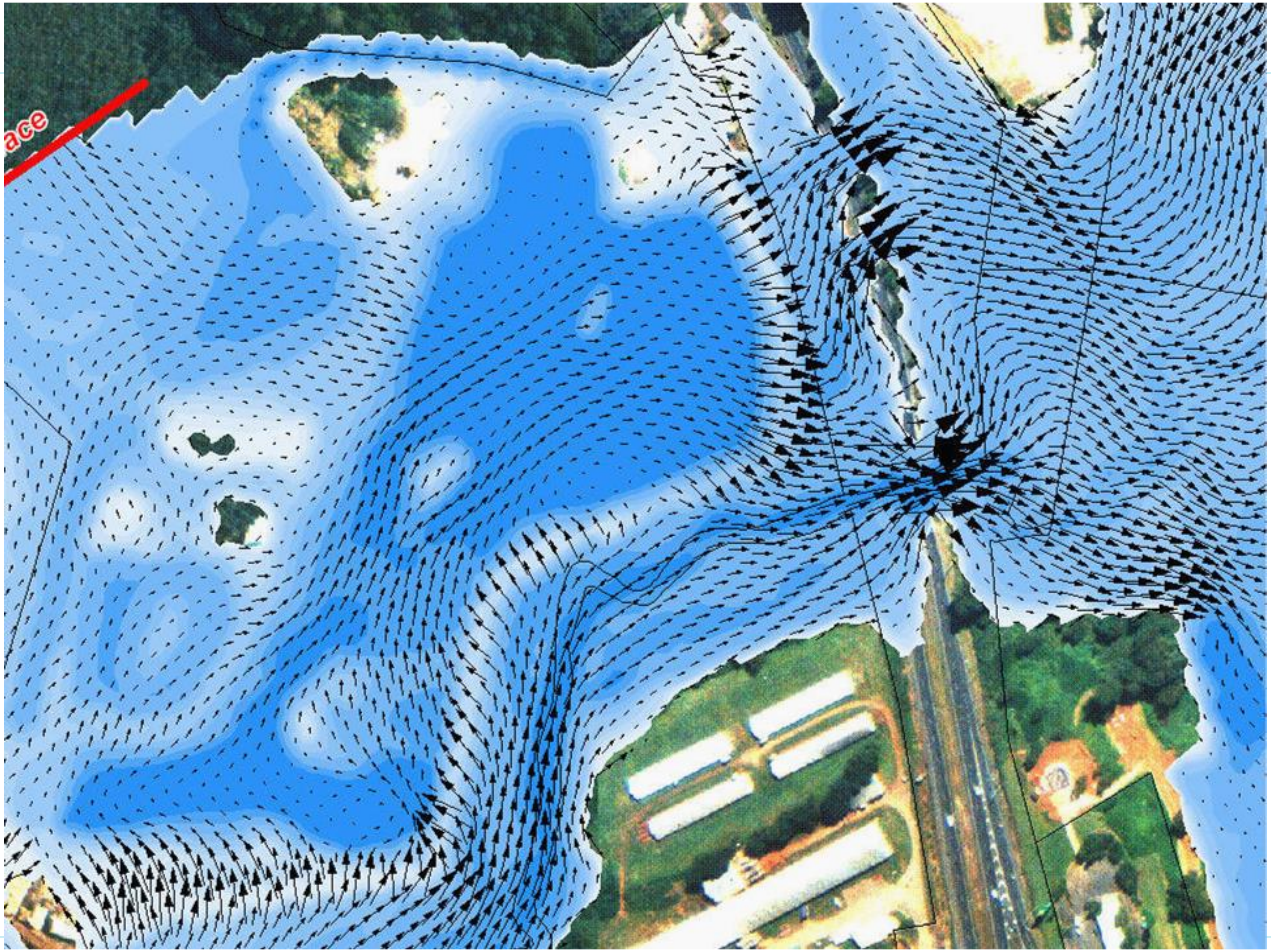
Using 2D Schemes to Model Energy Losses at Structures and Bends – Beware of Pretty Images!

Bill Syme

BMT WBM
Software Business Manager

2D: Looks impressive, but is it accurate?



Form Losses

Energy dissipated as heat due to changes in velocity magnitude and direction

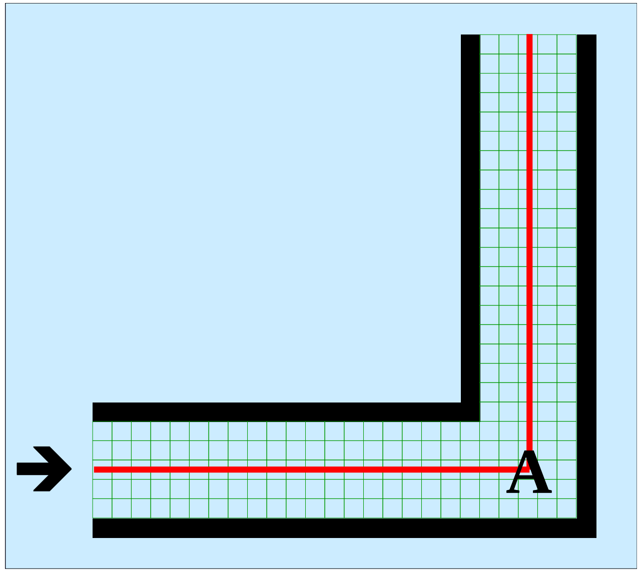
Pronounced at

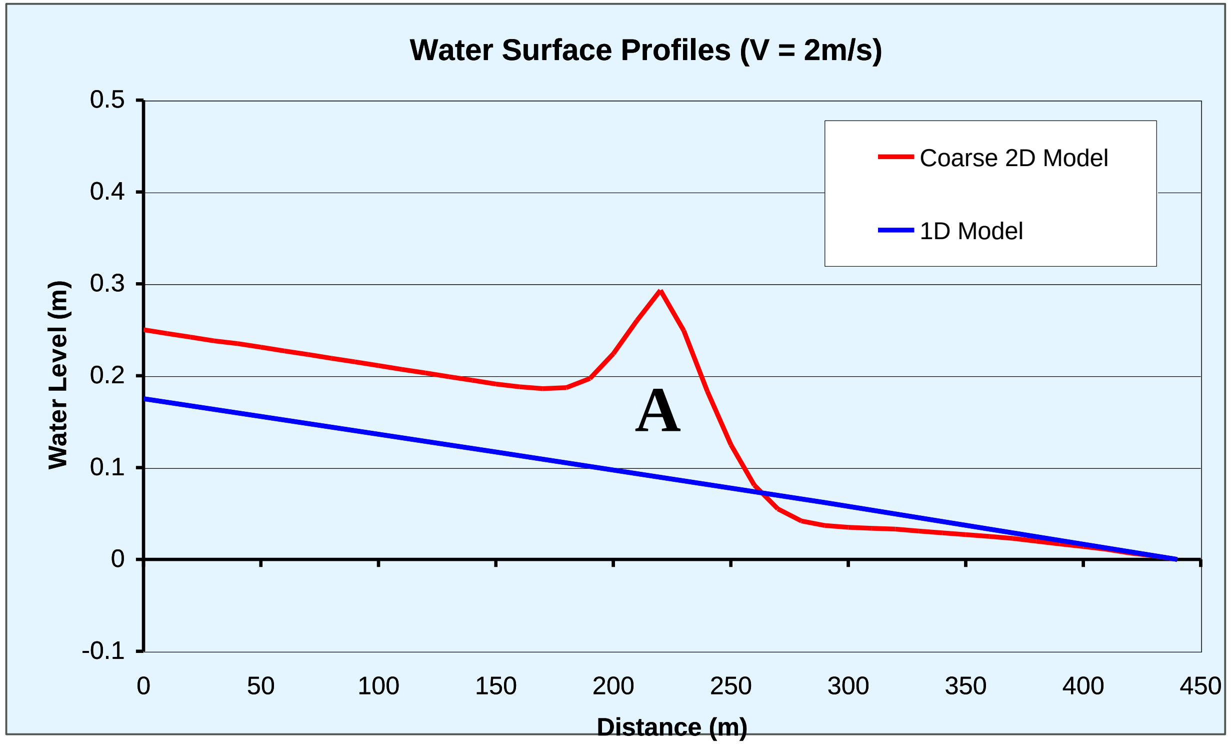
- Bends
- Flow constrictions (structures)

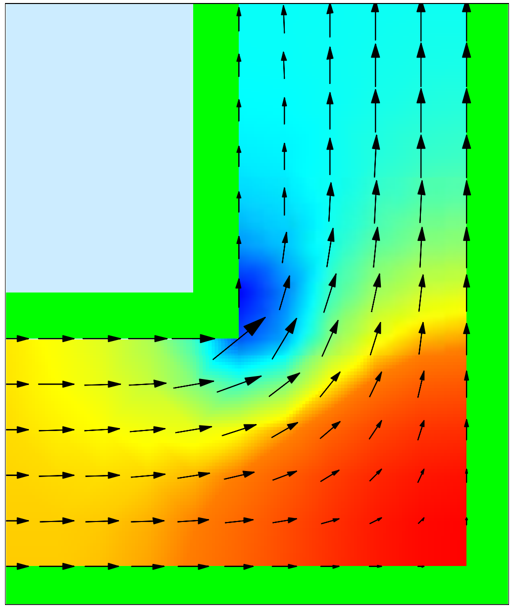
Form loss coefficient

- Proportion of dynamic head ($V^2/2g$) lost
- V = 1m/s; Dynamic Head = 0.05m
- V = 4m/s; Dynamic Head = 0.82m

Right-Angled Bend
1D vs 2D







River Bends

Average Vel 3-4 m/s, 20 m deep, 0.7m superelevation

1D Equations

- Don't simulate bend losses
- Need to apply additional losses
  (eg. higher n or energy loss)
- Superelevation not modelled

