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.

Model Applicability

**Ideal**

**Poor**

**Well-Suited**

**Acceptable**
2D MODELING

Steps in 2D Modeling

1. Digital Terrain Modeling
   - Visualization
   - Editing
   - Augmentation
   - Interpolation

2. Hydrodynamic-Based Modeling
   - 2D-Hydrodynamic Model
     - Mesh Discretization
     - Boundary Condition Definition
     - Parameterization
     - Simulation
     - 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/m² 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.
**2D MODELING**

**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.

(Pasternack et al., 2006)

Example of a really bad cross-section

**2D MODELING**

**Hydrological Data Needs**

*Flow Inputs*

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

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

2D MODELING

Hydrological Data Needs- Flow Accretion

2D MODELING

Hydrological Data Needs- Downstream WSE v Q

(Coping with distance from gage and long time lags…)
**Eddy Viscosity Coefficient (C_l) 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 \( \nu_t \), which can then be compared to model estimates at the same locations.

Dye or Cl\(^{-}\) tracer studies may also be used to estimate \( C_l \).

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**Model Parameter- Manning’s n Roughness**

- Hydrodynamics involves 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.

- 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.
2D MODELING

USGS Roughness Photo Library


\[ n = 0.03 \]

\[ n = 0.04 \]

\[ n = 0.075 \]

2D MODELING

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 $WSE_{\text{pred}}$ systematically higher or lower than $WSE_{\text{obs}}$?
- If model overpredicts WSE, then decrease roughness.
- If model underpredicts WSE, then increase roughness.

Measure velocity magnitude over the range of occurring velocities. Are $V_{\text{pred}}$ systematically higher or lower than $V_{\text{obs}}$?
- 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.

Traditional Roughness Patches

1. Use remote sensing to classify landscape into cover classes.
2. Use literature-based tables to estimate roughness for each type
Quantify Roughness of Relative Element Height

- Katul (2002) takes equations from atmospheric mixing layer theory above vegetation canopies and applies them to shallow streams.
- Vertical velocity distribution is function of roughness height (D), water depth (z)

Derivation of Equations

\[
\frac{\bar{u}}{u_o} = 1 + \tanh \left( \frac{z - D}{L_s} \right) \quad (1)
\]

\[
\frac{U}{u_o} = \frac{1}{h} \int_0^h \left[ 1 + \tanh \left( \frac{z - D}{\alpha D} \right) \right] dz = 1 + \frac{\alpha D}{h} \ln \left( \frac{\cosh \left( \frac{h}{D} \right)}{\cosh \left( \frac{1}{\alpha D} \right)} \right) \quad (2)
\]

\[
u_o = C_u u_o, \quad \xi = \frac{h}{D}, \quad f(\xi, \alpha) = 1 + \alpha \frac{\xi}{2} \ln \left( \frac{\cosh \left( \frac{\xi}{2} \right)}{\cosh \left( \frac{1}{\alpha} \right)} \right) \quad (3)
\]

\[
\frac{U}{u_o} = C_u f(\xi, \alpha) \quad (4)
\]

\[
U = \frac{1}{n} h^{2/3} S^{1/2} \quad (5)
\]

\[
n = \frac{h^{1/6}}{\sqrt{g} C_u f(\xi, \alpha)} \quad (6)
\]
Data Needs for Spatially Distributing Roughness

- Have vegetation canopy height for ‘D’ (LiDAR)
- Need an estimate for water depth ‘h’ to solve for Manning’s roughness
- Use 2D model run with constant roughness mesh to obtain initial water depth
- Superimpose water depth raster from unvegetated run onto veg height raster using ArcGIS to obtain manning’s n raster

2D MODELING

Procedural Flowchart

Vegetation Canopy Height Raster (D) → Unvegetated Water Depth Raster (h)

- 0.2 < h/D < 7?
  - NO → n = 0.04
  - YES → $f = \frac{(D/h)\ln[\cosh(1-h/D)/1.543]}{2}$

- $n = (h^{0.1667}) / (14.0944 - f)$

- $n < 0.04$?
  - NO → n > 0.04 is spatially distributed

Must use SI units!

