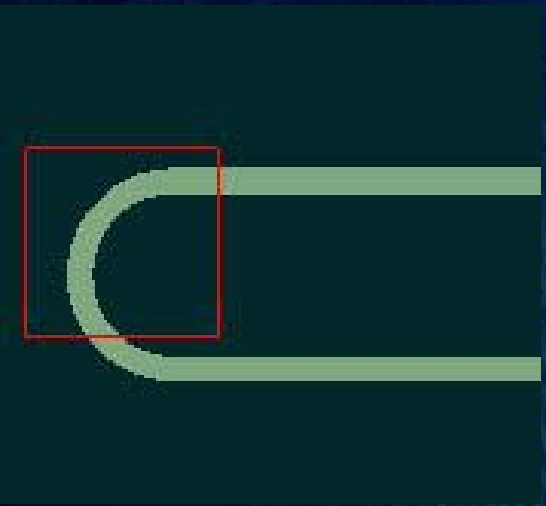
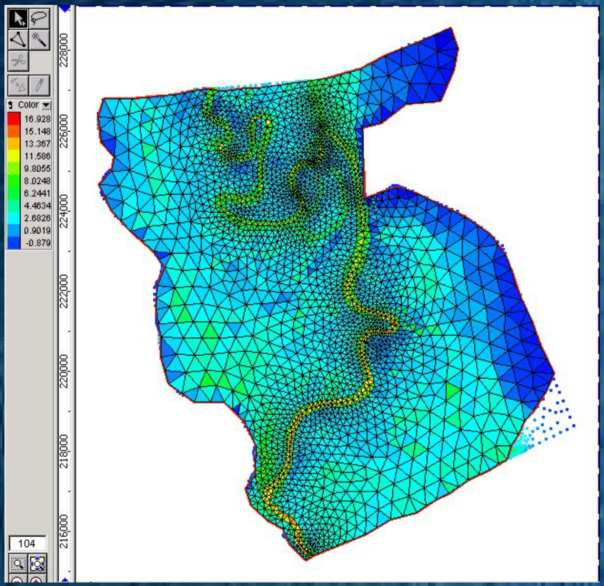
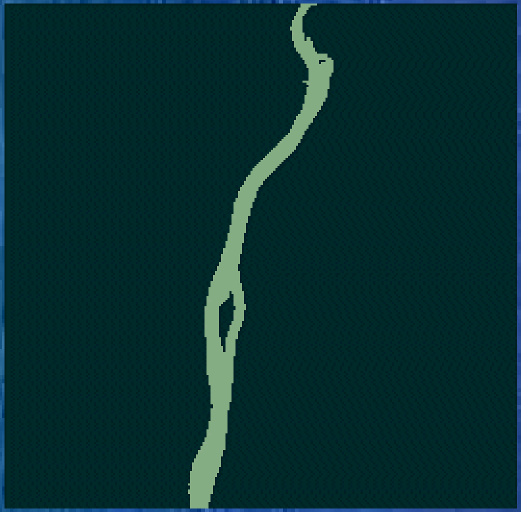
The UnTRIM Model for Rivers, Lakes and Estuaries

An Introduction to UnTRIM Model







Ralph T. Cheng
U. S. Geological Survey
Menlo Park, California 94025

Introduction

- **General Viewpoint of Numerical Modeling of Environmental Flows**

An Overview of the TRIM Family of Models

Extension from TRIM to Unstructured Grid

- **UnTRIM model**

Practical Applications of UnTRIM model

- **San Francisco Bay**
- **Upper St Claire River, Michigan**
- **White River, Arkansas**
- **Upper Klamath Lake, Oregon**

Discussion and Conclusion

General Viewpoint of Numerical Modeling of Environmental Flows

Scales: Physical Properties or Physical Processes

Spatial (m)	and	Temporal (sec)
$10^{(-2, -1)}$		$10^{(-1, 0, 2)}$
$10^{(0 \text{ to } 5)}$		$10^{(2 \text{ to } 6)}$
m, km, 1-100 km		min, hours, days, month, years
$10^{(> 6)}$		$10^{(>7)}$

Need the <u>Right Model</u> to represent the proper physical properties and to resolve the physical processes of the environmental problem

Considerations in Formulating a Numerical Algorithm for a Model

Desirable Properties of a Numerical Model:

1. Stability
2. Accuracy (Require compromise)
3. Efficiency

Numerical Algorithm →

From PDE to Discrete Algebraic System:

Spatial discretization:

Finite difference, Finite Element, Finite Volume

Temporal discretization:

Explicit scheme, Implicit scheme, Semi-implicit

An Overview
The TRIM Family of Models
From TRIM to UnTRIM

- Solution of Shallow Water Equations, 3D
- Transient, Mulit-Dimensional (3D, 2D, 1D)
- Simultaneous Solution of Transport Variables
- Semi-implicit Finite-Difference Method
- Boundary Fitting Unstructured Grid Mesh

Applications and Potential Applications in Surface Water Hydraulics

- **Flows in Bays and Estuaries**
  San Francisco Bay and Delta (TRIM Classic and UnTRIM) Chesapeake Bay (VIMS)
  Delaware Bay (Drexel Univ.)
- **Multi-Dimensional Flood Routing**
- **Studies of Bridge Crossing and Scouring**
- **Floodplain Inundation Mapping and Real-Time Flood Warning**
- **Wind-driven Circulation in Lakes**
- **Basic Flow Field for Transport Processes**
  Eutrophication and WQ Modeling

Numerical Foundation of TRIM (Background)

Casulli, V., 1990, Semi-implicit Finite-difference Methods for the Two-dimensional Shallow Water Equations, J. Comput. Phys., V. 86, p. 56-74.

Desirable Properties of a Numerical Model:
1. Stability 2. Accuracy 3. Efficiency
(Compromise)

Stability Analysis: **Gravity wave terms and velocities in Continuity Eq. control the numerical stability**

Method of Solution:

1. **Treat those terms implicitly, and the remaining terms explicitly.**

2. **Substituting momentum Eqs. into continuity Eq., resulting a matrix equation that determines the water surface of the entire domain.**

2D Depth-Averaged Shallow Water Equations

Continuity Eq.:

$$\frac{\partial \varsigma}{\partial t} + \frac{\partial[(h+\varsigma)U]}{\partial x} + \frac{\partial[(h+\varsigma)V]}{\partial y} = 0$$

X-Momentum Eq.:

$$\frac{DU}{Dt} - fV = -g\frac{\partial \varsigma}{\partial x} + \frac{1}{\rho_o(h+\zeta)}(\tau_x^w - \tau_x^b) + A_h \nabla^2 \mathrm{U} - \frac{g}{2\rho_o}(h+\varsigma)\frac{\partial \rho}{\partial x}$$

Y-Momentum Eq.:

$$\frac{DV}{Dt} + fU = -g\frac{\partial \varsigma}{\partial y} + \frac{1}{\rho_o(h+\zeta)}(\tau_y^w - \tau_y^b) + A_h \nabla^2 \mathrm{V} - \frac{g}{2\rho_o}(h+\varsigma)\frac{\partial \rho}{\partial y}$$

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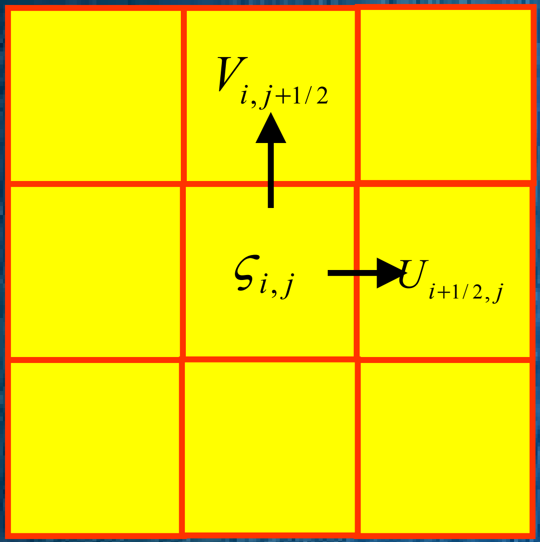
Semi-implicit FD: Algebraic Eq. of $\varsigma_{i,j}^{n+1}, U_{i+1/2,j}^{n+1}, \varsigma_{i+1,j}^{n+1}$



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Semi-implicit FD: Algebraic Eq. of $\varsigma_{i,j}^{n+1}, V_{i,j+1/2}^{n+1}, \varsigma_{i,j+1}^{n+1}$

Substituting the momemtum Equations into

Continuity Eq.: $$\frac{\partial \varsigma}{\partial t}+\frac{\partial[(h+\varsigma)U]}{\partial x}+\frac{\partial[(h+\varsigma)V]}{\partial y}=0$$

$$(1+A_{i+1,j}+B_{i-1,j}+C_{i,j+1}+D_{i,j-1})\varsigma_{i,j}^{n+1}$$
$$-A_{i+1,j}\varsigma_{i+1,j}^{n+1}-B_{i-1,j}\varsigma_{i-1,j}^{n+1}-C_{i,j+1}\varsigma_{i,j+1}^{n+1}-D_{i,j-1}\varsigma_{i,j-1}^{n+1}=E_{i,j}^{n}$$

With all coefficients are positive.

The governing matrix equation is symmetric, diagonally dominant, and positive definite. Numerical solution is achieved by a preconditioned conjugate gradient method.

Some Numerical Properties

- Convective terms- Eulerian-Lagrangian method used
- Gravity wave terms - unconditionally stable
- Discretized equation - properly accounts for positive and zero depths
- Wetting and drying of cells are treated correctly
- Pentadiagonal solution matrix - solved efficiently by preconditioned conjugate gradient method
- TRIM2D successfully implemented to reproduce sharp hydrographs of riverine flows and for estuaries
- The model is robust and efficient

TRIM_2D: Extensive applications in San Francisco Bay

Cheng, R. T., V. Casulli, and J. W. Gartner, 1993, Tidal, residual, intertidal mudflat (TRIM) model and its applications to San Francisco Bay, California, Estuarine, Coastal, and Shelf Science, Vol. 36, p. 235-280.

What does TRIM model stand for?

TRIM stands for Tidal, Residual, Inter-tidal Mudflat

TRIM also implies simple and elegant in numerical algorithm and model code, a goal that we are striving for!

From TRIM Series of Models to UnTRIM

Systematic Development of TRIM Models:

TRIM_3D: Applications in San Francisco Bay and others

Casulli, V. and R. T. Cheng, 1992, Inter. J. for Numer. Methods in Fluids

Casulli, V. and E. Cattani, 1994, Comput. Math. Appl., Stability, accuracy and efficiency analysis of TRIM_3D, θ-method for time-difference

Cheng, R. T. and V. Casulli, 1996, Modeling the Periodic Stratification and Gravitational Circulation in San Francisco Bay, ECM-4.

TRIM_3D: Non-hydrostatic

Casulli, V. and G. S. Stelling, 1996, ECM-4

Casulli, V. and G. S. Stelling, 1998, ASCE, J. of Hydr. Eng

UnTRIM model:

Casulli, V. and P. Zanolli, 1998, A Three-dimensional Semi-implicit Algorithm for Environmental Flows on Unstructured Grids, Proc. of Conf. On Num. Methods for Fluid Dynamics, University of Oxford.

Extension to Unstructured Grid Model -- UnTRIM

TRIM Modeling Philosophy:

1. Semi-implicit Finite-Difference Methods
2. Θ-Method for time difference
3. Solutions in Physical Space, regular mesh, no coordinate transformations in x-, y-, or z-directions
4. In complicated domain, refine grid resolution if necessary
5. Pursue computational efficiency and robustness

UnTRIM (Unstructured Grid TRIM model) follows the SAME TRIM modeling philosophy, except the finite-difference cells are boundary fitting unstructured polygons!

Numerical Algorithm for UnTRIM

Governing equations (Hydrostatic Assumption)

Continuity and Free-surface Equations

$$Div(\vec{U}) = 0$$ Incompressibility

$$\frac{\partial}{\partial}\frac{\varsigma}{t} + \nabla \bullet \left[\int_{-h}^{\varsigma} \vec{V}\, dz \right] = 0$$ Free-surface equation

<u>Horizontal</u> Momentum Equation in $\vec{N}_j$ direction for velocity V_j

$$\frac{DV_j}{Dt} - f(\nabla \times \vec{V}) \bullet \vec{N}_j = \frac{\partial}{\partial z}(\nu_v \frac{\partial}{\partial z} V_j) + \nu_h \nabla^2 V_j - g\frac{\partial}{\partial}\frac{\varsigma}{N_j} - \frac{g}{\rho_o}\frac{\partial}{\partial N_j}\int_z^{\varsigma}(\rho - \rho_o)dz'$$

where $\nabla\times(\ )$ is cross product, $\nabla\bullet(\ )$ is inner product, $\nabla^2(\ )$ is the Laplacian, and $\vec{V}$ is the velocity in the horizontal plane.

Transport Equations

$$\frac{D}{Dt}C_j = \frac{\partial}{\partial z}(K_v \frac{\partial}{\partial z} C_j) + K_h \nabla^2 C_j \qquad j = 1, 2, 3, \ldots$$ **Lagged one time-step**

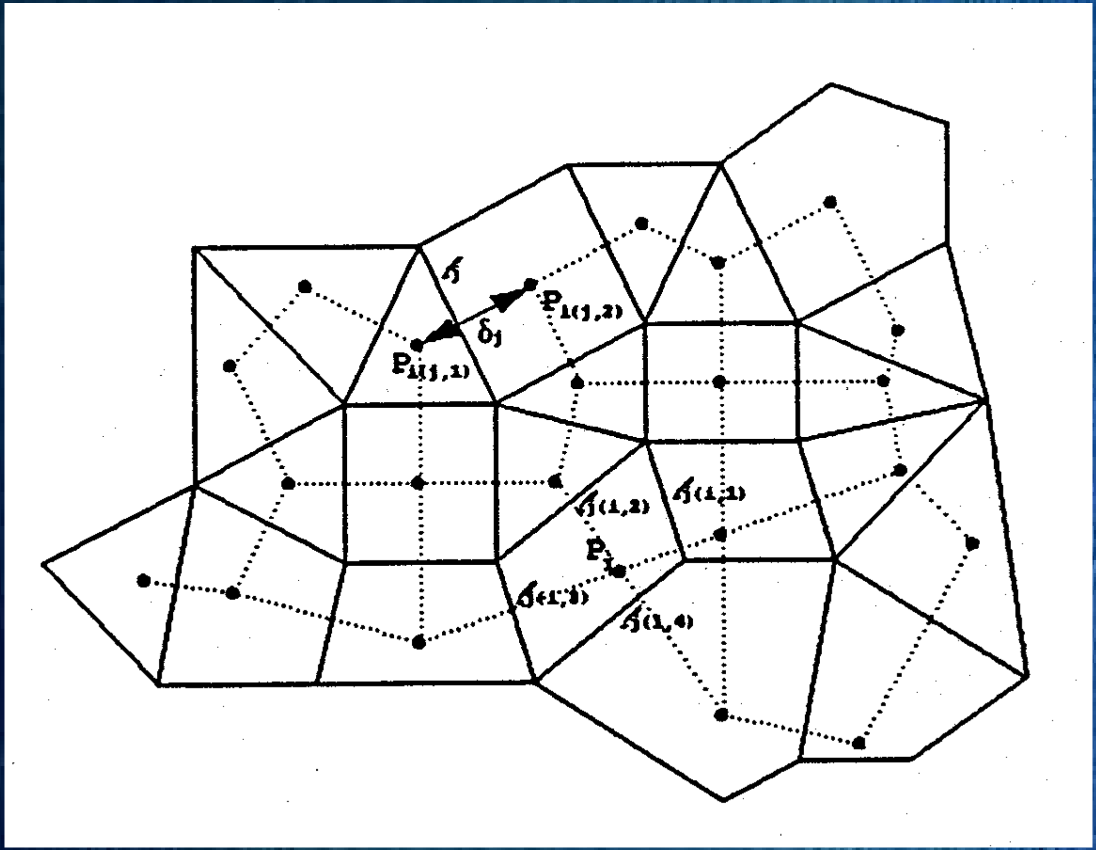
And an equation of State

UnTRIM model:

Casulli, V. and P. Zanolli, 1998, A Three-dimensional Semi-implicit Algorithm for Environmental Flows on Unstructured Grids, Proc. of Conf. On Num. Methods for Fluid Dynamics, University of Oxford.

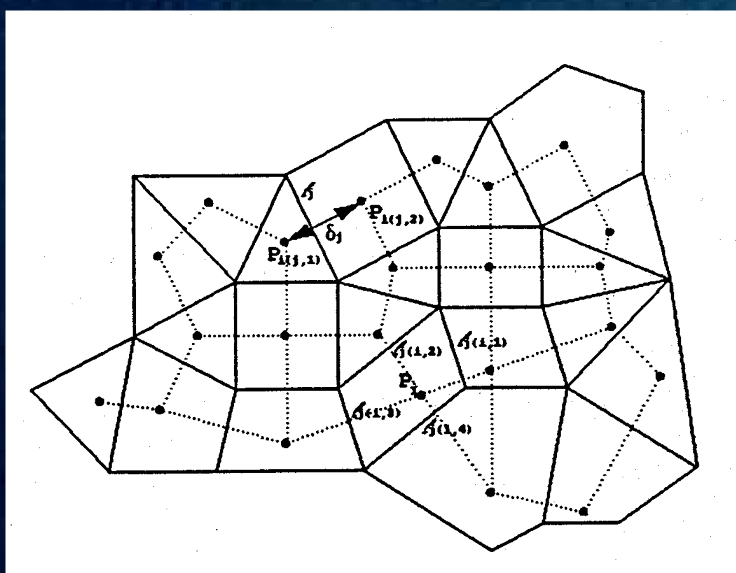
Casulli, V., and R. A. Walters, 2000, An unstructured grid, three-dimensional model based on the shallow water equations, Inter. J. for Num. Methods in Fluids, Vol. 32, p. 331-348.

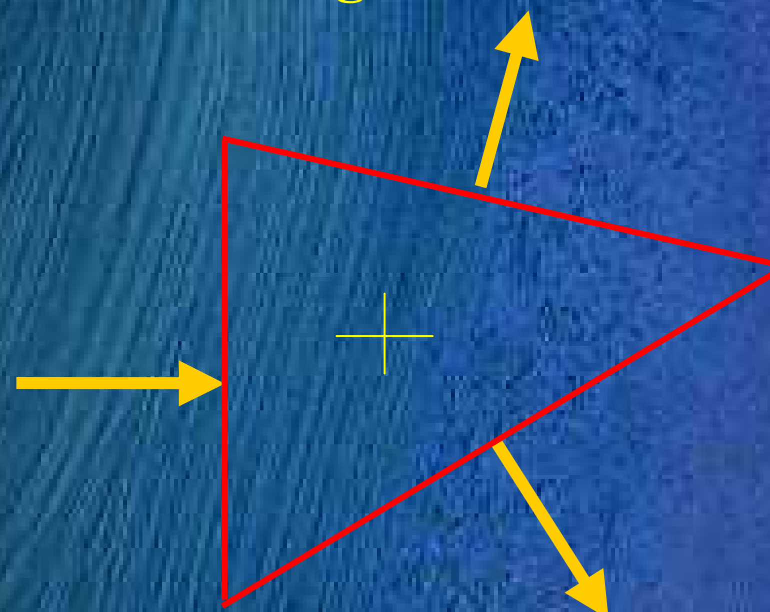
Orthogonal unstructured grids



1. **Semi-implicit finite-difference of momentum Eq. in the normal direction to each face is applied!**
2. **Applied the Finite-Volume integration of the free surface equation!**

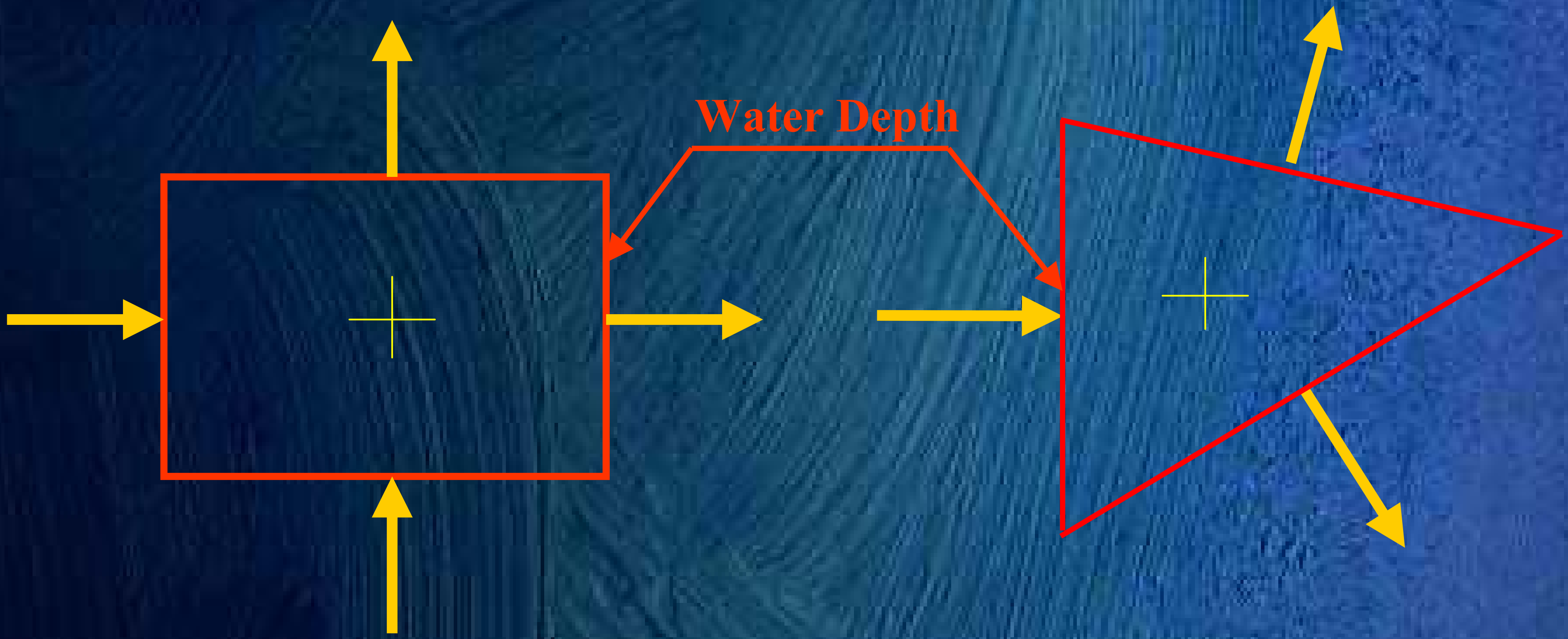
   Local and global conservation of volume is guaranteed!





3. **The resultant matrix equation determines the water surface elevation for the entire field.**

1. Semi-implicit finite-difference of momentum Eq. in the normal direction to each face is applied!
2. Applied the Finite-Volume integration of the free surface equation!
   Local and global conservation of volume is guaranteed!



3. The resultant matrix equation determines the water surface elevation for the entire field.

Summary of Numerical Algorithm

Momentum Equation in $\vec{N}_j$ direction for velocity V_j relates

V_j and ζ (left) and ζ (right) on each face of a polygon

Continuity and Free-surface Equations

$$Div(\vec{U}) = 0$$

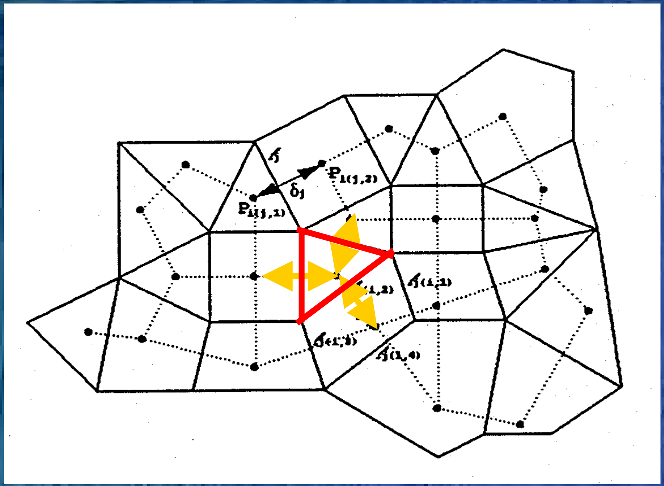
$$\frac{\partial \varsigma}{\partial t} + \nabla \bullet \left[\int_{-h}^{\varsigma} \vec{V}\, dz \right] = 0 \qquad => \qquad \frac{\partial \varsigma}{\partial t} + \oint \left(\int_{-h}^{\varsigma} \vec{V} dz \right) \bullet d\vec{s} = 0$$

Finite Volume integration over each polygon =>
V's are eliminated giving a Matrix Eq. for ζ

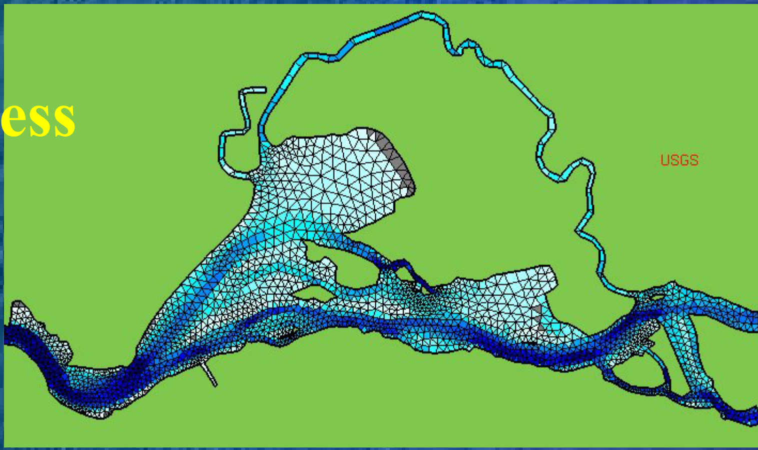
The continuity equation and the momentum equations are truly coupled in the solution. No mode splitting is used!