Calibration at 45° to 180° Bends

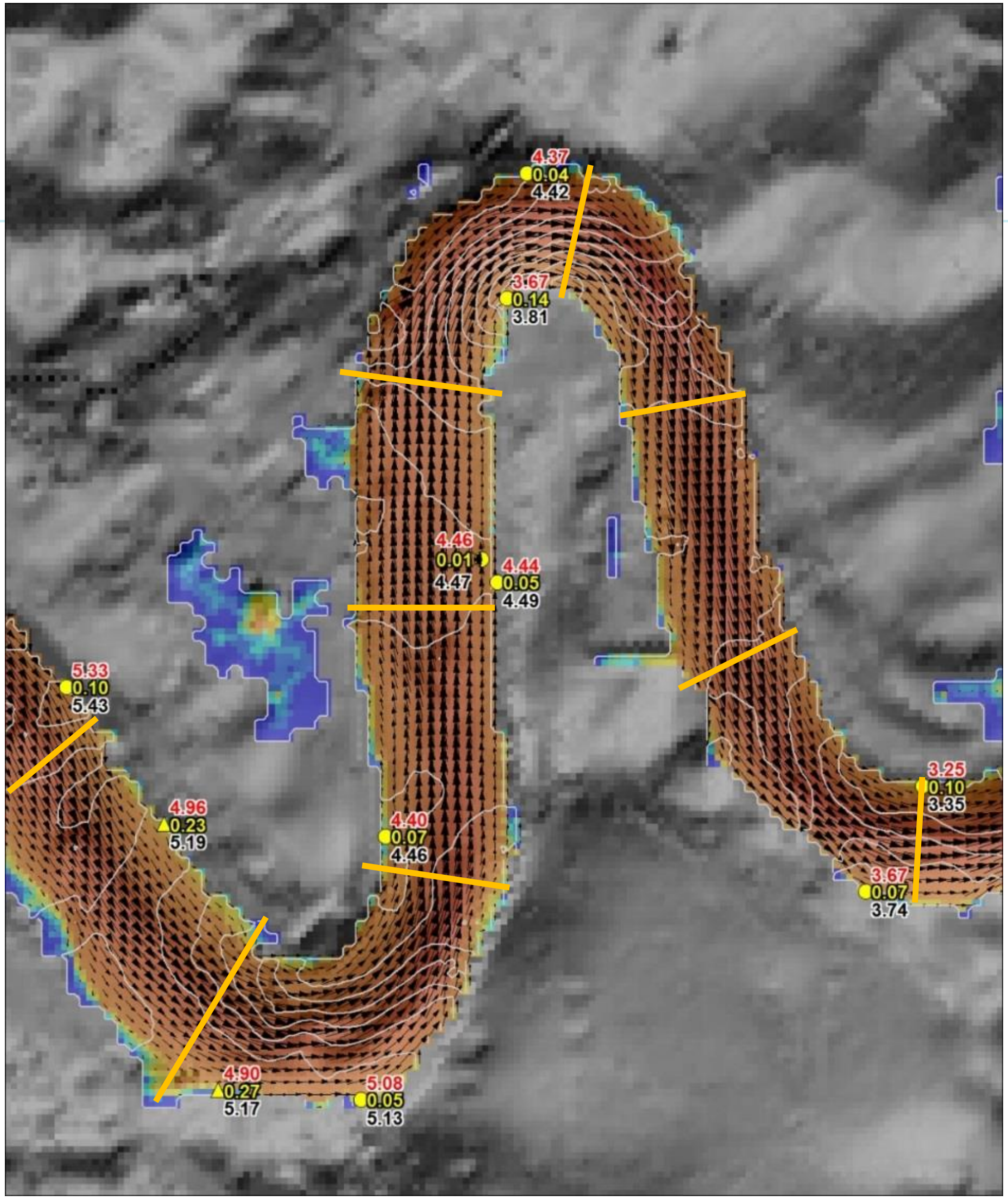
- 1D FLC: 0.5 to 1.5
- 2D FLC: 0.1 to 0.4

2D Equations

- Simulates bend losses and superelevation
- Don't simulate all losses such as those in the vertical
  (eg. helicoidal circulations)

3D Equations

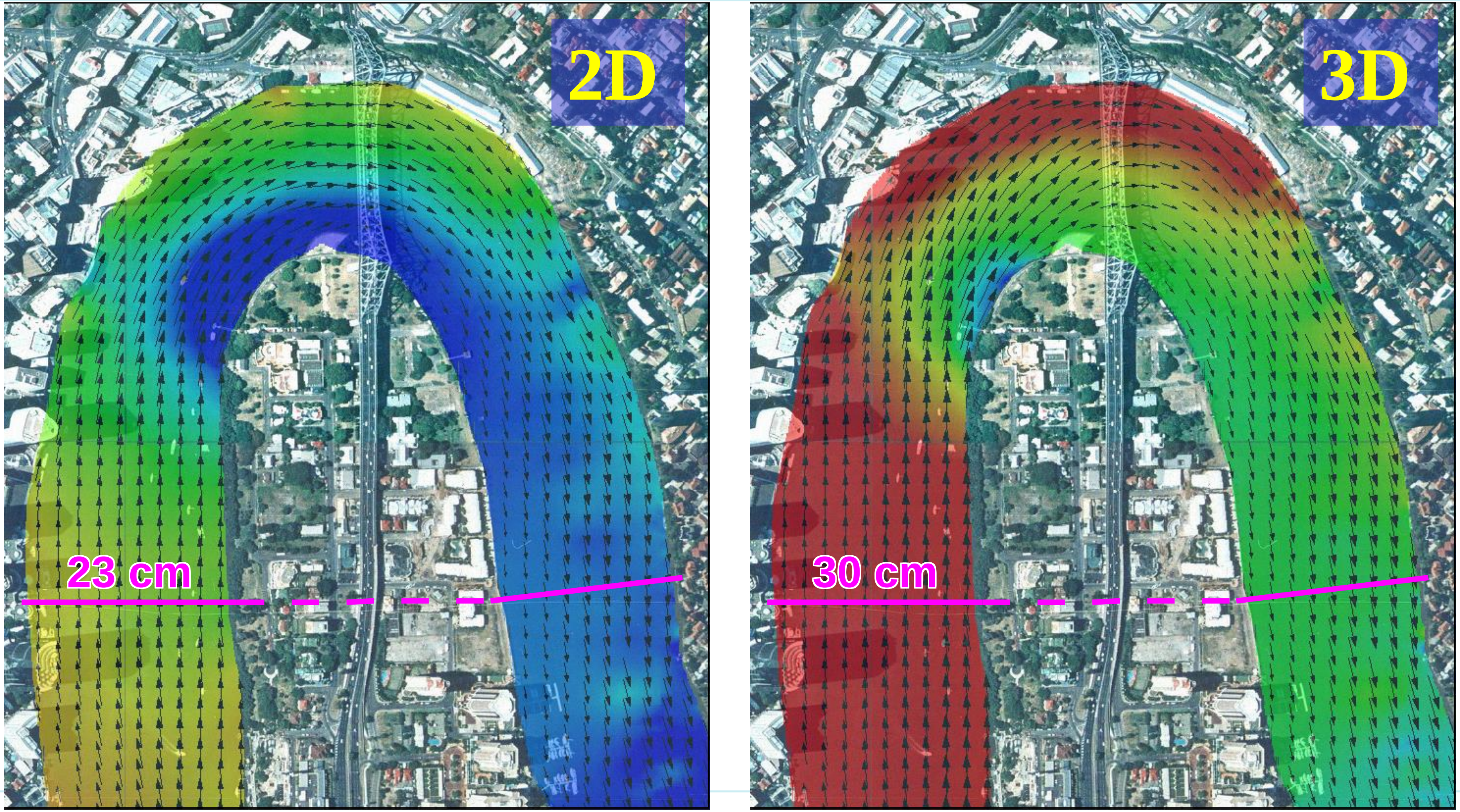
- Layered 3D should be closer again, but there are assumptions
- CFD using the Navier-Stokes equations should be closest



BMT WBM

TUFLOW

2D vs 3D?
(from a presentation in 2001)

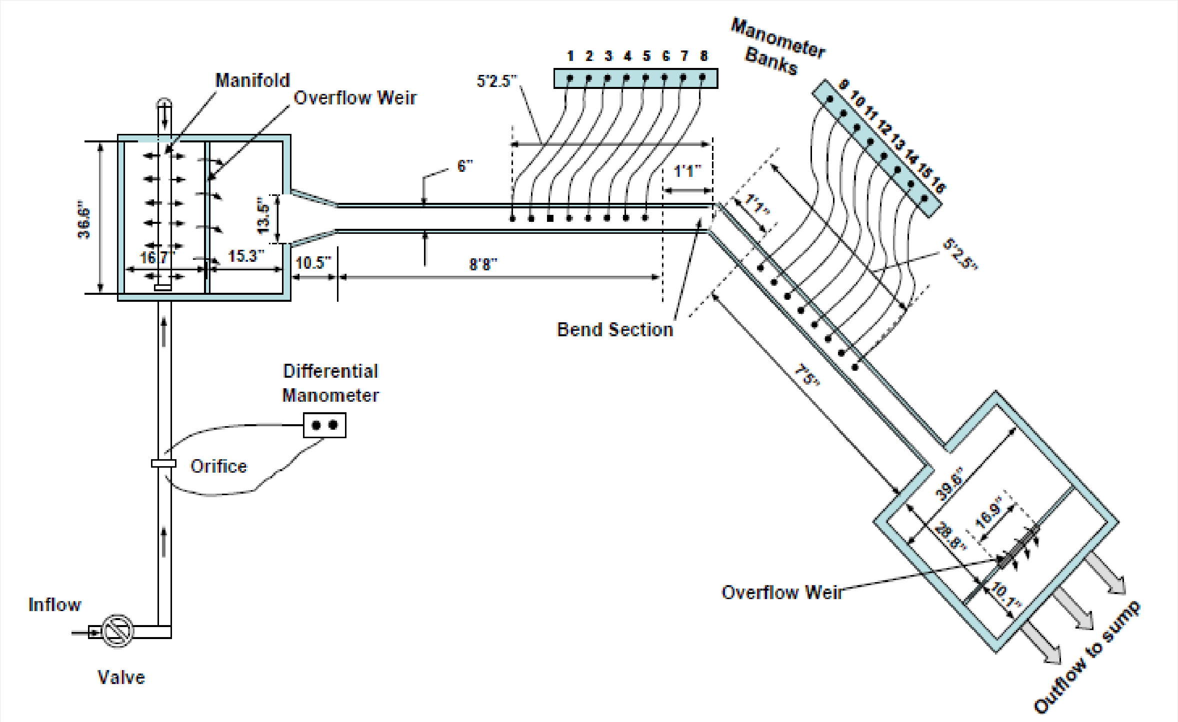


BMT WBM

TUFLOW

Test Case:
Bend Loss

- Aim: Assess the estimated losses resulting from an abrupt bend
- Validate against laboratory experiment results (Malone 2008)



Report No. K-TRAN: KU-05-5
FINAL REPORT

BEND LOSSES IN RECTANGULAR CULVERTS

Travis Malone
A. David Parr, Ph.D.
The University of Kansas
Lawrence, Kansas

SEPTEMBER 2008

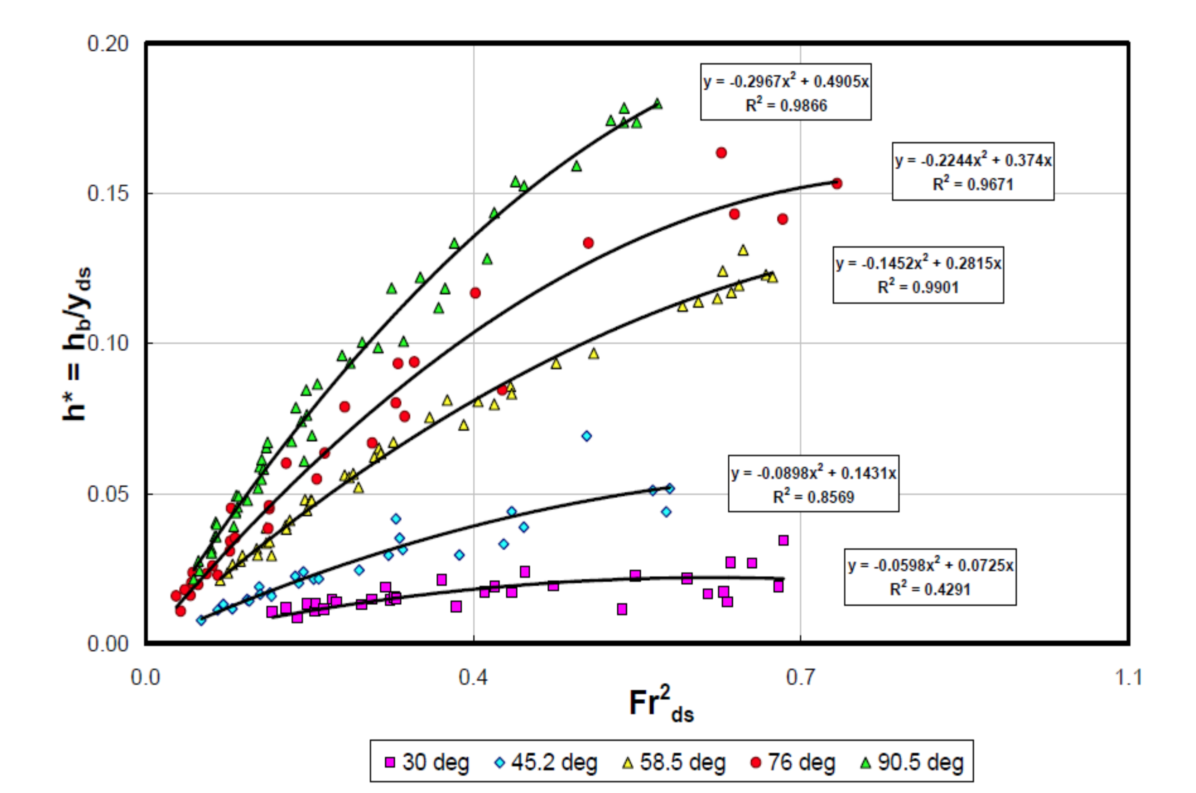
A COOPERATIVE TRANSPORTATION RESEARCH PROGRAM BETWEEN:

KANSAS DEPARTMENT OF TRANSPORTATION
KANSAS STATE UNIVERSITY
THE UNIVERSITY OF KANSAS

KANSAS DEPARTMENT OF TRANSPORTATION

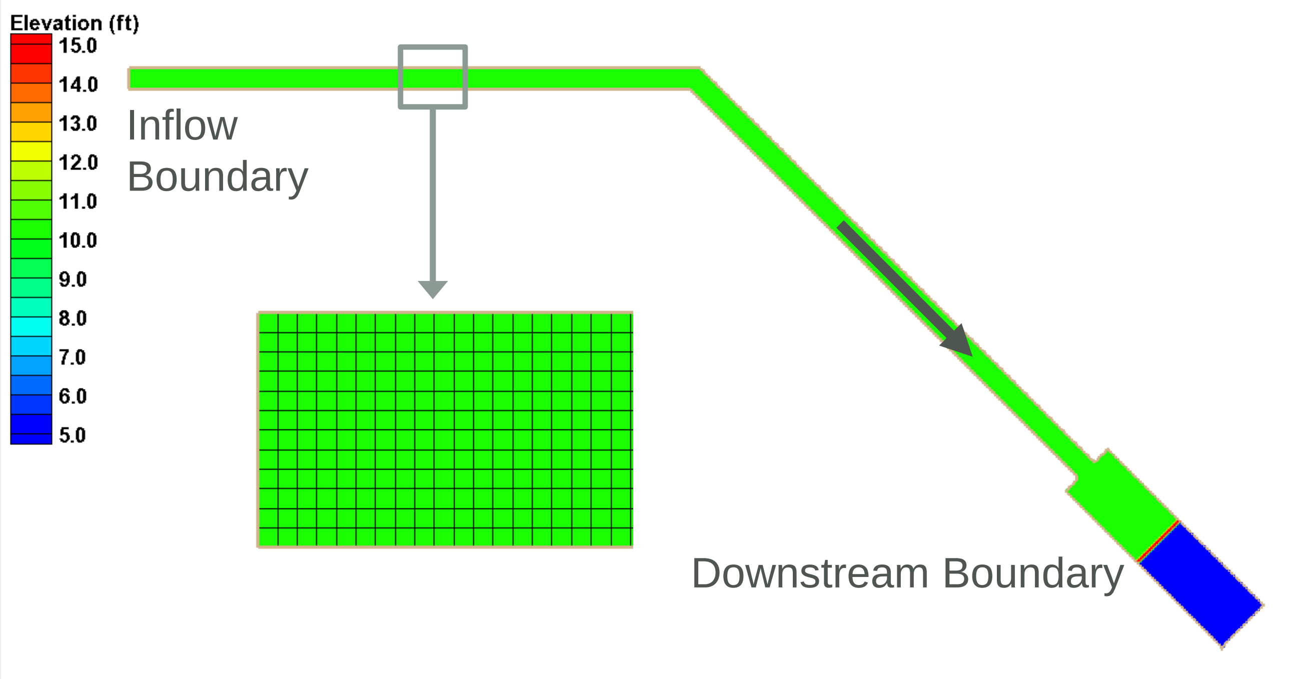
Test Case:
Bend Loss

Empirical equations from laboratory results

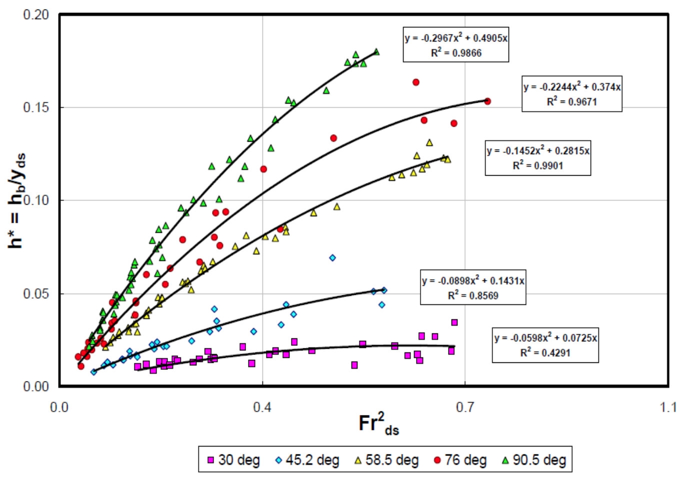


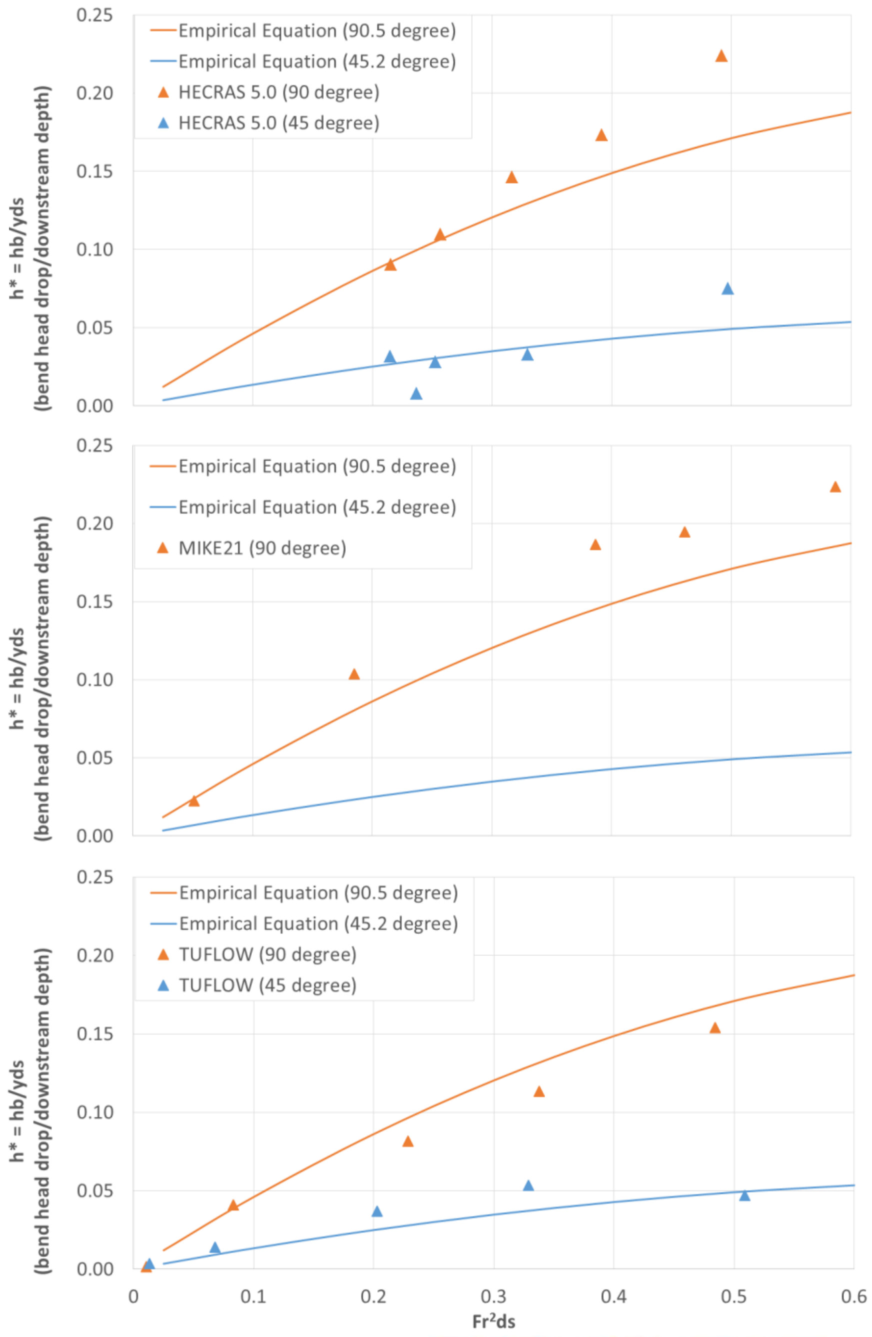
Bend Loss:
Model Configuration

- Scaled to match dimensions of laboratory test
- 0, 45 and 90 degree scenarios. 15ft grid resolution.
- Free overfall conditions at the downstream boundary



Initial Model Comparisons





Differences between schemes most likely due to different numerical solutions

Schemes thus far tested show reasonable correlation

Note that flume test results have scatter

3D effects or energy losses are not modelled therefore should 2D schemes under predict?

