Bubbly Creek Sediment Oxygen Demand Study and Implications for Water Quality Improvement

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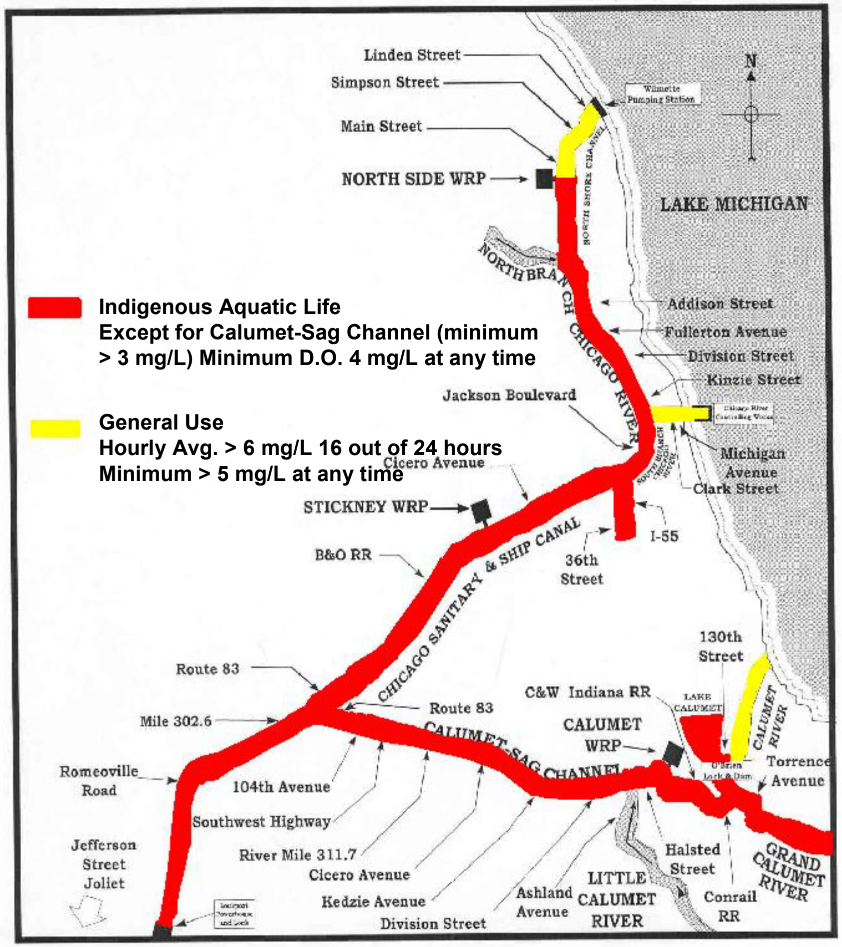
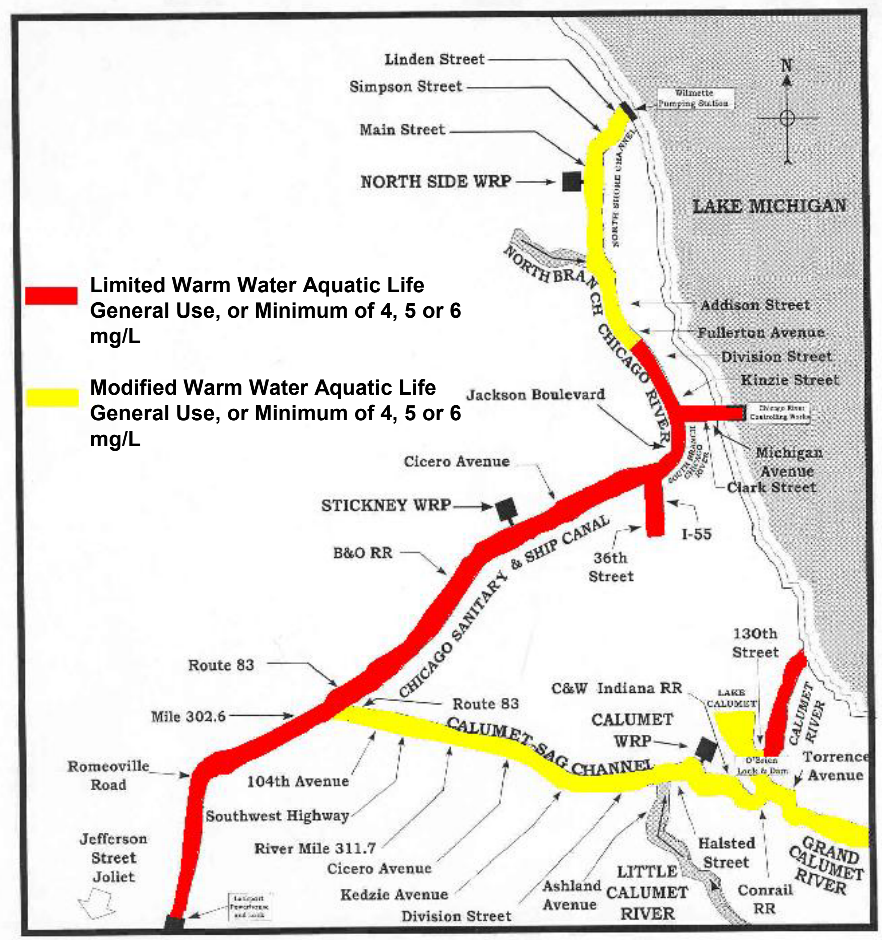
OUTLINE:

1. Background
   a. Water quality standards (UAA)
   b. Hydrology of Bubbly Creek
   c. 2D modeling of Bubbly Creek
   d. 3D modeling of Chicago waterways
2. SOD field observations
3. 3D modeling with SOD from field observations
4. Remediation alternatives in light of SOD studies
5. Implications for water quality management
6. Conclusions

Water quality standards (UAA)



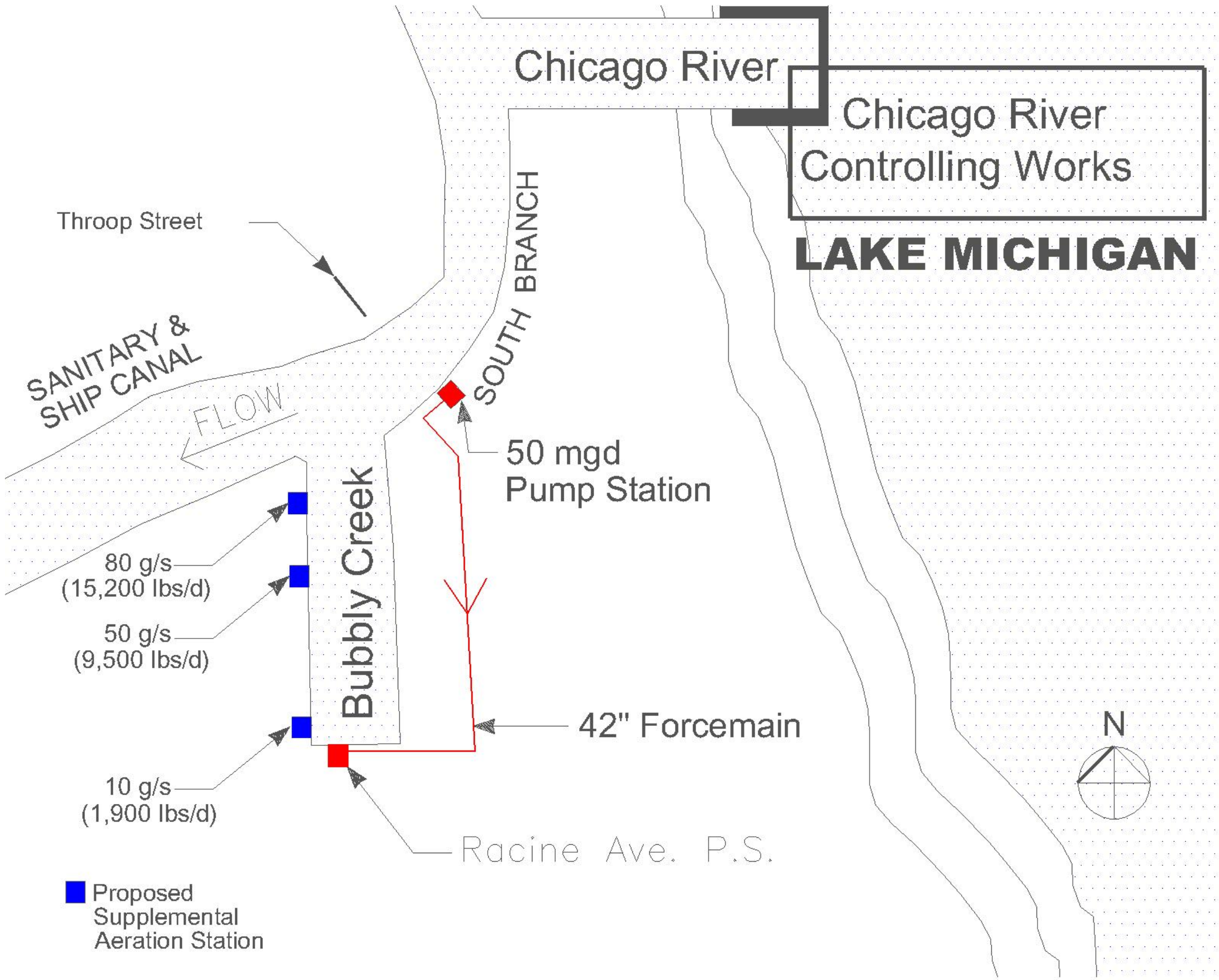
Current Chicago Waterway System Dissolved Oxygen Standards