Issues of unstructured grids

User must define:



1. Number and locations of nodes
2. Polygon number and its relation with nodes (connectivity)
3. Each side is numbered, left and right polygons are defined (connectivity)
4. Center coordinates of each polygon
5. Vertical layers are of constant thickness (variable in z) except the bottom and free-surface; a stack of prisms
6. Water depth and normal velocity are defined on the sides
7. Water elevation is defined at the center of the polygon

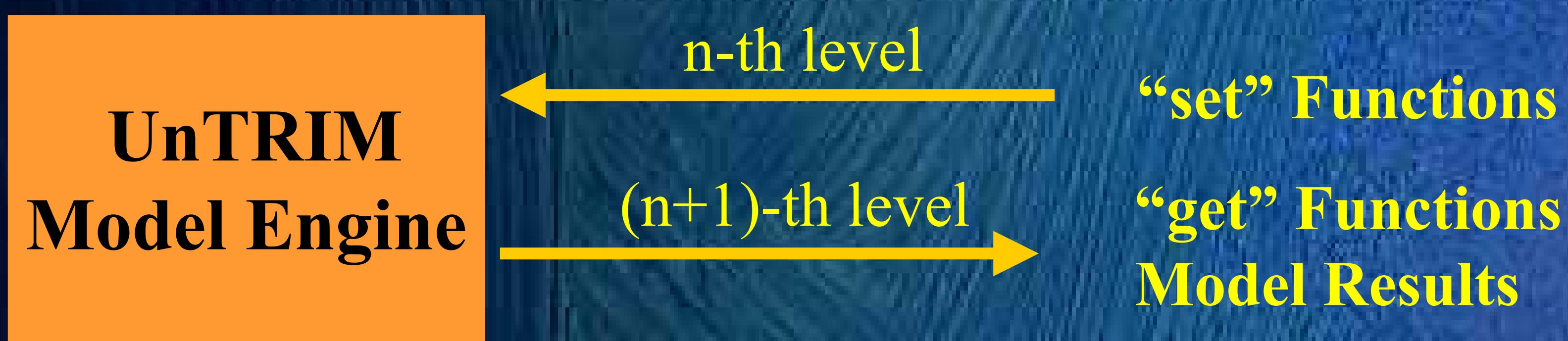


Features of Numerical Code:

Fortran 90/95, Fully Modular
Dynamic allocation of memory

Model Engine + User Interface Module

Full library of "get" functions	**User supplies sub-models such as turbulence closure**
Full library of "set" functions	**all forcing functions and all source and sink terms**



<u>**Maximum Efficiency**</u> <u>**Maximum Flexibility**</u>

Features of Numerical Code:

USGS has purchased a site-license of UnTRIM

Model Engine + User Interface Module

UnTRIM Model Engine	→ ←	User Interface USGS3D(UnTRIM_inside)

Developed by Casulli:

Managed and Maintained by Casulli as quality (safety) control

Developed by users:

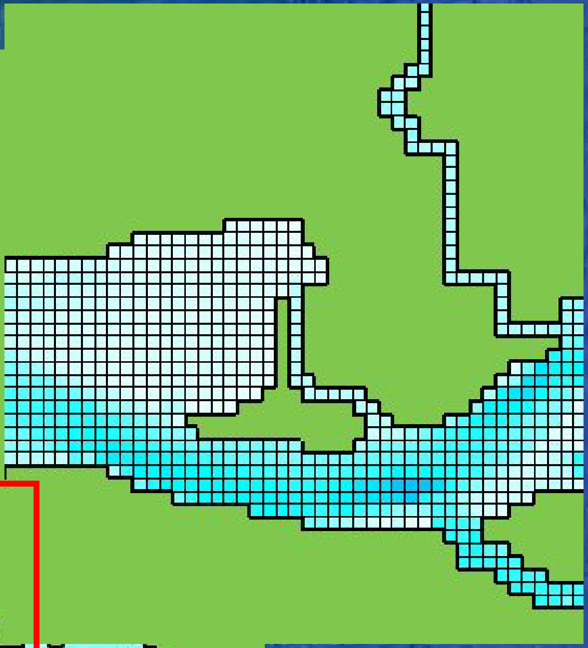
Allows <u>Creativity</u> in numerical modeling

Examples of Unstructured Grids

Conversion of regular grids:

1. Regular finite-difference grid is also an 'Unstructured' Grid

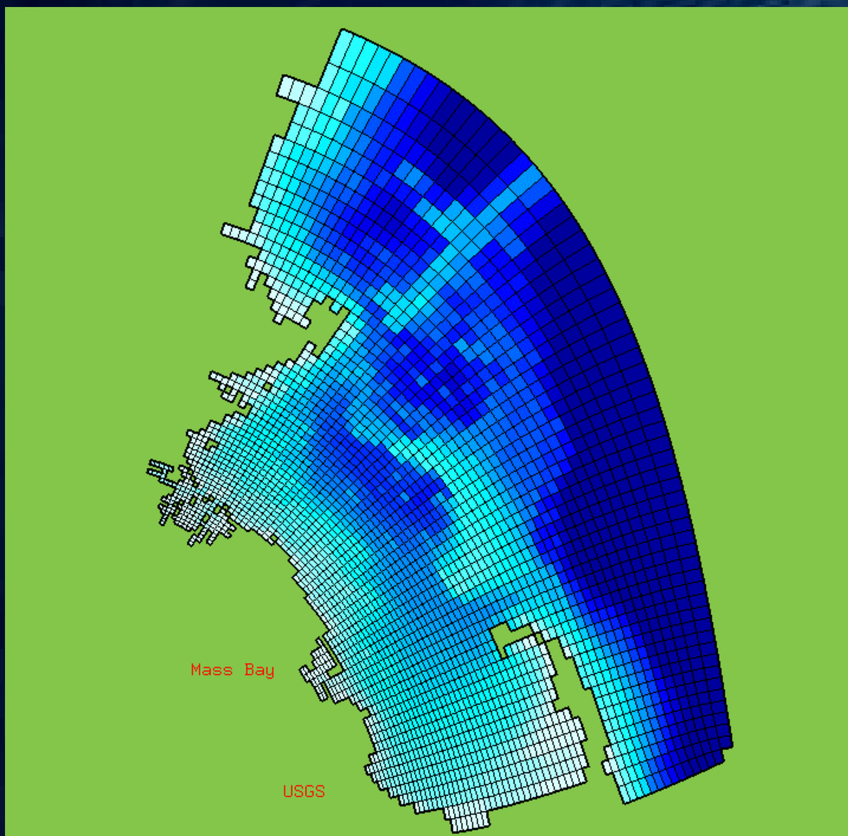


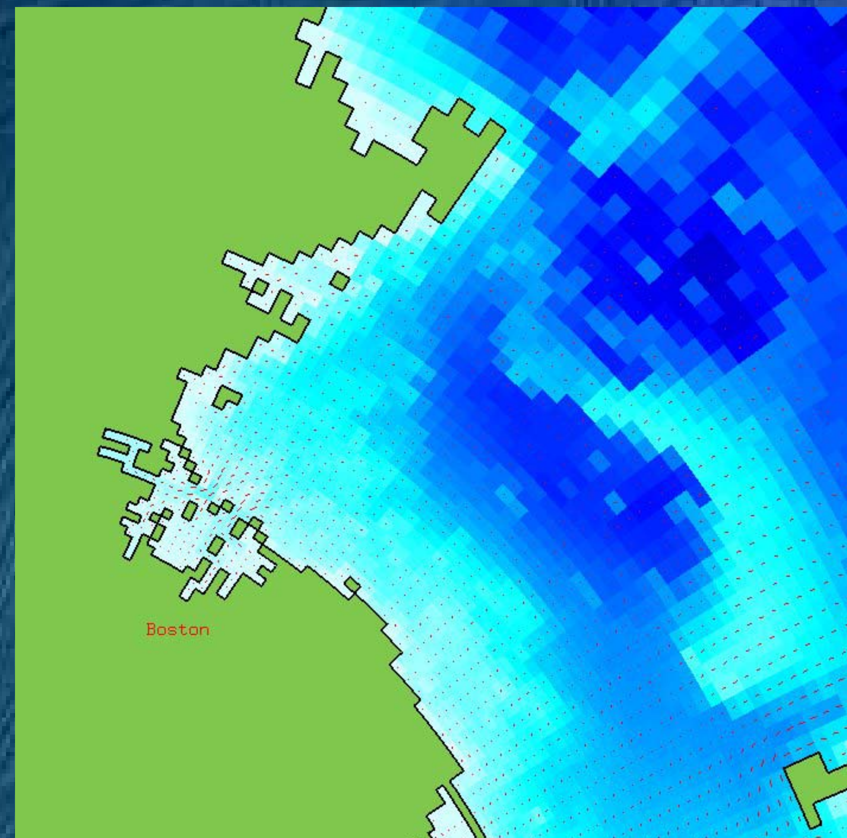


Examples of Unstructured Grids

Conversion of regular grids

2. Orthogonal Curvilinear Grids are also Unstructured Grids

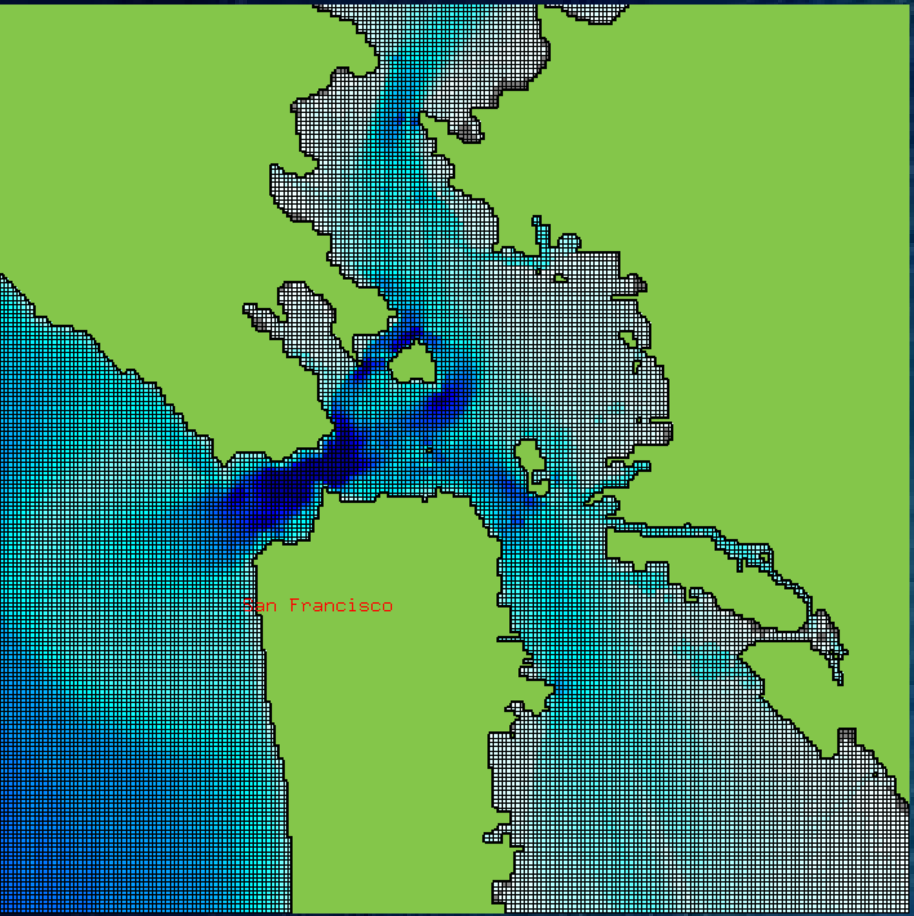


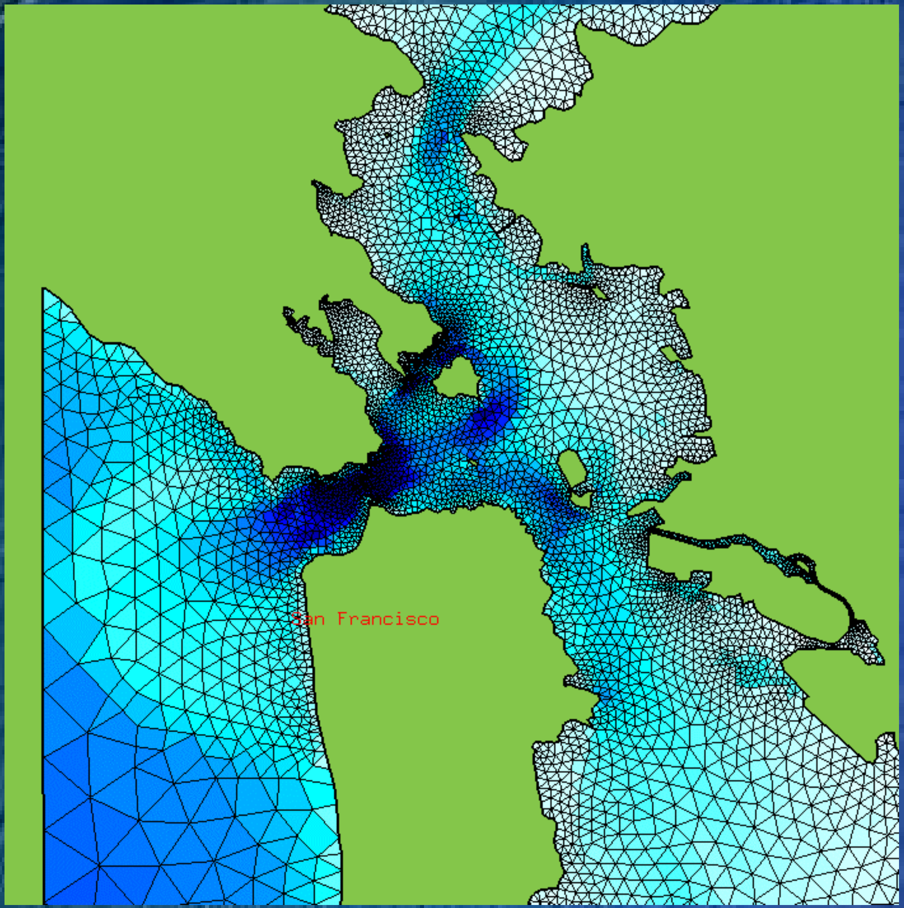


8550 nodes, 3160 polygons and 6601 sides on the top layer
25 layers, 80 K faces, Δt = 900, side length between 30 and 8000 m
15 days simulation requires 27 min (R= 800) CPU on 1.7 GHz PC

San Francisco Bay, California

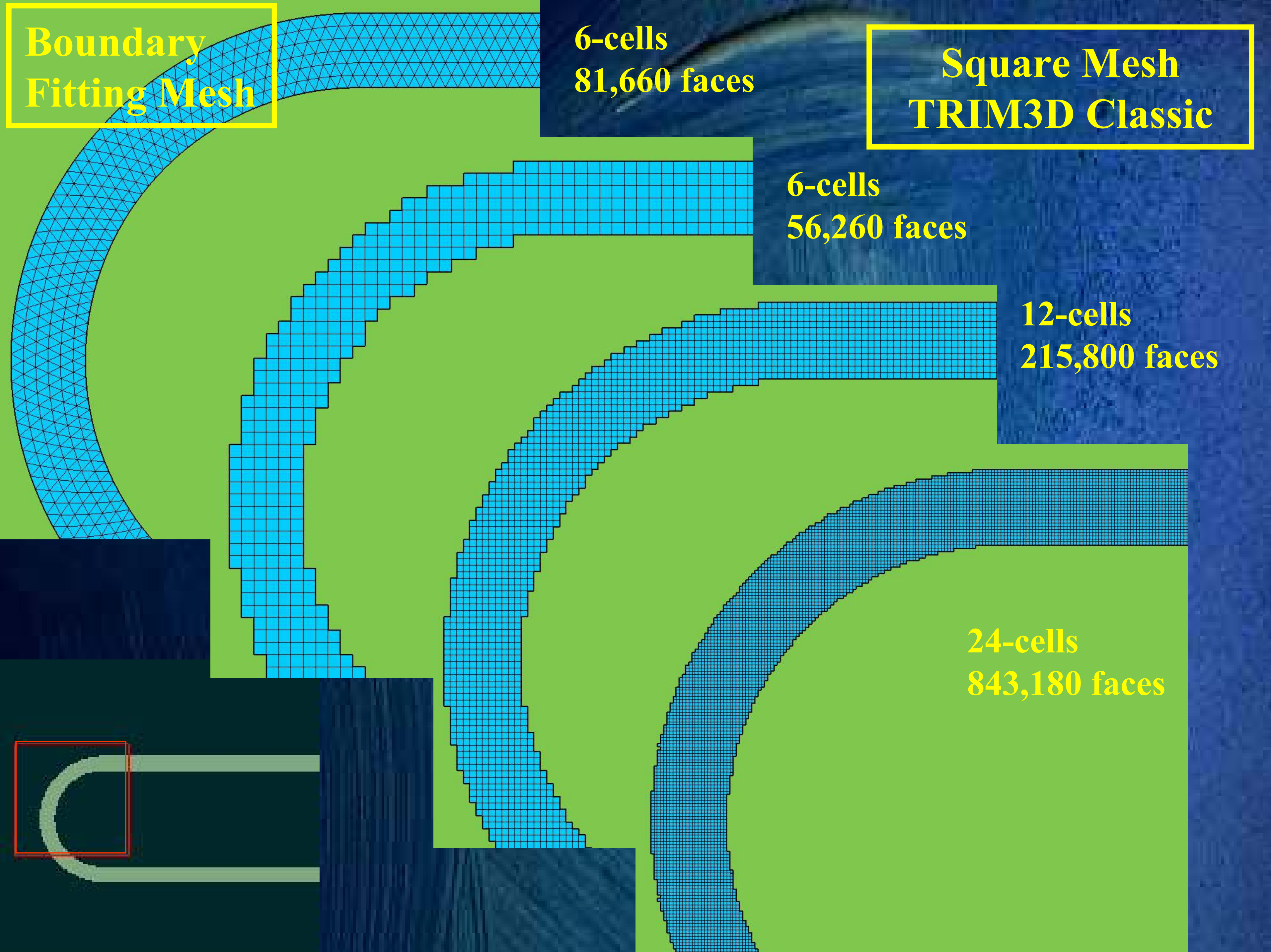
(All Rectangles) (Mixed Polygons)

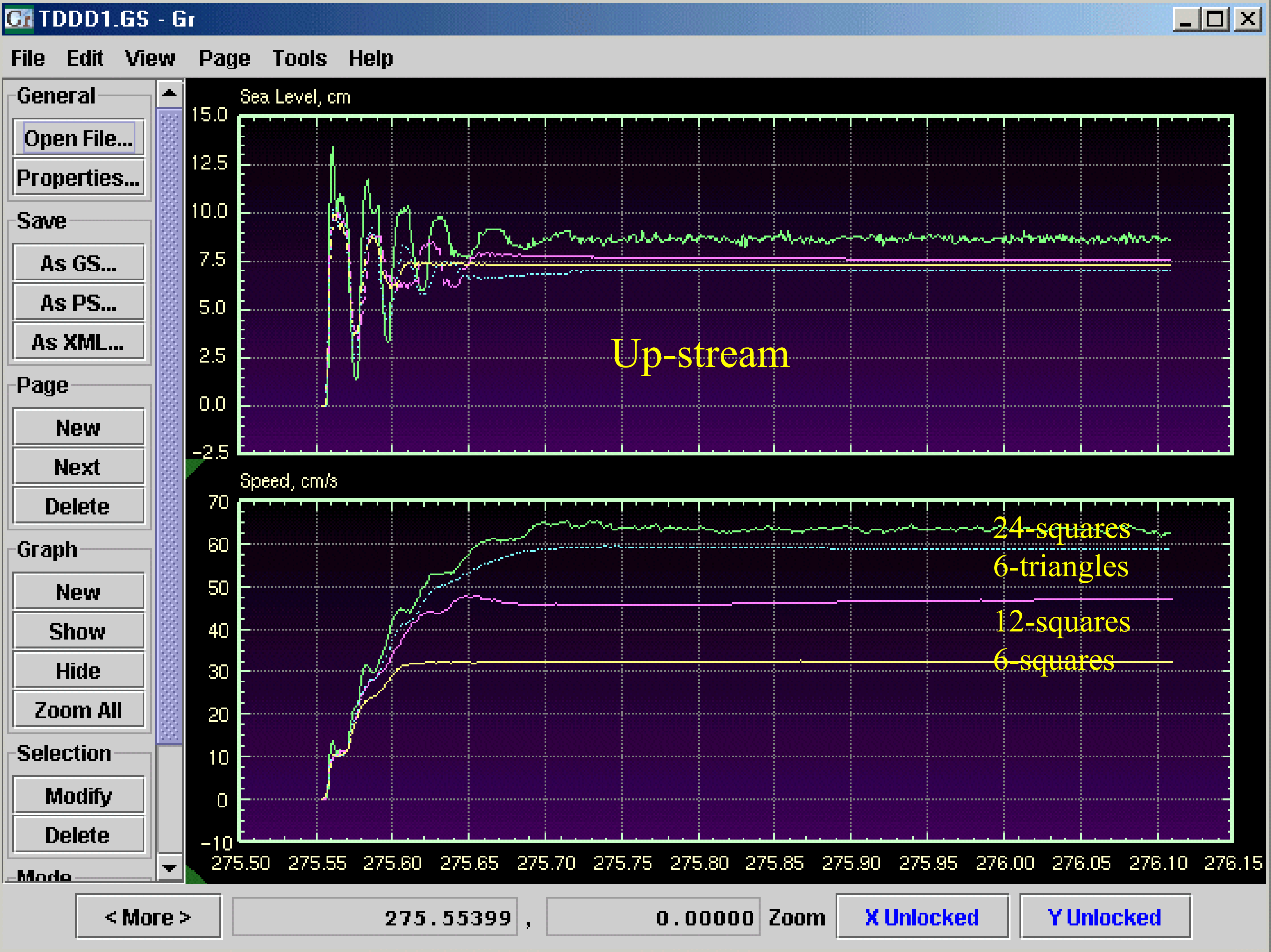




48506 nodes, 45841 polygons
94374 sides on the top layer
42 layers, 1,160 K faces, $\Delta t = 180$
72 hours simulation requires 5.26 hours (R= 13.7) CPU on 1.7 GHz PC

12682 nodes, 20126 polygons
32827 sides on the top layer
42 layers, 295 K faces, $\Delta t = 180$
72 hours simulation requires 1.33 hours (R= 54) CPU on 1.7 GHz PC


Boundary Fitting Mesh
6-cells
81,660 faces
Square Mesh TRIM3D Classic
6-cells
56,260 faces
12-cells
215,800 faces
24-cells
843,180 faces



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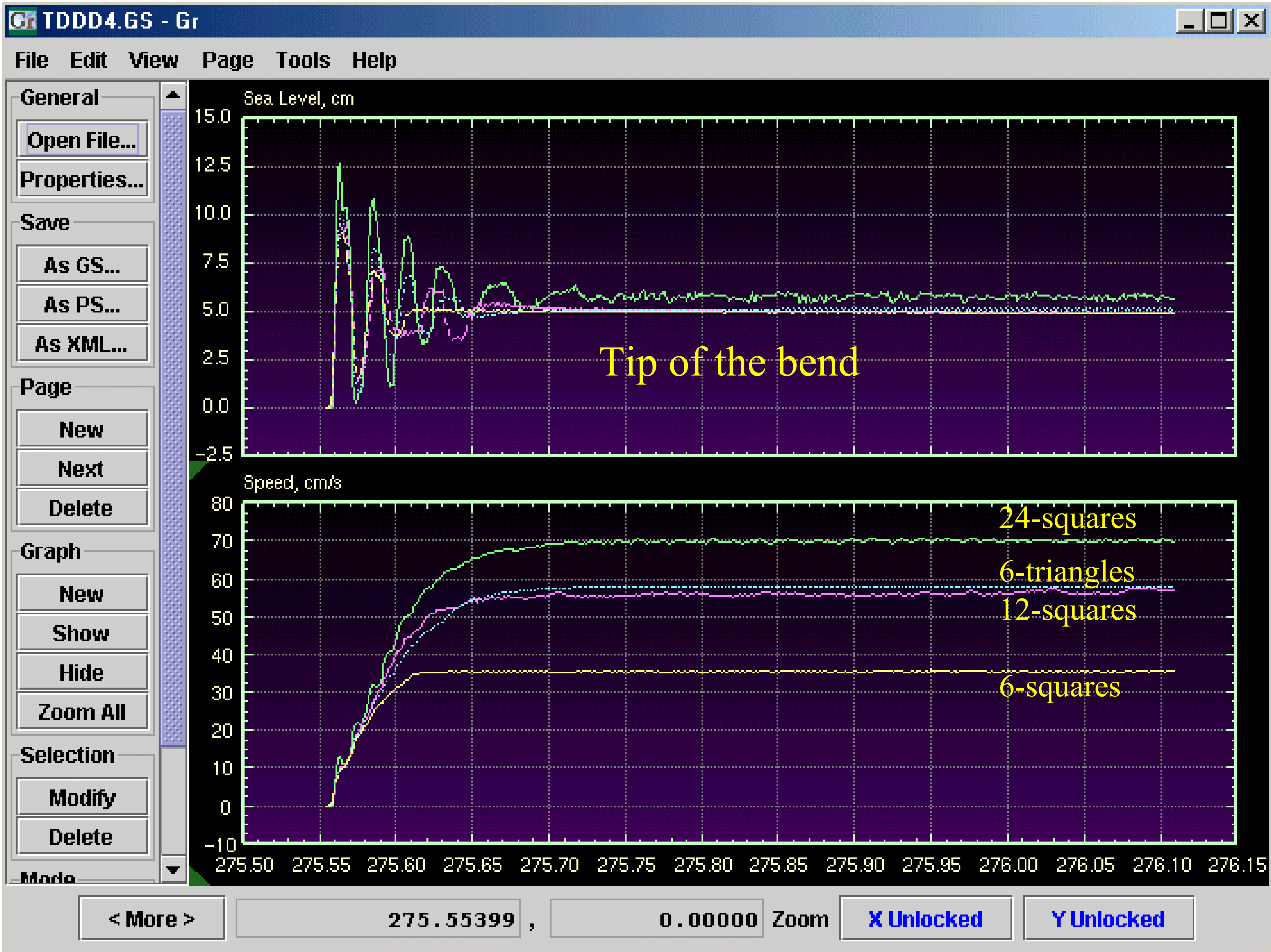
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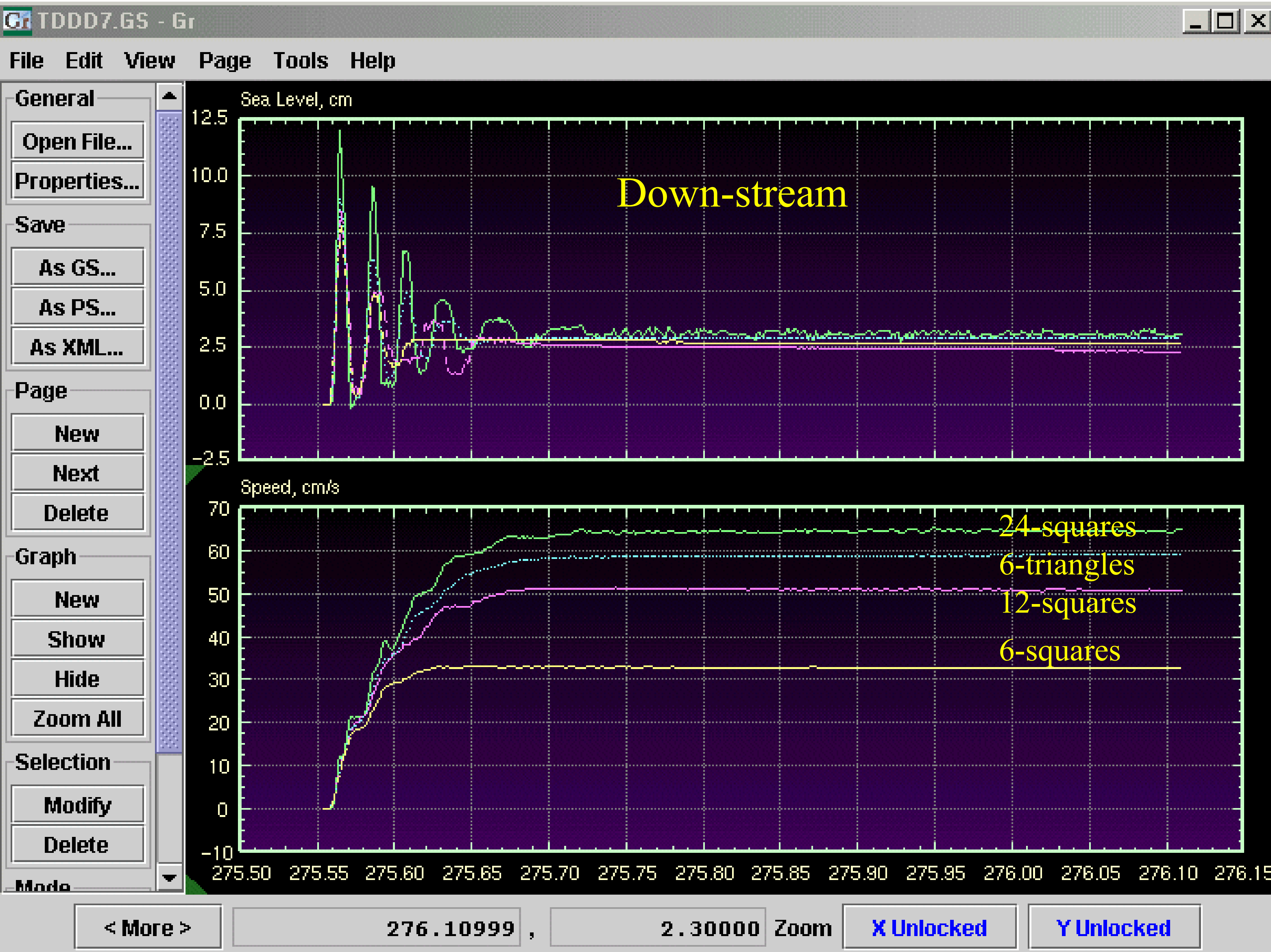
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Model Statistics