- If scheme under predicts, can calibrate by adding additional form losses for 3D (vertical) and fine-scale losses
- If scheme over predicts, can’t calibrate or allow for 3D/fine-scale losses unless a **negative** form or energy loss is applied…

Bends – Conclusions
1D and 2D Approaches

1D

Apply extra losses by

- Form loss coefficient, or
- Increasing Manning's n

Do not model superelevation

2D

Form losses inherent / Models superelevation

However

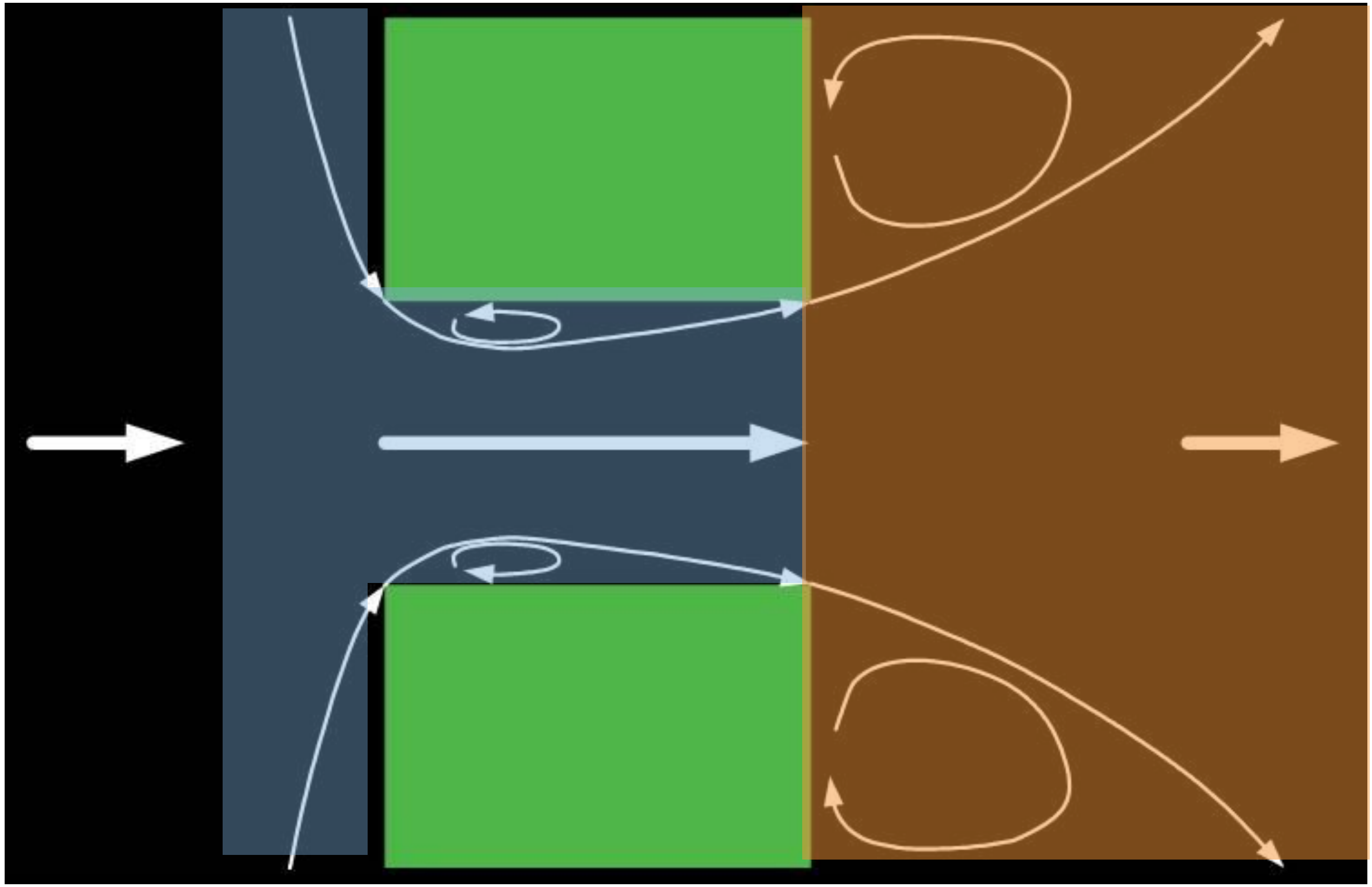
- Are model elements too coarse to simulate all losses?
- Are there losses in the vertical plane? (eg. helicoidal circulations)

Additional form losses may be required (hard to apply/justify if scheme over predicts)

Does your 2D scheme under or over predict losses at bends?

Contraction and Expansion Losses

1D: Traditional Approach
Uses Contraction/Expansion Losses



1D Structure Entrance and Exit Loss Coefficients

Coefficients adjusted according to approach and departure velocities in a 1D network (not yet available when connected to 2D)

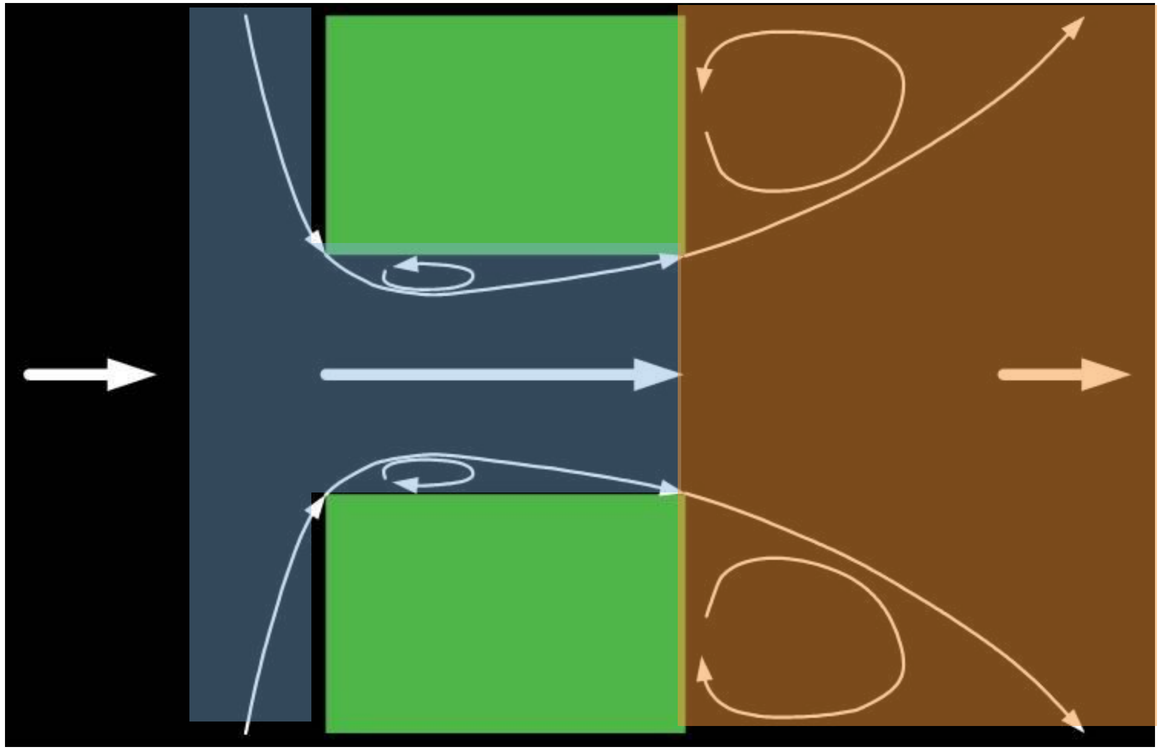
Default unadjusted values typically 0.5 and 1.0

Can fix losses (ie. no adjustment) if desired

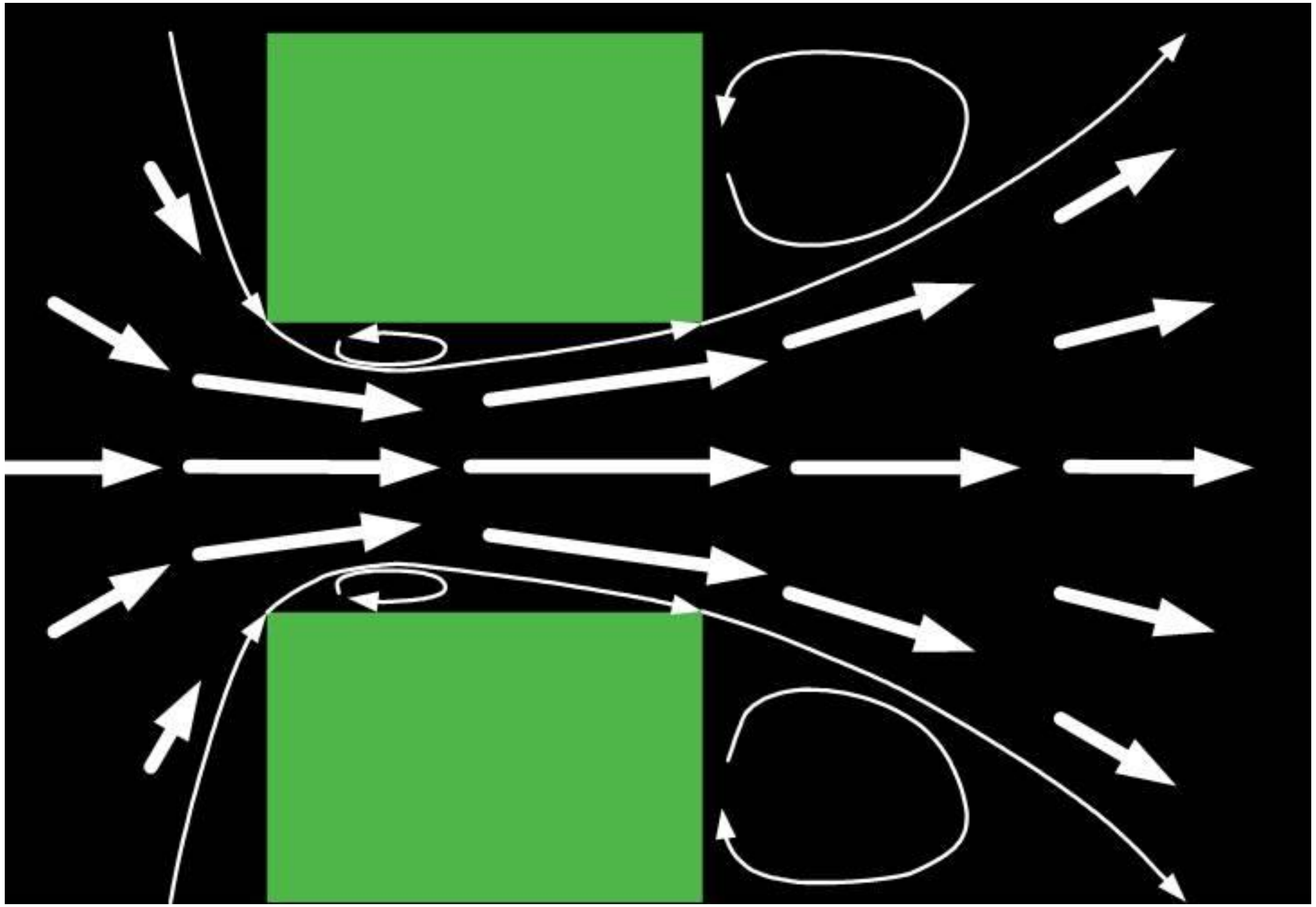
Energy loss is C*V_s^2/2g

$$C_{entrance\_adjusted} = C_{entrance}\left[1 - \frac{V_{approach}}{V_{structure}}\right]$$

$$C_{exit\_adjusted} = C_{exit}\left[1 - \frac{V_{departure}}{V_{structure}}\right]^2$$