Proposed Chicago Waterway System Dissolved Oxygen Standards

From CTE, Zenz (2007)

Flow Augmentation & Supplemental Aeration of Bubbly Creek



From CTE, Zenz (2007)

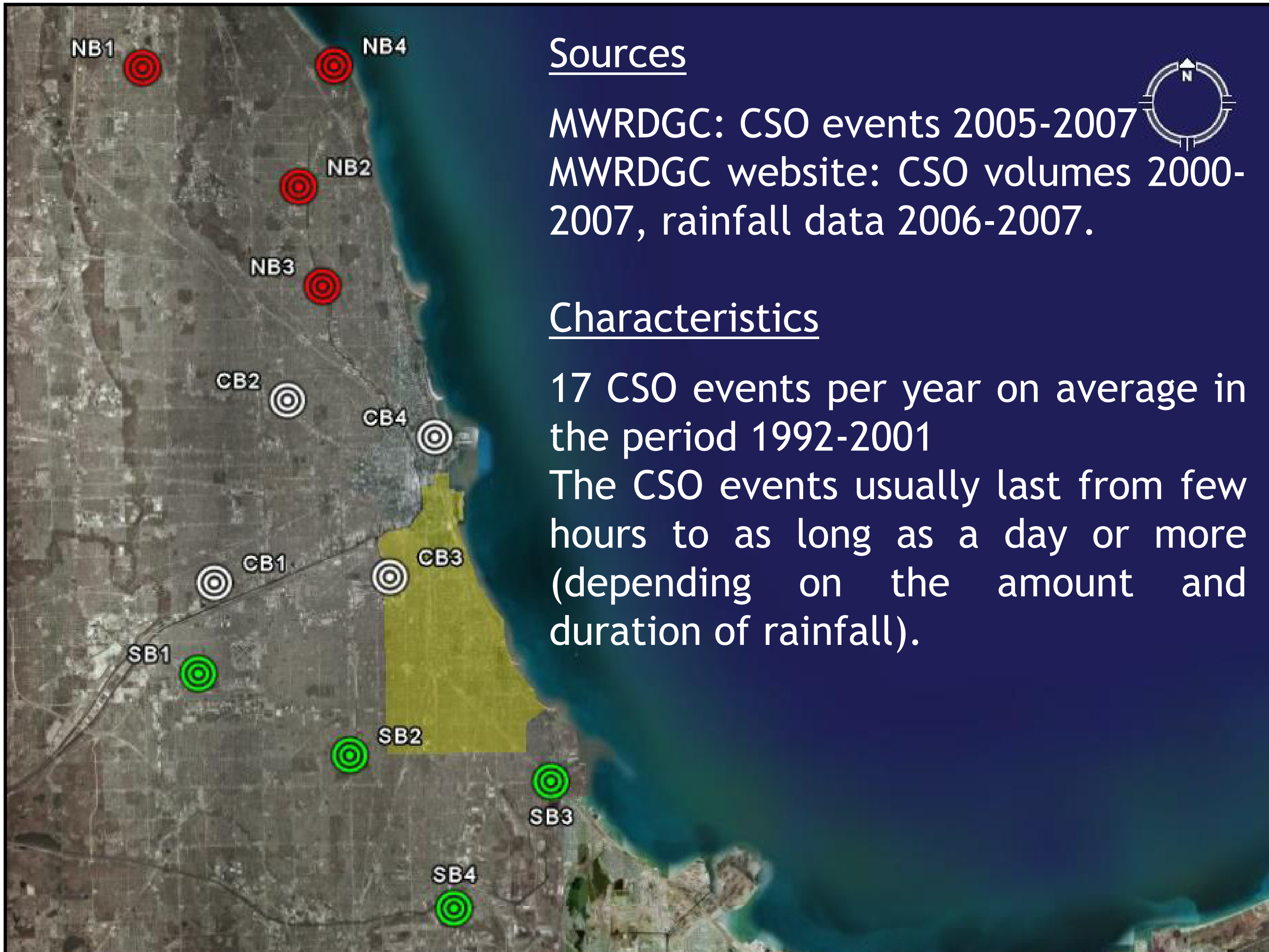
Costs for Flow Augmentation and Supplemental Aeration of Bubbly Creek

- Capital Costs of 60.4 million to $102.9 million
- Annual costs of $1.0 million to $2.8 million

From CTE, Zenz (2007)

Hydrology of Bubbly Creek

HISTORIC CSO EVENTS



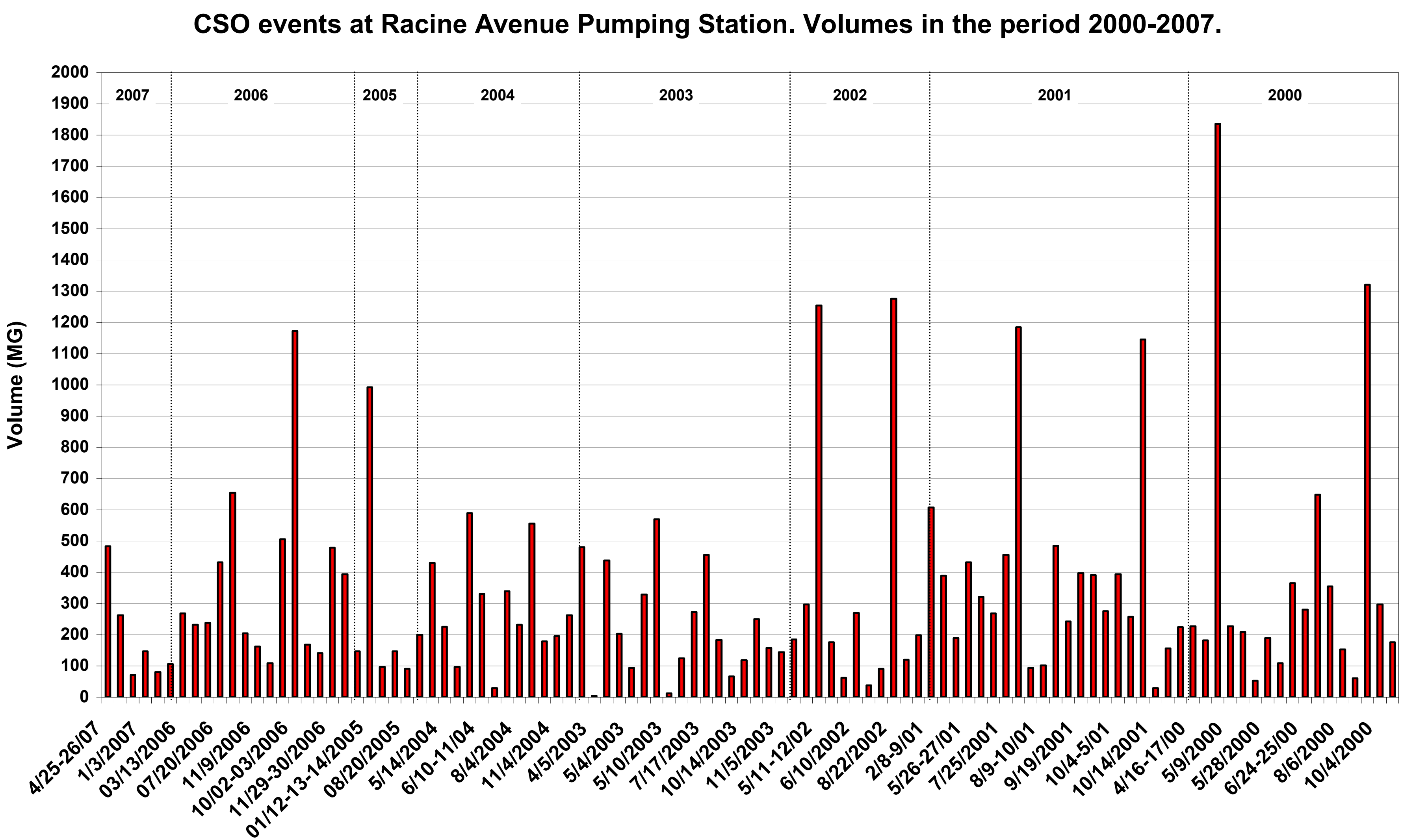
Sources

MWRDGC: CSO events 2005-2007
MWRDGC website: CSO volumes 2000-2007, rainfall data 2006-2007.