Modeled Area: 4 km x 1.12 km

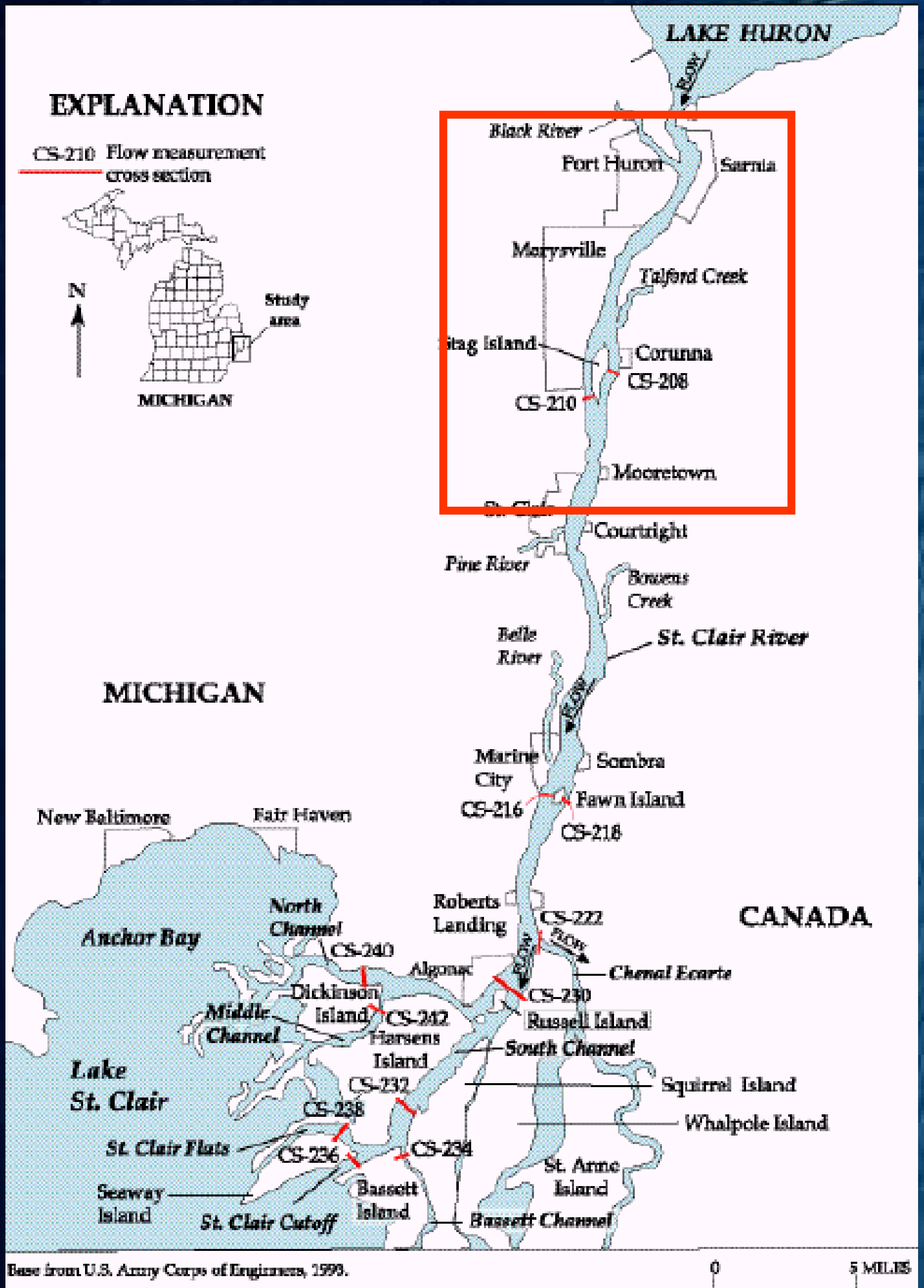
Δx = 20 m (6-square), Δt = 150 sec

Grid	# of grids		CPU time	
6-square	56,260	(1.00)	455 s (7.6 m)	(1.00)
12-square	215,800	(3.84)	2372 s (39.6 m)	(5.21)
24-square	843,180	(14.99)	18726 s (312.1 m)	(41.16)
Triangles	81,660	(1.45)	786 (13.1 min)	(1.73)

Some Practical Applications!

☺

Upper St. Clair River



Example One

Using Numerical Model to Estimate the Volumetric Transport of Water from Lake Huron to Lake St. Clair

To compare the model results with 3D ADCP data

Project Chief:
David J. Holtslag
Michigan District

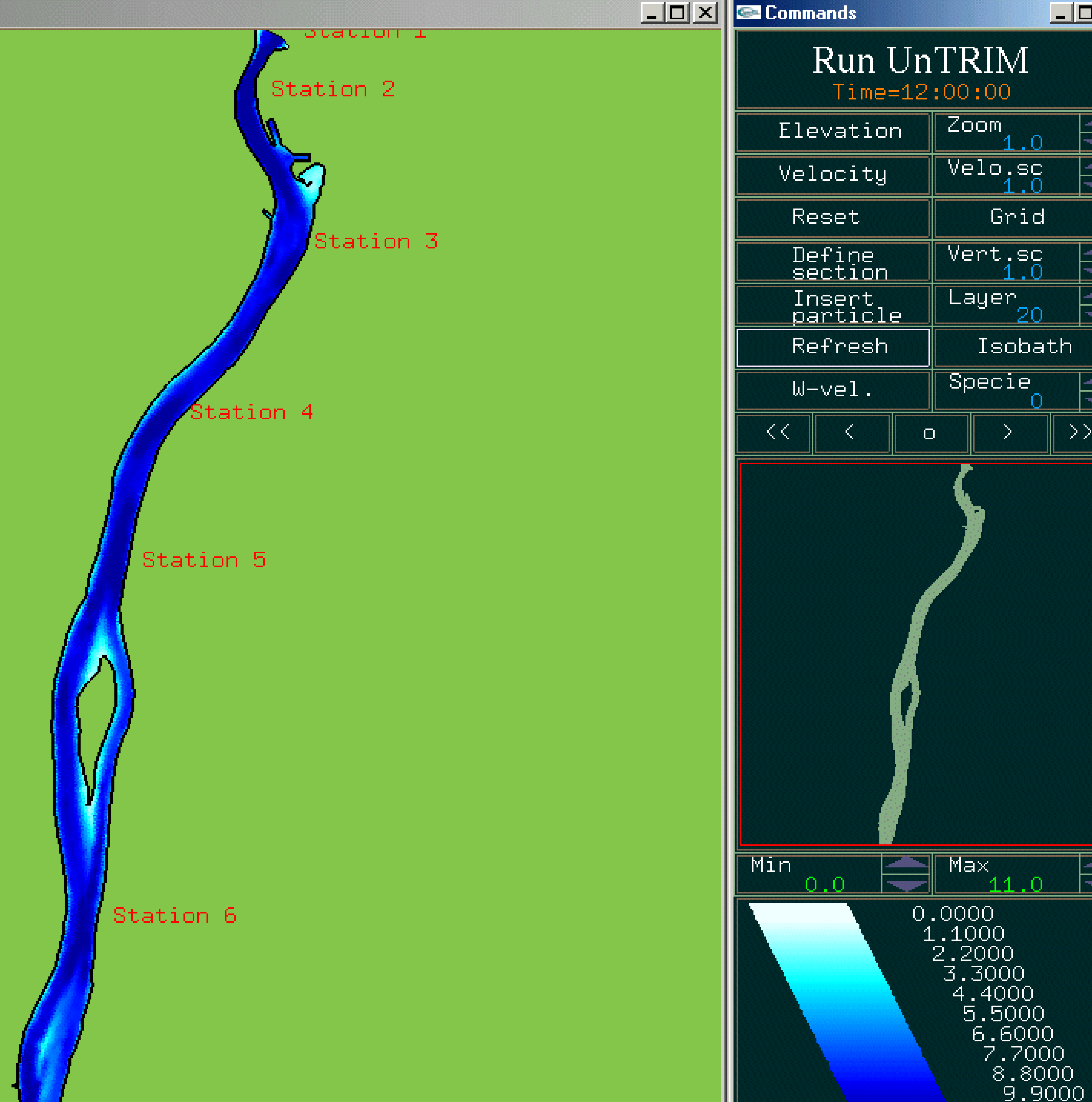
Modeled Area:

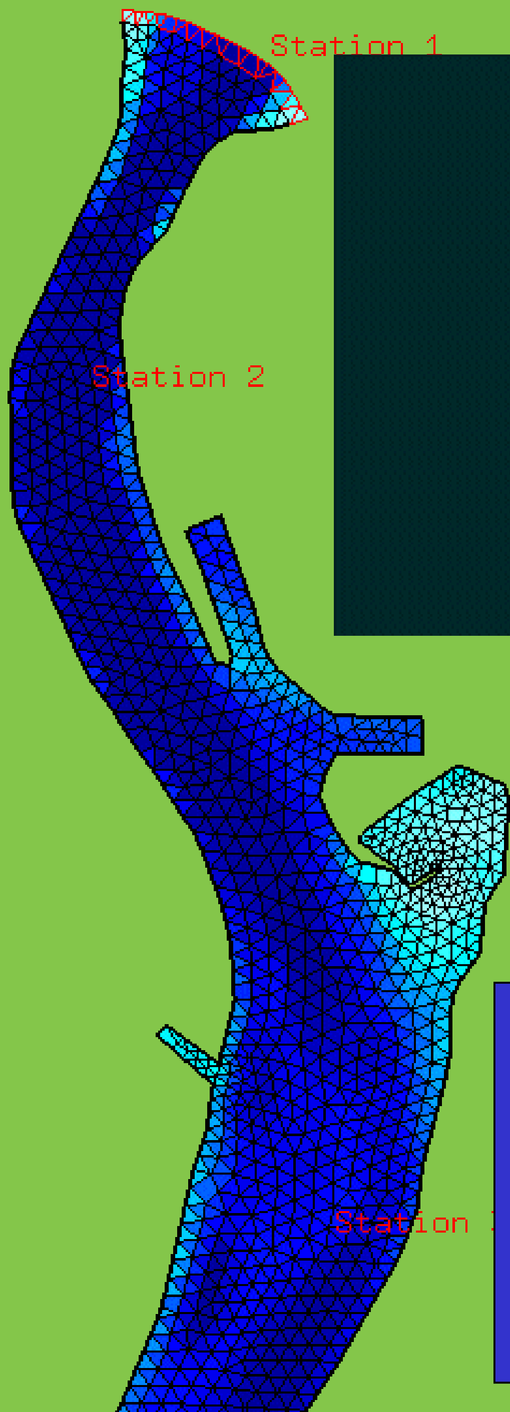
6 km x 22 km

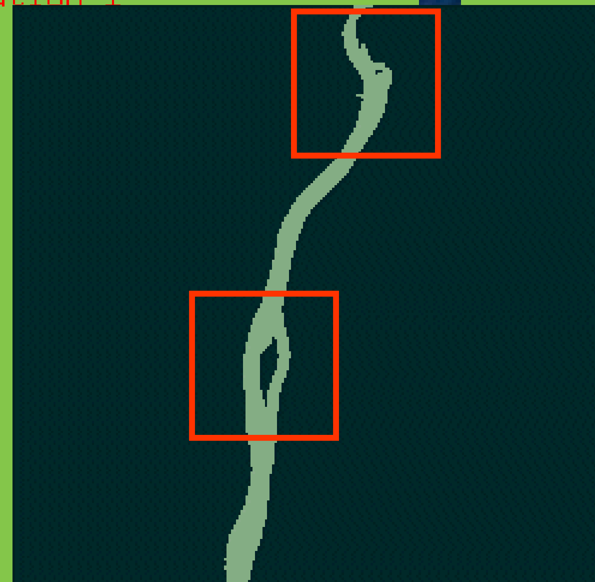
20 layers

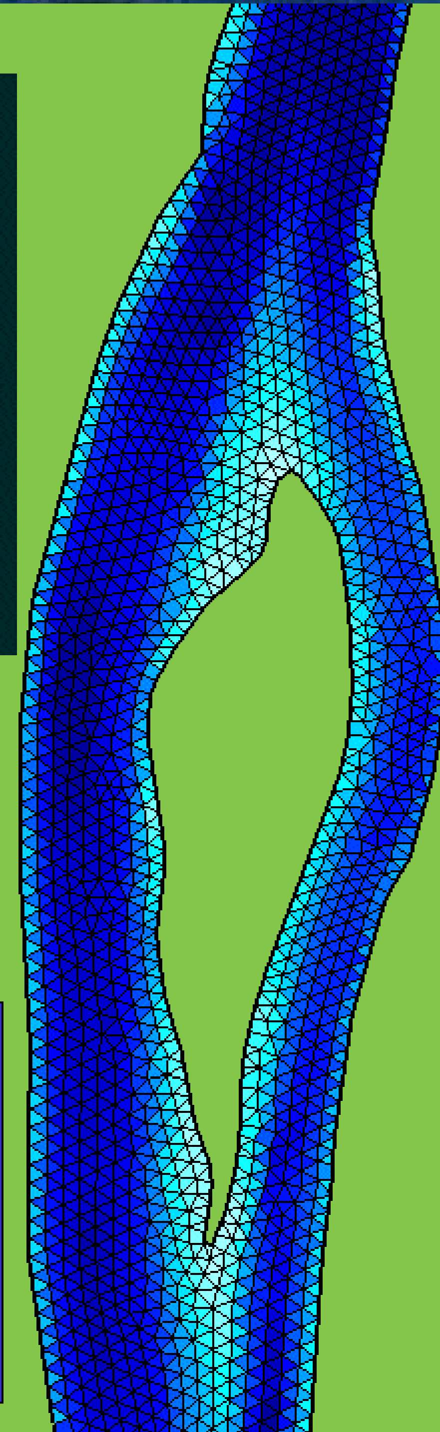
12997 sides

114,462 faces



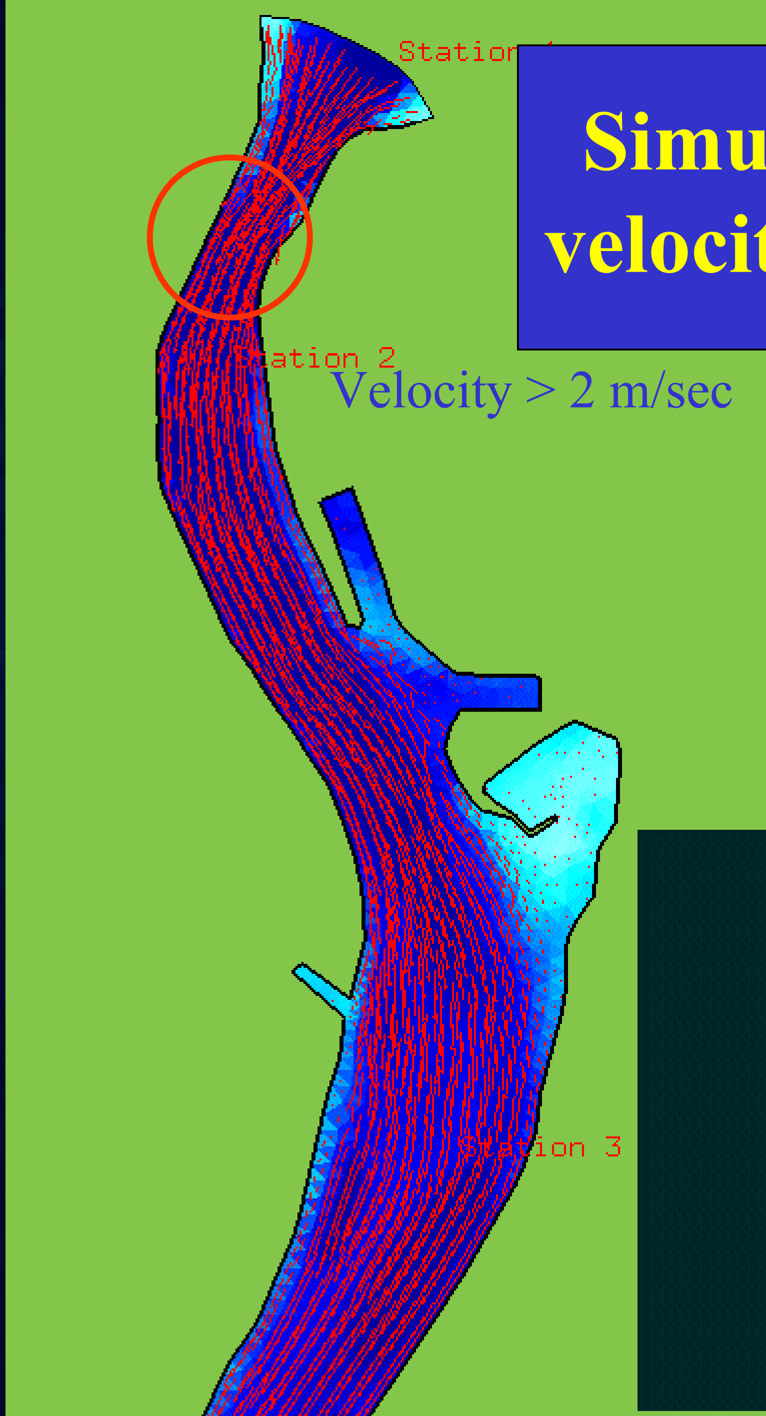


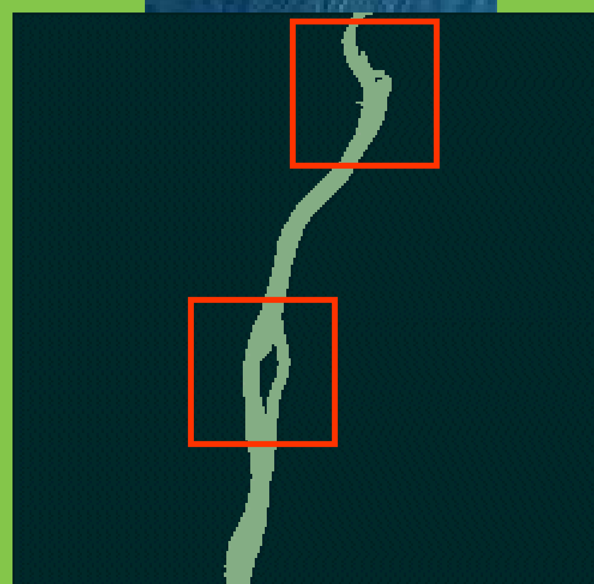


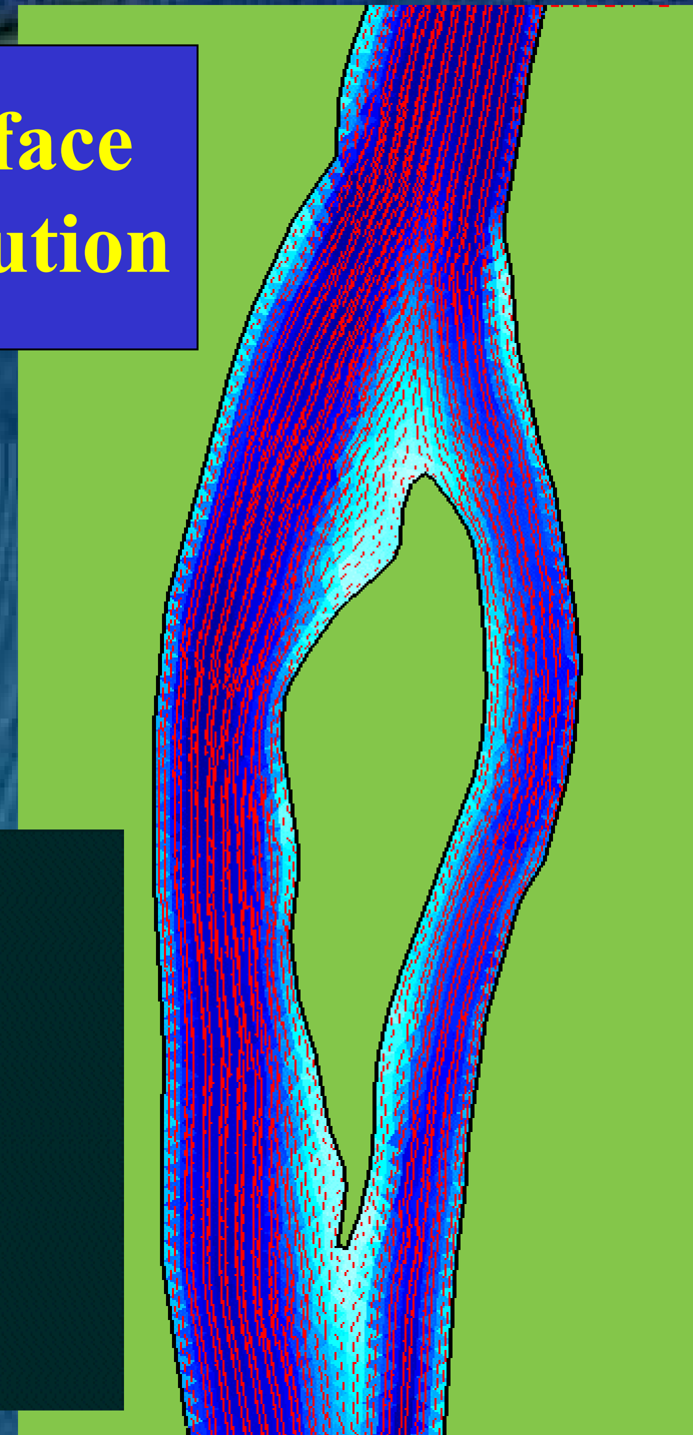


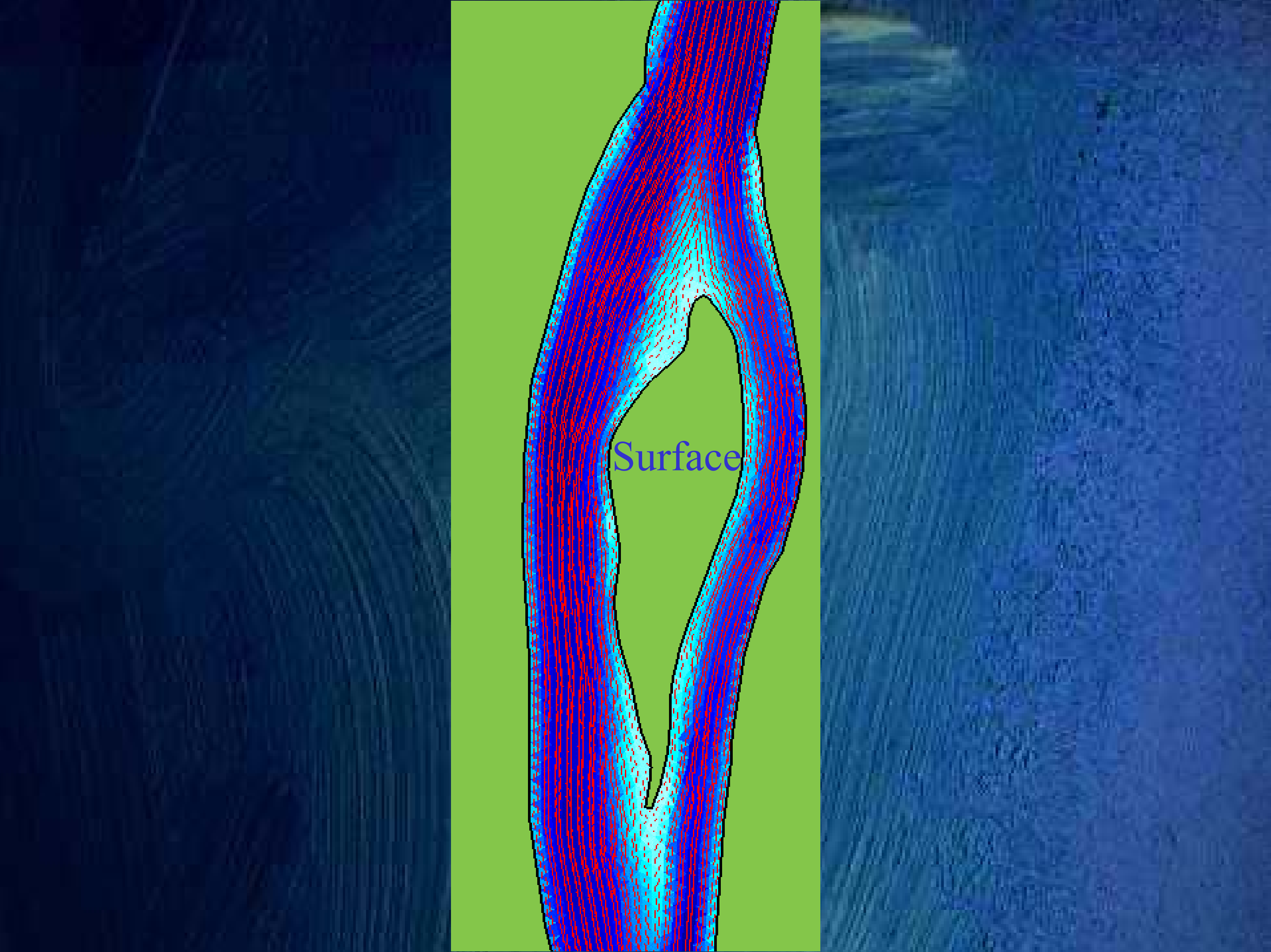
Unstructured Grid Representation of the River