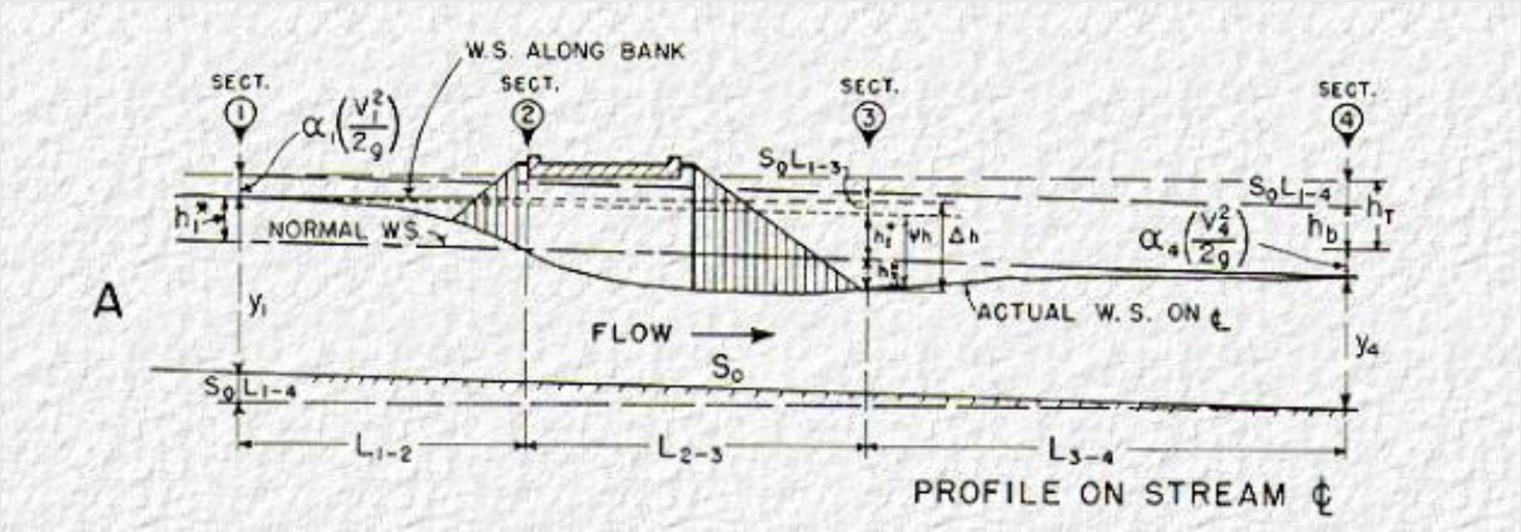


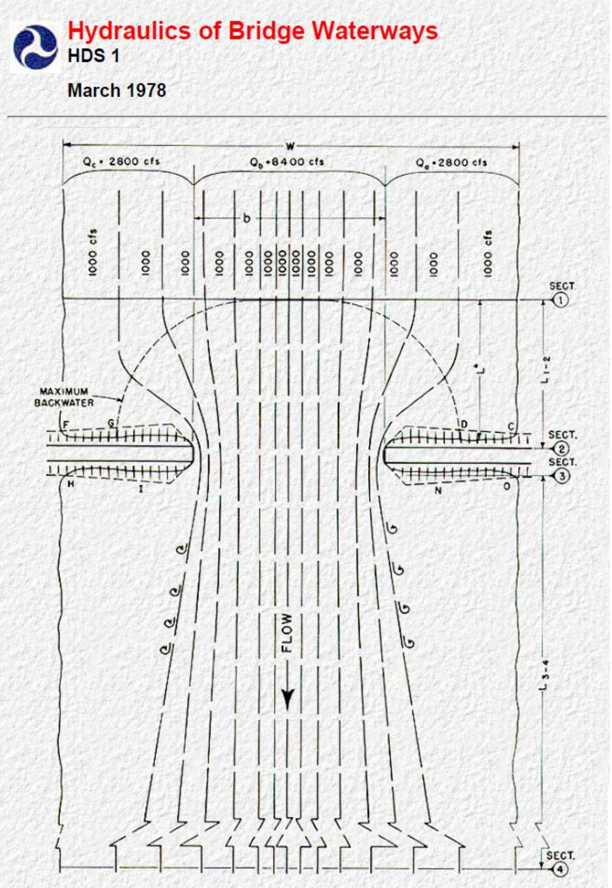
2D: Contraction/Expansion Losses are not specified
Or should they be…?



Constriction Test Case

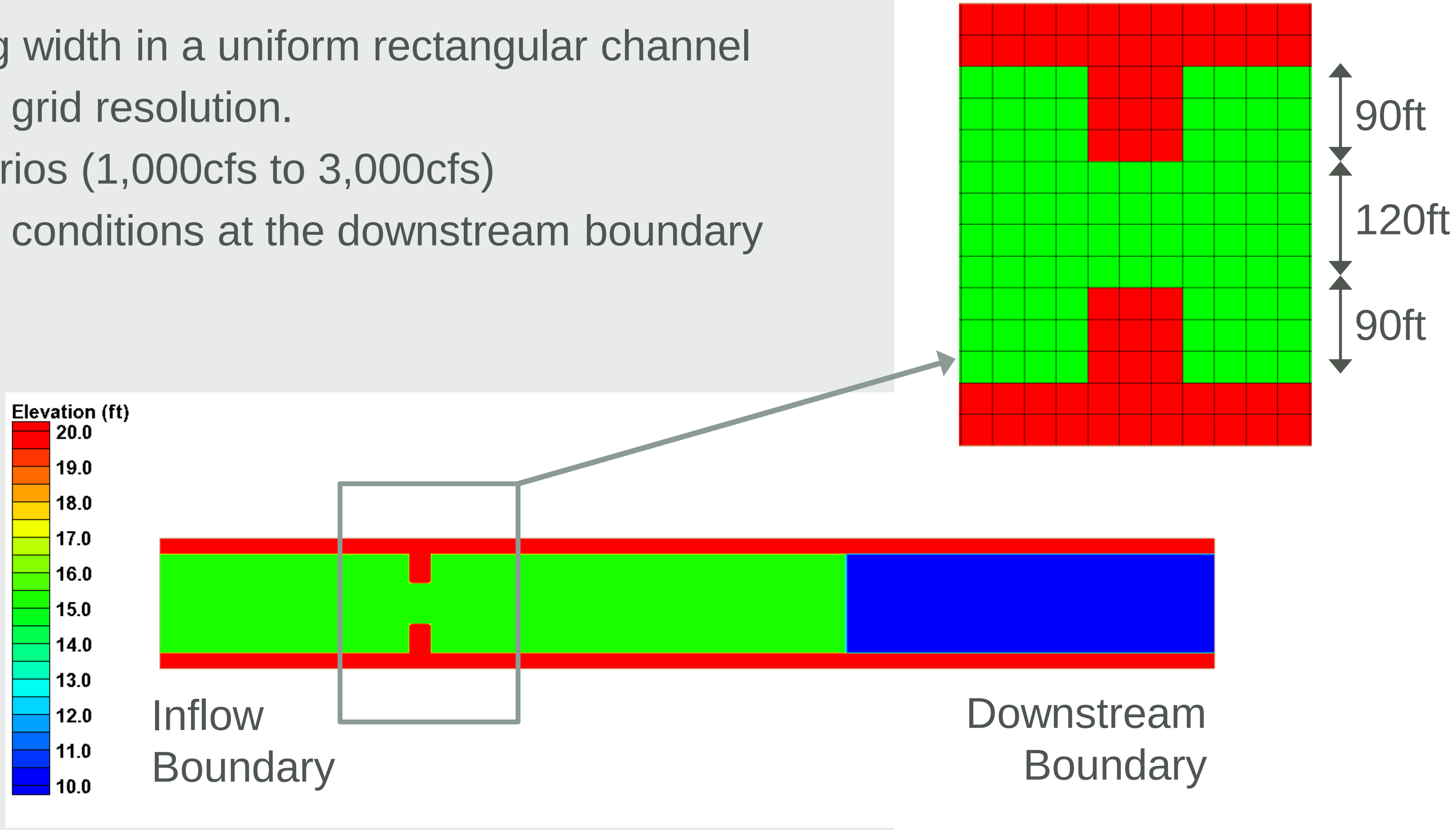
- Assess models estimate of losses resulting from a constriction (eg. bridge abutments)
- Test for cell size spatial convergence
- Compare with Federal Highways Administration Equations (Hydraulics of Bridge Waterways, Bradley, 1978)





Constriction Model Configuration

- 40% opening width in a uniform rectangular channel
- 10ft and 30ft grid resolution.
- 3 flow scenarios (1,000cfs to 3,000cfs)
- Free overfall conditions at the downstream boundary



Initial Model Comparisons

HEC-RAS 5.0 Diffusive Wave is very diffusive!

HEC-RAS 5.0 Momentum diffuses rapidly downstream / tends to over predict cf FHA

MIKE21 tendency to over predict cf FHA

TUFLOW Classic tendency to under predict

Differences most likely due to different numerical solutions

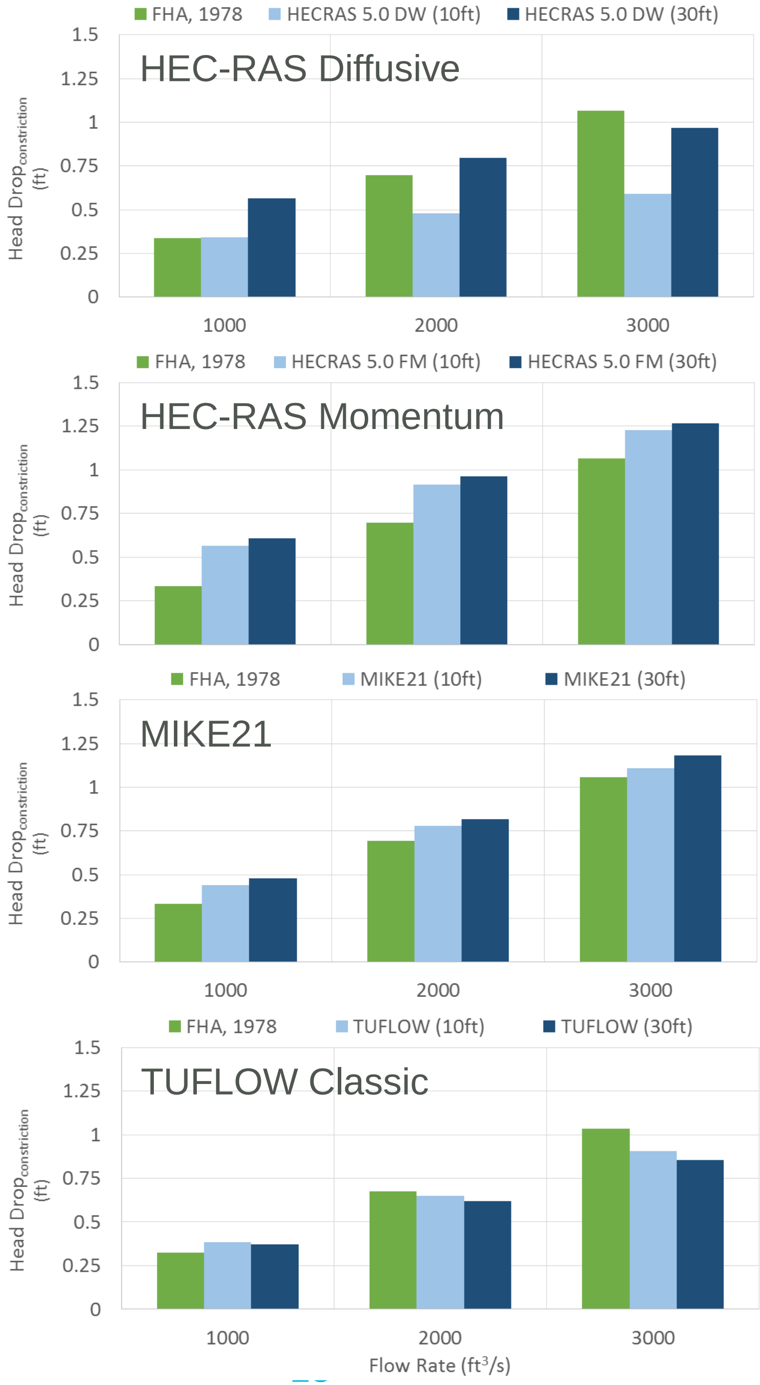
- Results/trends between schemes consistent with bend tests