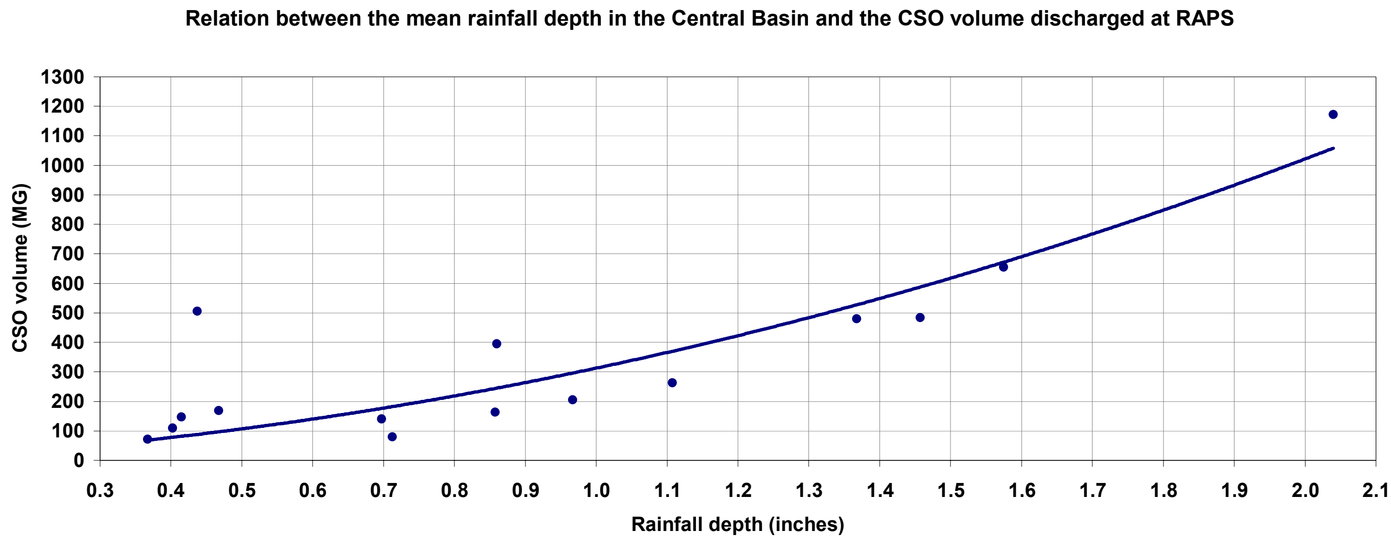
Characteristics

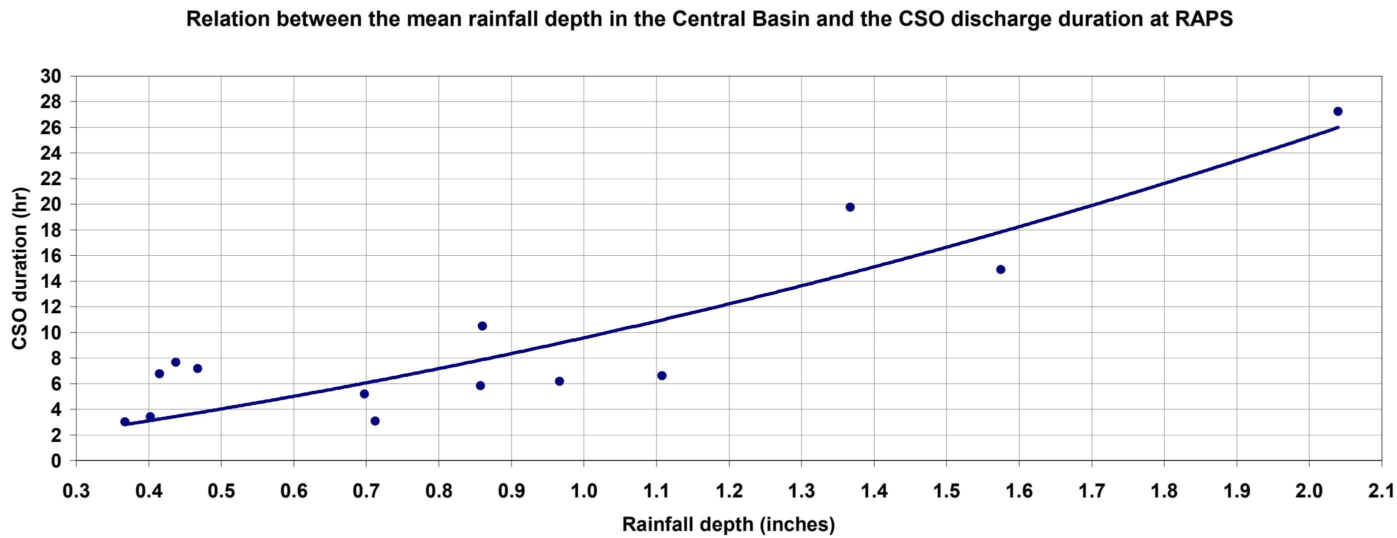
17 CSO events per year on average in the period 1992-2001
The CSO events usually last from few hours to as long as a day or more (depending on the amount and duration of rainfall).

CSO VOLUMES 2000-2007



CORRELATIONS RAINFALL-VOLUME-DURATION





RAPS Service Area

Catchment Description

- The service area contributing to the Racine Pumping Station (RAPS)
- Area ~ 36 square miles,
- Population ~463400
- households ~169900, all susceptible to basement backup flooding

