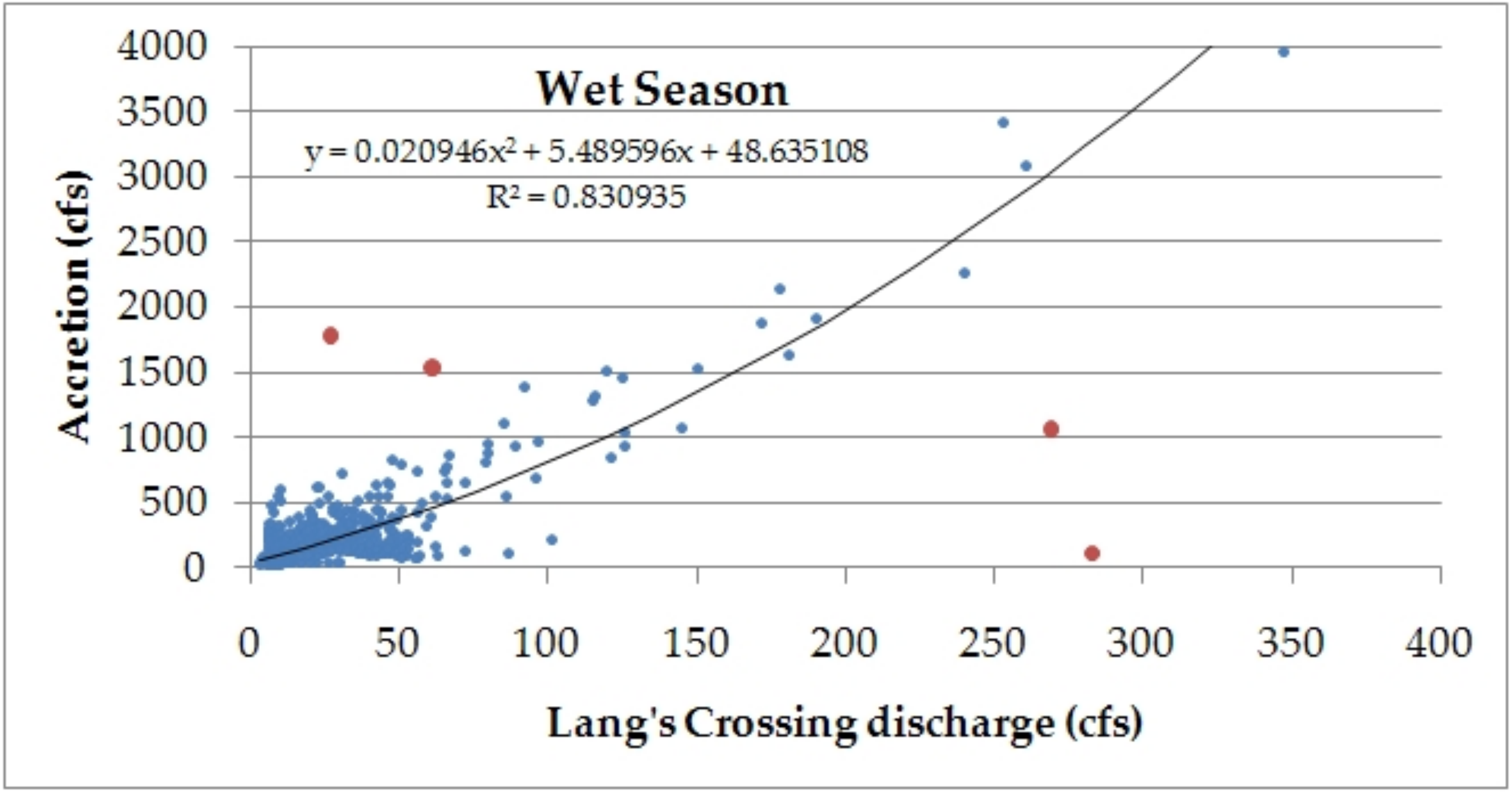




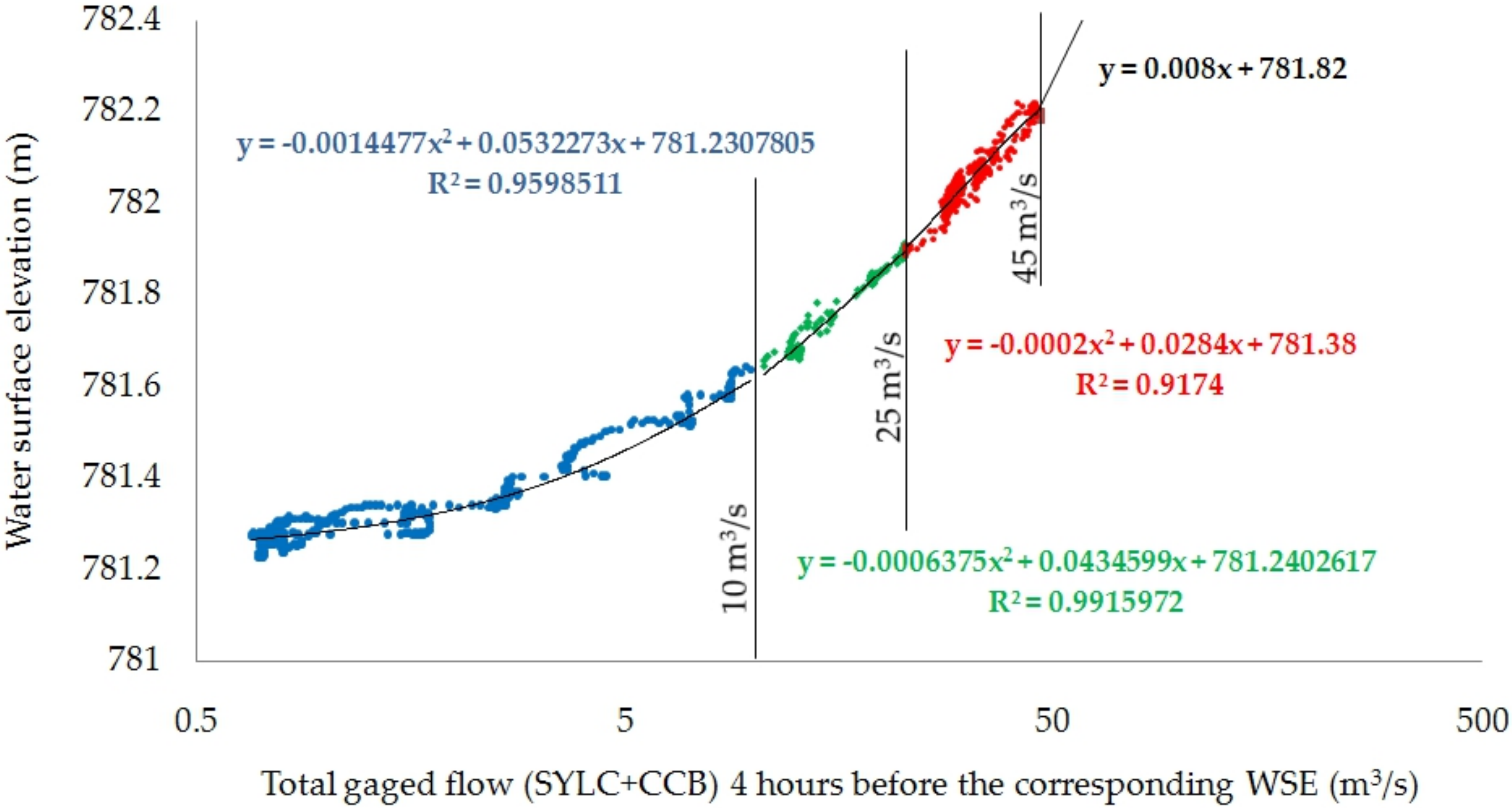


Hydrological Data Needs- *Flow Accretion*

Unregulated tributaries and groundwater baseflow can add a surprising amount of flow to a long model reach. Field testing for accretion is highly recommended.



Hydrological Data Needs- *Downstream WSE v Q*



(Coping with distance from gage and long time lags…)

Model Parameter- Manning's n Roughness

- According to the fluid mechanics of open channel hydraulics, hydrodynamics boils down to a balance between gravity-driven flow and frictional resistance.
- Internal fluid friction is built into the analytical equations.
- Bottom friction associated with resolved bedform topography (e.g., rock riffles, boulders, gravel bars, etc.) represented in the topographic DEM is also built into the equations.
- Therefore, what remains to be accounted for is all of the frictional resistance associated with unresolved bottom/bank features and other miscellaneous sources of friction.
- The classic solution to the problem is to use a simple coefficient to account for all sources of unresolved friction.

USGS Roughness Photo Library

http://wwwrcamnl.wr.usgs.gov/sws/fieldmethods/Indirects/nvalues/index.htm

n = 0.03

n = 0.075

n = 0.04

2D Modeling Concepts for First Estimate of Manning's n Roughness

- I recommend that you make a first model with a constant Manning's n and evaluate that performance before spending a lot of time/resources developing a complex roughness characterization.

- The roughness parameter has low sensitivity at 0.001 resolution, but moderate sensitivity at 0.01 resolution. Testing increments smaller than 0.005 tends not to be worth the effort/cost.