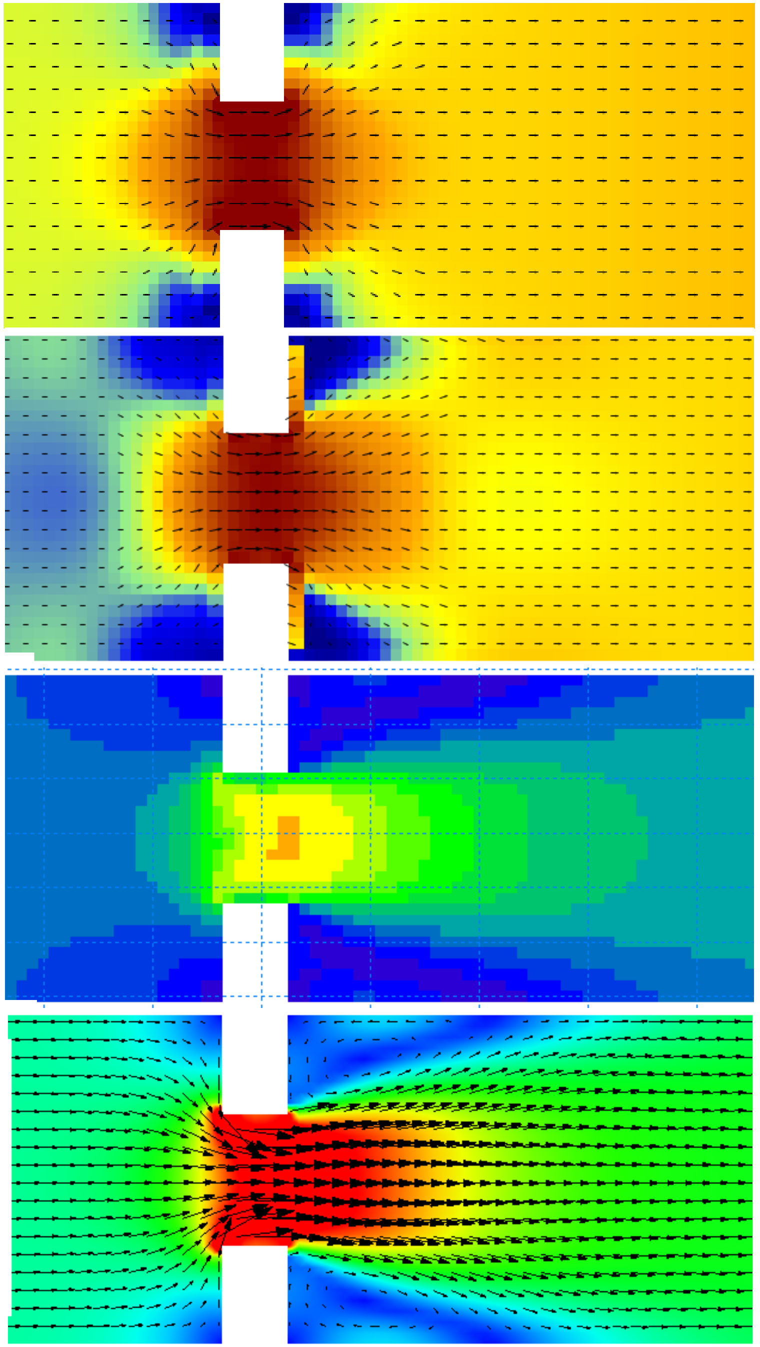
3D (vertical) and fine-scale losses (eg. vena-contracta) not modelled therefore should 2D schemes under predict?

- Same trends / issues as for bends

All except HEC-RAS Diffusive Wave have reasonable cell size spatial convergence

Testing very preliminary, but illustrate that different schemes will produce somewhat different results





BMT WBM

Box Culverts

2D Cell Modifications
(2d_fc or 2d_fcsh layers)