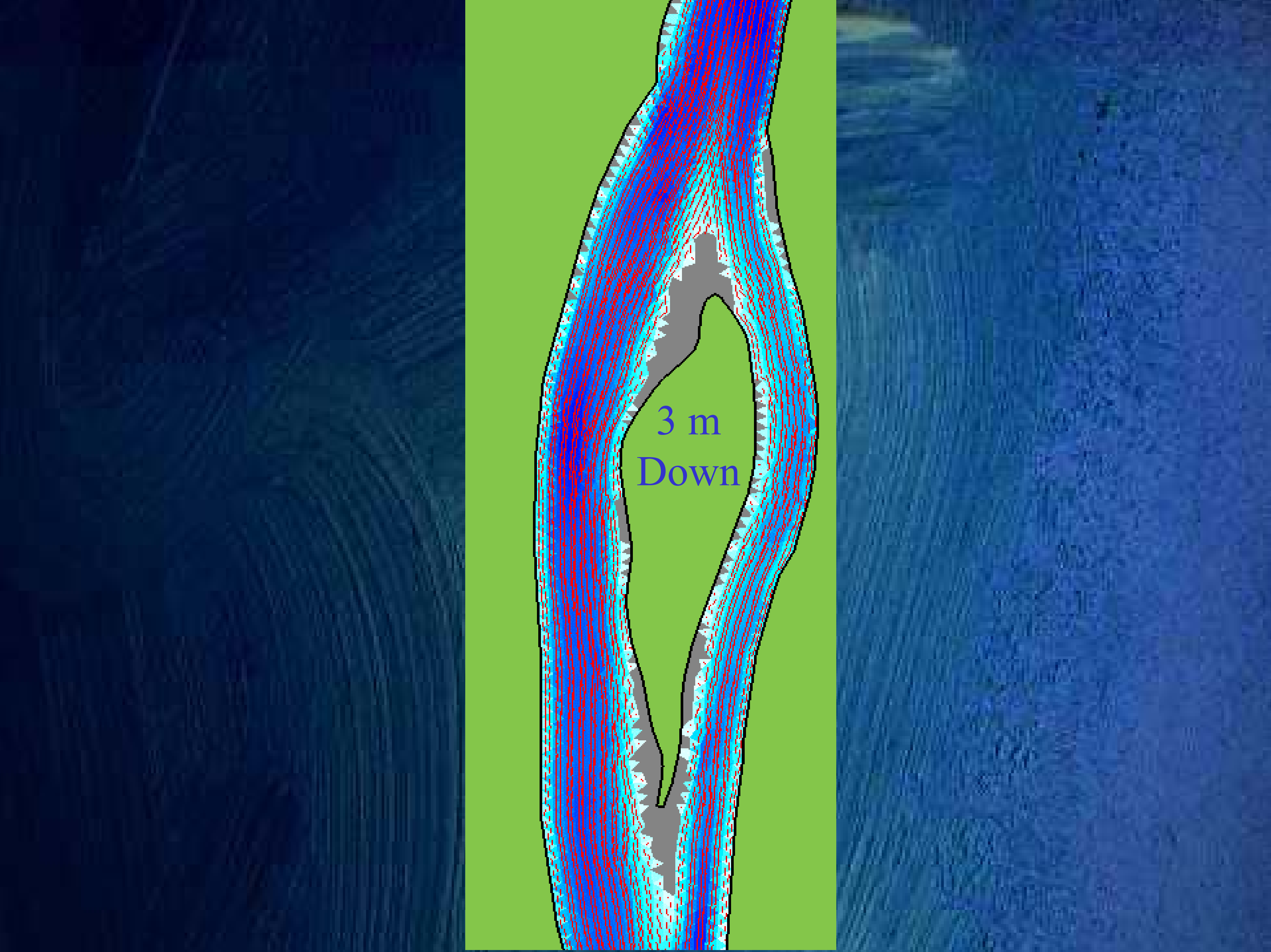
Simulated surface velocity distribution








Surface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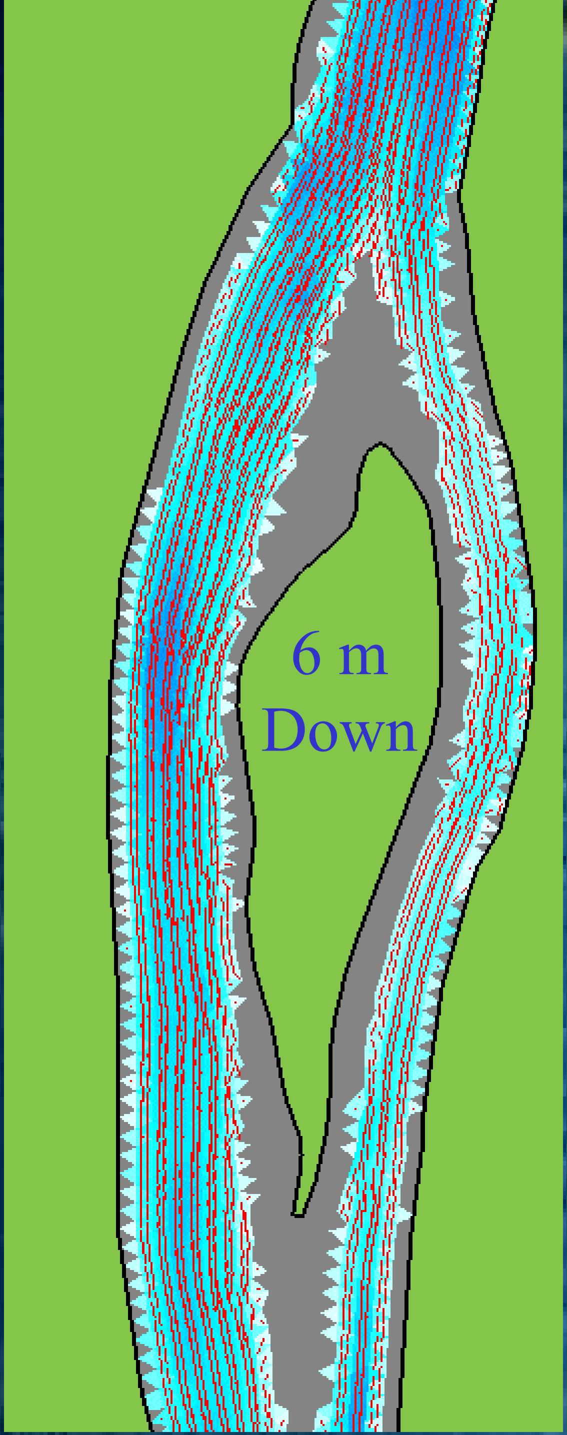
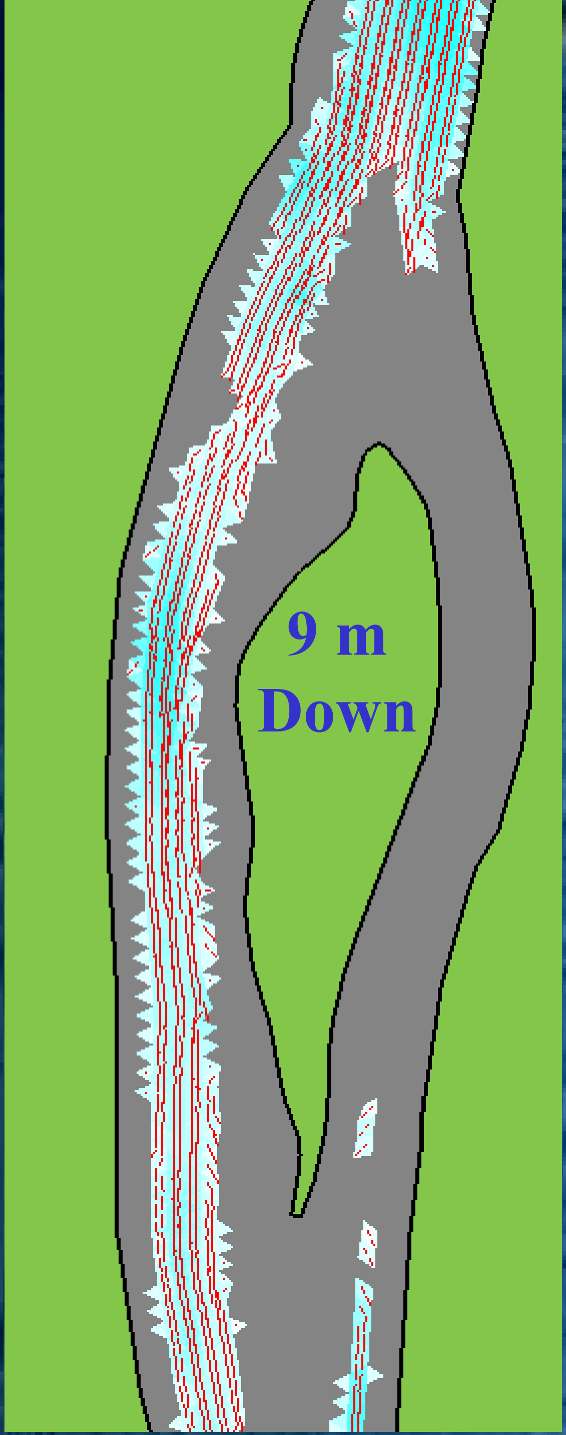
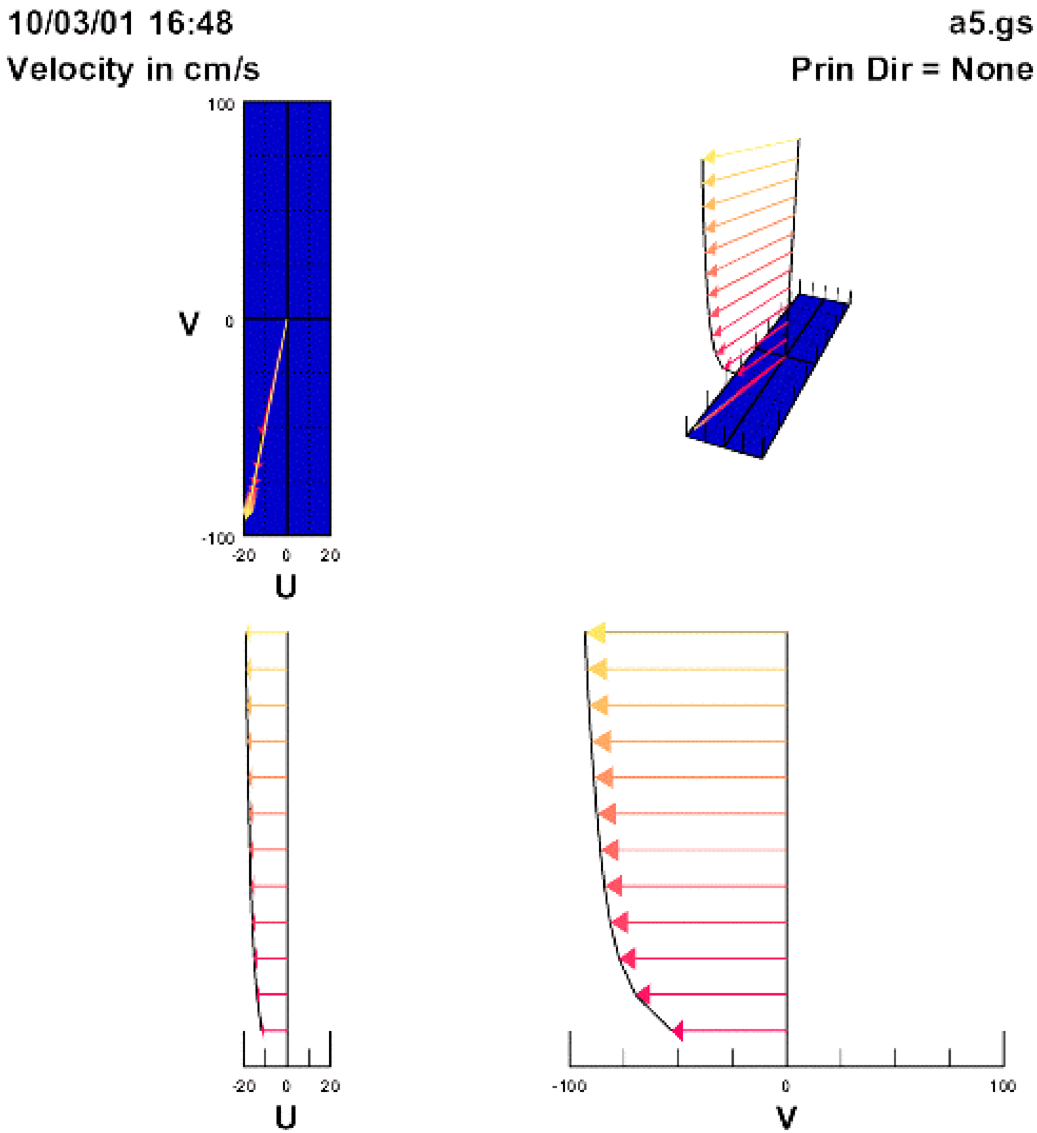
Down


6 m
Down


9 m
Down

3-D Velocity at Station 5



Project: Water Transport in a Large River

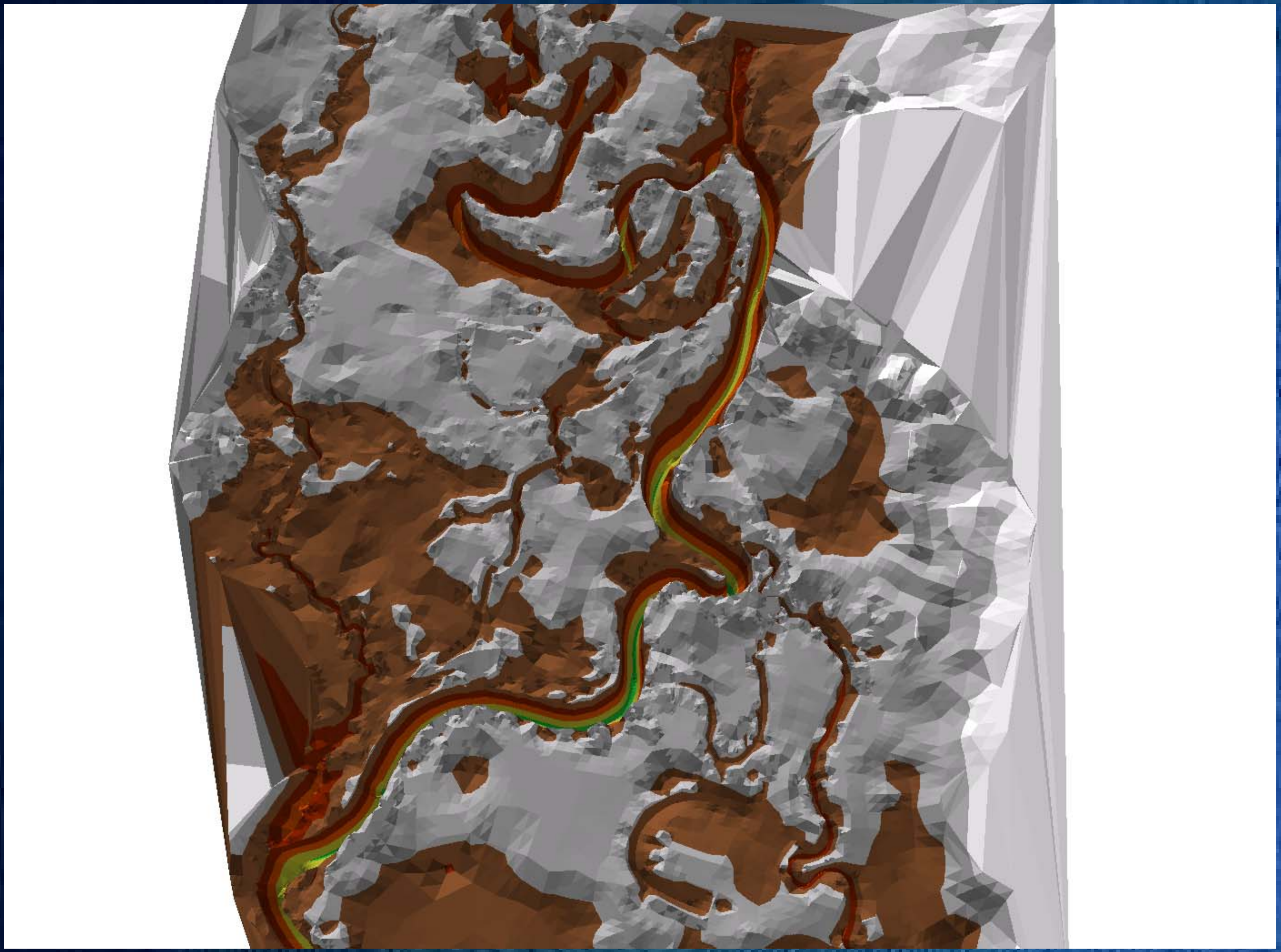
Using a 3D UnTRIM Hydrodynamic Numerical Model to Estimate the Volumetric Transport of Water from Lake Huron to Lake St. Clair

Project: Modeling Study of White River, Arkansas
Project: Jaysson Funkhouser and C. Shane Barks

- Study area (34 mi^2) Encompasses parts of two National Wildlife Refuges
- Floodplain Inundation Mapping
- Backwater and Velocity concerns
- Provide Inputs to Highway Bridge Design and Placement
- Highway Bridge Scouring

Approximate Area Modeled

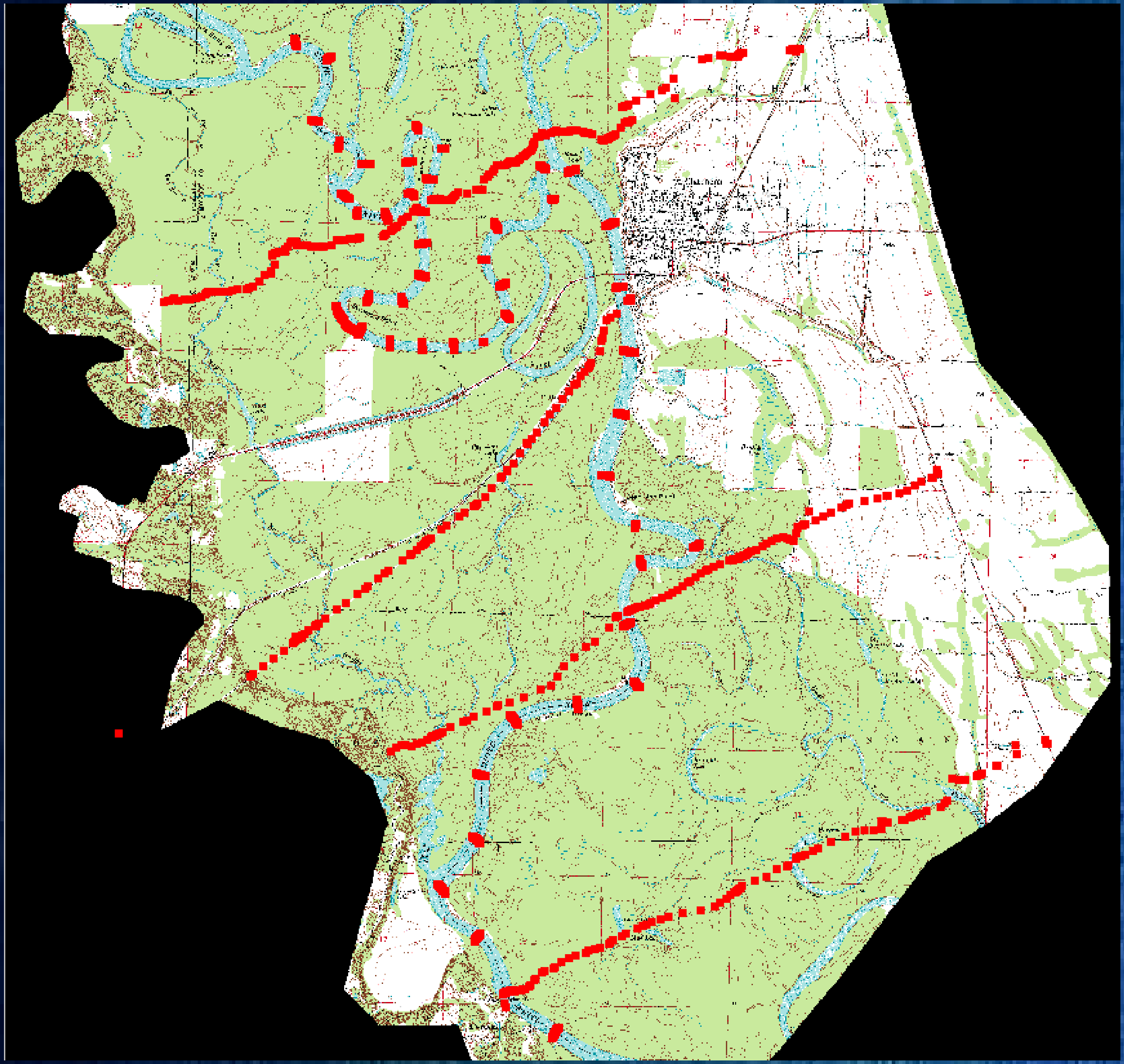
Defining the River Basin
Digital Elevation Model (DEM)