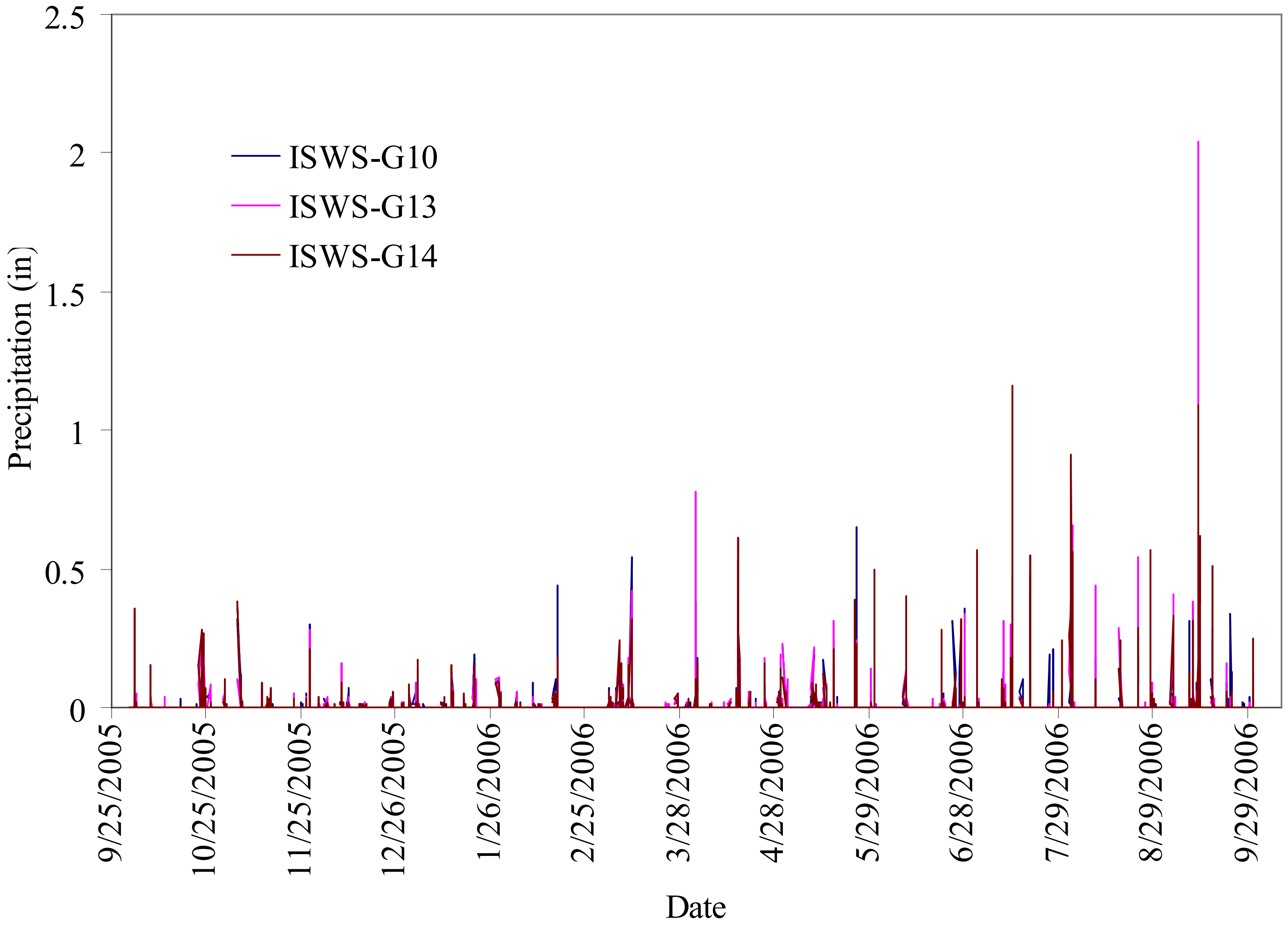
Pumping Station

- The Racine Pumping Station (RAPS) receives flows from the entire service area. This station currently pumps flows to the Stickney Water Reclamation Plant (SWRP) and also pumps overflows during CSO events to the South Fork of the South Branch (SFSB) of the Chicago River.

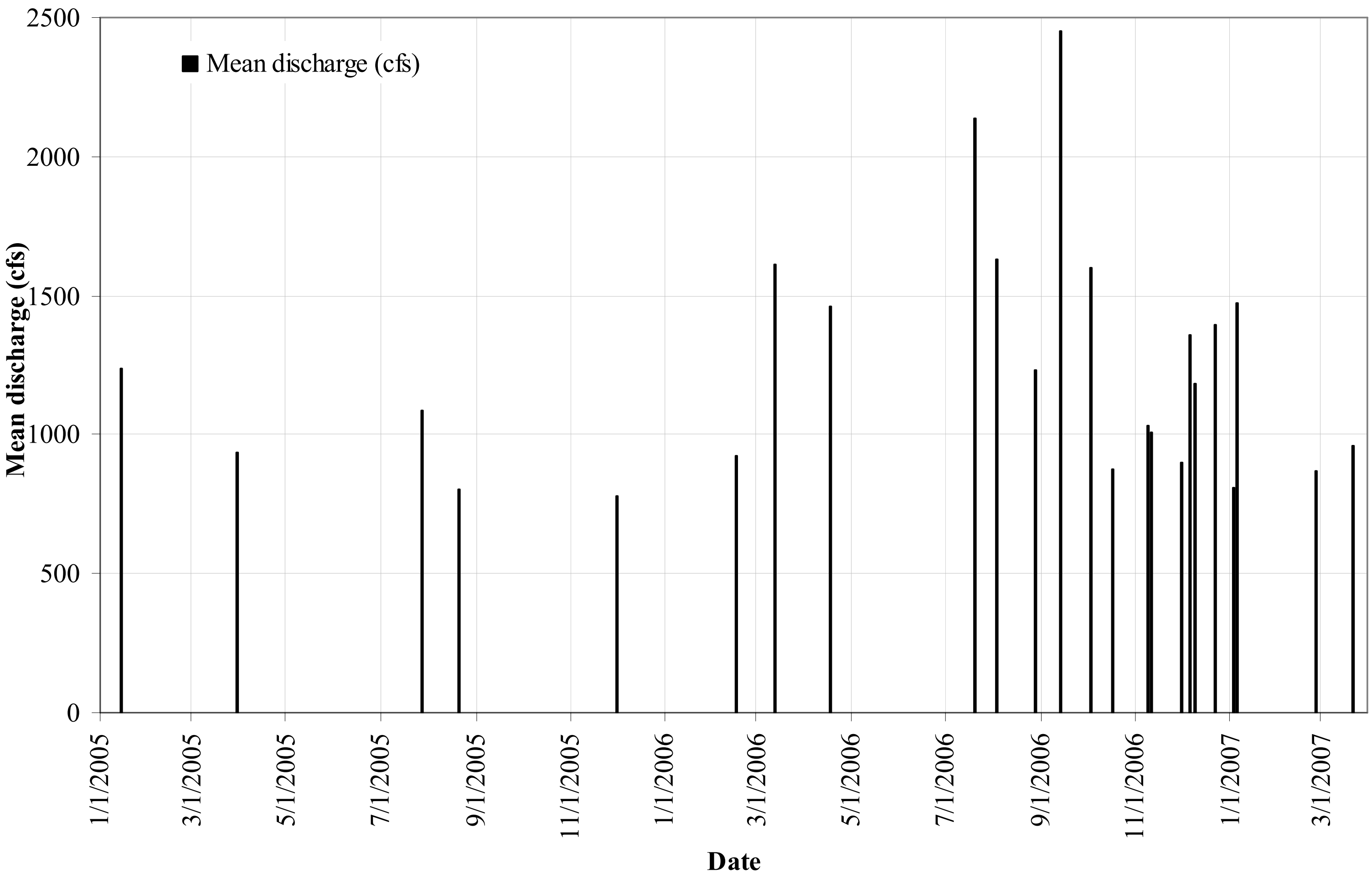
- The existing station has fourteen individual pumps. Five pumps pump to SWRP and the remaining nine pumps pump to the SFSB during CSO events.

Data

Long Term Rainfall Data (ISWS Rain Gages)