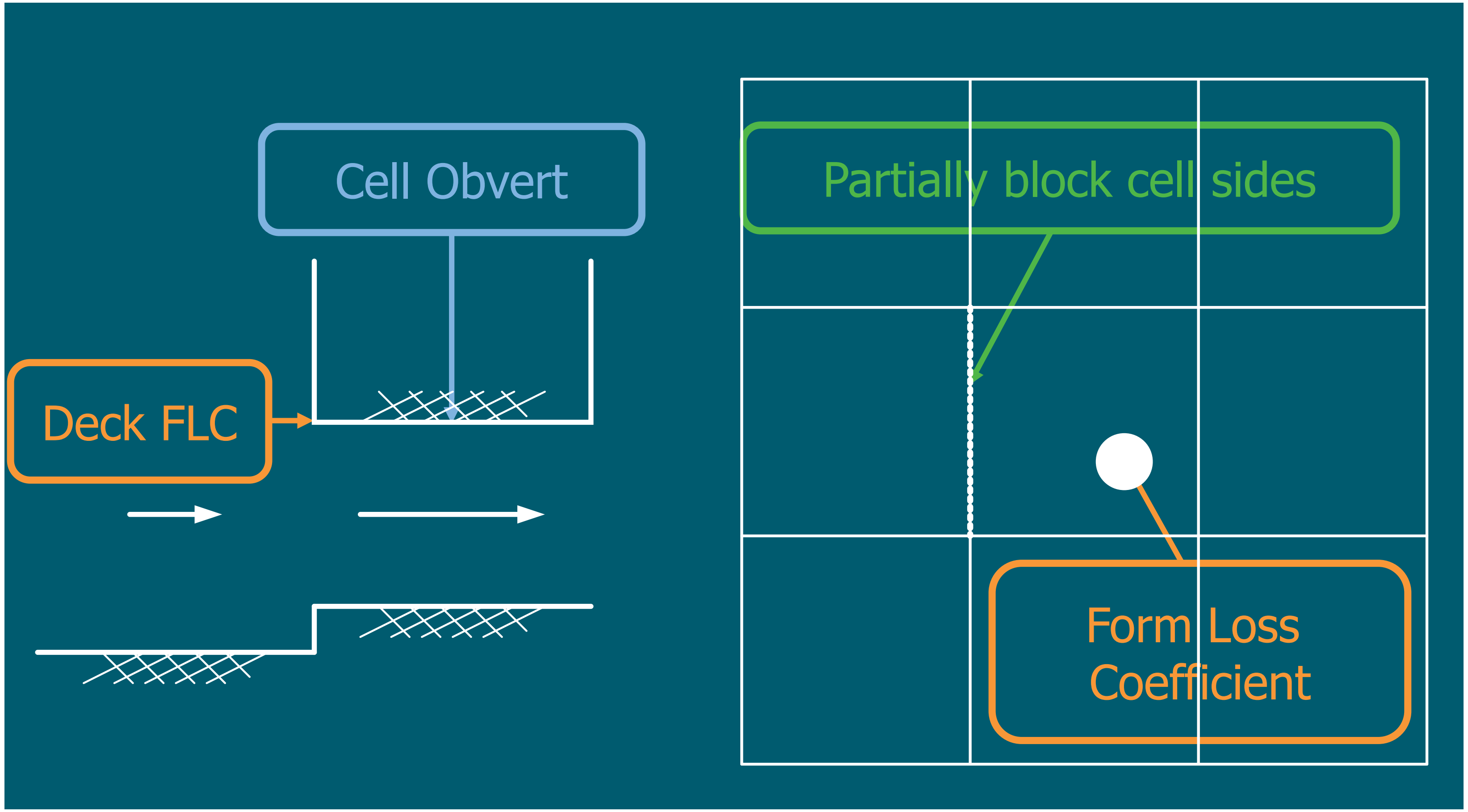
Bridge decks

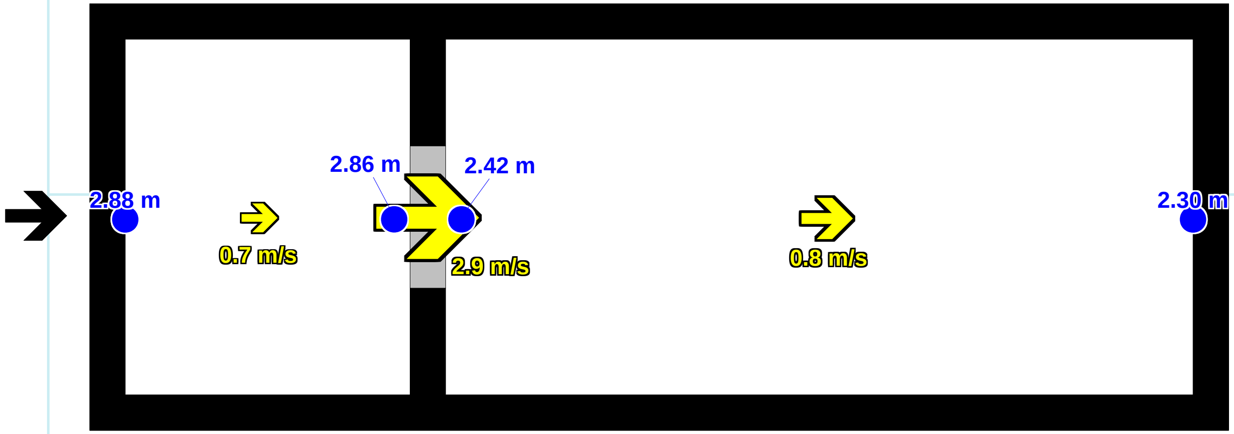
Box culverts

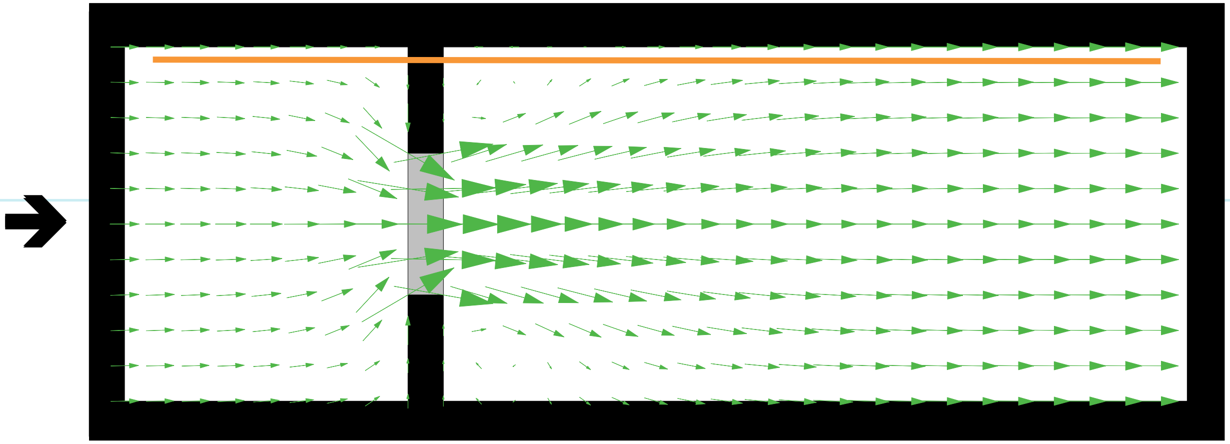
Additional losses

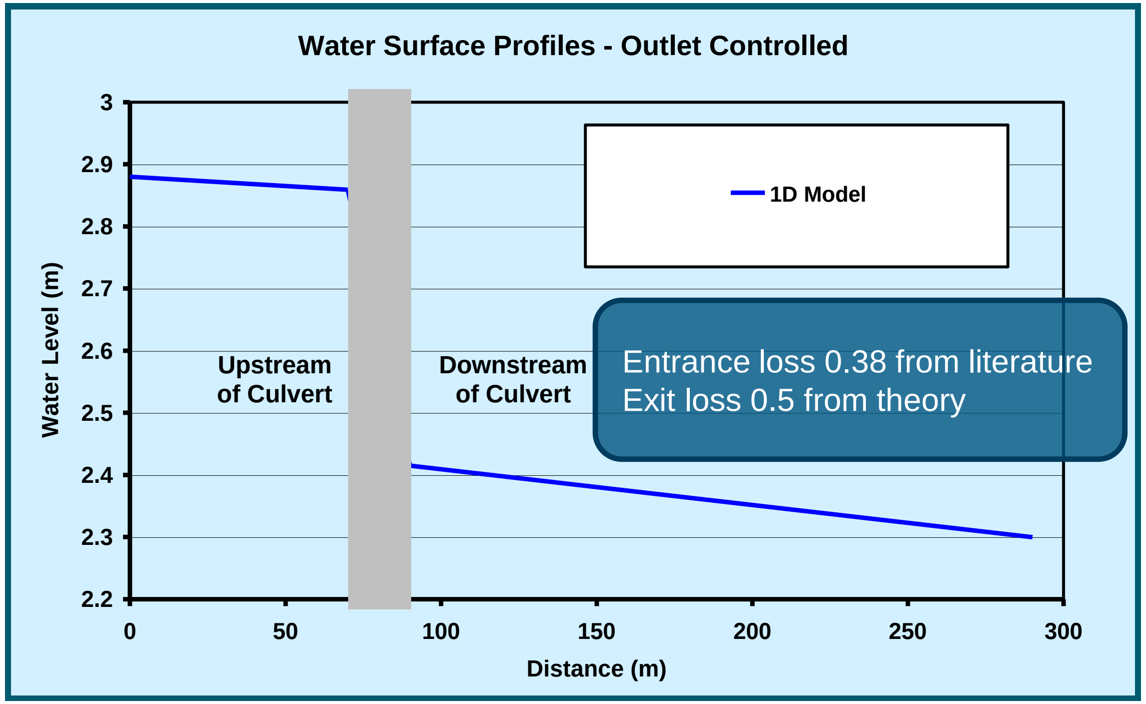
- Deck surcharging
- Piers
- Vena-Contracta

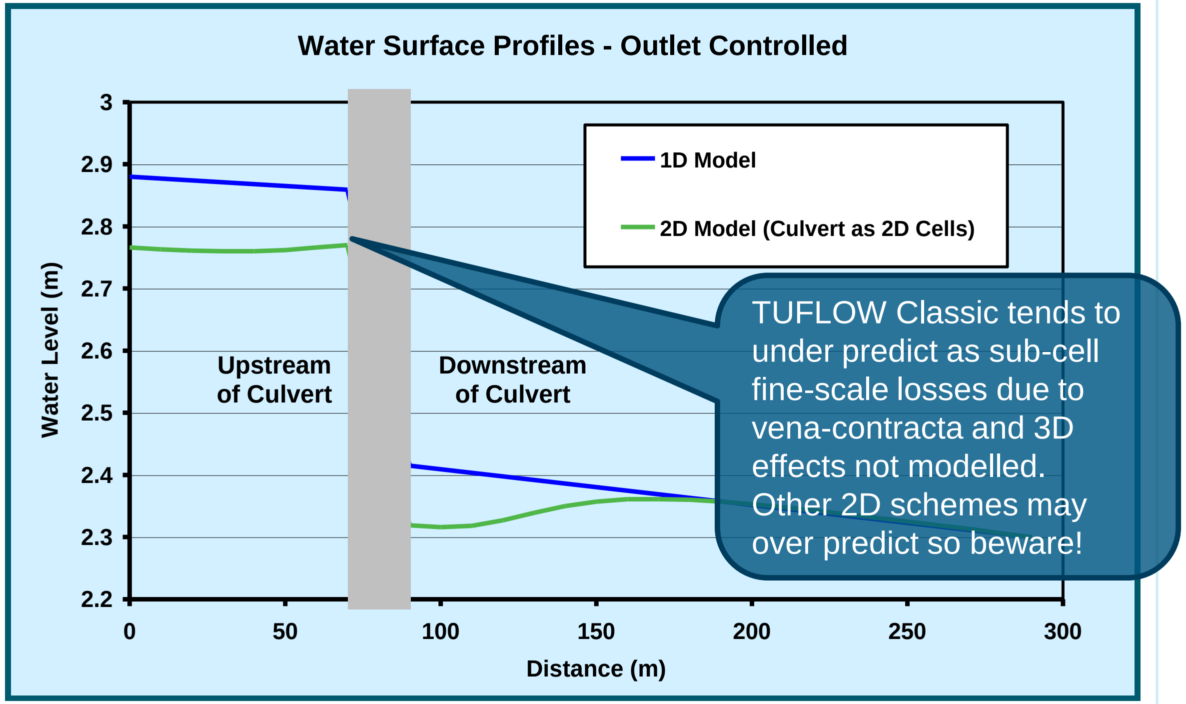
Partial blockage



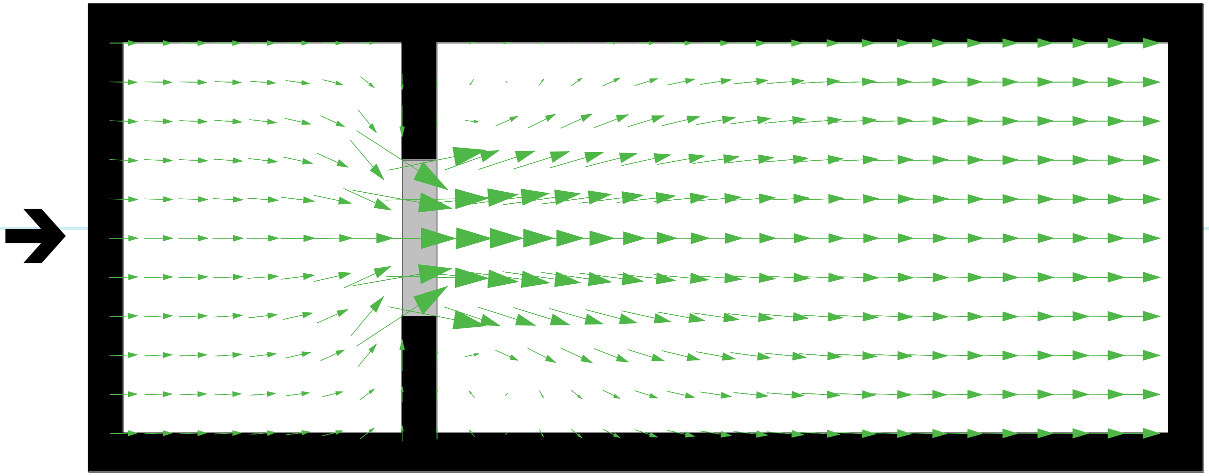

2.88 m
0.7 m/s
2.86 m
2.42 m
2.9 m/s
0.8 m/s
2.30 m




Water Surface Profiles - Outlet Controlled
1D Model
Upstream of Culvert
Downstream of Culvert
Entrance loss 0.38 from literature
Exit loss 0.5 from theory
Water Level (m)
Distance (m)
3
2.9
2.8
2.7
2.6
2.5
2.4
2.3
2.2
0
50
100
150
200
250
300


Water Surface Profiles - Outlet Controlled
1D Model
2D Model (Culvert as 2D Cells)
Upstream of Culvert
Downstream of Culvert
TUFLOW Classic tends to under predict as sub-cell fine-scale losses due to vena-contracta and 3D effects not modelled. Other 2D schemes may over predict so beware!
Water Level (m)
Distance (m)
3
2.9
2.8
2.7
2.6
2.5
2.4
2.3
2.2
0
50
100
150
200
250
300

“Calibrating” 2D Structures

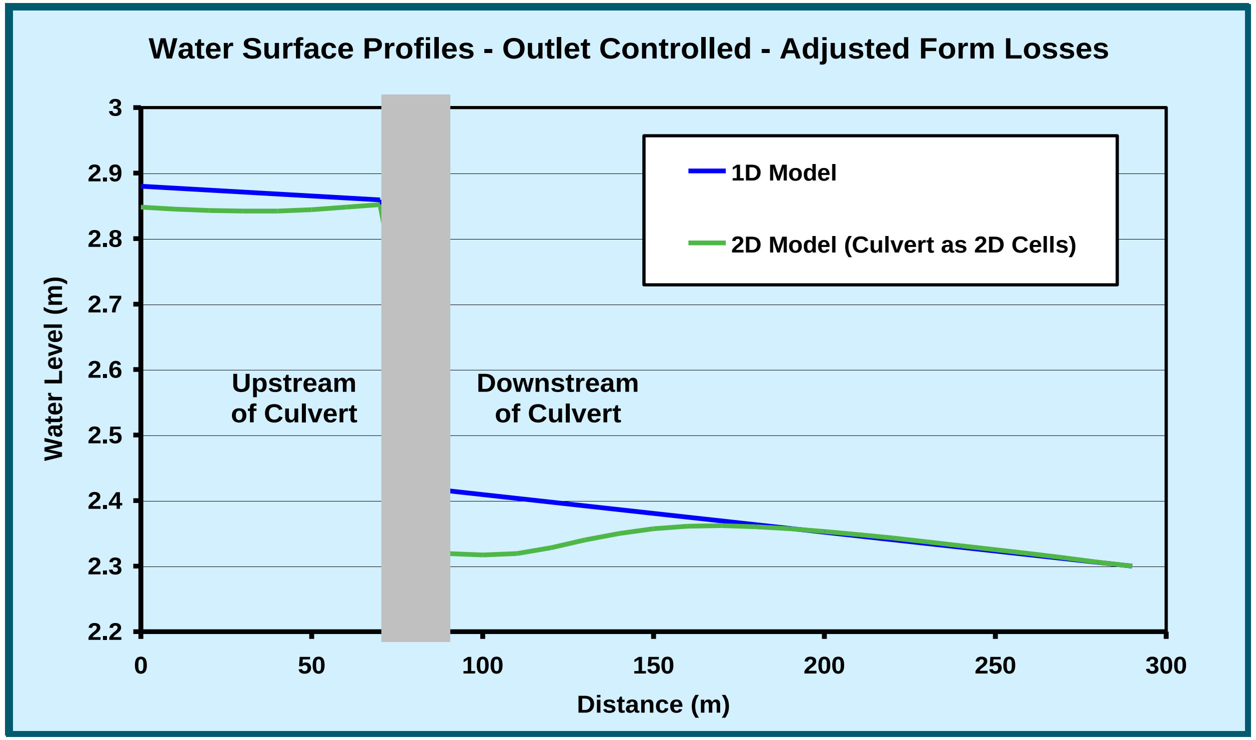


For example, if we apply a 0.2 FLC, ie. add $0.2*V^2/2g$ energy loss

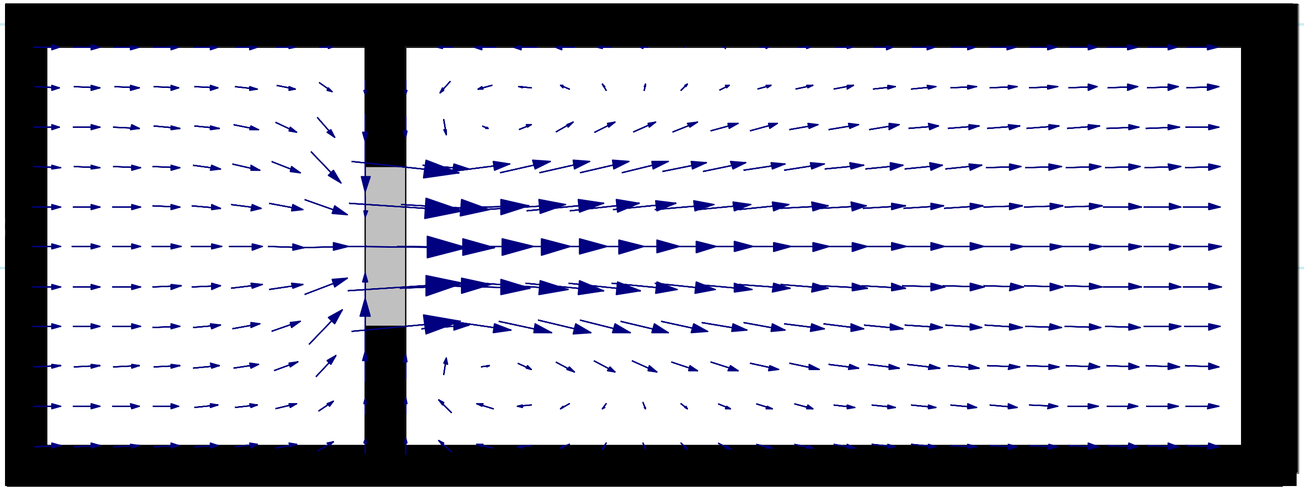
TUFLOW Classic tends to require some additional form loss for sub-cell fine-scale losses and any 3D effects