10-Meter DEM data obtained from USGS Mapping Division in Rolla, MO

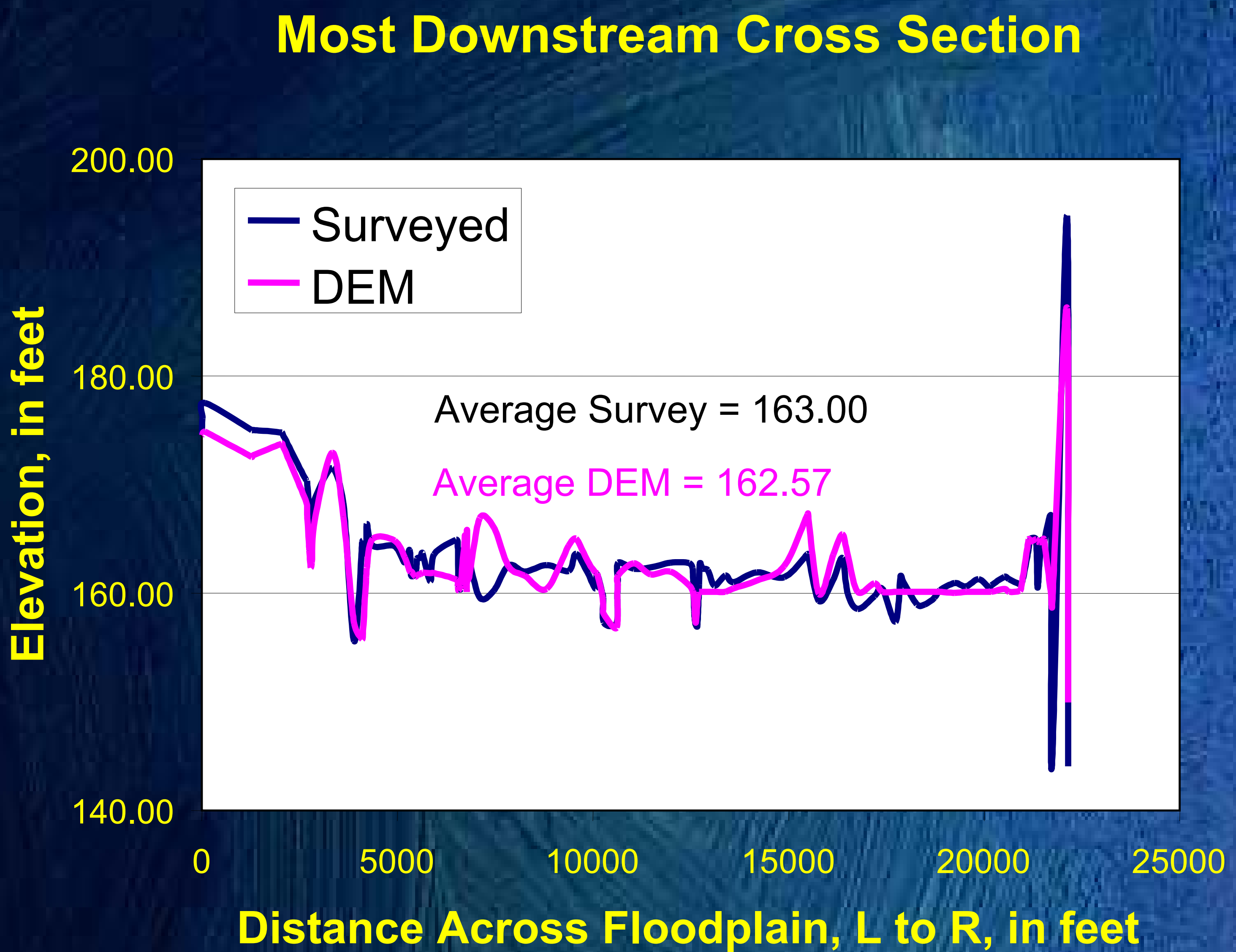
Funkhouser

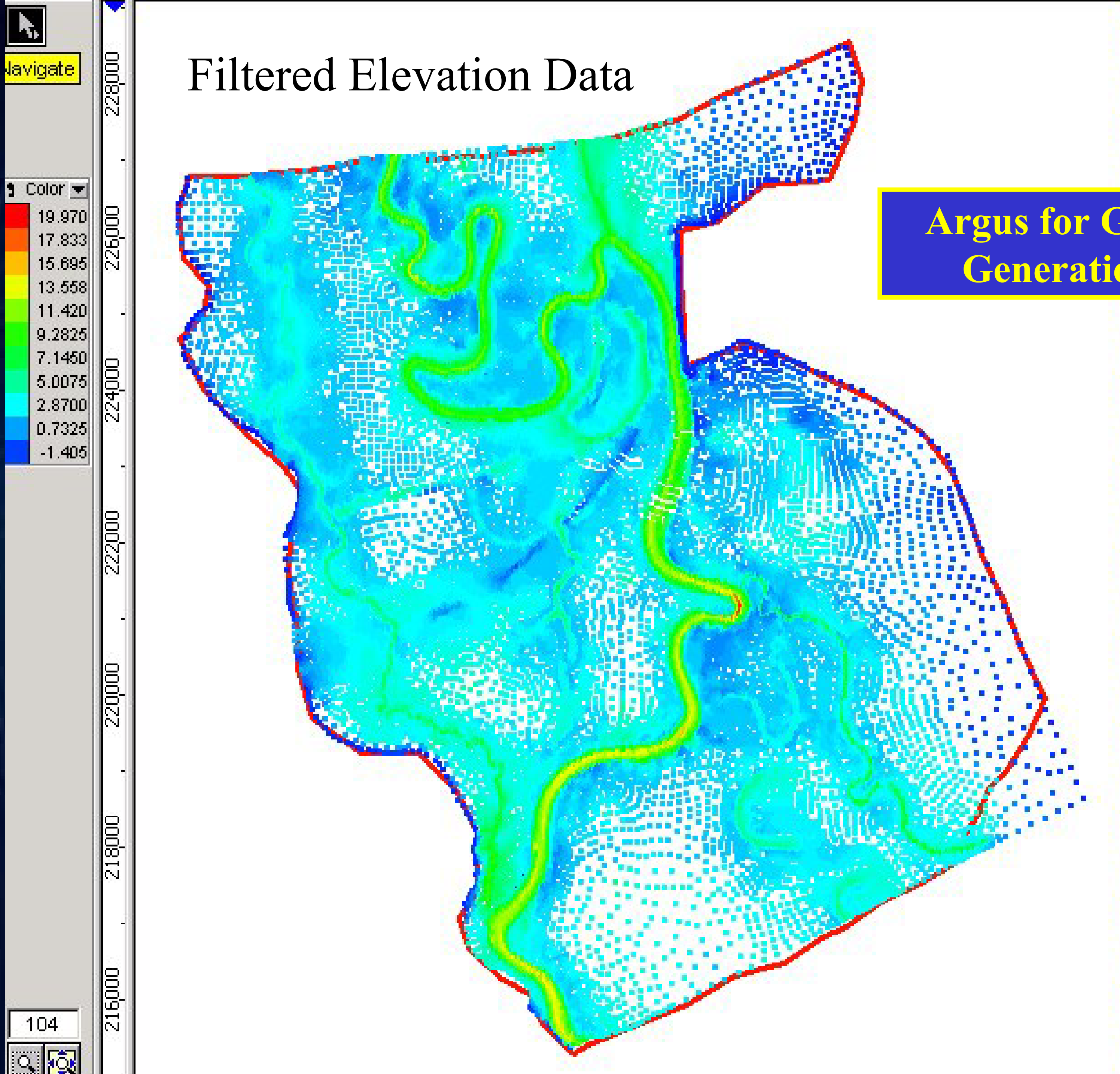
Additional Survey Data



Funkhouser

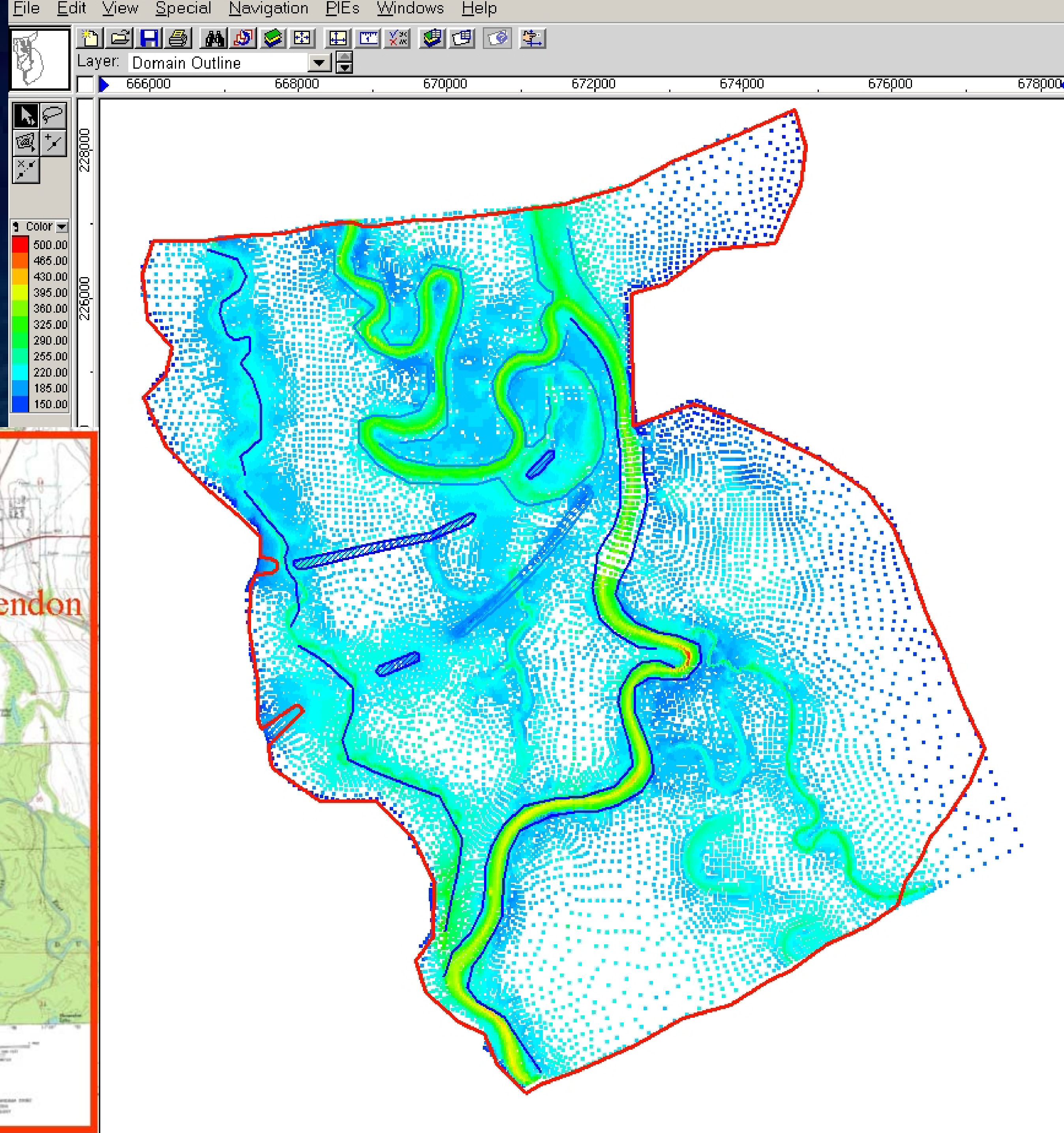
DEM Verification

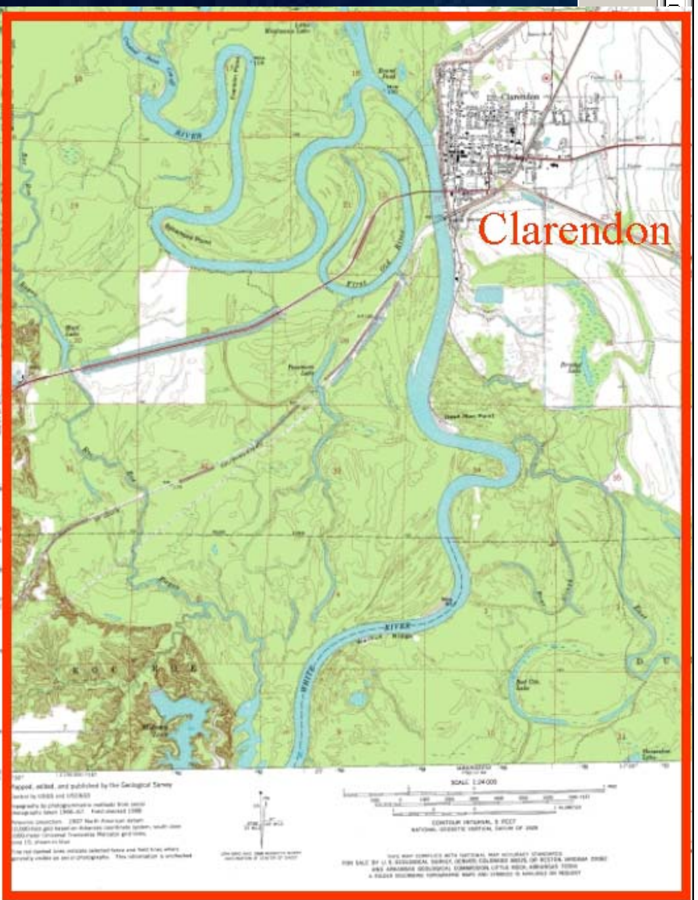




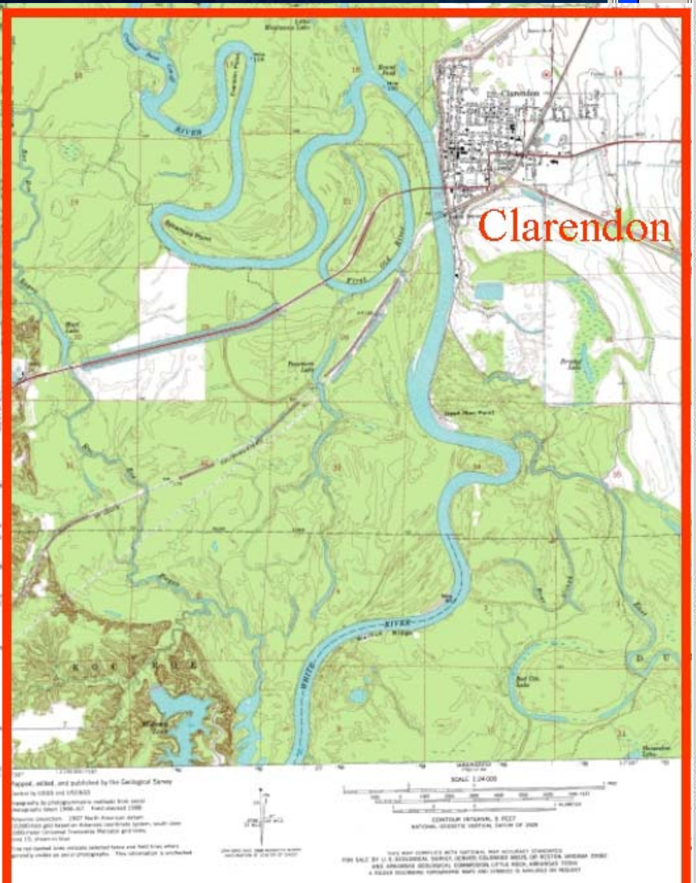
Argus for Grid Generation

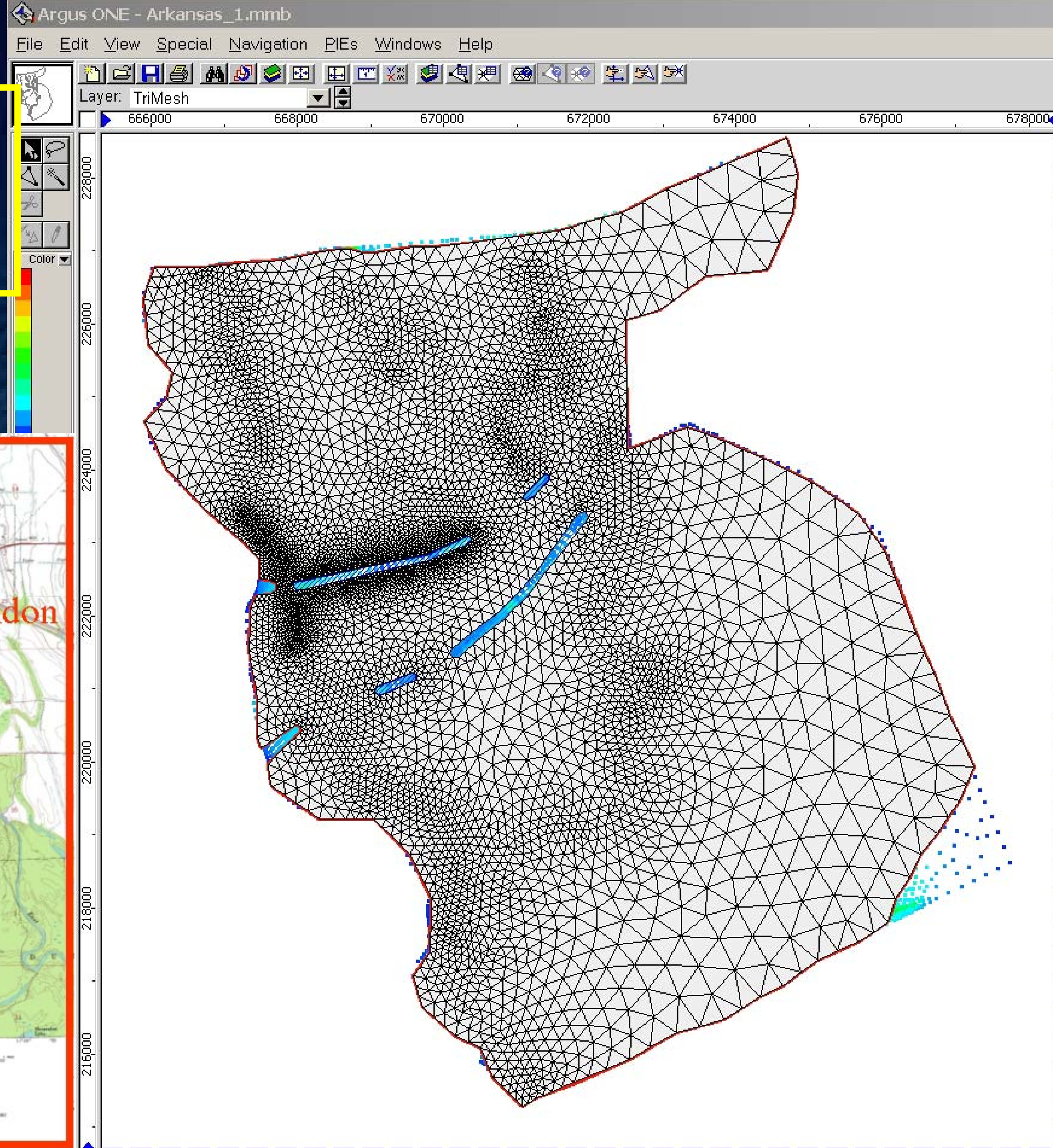
Internal Contours to guide and control mesh generation





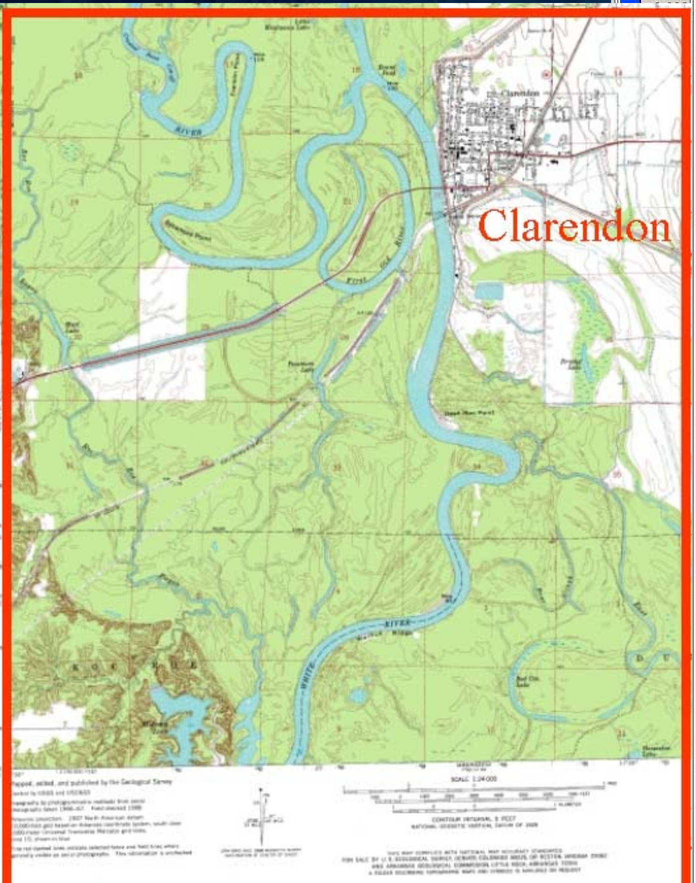
Generated Mesh:
 # Polygons = 10,259
 # Sides = 15,851

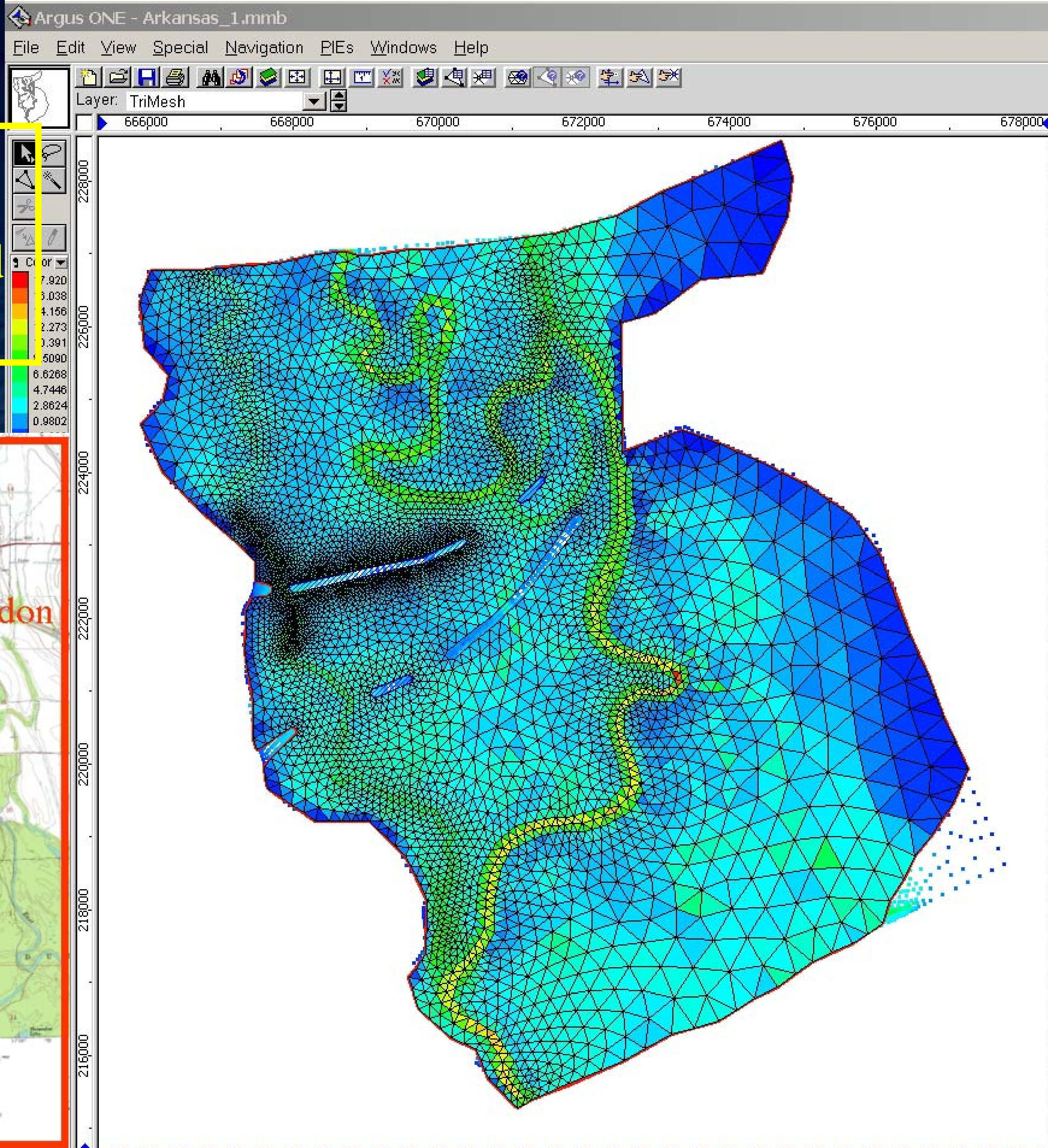




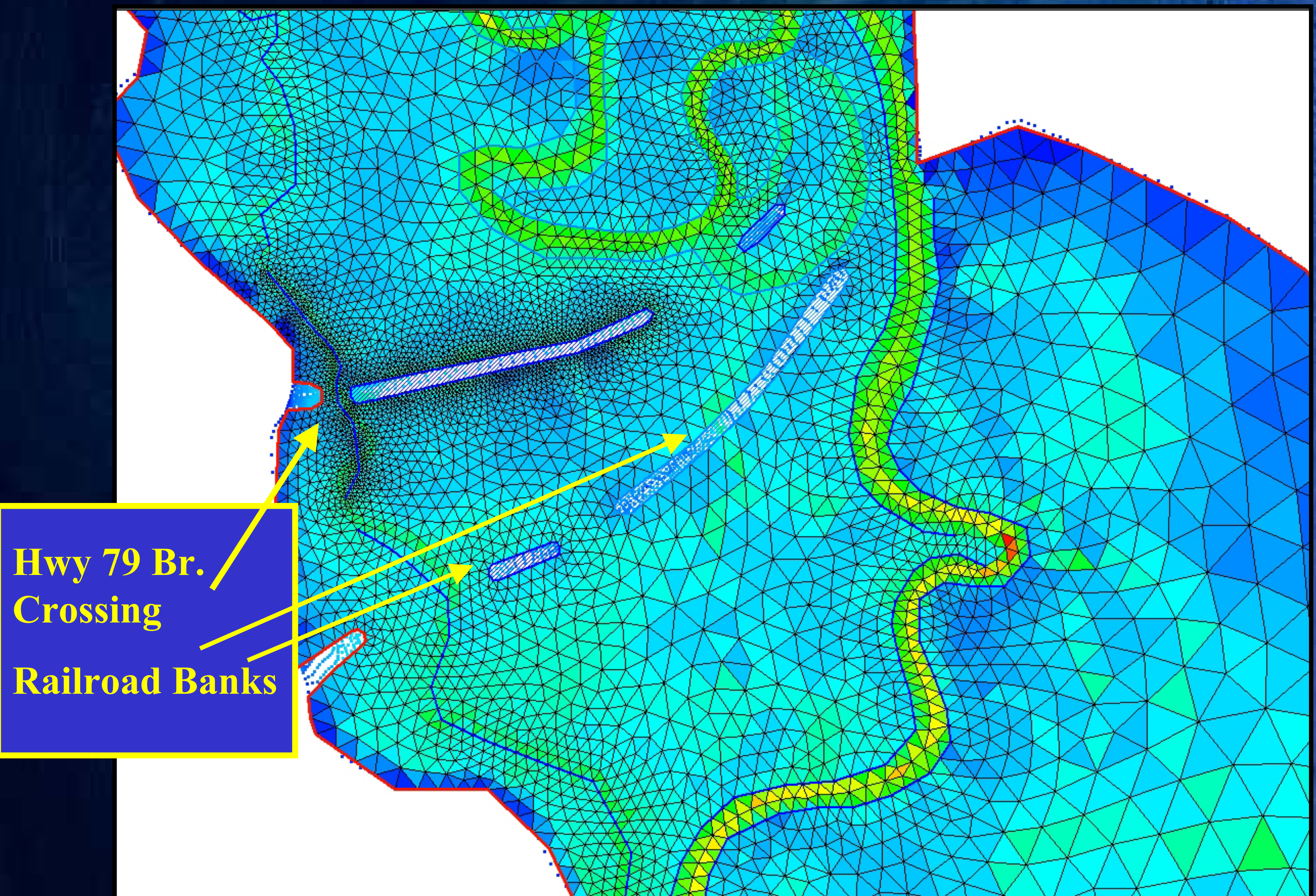
Generated Mesh:

Depth Superimposed (Boundary Fitting)