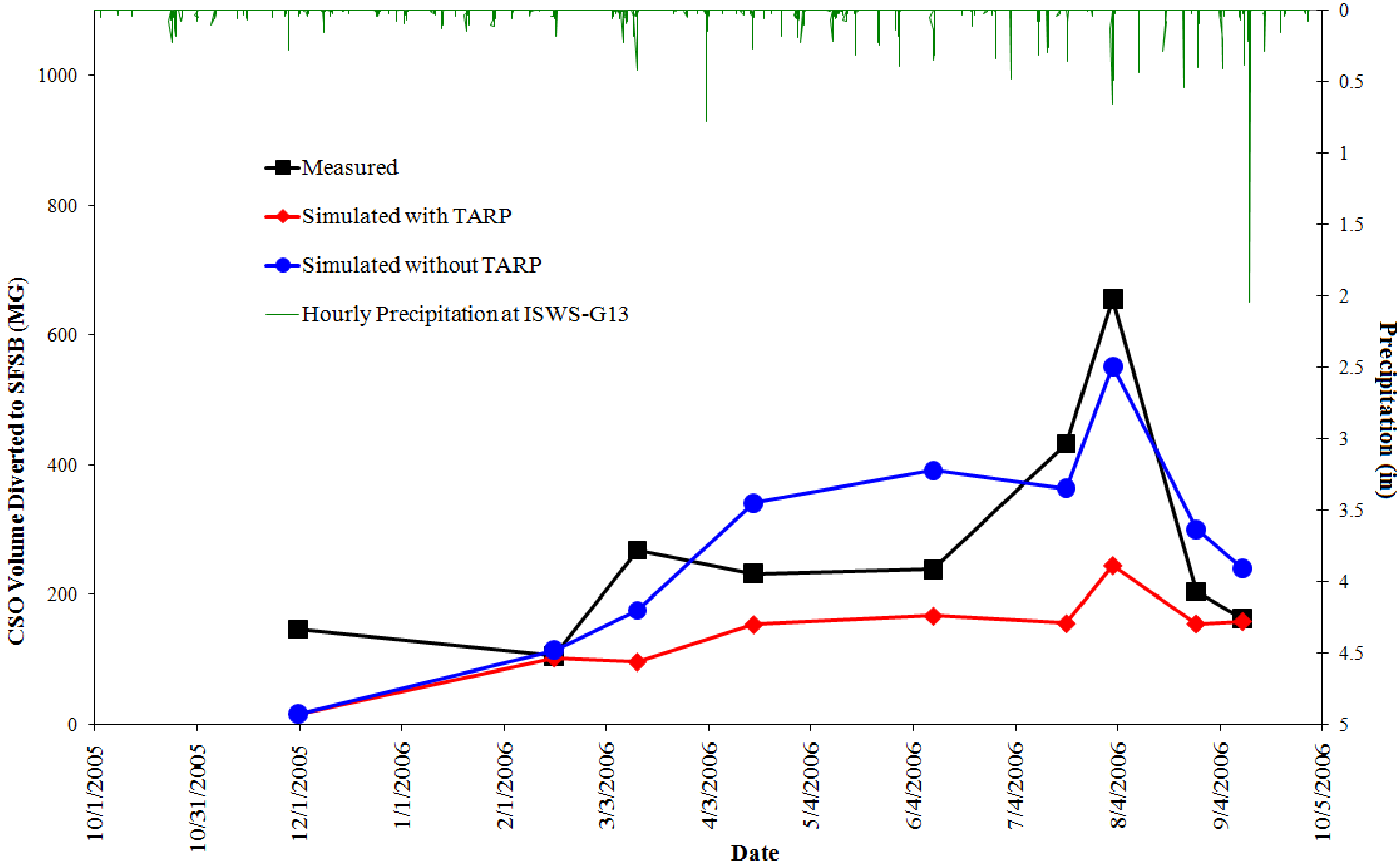
CSO Flow Data



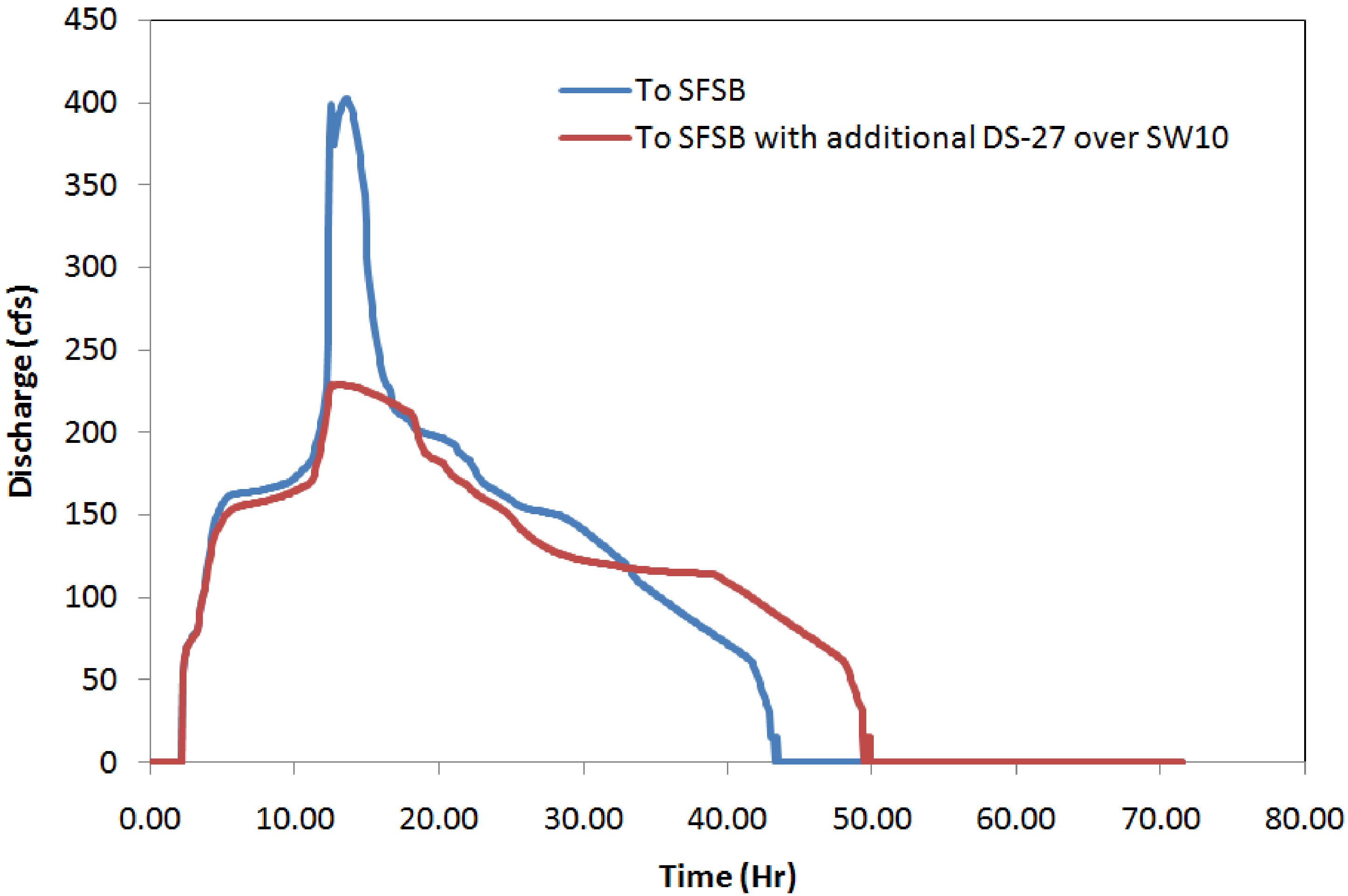
- Daily mean discharges diverted to the Bubbly Creek during CSO events. Period 01/01/2005 to 3/30/2007.

Modeling Results

A. Historical Long term rainfall runoff simulations



Comparison of simulated and measured CSO volumes discharged to Bubbly Creek.
Connection to TARP included (DS-27, DS-28, DS-29).



The effect of an additional DS on the SW10-39St conduit on CSO diverted to Bubbly Creek (SFSB).

Summary

- Even though five sub-catchments were adopted for the analysis to characterize the service area of each one of the main interceptors draining to the pump station, reasonable estimates of the inflows to RAPS are obtained after comparing with measured outflows to SFSB during CSO events for Historical run made for the WY2006.

- Discharging into TARP via drop shafts 27, 28, and 29 decreases the total inflow to RAPS.

- Adding another drop shaft could reduce the inflow to RAPS and therefore to Bubbly Creek.

- Exclusion of snow depths on the simulations of continuous rain, WY2006, will lead to miscalculation of more realistic infiltration and runoff values, hence affecting the calculations of the total amount of flows draining to the pump station.

2D modeling of Bubbly Creek (2008)

Bubbly Creek, South Fork of the South Branch of the Chicago River

- **historically** used as a drainage channel for the waste resulting from Chicago's stockyards;
- **nowadays** there is flow in the creek only during rainfall events resulting in Combined Sewer Overflows (CSO) and water quality is a very important issue, particularly during the summer months. Revived interest in Bubbly Creek.