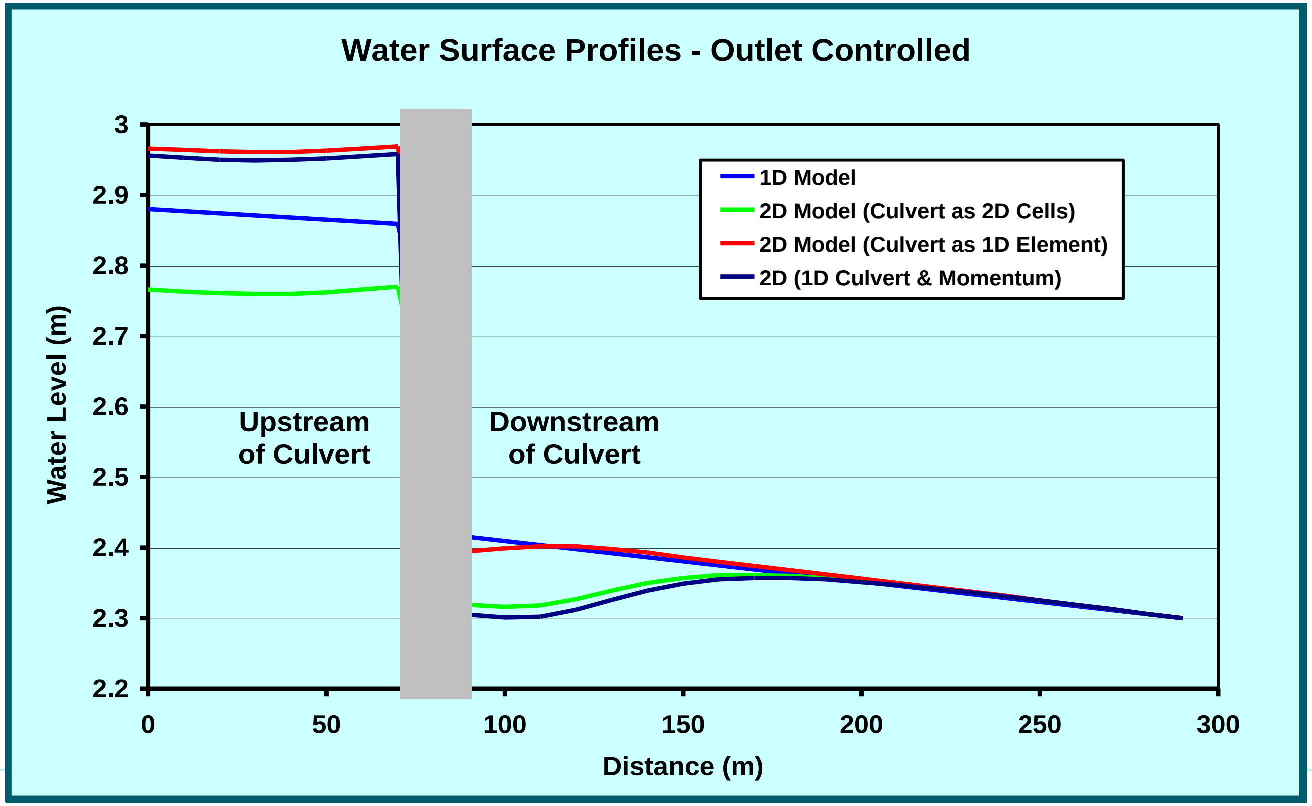
- Typically 20 to 30% of 1D energy loss values

May not be applicable to other 2D schemes, especially those that over predict losses



1D/2D Link Options





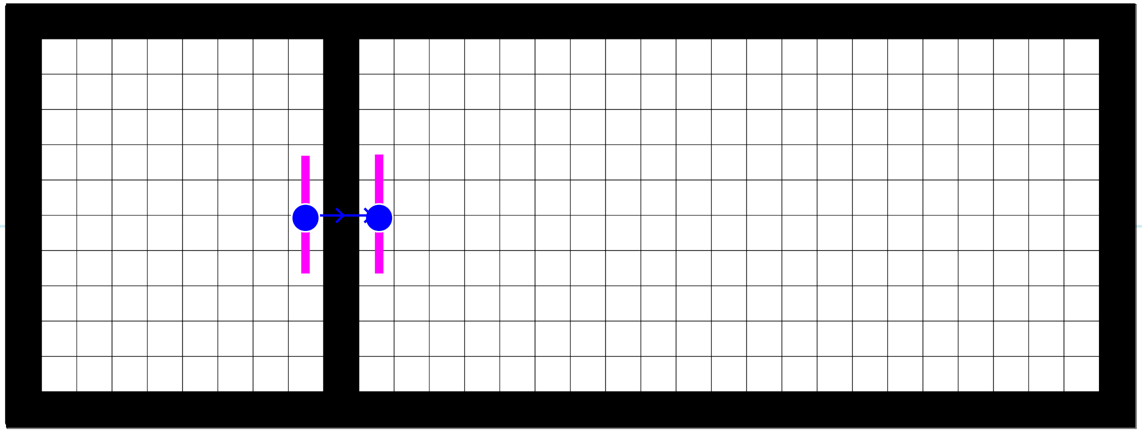
SX Link

HX Link (Preserves momentum)

Both SX and HX dissipate energy downstream due to 2D solution expanding the flow

Applying full exit loss on 1D duplicates downstream energy loss

"Calibrating"
1D Culvert linked into 2D

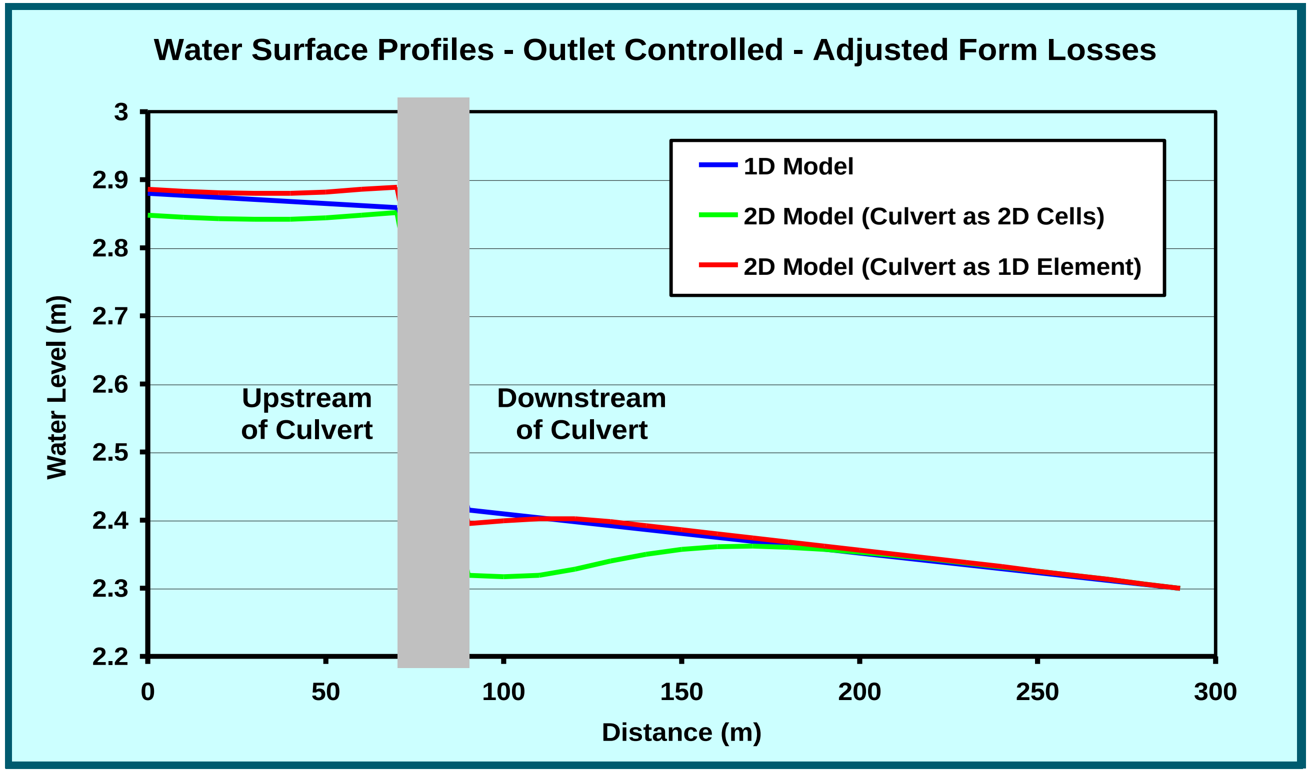


Calibrated 2D Only Scenario

- Added 0.2 form loss

Culvert as 1D Element (SX or HX Link)

- Reduce exit (form) loss coefficient by 0.2



BMT WBM

TUFLOW

Modelling Decks and Culverts – Conclusions

Culvert as 2D Cell(s)

- TUFLOW Classic 2D solution models 70 to 80% of losses
- Sub cell fine-scale losses (eg. vena-contracta) and 3D effects can't be modelled by a 2D scheme
- Need 20 to 30% additional form or energy loss

Culvert as 1D Element

- Over predicts losses by 0 to 70%
- Small – 0% over prediction
- Large – up to 70% over prediction
- Reduce inlet / outlet losses of 1D element(s)

25

Overall Conclusions

2D contracts and expands flow lines

- Inherently models form losses due to contraction and expansion of flow

Not all losses are represented

- 3D (vertical) and sub-cell, fine-scale losses
- Need ability to add form losses (calibrate)

Need momentum and viscosity terms

Some 2D schemes may over predict losses – benchmark your scheme

Linking 1D structures into 2D

- Useful when the structure is small
- Large structures (relative to 2D cell size) may duplicate (over predict) losses
- May need to reduce inlet / outlet losses (calibrate)

Benchmark, check and UNDERSTAND your results

thank you