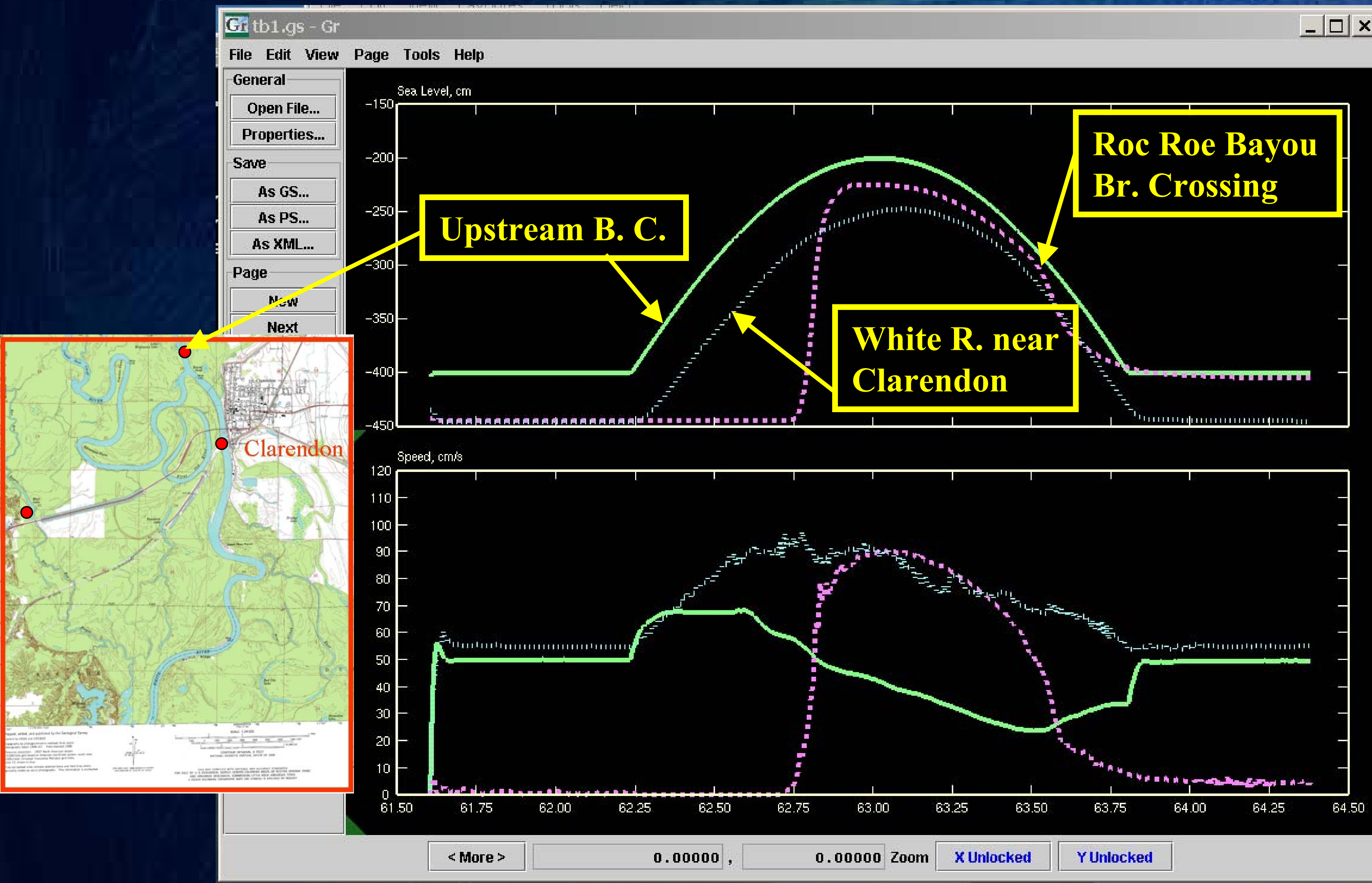


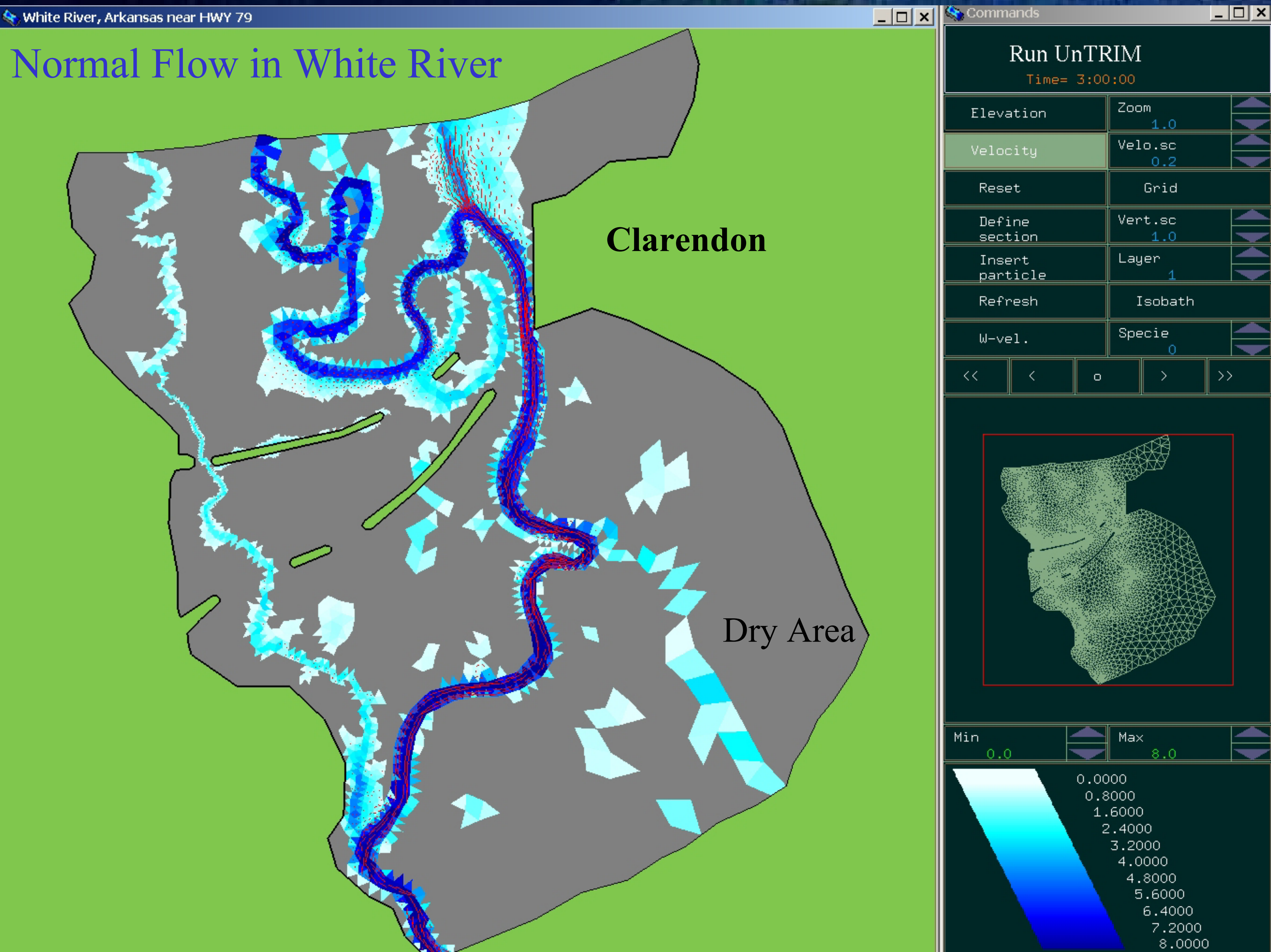


Closer look at mesh guided by internal contours

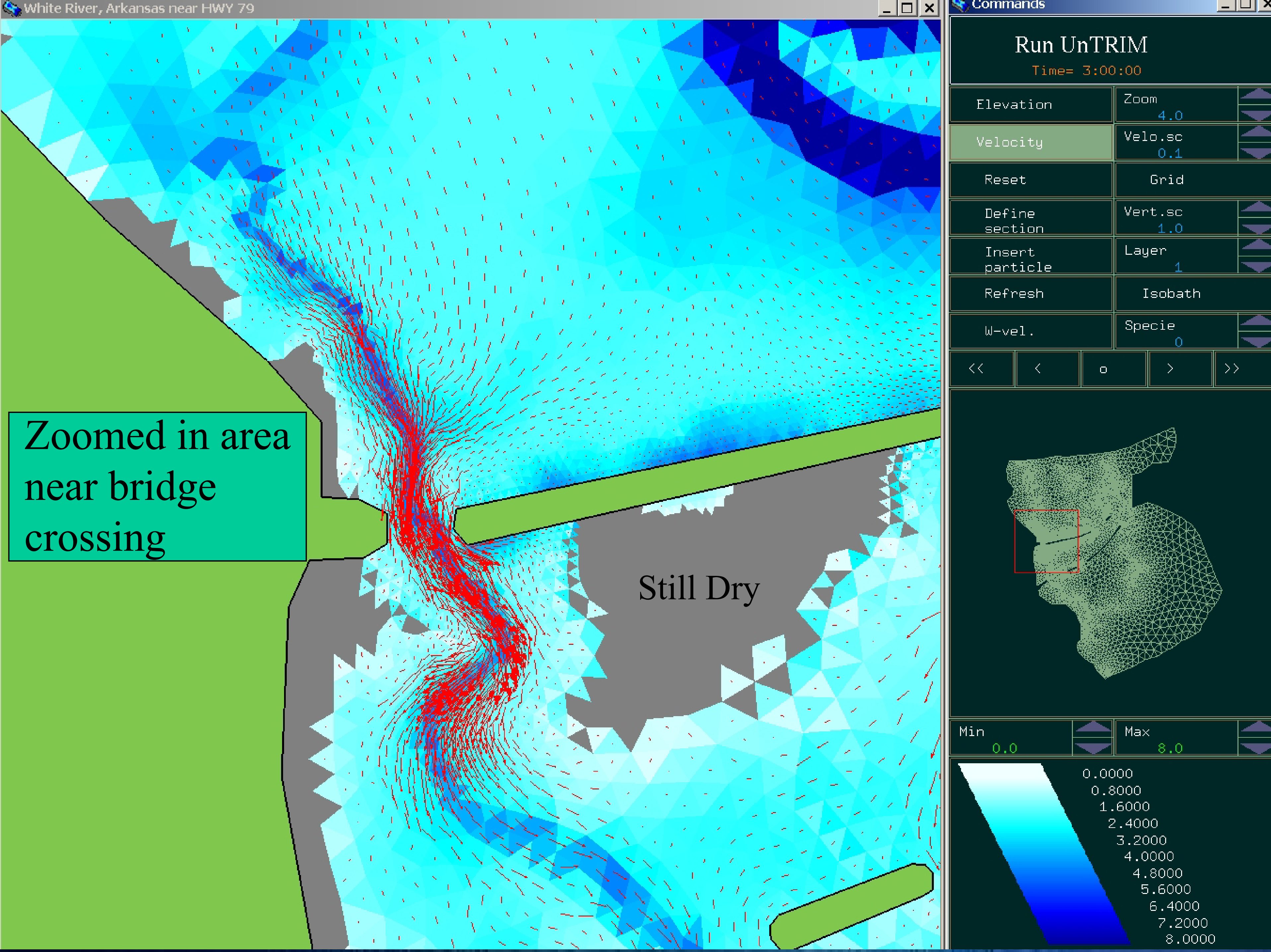


Hydrograph and time-series of a simulated flood

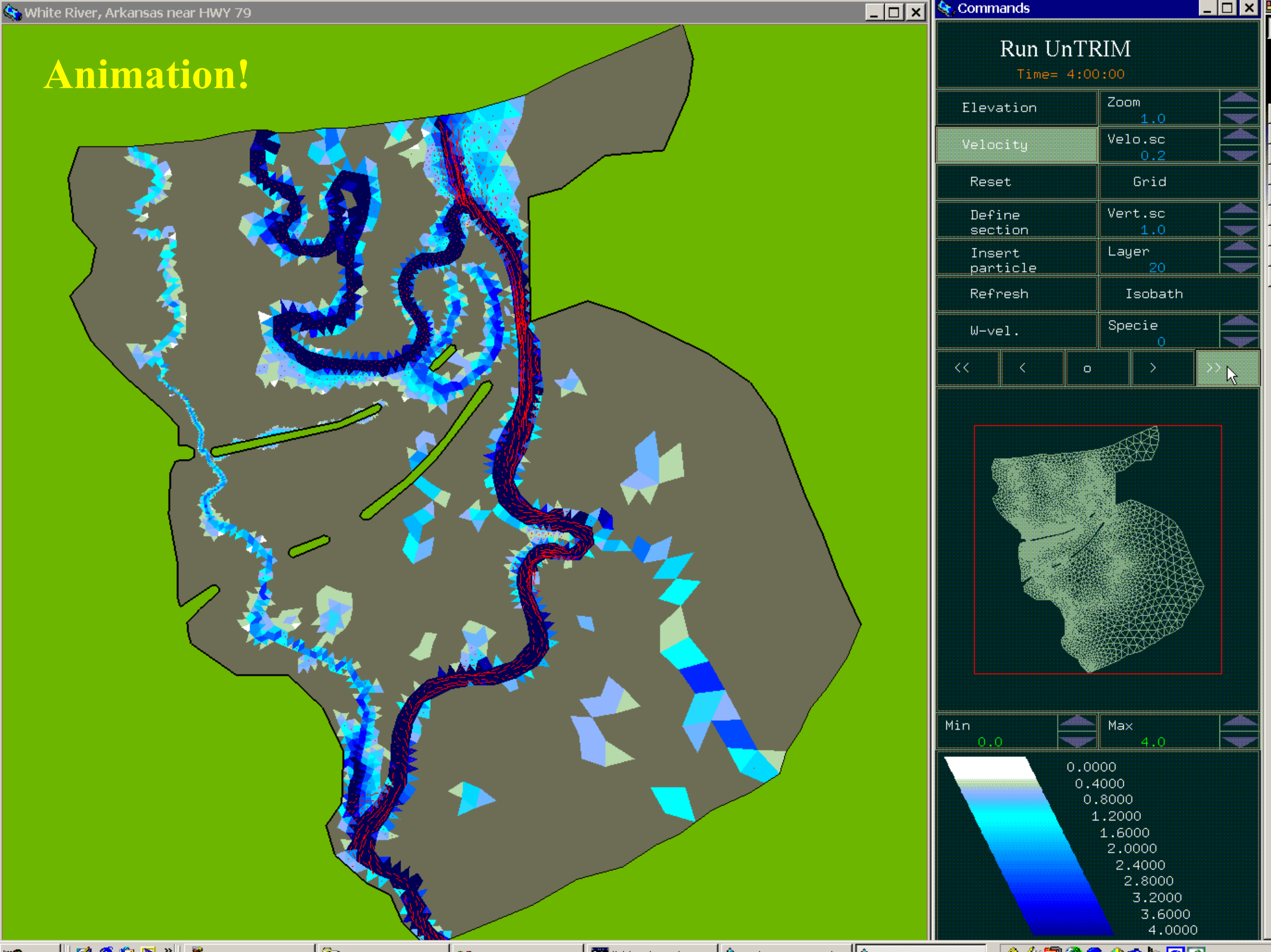




White River, Arkansas near HWY 79
Normal Flow in White River
Clarendon
Dry Area
Commands
Run UnTRIM
Time= 3:00:00
Elevation
Zoom
1.0
Velocity
Velo.sc
0.2
Reset
Grid
Define section
Vert.sc
1.0
Insert particle
Layer
1
Refresh
Isobath
W-vel.
Specie
0
Min
0.0
Max
8.0
0.0000
0.8000
1.6000
2.4000
3.2000
4.0000
4.8000
5.6000
6.4000
7.2000
8.0000



White River, Arkansas near HWY 79
Zoomed in area near bridge crossing
Still Dry
Commands
Run UnTRIM
Time= 3:00:00
Elevation
Zoom
4.0
Velocity
Velo.sc
0.1
Reset
Grid
Define section
Vert.sc
1.0
Insert particle
Layer
1
Refresh
Isobath
W-vel.
Specie
0
Min
0.0
Max
8.0
0.0000
0.8000
1.6000
2.4000
3.2000
4.0000
4.8000
5.6000
6.4000
7.2000
8.0000


White River, Arkansas near HWY 79
Animation!
Commands
Run UnTRIM
Time= 4:00:00
Elevation
Zoom
1.0
Velocity
Velo.sc
0.2
Reset
Grid
Define section
Vert.sc
1.0
Insert particle
Layer
20
Refresh
Isobath
W-vel.
Specie
0
<<
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o
>
>>
Min
0.0
Max
4.0
0.0000
0.4000
0.8000
1.2000
1.6000
2.0000
2.4000
2.8000
3.2000
3.6000
4.0000

The UnTRIM model has been used to study:

- **Flows near two National Wildlife Refuges during flood**
- **Floodplain Inundation Mapping**
- **Backwater and Velocity concerns**
- **Provide Inputs to Highway Bridge Design and Placement**
- **Highway Bridge Scouring**

Preliminary Modeling Results of Hydrodynamics in Upper Klamath Lake

Ralph T. Cheng*

Jeffrey W. Gartner*

Tamara Wood**

*U. S. Geological Survey, Menlo Park, CA

**U. S. Geological Survey, Portland, OR

I. Background

II. ADCP Deployment and Results

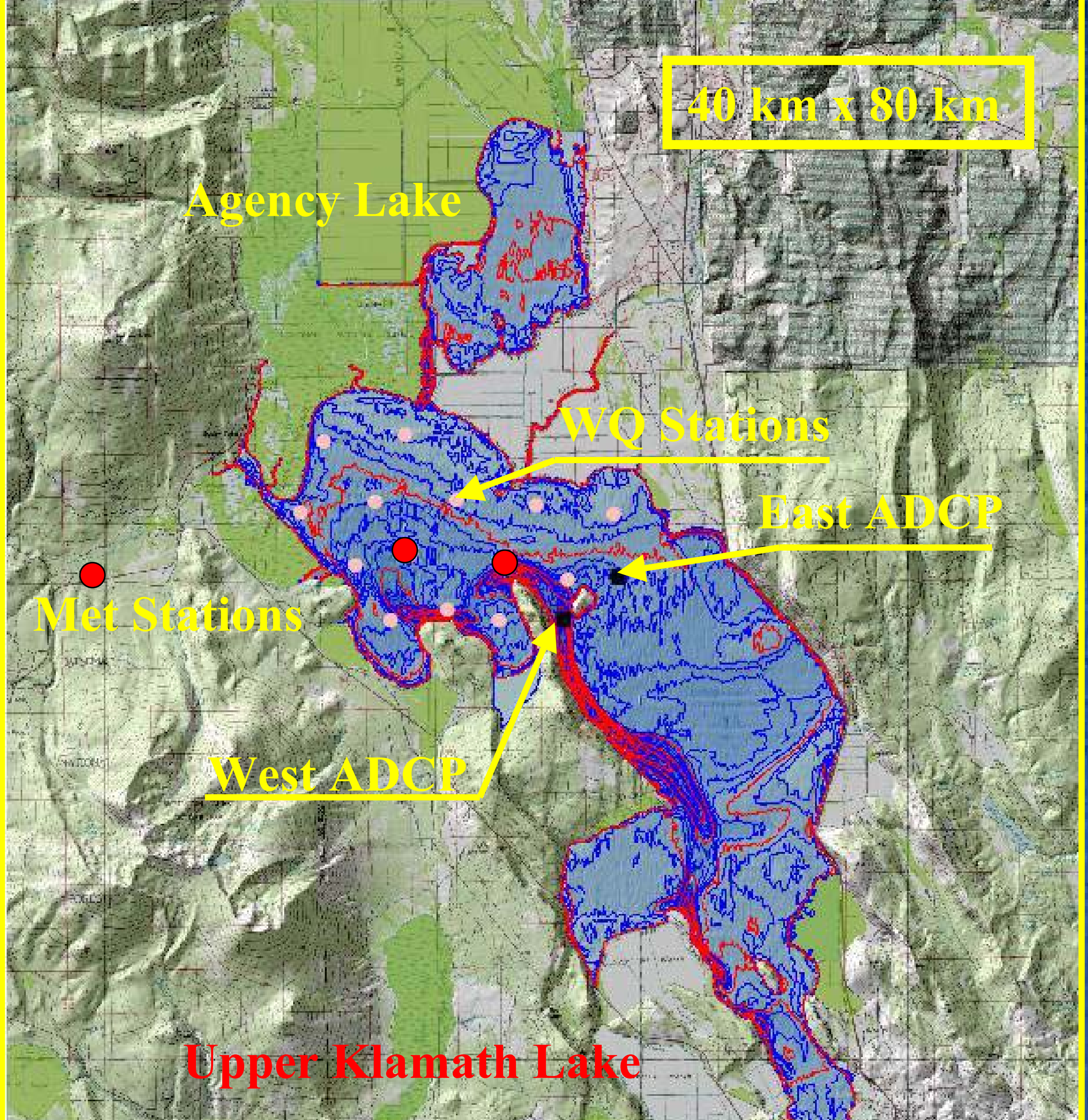
III. Time-series of Wind Observations

IV. Wind-Driven Circulation

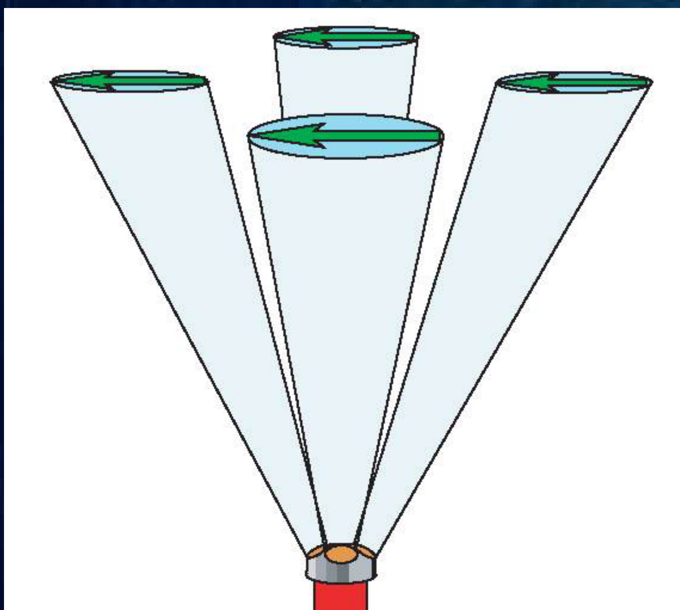
V. Reproducing ADCP Observations

VI. Analyze This and Analyze That

VII. Conclusion (Physics Rules!)


40 km x 80 km
Agency Lake
WQ Stations
East ADCP
Met Stations
West ADCP
Upper Klamath Lake

What is an ADCP and how does it work?



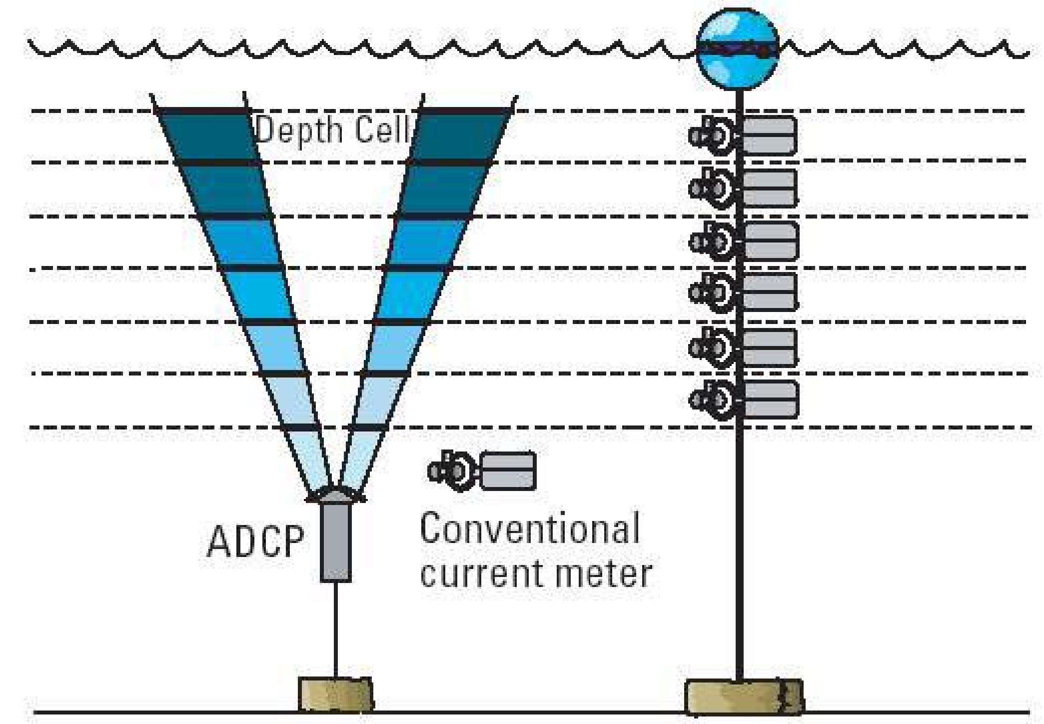


Figure 1.15. Analogy of a conventional current-meter string to an acoustic Doppler current profiler (ADCP) profile.

West ADCP Station:

Water depth ~ 8 m

Bin size = 0.2 m

Sampling rate = 30.0 min

Total bins = 34

East ADCP Station:

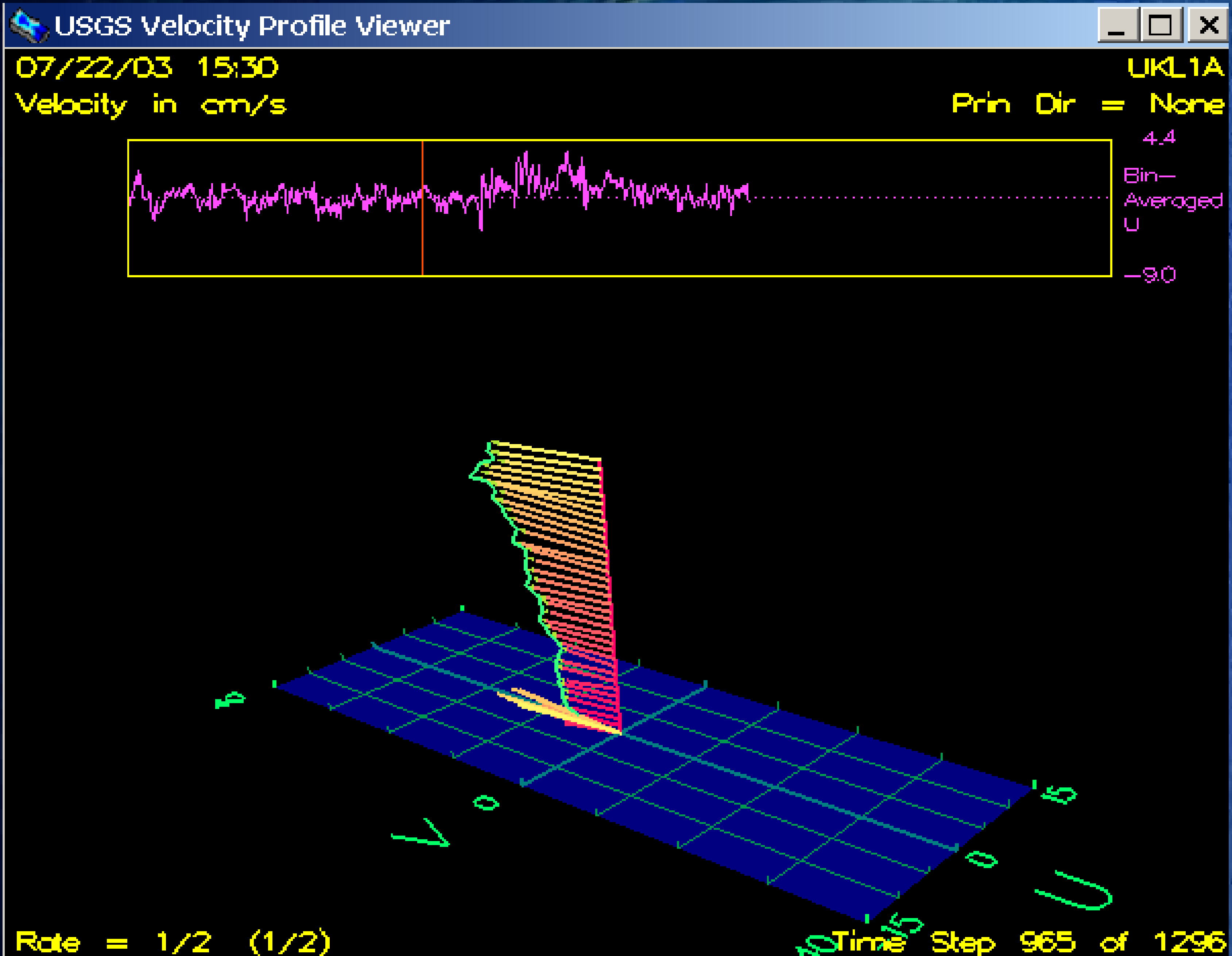
Water depth ~ 3.5 m

Bin size = 0.2 m

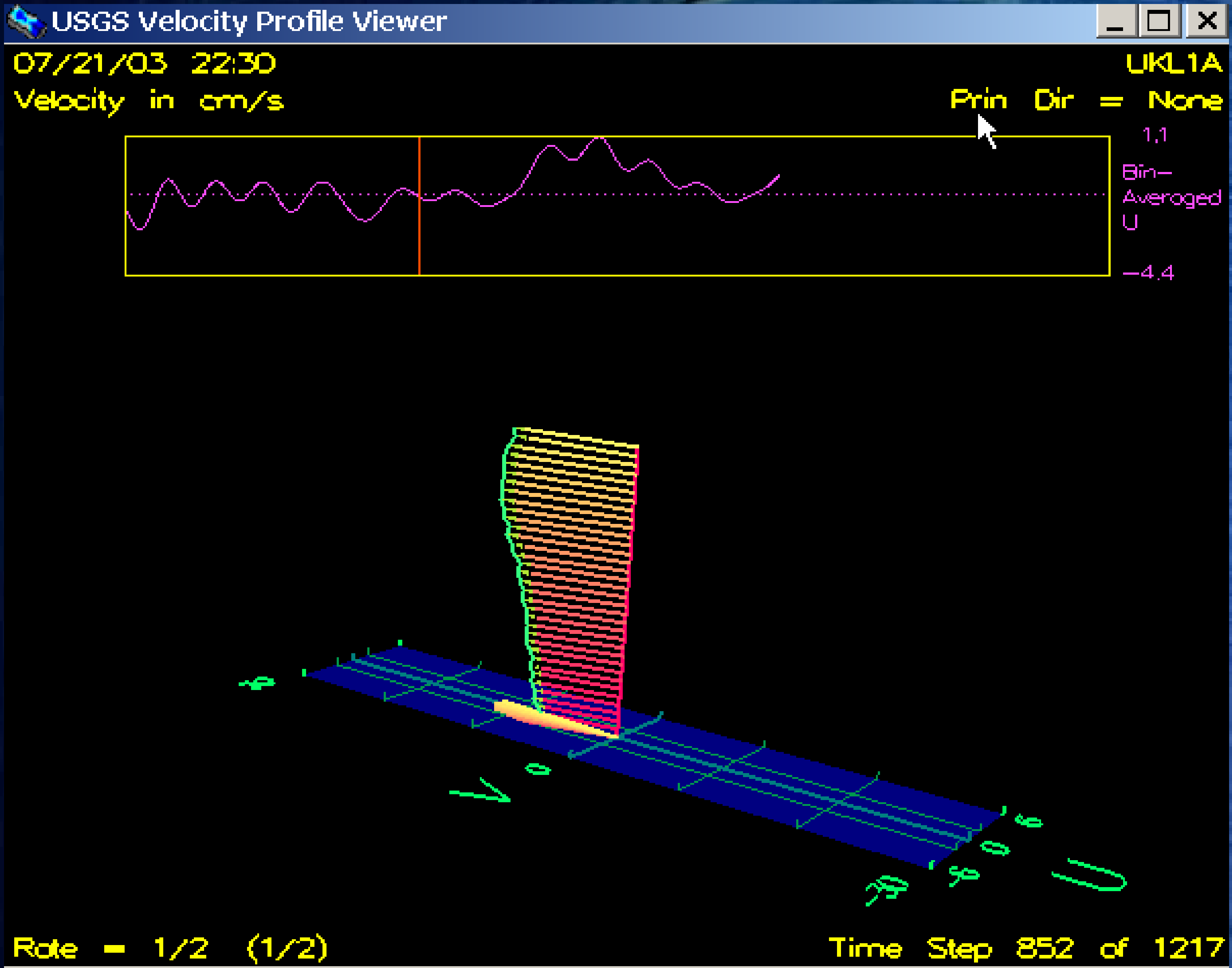
Sampling rate = 30.0 min

Total bins = 12

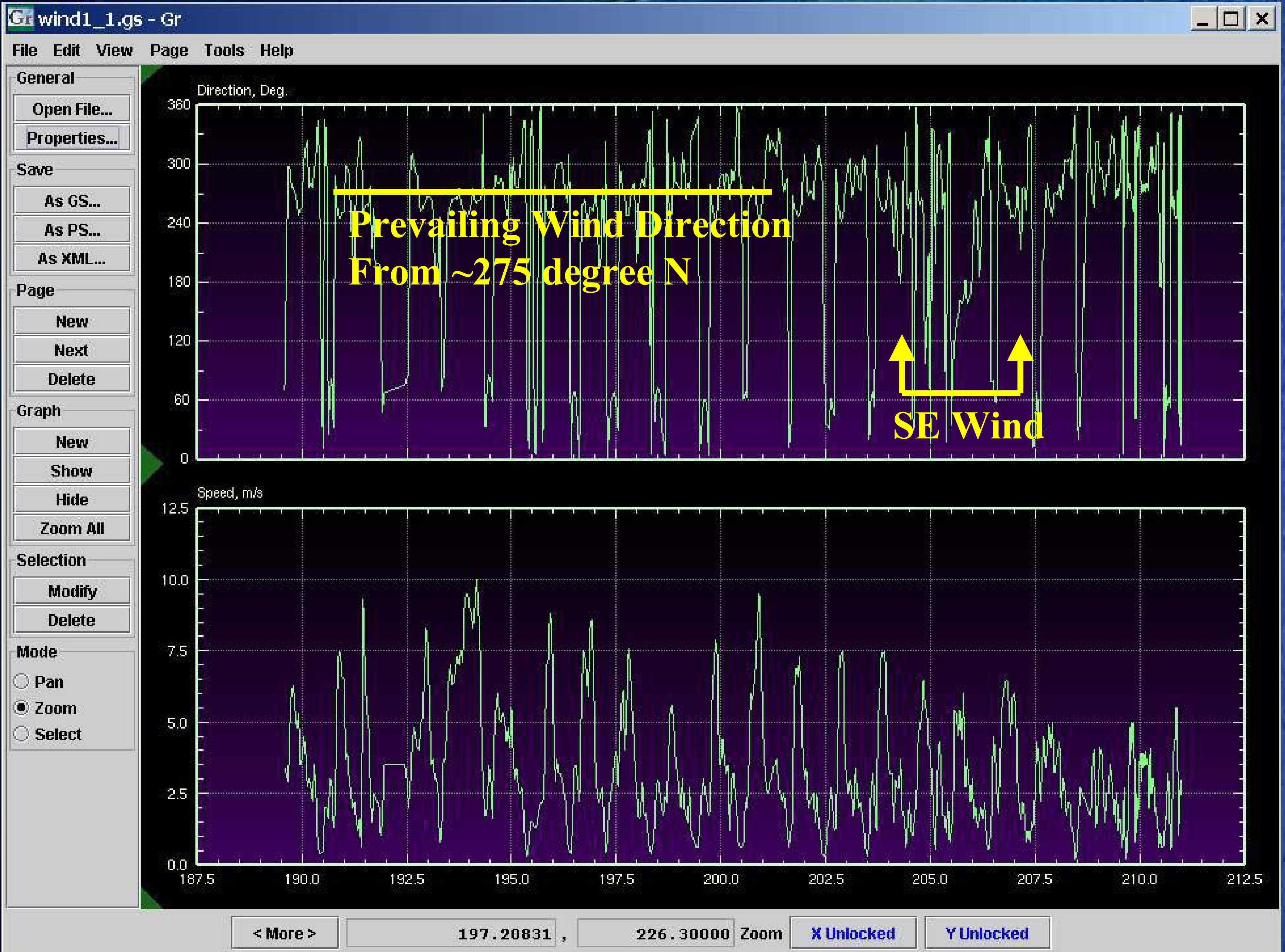
Unfiltered 3D ADCP Time-Series

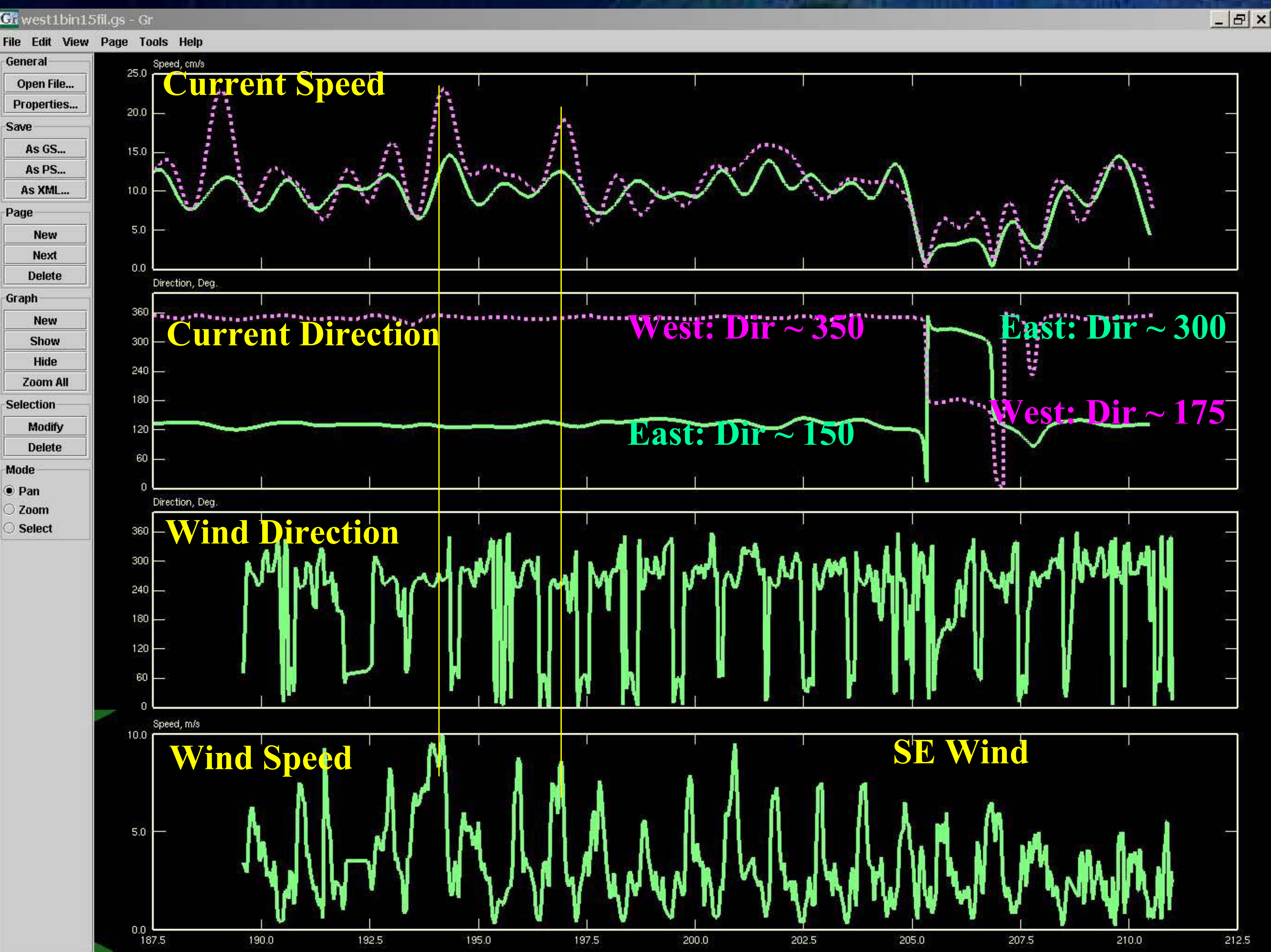


Filtered 3D ADCP Time-Series



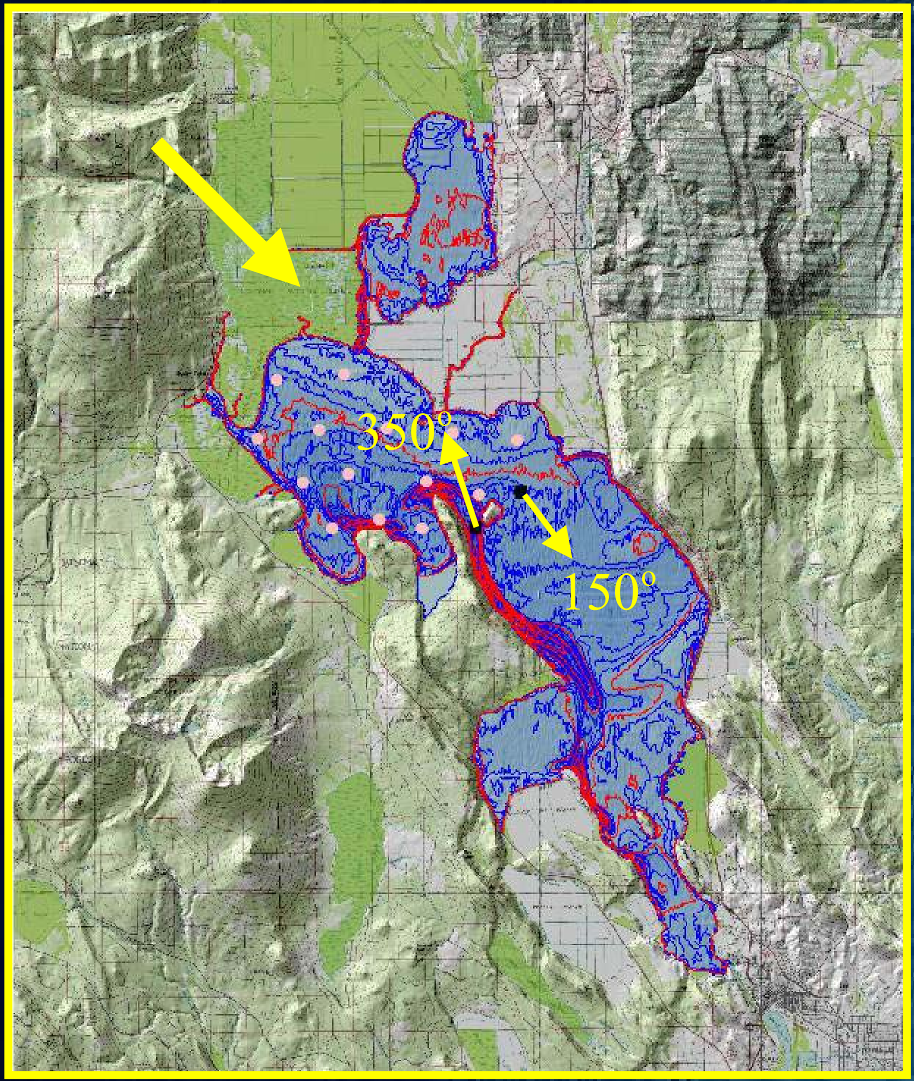
Wind Speed and Direction Time-Series



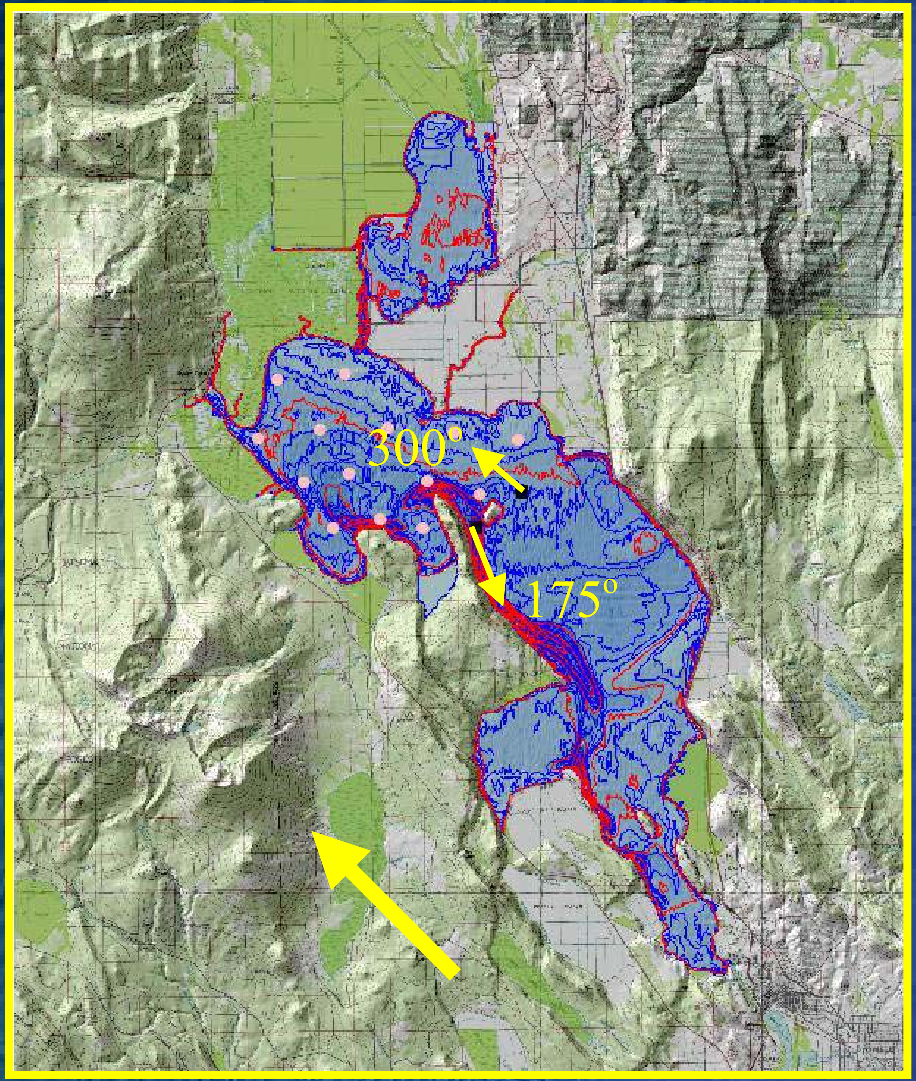


west1bin15fil.gs - Gr
File Edit View Page Tools Help
General
Open File...
Properties...
Save
As GS...
As PS...
As XML...
Page
New
Next
Delete
Graph
New
Show
Hide
Zoom All
Selection
Modify
Delete
Mode
Pan
Zoom
Select
Speed, cm/s
Current Speed
Direction, Deg.
Current Direction
West: Dir ~ 350
East: Dir ~ 300
West: Dir ~ 175
East: Dir ~ 150
Direction, Deg.
Wind Direction
Speed, m/s
Wind Speed
SE Wind
187.5
190.0
192.5
195.0
197.5
200.0
202.5
205.0
207.5
210.0
212.5

Synopsis of Wind-driven Circulation



Prevailing NW Wind



SE Wind

Universal Paucity of Field Data

Answer (?)

Numerical Model as a Tool for Spatial and Temporal Interpolations

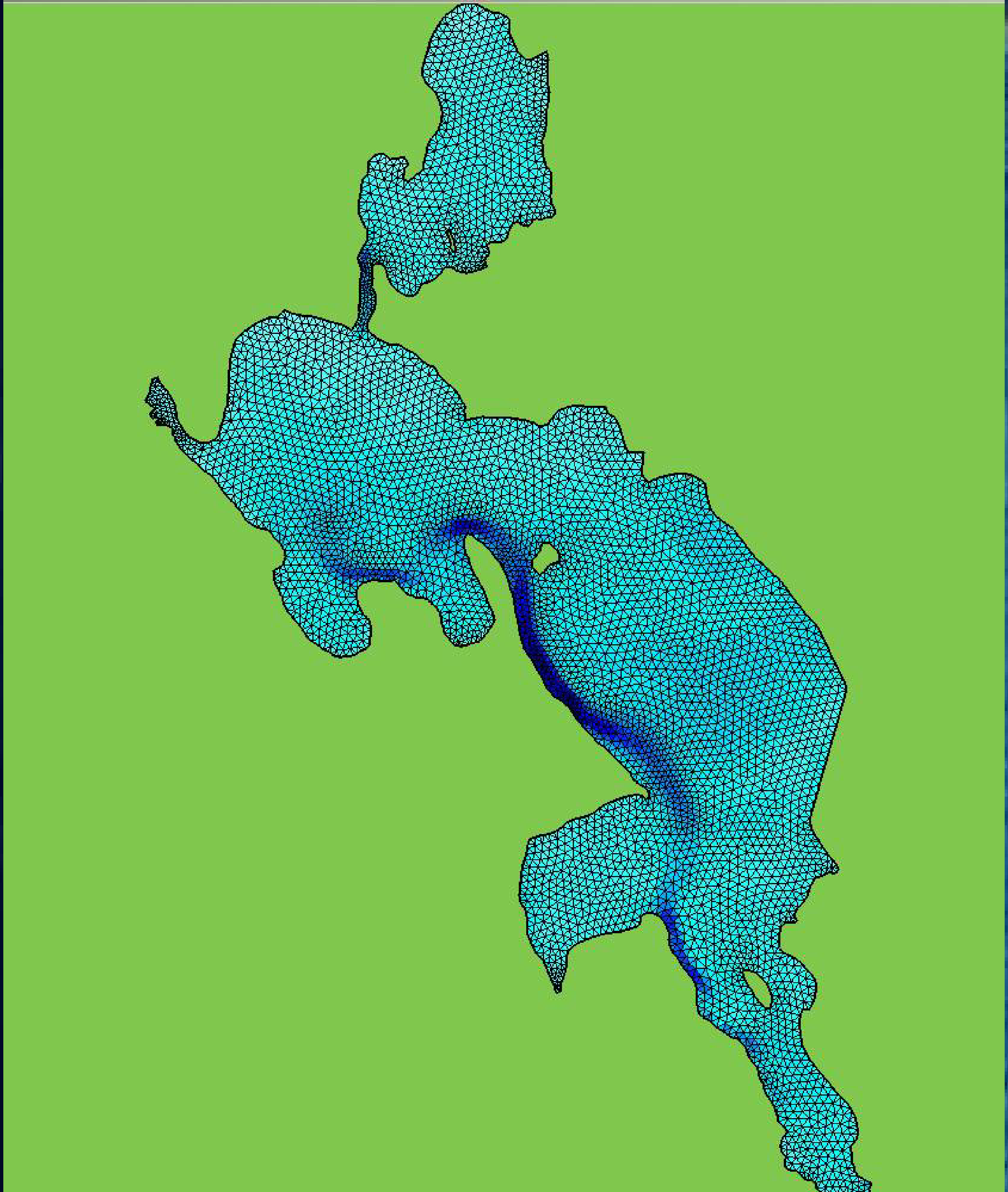
The UnTRIM Model

Unstructured grid, 3D, Transient, Variable Density, Transport of Solutes

Turbulence Closure

Semi-implicit Finite-Difference Method

A Robust and Efficient Model



Unstructured Grid Model:

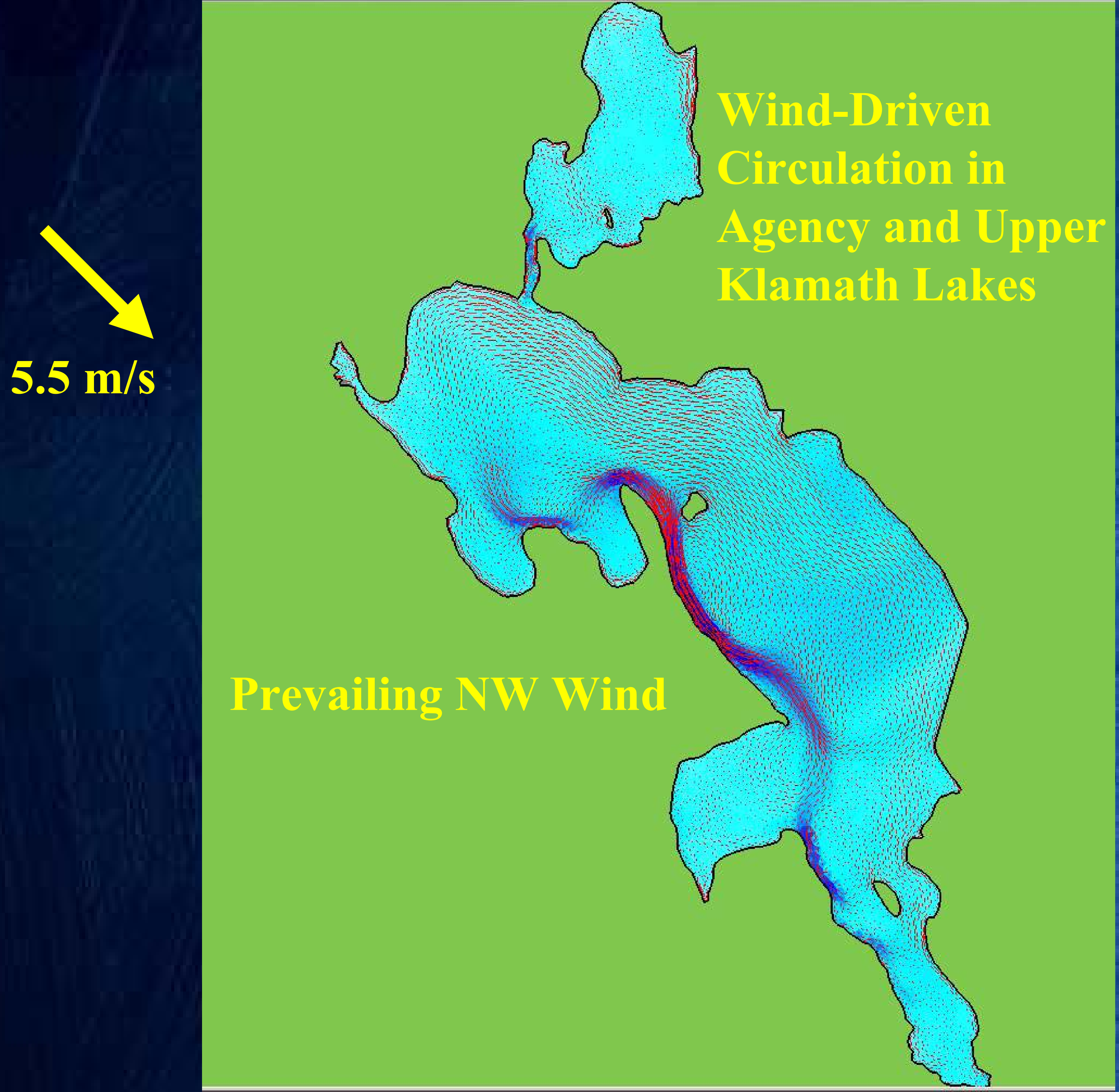
Upper Klamath Lake and Agency Lake:

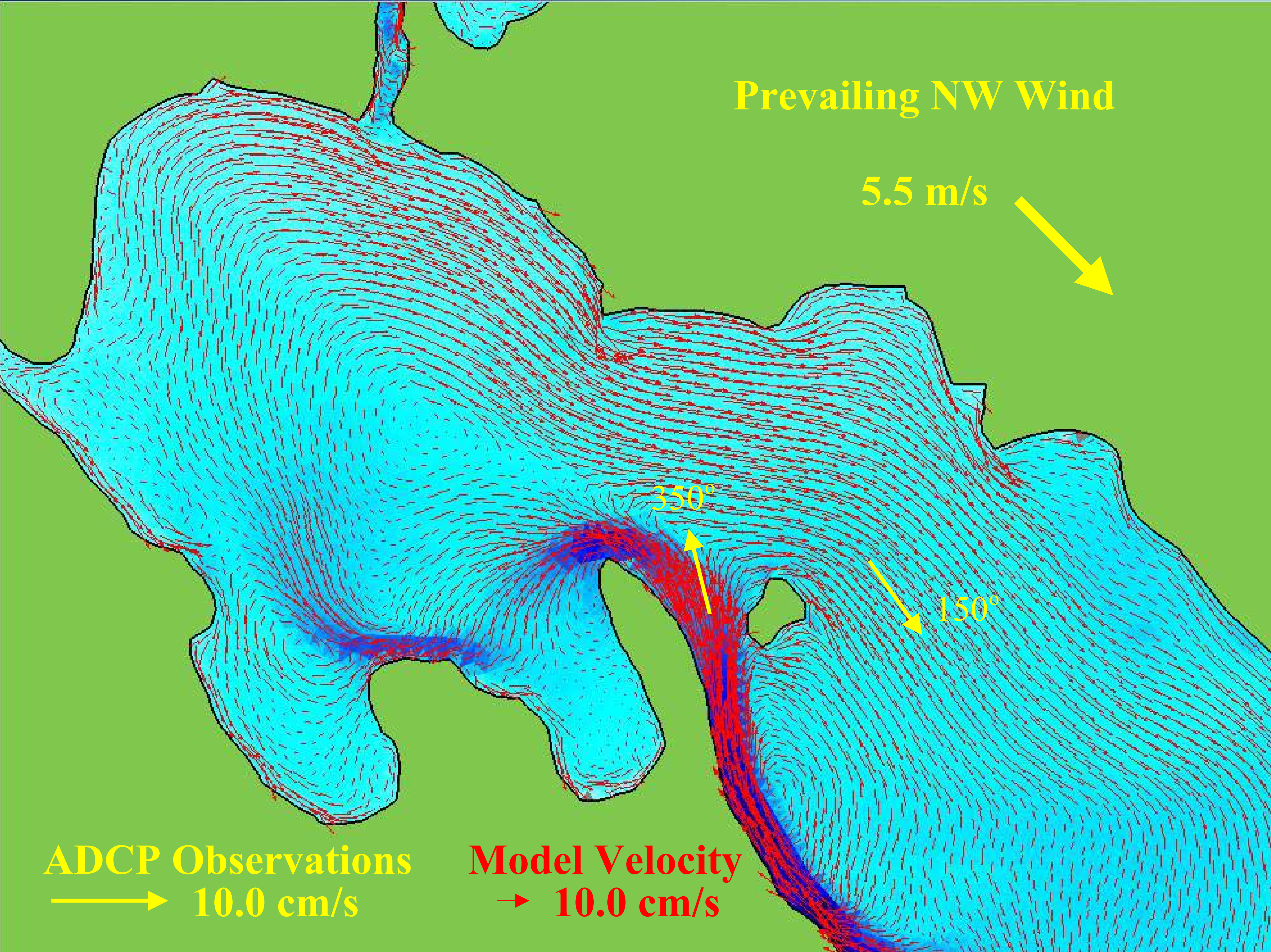
nv = 4712

ne = 8550

Side length 40 to 250 m

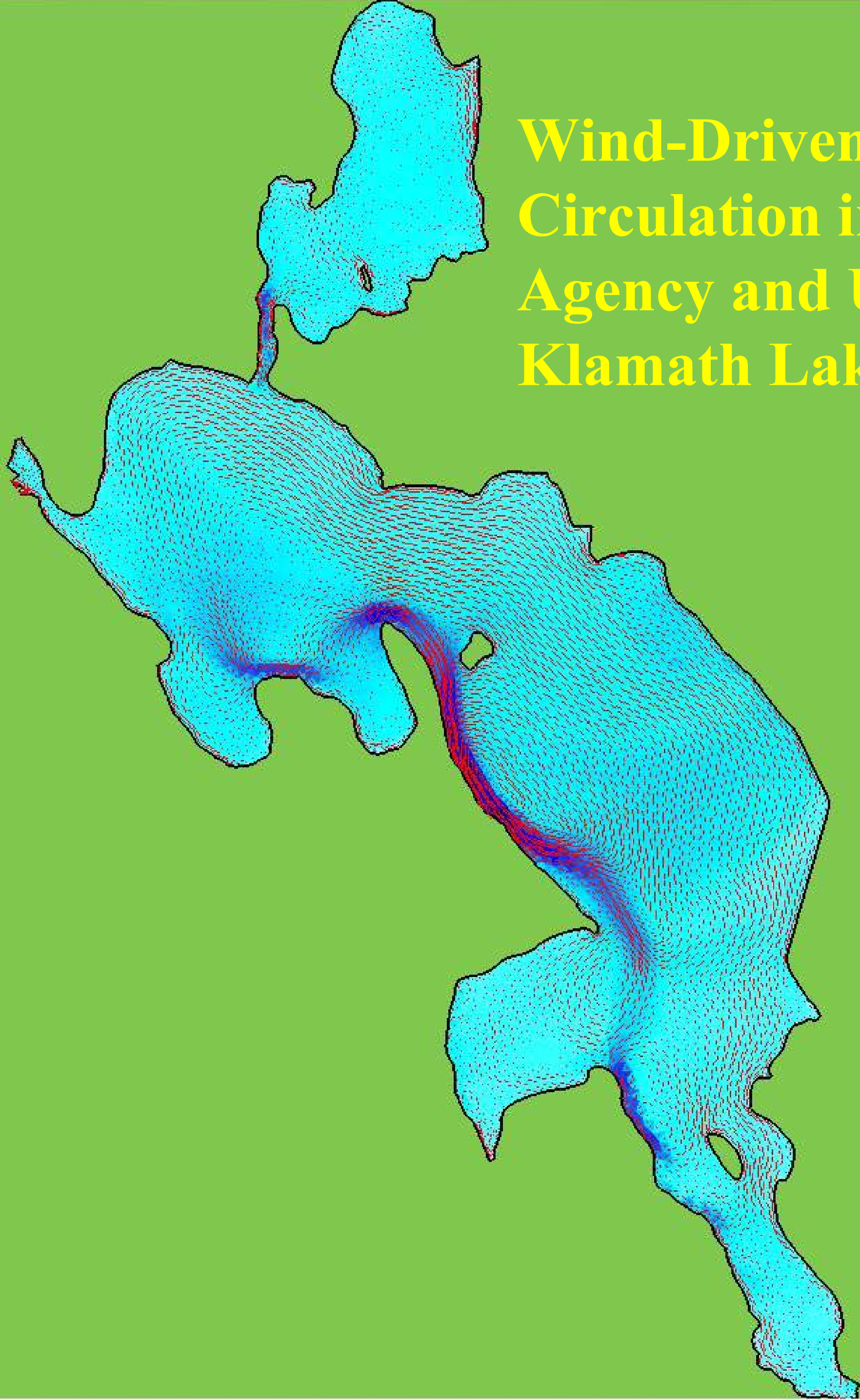
Grids are boundary fitting Fine resolution grids for high spatial variability.