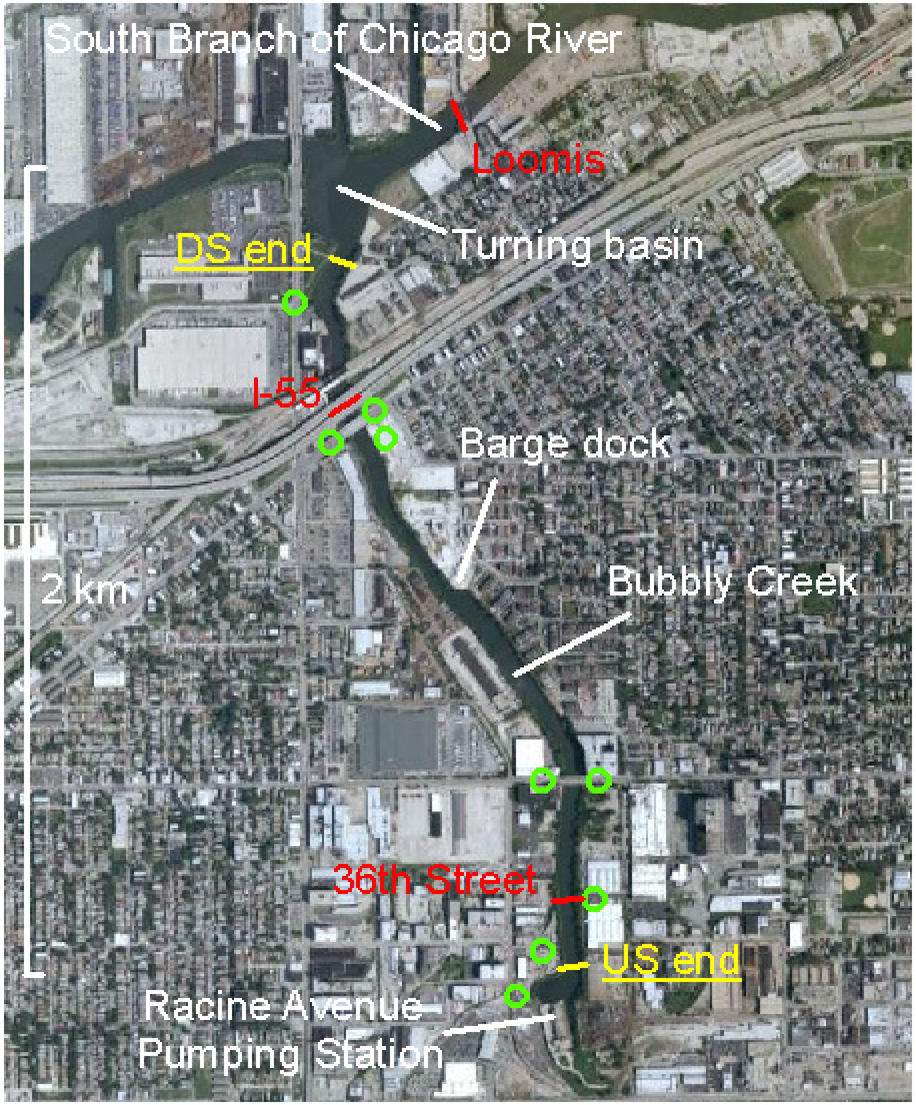
Two scenarios analyzed

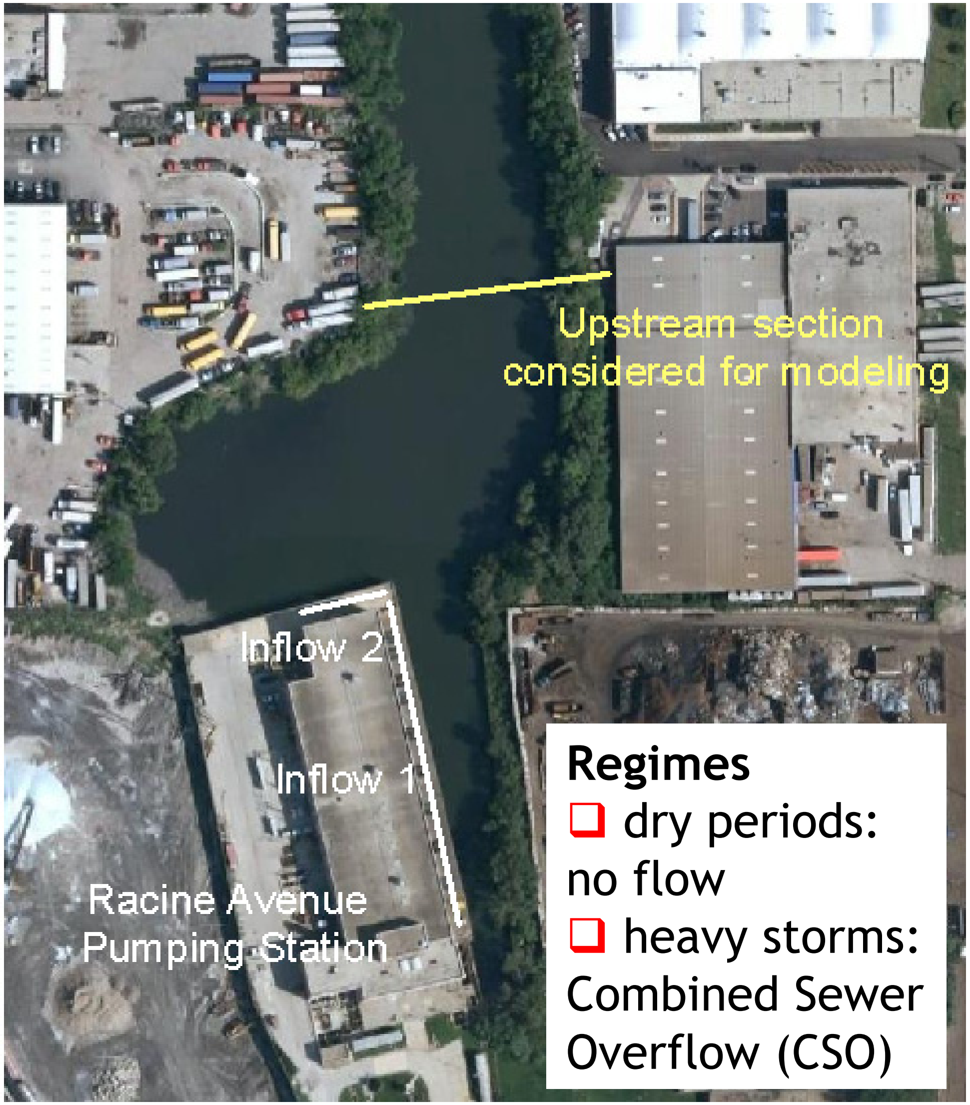
- **CSO events;**
- **potential "purification" solutions**, such as flow augmentation and supplemental aeration, with the goal of increasing the DO levels in the creek during dry weather periods.

Modeling

2-D depth-averaged numerical model **STREMR-HySedWq** which couples **hydrodynamics**, **sediment transport** and **water quality (BOD-DO)**.