- The bed-roughness parameter can vary spatially in a 2D model to account for variable bed sediment facies, if that information is available.

Roughness Parameterization Evaluation Concept

Measure water surface elevations (WSEs) along the bank of the river along the length of the model domain. Are WSE_{pred} systematically higher or lower than WSE_{obs}?
- If model overpredicts WSE, then decrease roughness.
- If model underpredicts WSE, then increase roughness.

Measure velocity magnitude over the range of occurring velocities. Are V_{pred} systematically higher or lower than V_{obs}?
- If model overpredicts V, then increase roughness.
- If model underpredicts V, then decrease roughness.

Note that WSE and V have inverse response to n.

If both WSE and V need to increase, then that indicates Q is too low.
If both WSE and V need to decrease, then that indicates Q is too high.

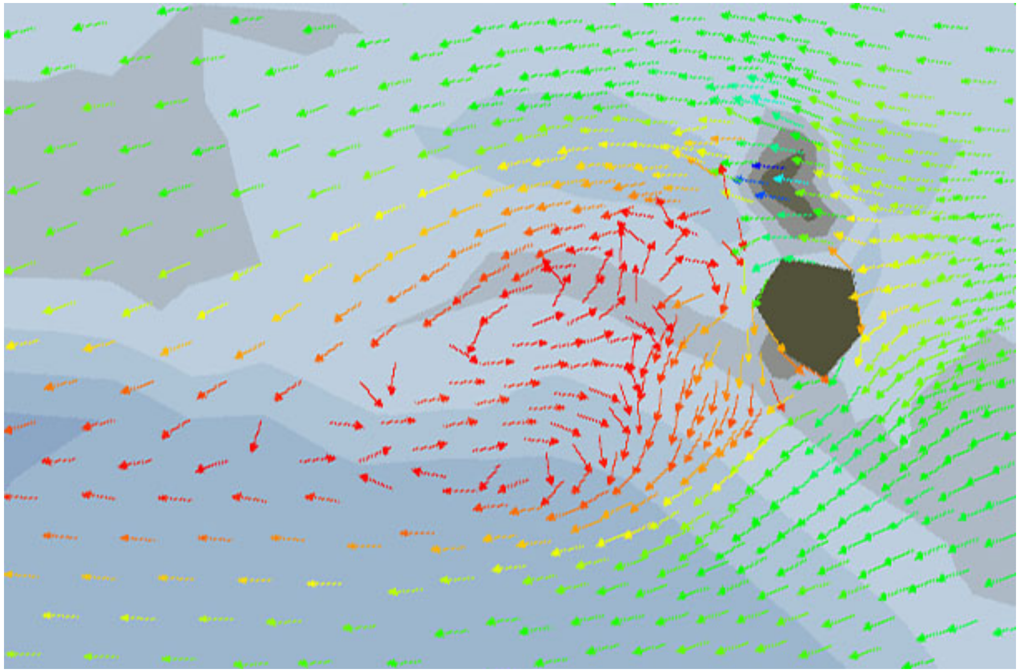
Eddy Viscosity Coefficient (C_t) Evaluation Concept

Turn on velocity vectors and zoom in on several sites with abrupt flow obstructions, such as bank protrusions and boulder clusters.

If vectors smoothly wrap around obstructions without causing recirculating eddies, then the momentum transfer is too efficient and the eddy viscosity coefficient needs to be decreased.

Field observations of D, V can be used to estimate u^* and ν_t , which can then be compared to model estimates at the same locations.

Dye or Cl^- tracer studies may also be used to estimate C_t.



Model Limitations

Key assumptions:

- ✧ Flow is horizontal (no slope and no vertical boils or whirlpools).
- ✧ Boundary friction can be parameterized with a Manning's n roughness scheme.
- ✧ Turbulence can be addressed through time averaging and a simple parameterization.

A 2D model can only be as good as the topographic, flow, and roughness data available to build it.

Even with ideal model inputs and design, a 2D model of a real river is unlikely to yield high-precision matching between predictions and observations in terms of having an $r^2 > 0.9$ and a mean absolute error of $<10\%$.

Chapter 2 References

MacWilliams, M. L., Wheaton, J. M., Pasternack, G. B., Kitanidis, P. K., Street, R. L. 2006. The Flow Convergence-Routing Hypothesis for Pool-Riffle Maintenance in Alluvial Rivers. Water Resources Research 42, W10427, doi: 10.1029/2005WR004391.

Pasternack, G. B., Gilbert, A. T., Wheaton, J. M., Buckland, E. M. 2006. Error Propagation for Velocity and Shear Stress Prediction Using 2D Models For Environmental Management. Journal of Hydrology 328:227-241.