Calculated for each flow modeled

(adaptation of Casas et al., 2010)
2D MODELING

Procedural Details

• Manning’s n polygons must be interpolated to the 2D mesh in SMS. Polygons do not conform to mesh element shapes. SMS assigns each element the material that corresponds with the the polygon that covers the centroid of the element.
• Model runs take ~ 1 week to complete
• Once vegetated results are obtained, must iterate once more to account for change in water depth (h)

2D MODELING

Limitations of Approach

• Simplifies the structural characteristics of vegetation to a singular parameter of “canopy height”
• This eliminates species specific classification that plays a role in hydraulic roughness (i.e. grasses, shrubs, trees, etc.)
• Manning’s roughness values obtained using this method are consistent with accepted literature values (Arcement, 1989), but still do not account for the full structure of floodplain vegetation, such as associated with species differences.
LYR Roughness Example Map For 21,100 cfs

21,100 cfs Roughness Distribution

Mannings

Count
LYR Example comparisons for using or ignoring vegetation

2D MODELING

Specific 2D Model Performance Benchmarks

WSE predicted vs observed:
- deviations centered on zero (bias indicates incorrect Manning’s n value or eddy viscosity coefficient value).
- deviations having similar statistical distribution as that for topo point QA/QC deviations.

Velocity predicted vs observed:
- $R^2$ 0.5-0.9 (watch out for reports of R, not $R^2$)
- Velocity error statistics for each point observation average error of 15-30%, with range up to 200% for low velocities.
- 1:1 linearity not commonly used, but should be >0.85 if no bias present
- Zero intercept not commonly used, but should be < 5% of $V_{max}$
  - Represents a bias in model to underpredict high velocities. Can be assessed by analyzing residuals.
- XS accuracy visually looks “good”.
- Flow Direction not commonly tested. Within 10°.
2D MODELING

WSE Performance Example

- Deviations centered on zero ✔
  - Mean raw deviation is -0.006’
- Deviation distribution as good as topo QA/QC distribution ✔
- 27% of WSE predictions within 0.1’
- 49% within 0.25’
- 70% within 0.5’
- 94% within 1’

Manning’s n value of 0.04 passes model performance tests ✔

2D MODELING

TLS & ALS DATA FOR MAPPING ROUGHNESS

- How does tamarisk influence channel narrowing?
- Ecogeomorphic feedbacks of vegetative roughness on flows and sedimentation patterns…
2D MODELING

WHAT CAN TLS GIVE US?

- Direct measure of stage-dependent flow blockage
- Patch-scale 2D hydraulic model to back out stage-dependent roughness

2D MODELING

USE ALS TO UPSCALE TLS ROUGHNESS

- Transfer function relating TLS to ALS

From Manners, Schmidt & Wheaton (Accepted) - JGR ES
Problems With Observational Velocity Data

Point-based velocity sensors do not measure depth averaged velocity.
Need to make assumptions about vertical velocity profile.
Commonly measure once at 0.4*D up from the bed, twice using average of 0.2D and 0.8D up from the bed, or three times using average of 0.2D, 0.4D, and 0.8D.
Each point measurement requires 40-60 sec times # of measurements in the vertical.

Point sensors often measure a tiny volume of water, which makes them very sensitive to the impacts of pebble clusters and other impediments to flow. 2D models are not intended to capture that tiny scale of variability, so comparison is not a test of 2D model performance.

ADCP does yield depth-averaged measurements and uses a larger volume, but is very time consuming and difficult to integrate with positional accuracy.

Cannot wade in high flows.

Rapid Velocity Data Collection

Surface velocity is commonly ~0.7-0.8 · U_{avg}.

Mount an RTK GPS on a kayaker, have kayaker get into the water and moving at the same speed, record GPS position every 5 sec. Back in office, calculate distance between positions and divide by 5 sec to get surface velocity. Can also calculate flow direction.

Can do this over a wide range of non-wadable flows.
2D MODELING

Rapid Velocity Method Test Results

- Derived conversion from surface velocity to mean velocity was found to be 0.72, which is a realistic value ✔️
- High coefficient of determination ($R^2$) = 0.787 ✔️
- Median error $\rightarrow$ 16% ; mean error $\rightarrow$ 21% ✔️
- Model lows are too high and highs are too low (common with 2D models).
- 2D model performance is better than almost all other published studies for RIVER2D, FESWMS, and SRH.
- Kayak approach worked great

Flow Direction Test Results

- Very high coefficient of determination ($R^2$) = 0.895 ✔️
- Median error $\rightarrow$ 3.8% ; mean error $\rightarrow$ 5.5% ✔️
- 61% of deviations within 5 deg
- 86% within 10 deg ✔️
- No pre-existing baseline for comparison, but these values seem very good.
- Kayak approach worked great