Bubbly Creek, Chicago

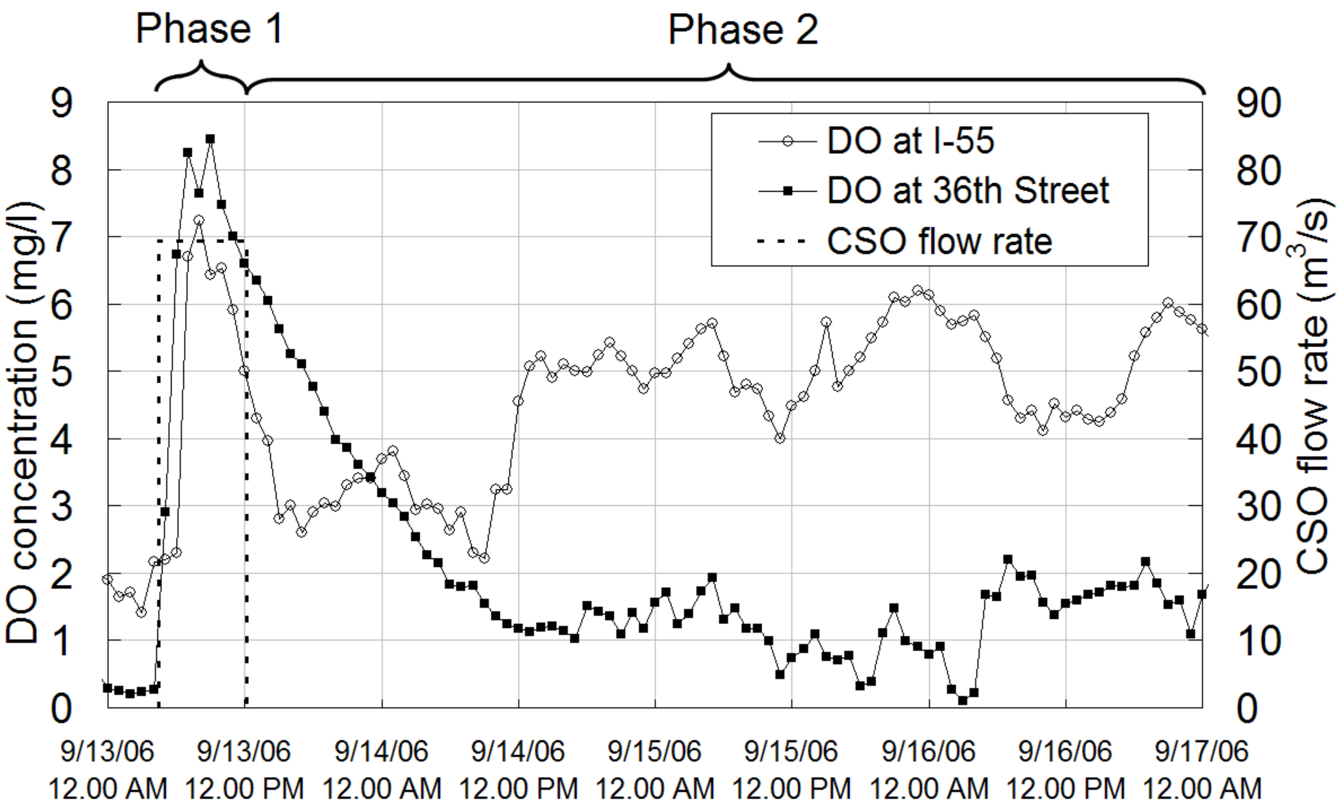




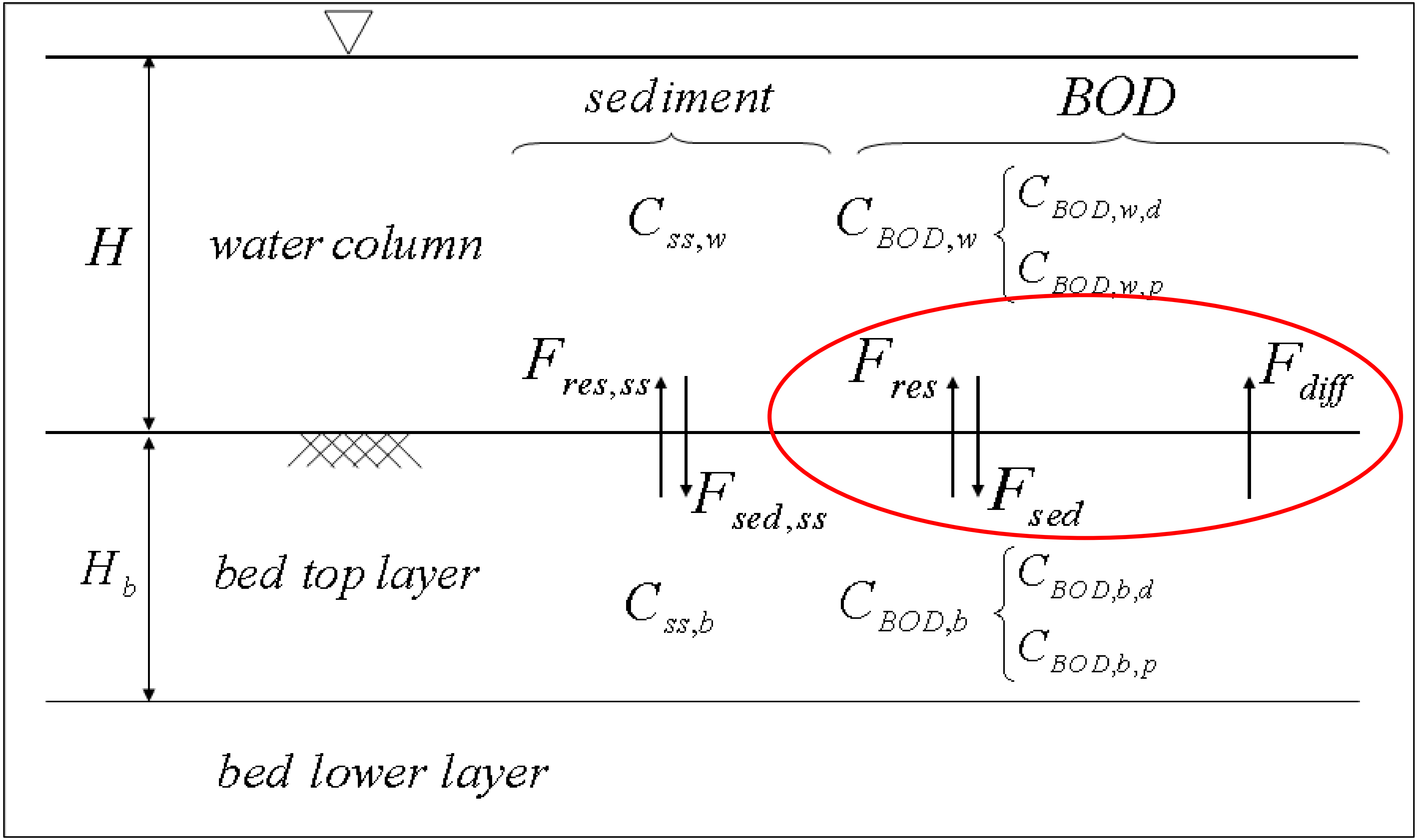
Regimes

- dry periods: no flow
- heavy storms: Combined Sewer Overflow (CSO)