Wind-Driven Circulation in Agency and Upper Klamath Lakes
5.5 m/s
Prevailing NW Wind

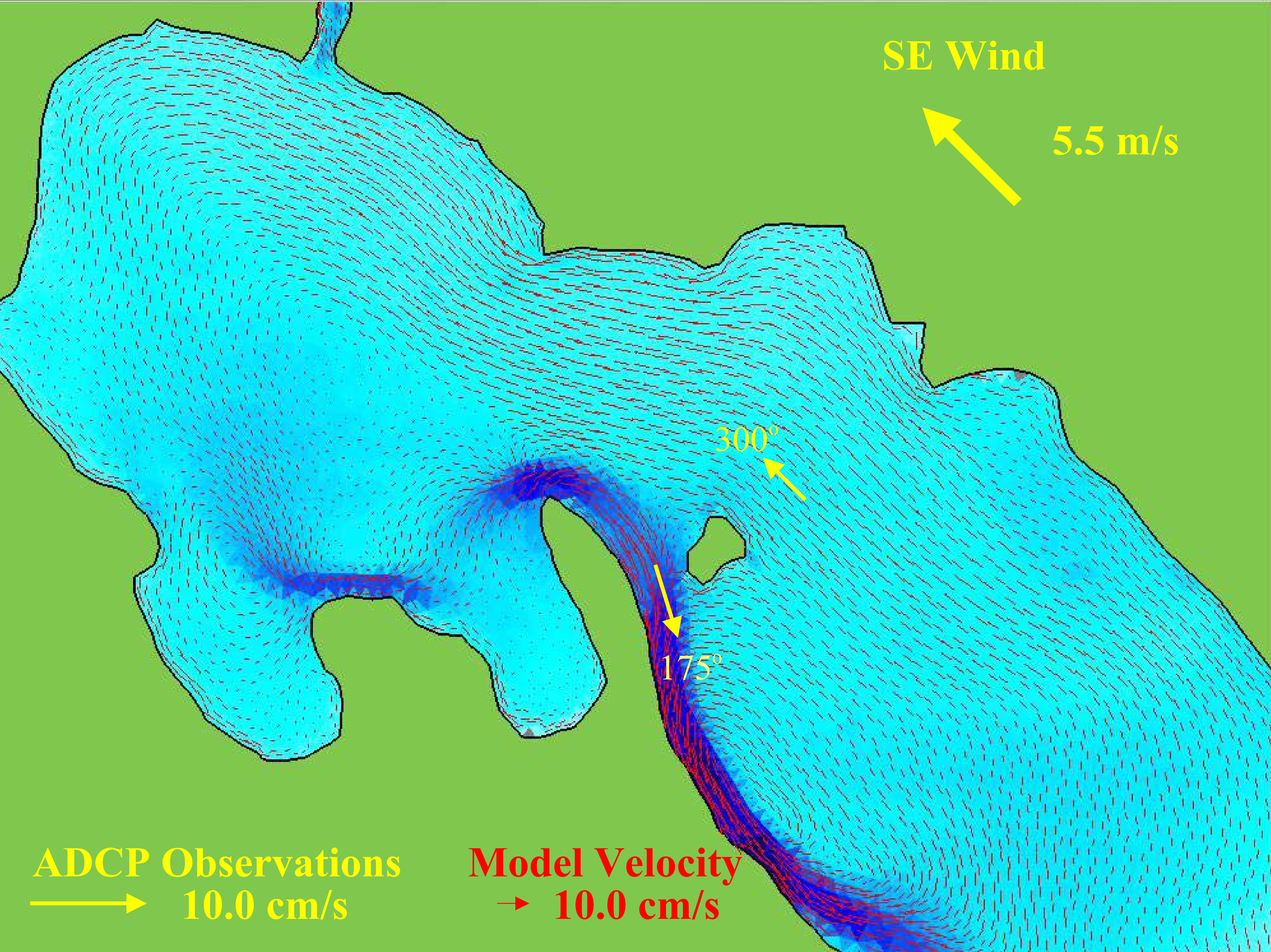


Prevailing NW Wind
5.5 m/s
350°
150°
ADCP Observations
10.0 cm/s
Model Velocity
10.0 cm/s

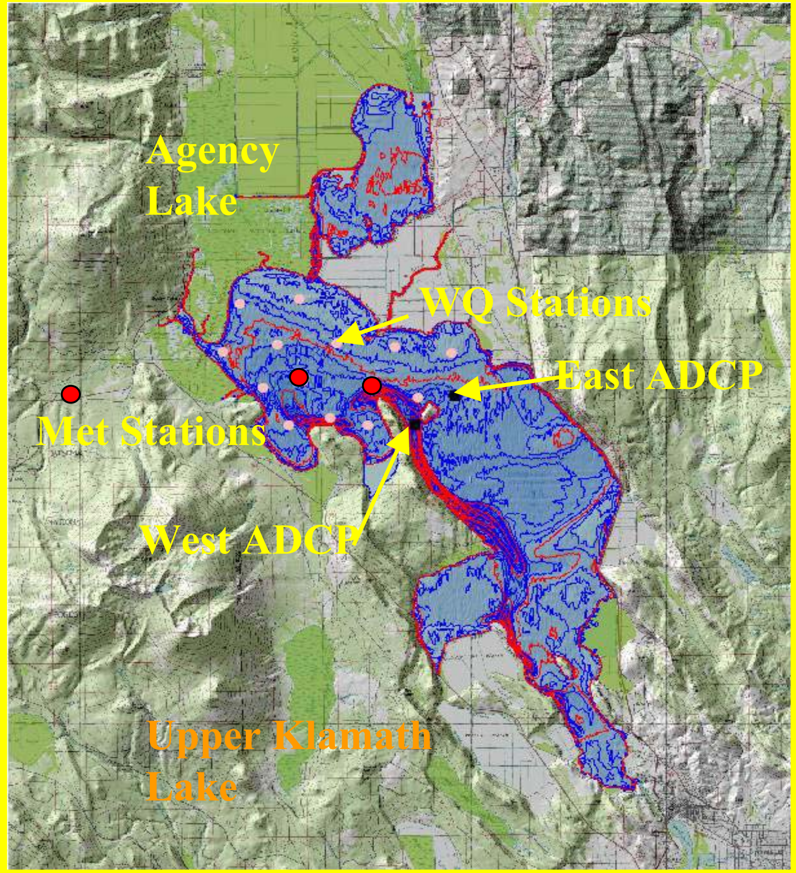
Wind-Driven Circulation in Agency and Upper Klamath Lakes



SE Wind
5.5 m/s


SE Wind
5.5 m/s
300°
175°
ADCP Observations
10.0 cm/s
Model Velocity
10.0 cm/s

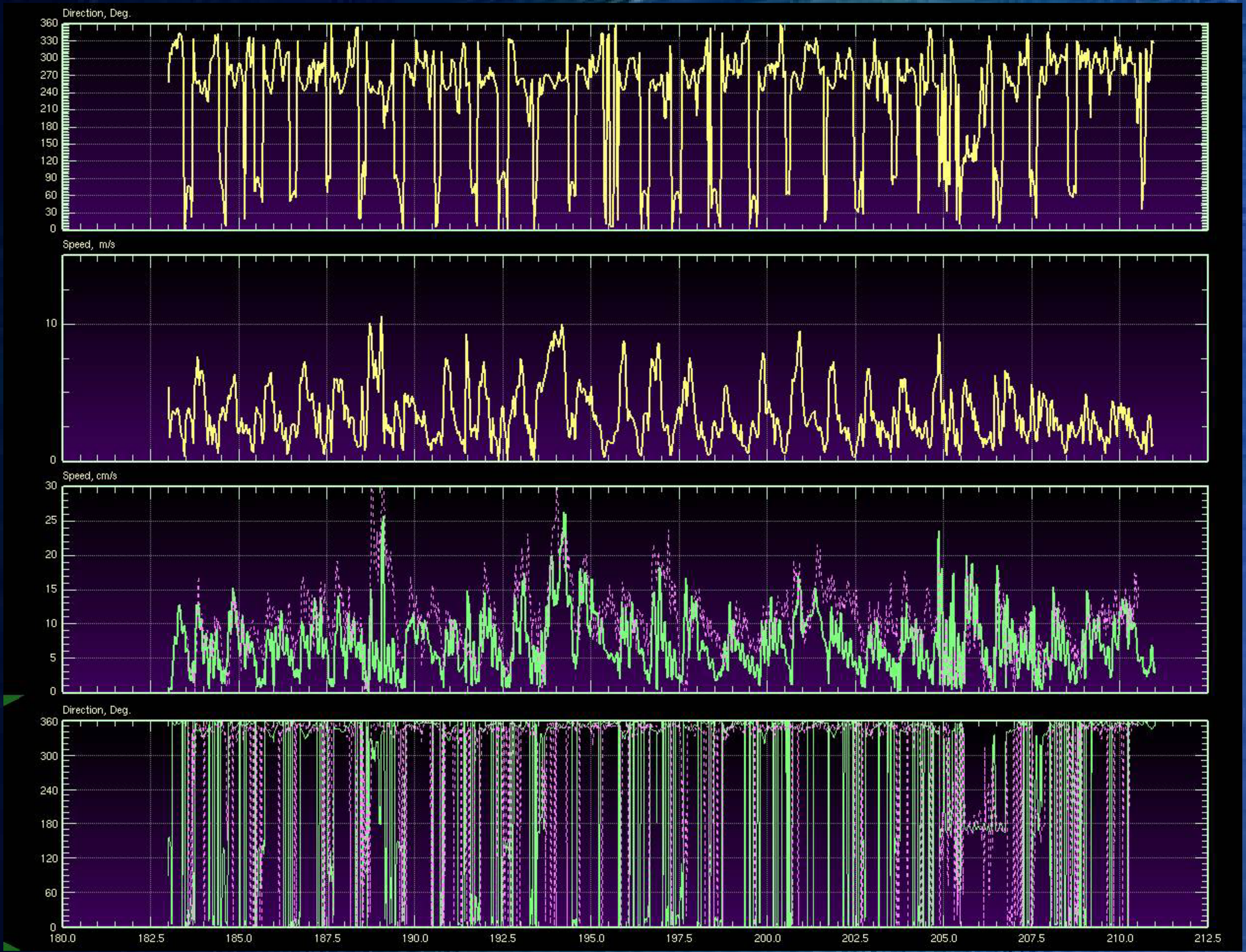
Simulations using the observed wind data



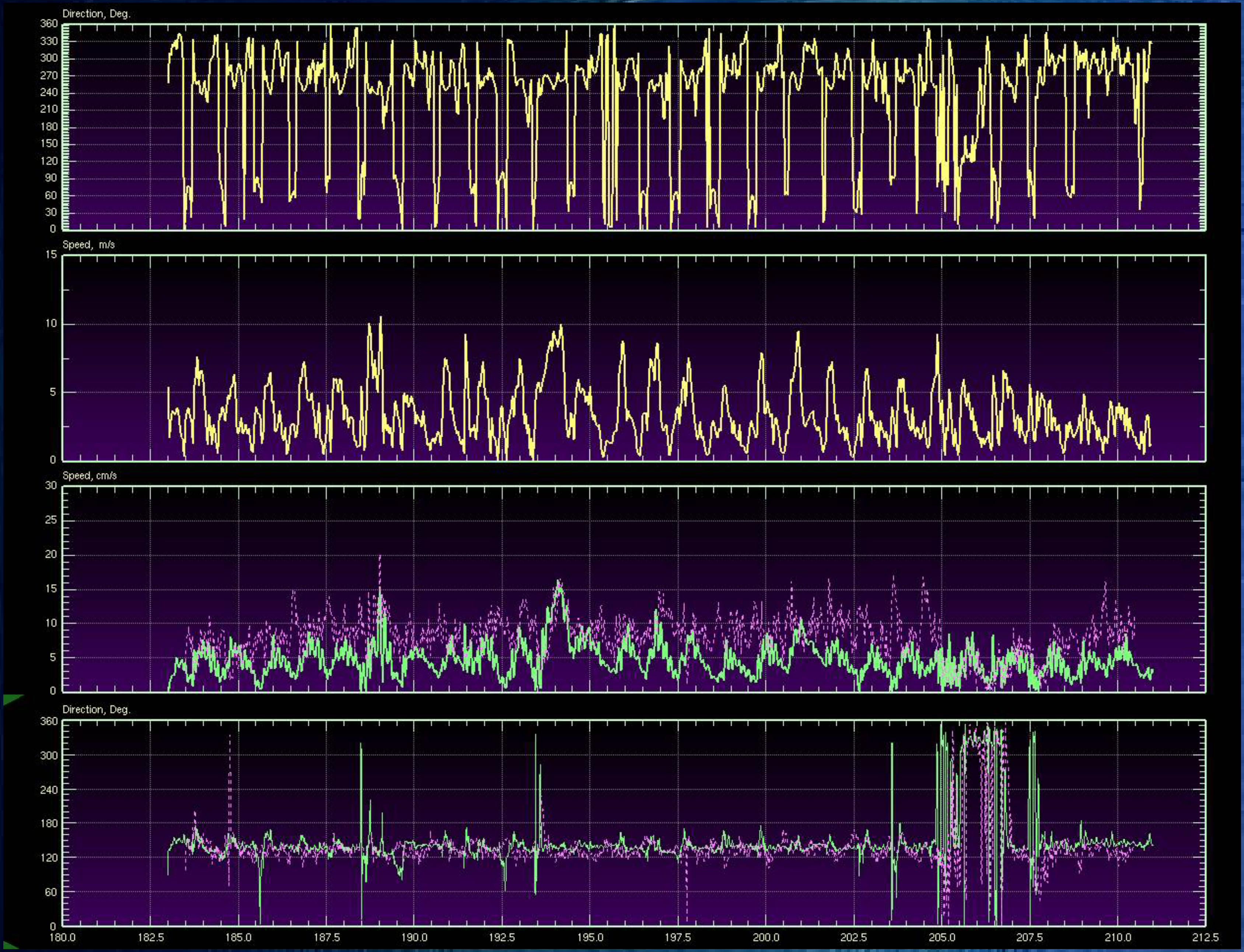
Issues with wind time-series:

1. **Magnetic north**
2. **Data gaps or irregular time intervals**

Model Results vs. ADCP Observations at Deep (West) Station



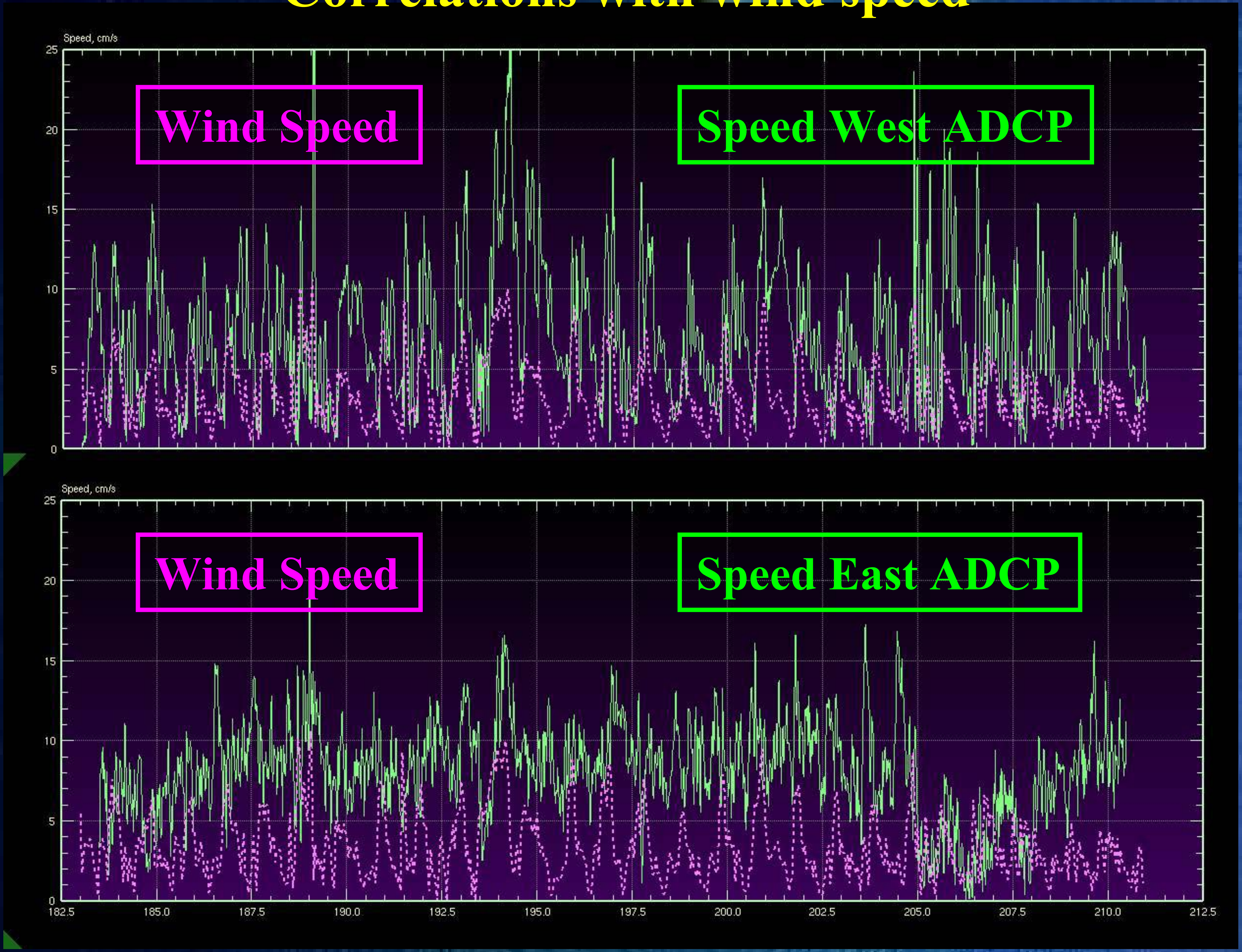
Model Results vs. ADCP Observations at Shallow (East) Station



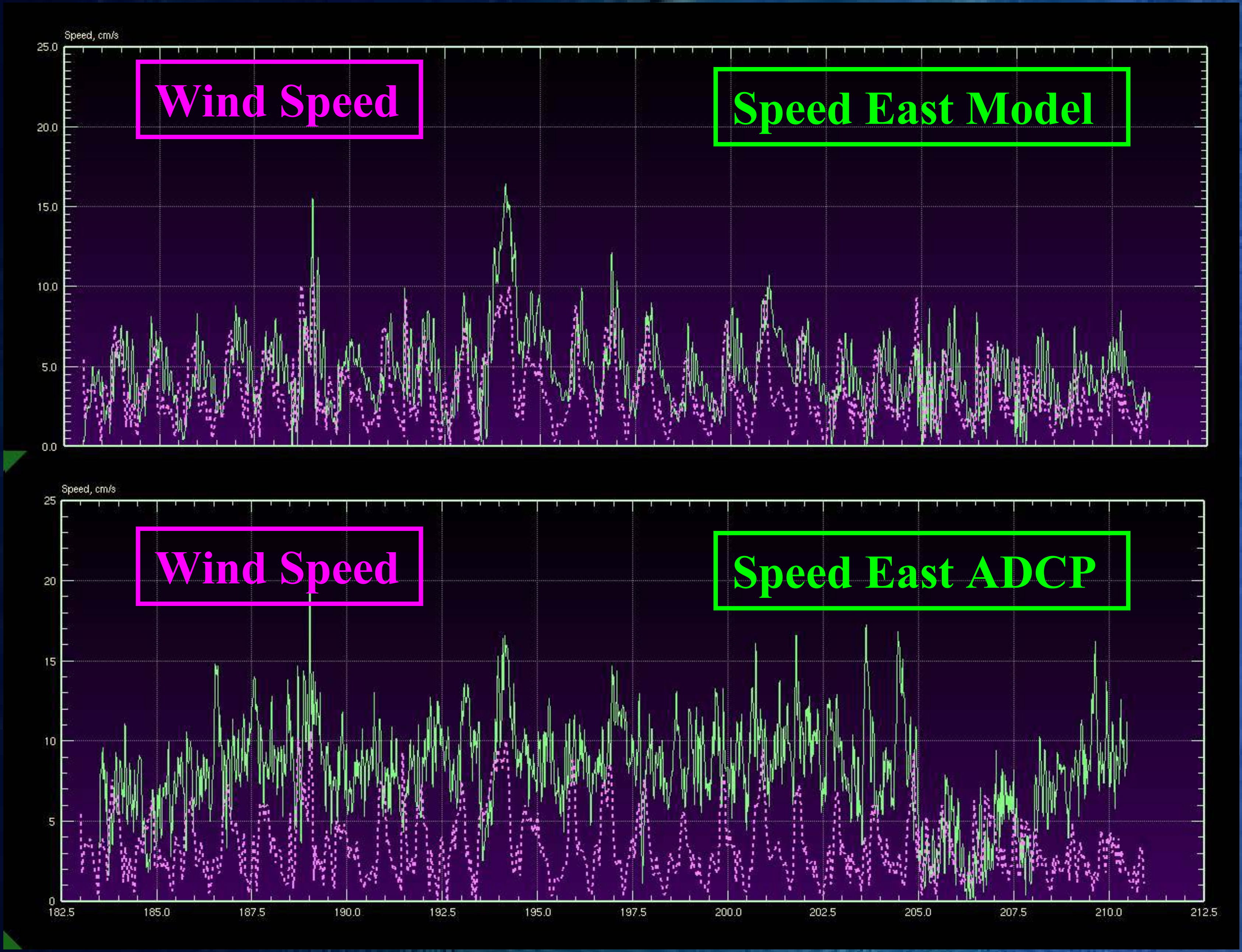
East Station: Good News and Bad News: Why???

East Station: Modeled velocity responded to diurnal wind pattern

Correlations with wind speed



Correlations with wind speed



Take Home Message:

Field Data Do not Necessarily Represent the Truth.

Recommendations:

Interpretation of Field Data Must be Consistent with the Correct Physics!

There might be uncertainties or hidden message in the data!

Receipt for successful modeling:

1. **Numerical Modeling and Physical Processes complement each other and thus must be considered together.**
2. **Choose the right numerical algorithm for the Physical Processes of the environmental flow problem (better chance of success)!**
3. **The ranges of spatial and temporal scales of environmental flow problems are very broad. Therefore, I do not believe that there exists a single model that can solve all environmental flow problems.**

Summary: Properties of UnTRIM

Mass Conservation

(local and global)

Conversion from uniform and regular meshes

CPU time is directly proportional to # of face velocities.

Numerical Stability Properties

Unconditionally stable for barotropic flows without horizontal dispersion

Baroclinic Flows

Internal wave speed controls the CFL stability condition

Degeneration to 2D and 1D domains

Flooding and Drying of sub-regions

Discussion:

UnTRIM model using unstructured grids preserves the numerical properties of semi-implicit finite-difference methods.

Unstructured grids allow local grid refinements as needed, the CPU time requirement is directly proportional to the number of "faces."

New modeling flexibility leads to new challenges: To take full advantage of the new flexibilities, the model grid generation should be guided by insights of the processes.

The needed insights may require a higher degree of modeling skill.

Conclusion

- An Unstructured Grid UnTRIM Model is available at the USGS
- Both pre- and post-processing programs have been developed
- Previous applications have shown that the UnTRIM model is numerically robust and computationally efficient.
- The UnTRIM Model is suitable for simulations of multidimensional, transient flows in rivers, estuaries, and lakes