CSO event of September 13, 2006

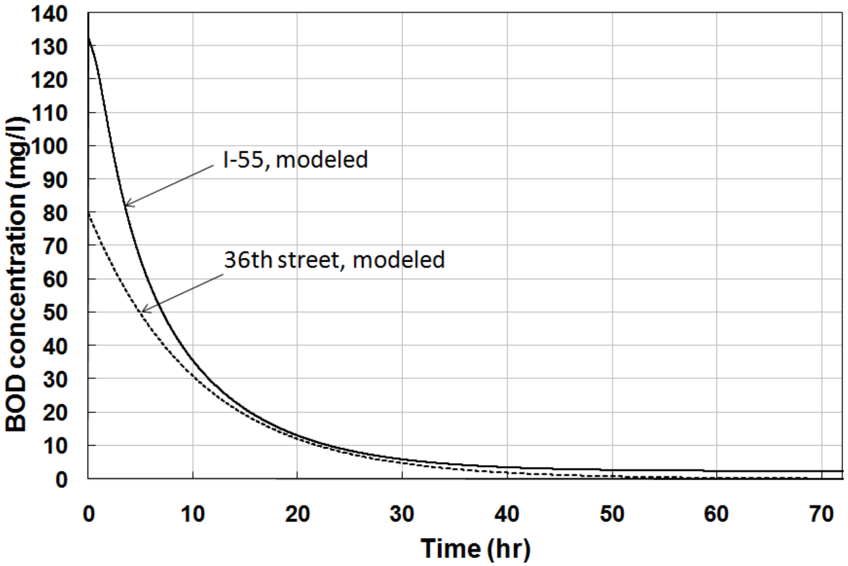


BOD bed/water column exchange

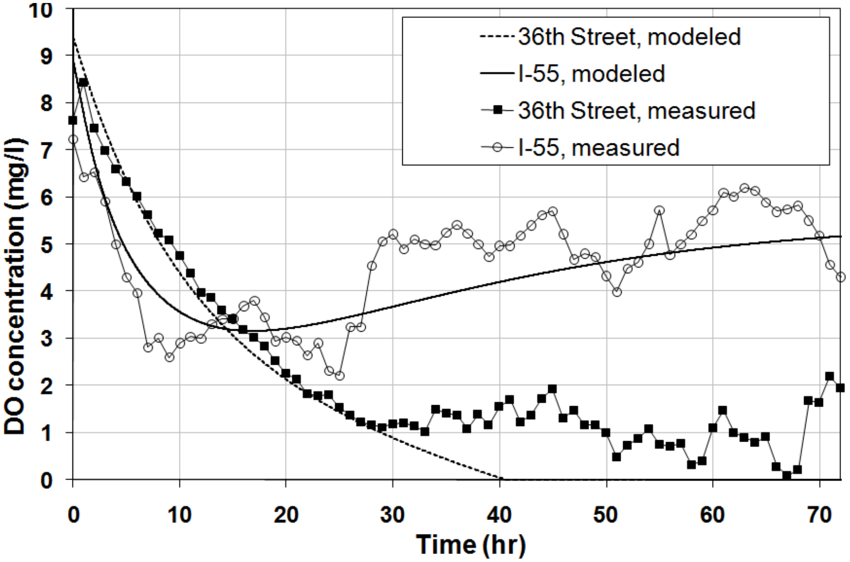


CSO event - “Phase 2” - BOD and DO evolution

BOD



DO



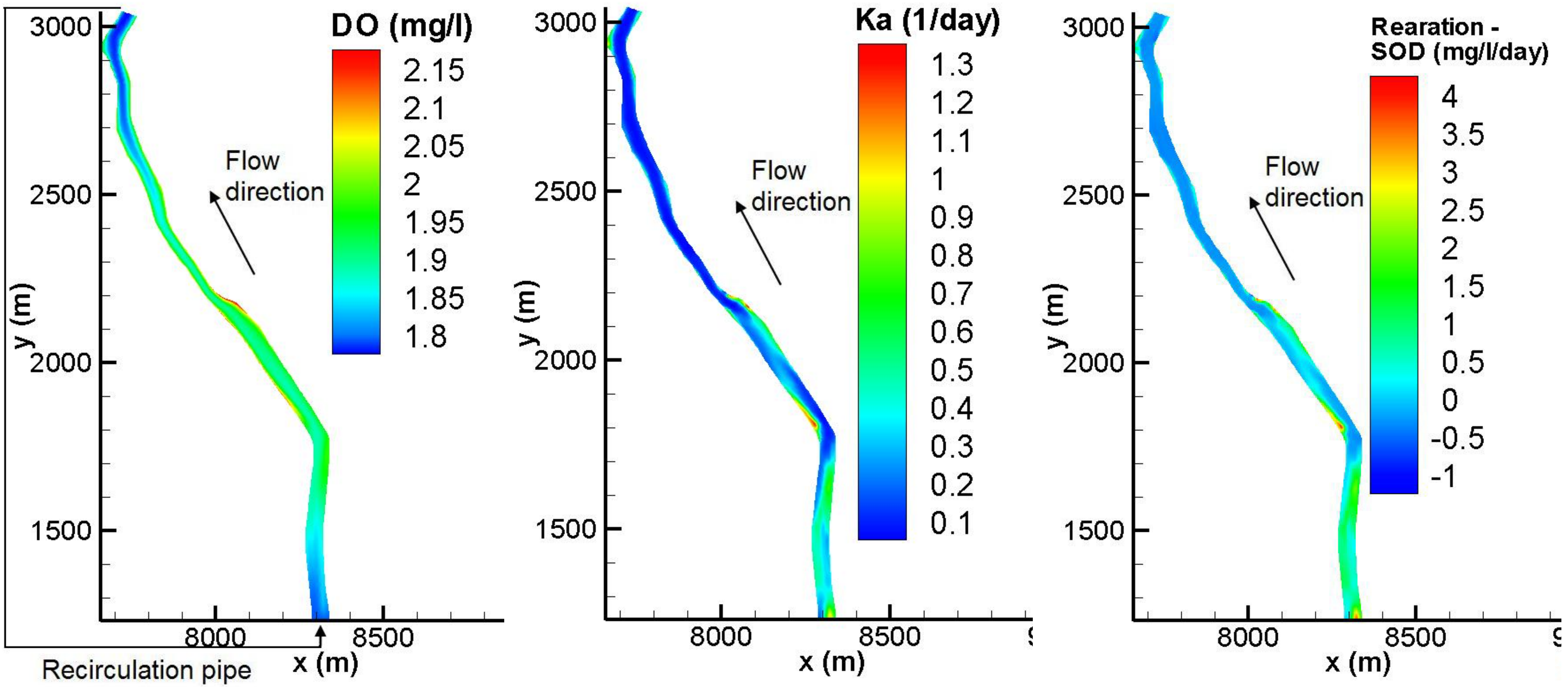
Motta, D., Abad, J.D., Garcia, M.H.
A modeling framework for organic sediment resuspension and oxygen demand: the case of Bubbly Creek in Chicago, Illinois
Journal of Environmental Engineering (Sep 2010)

"Purification" scenarios

<u>SCENARIO 1</u>: flow recirculation of 50 MGD (2.19 m^3/s), northward flow in the creek

Summer or after CSO event scenario; abstraction of daily fluctuation due to photosynthesis and respiration.

- **BOD:** oxidation and settling → BOD concentration decreases;
- **DO:** oxidation and sediment oxygen demand (SOD) from the bed → DO concentration decreases; reaeration from the atmosphere → DO concentration increases.

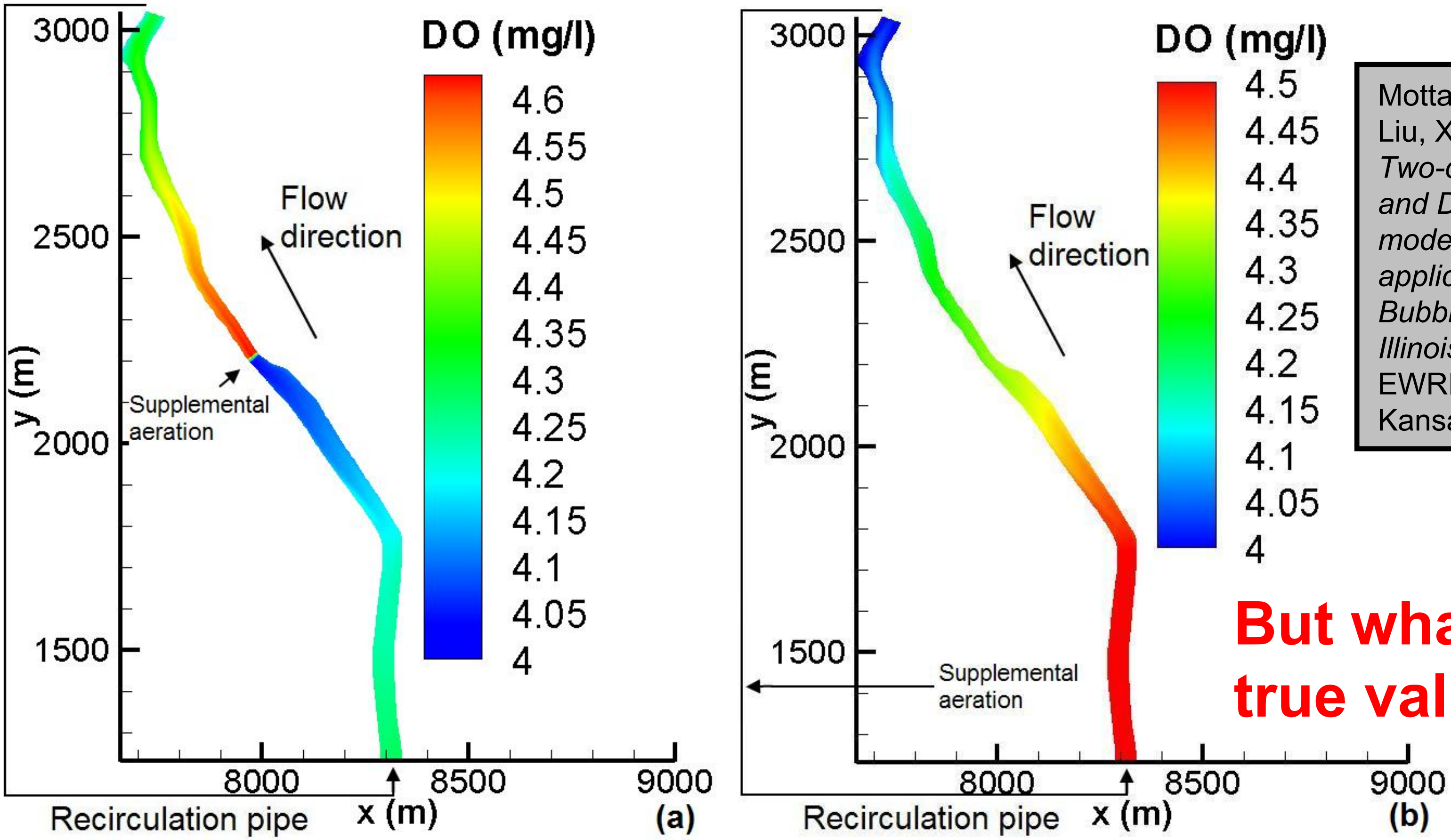


SOD = 2.32 $g/m^2/day$, no resuspension

“Purification” scenarios (contd.)

SCENARIO 2: flow recirculation (northward flow in the creek) plus supplemental aeration (1.31 g/s) in one location in the creek

SCENARIO 3: flow recirculation (northward flow in the creek) plus supplemental aeration (1.31 g/s) in the recirculation pipe



Motta, D., Abad, J.D., Liu, X., Garcia, M.H. *Two-dimensional BOD and DO water quality model for engineering applications: the case of Bubbly Creek in Chicago, Illinois* EWRI Conference (2009) Kansas City

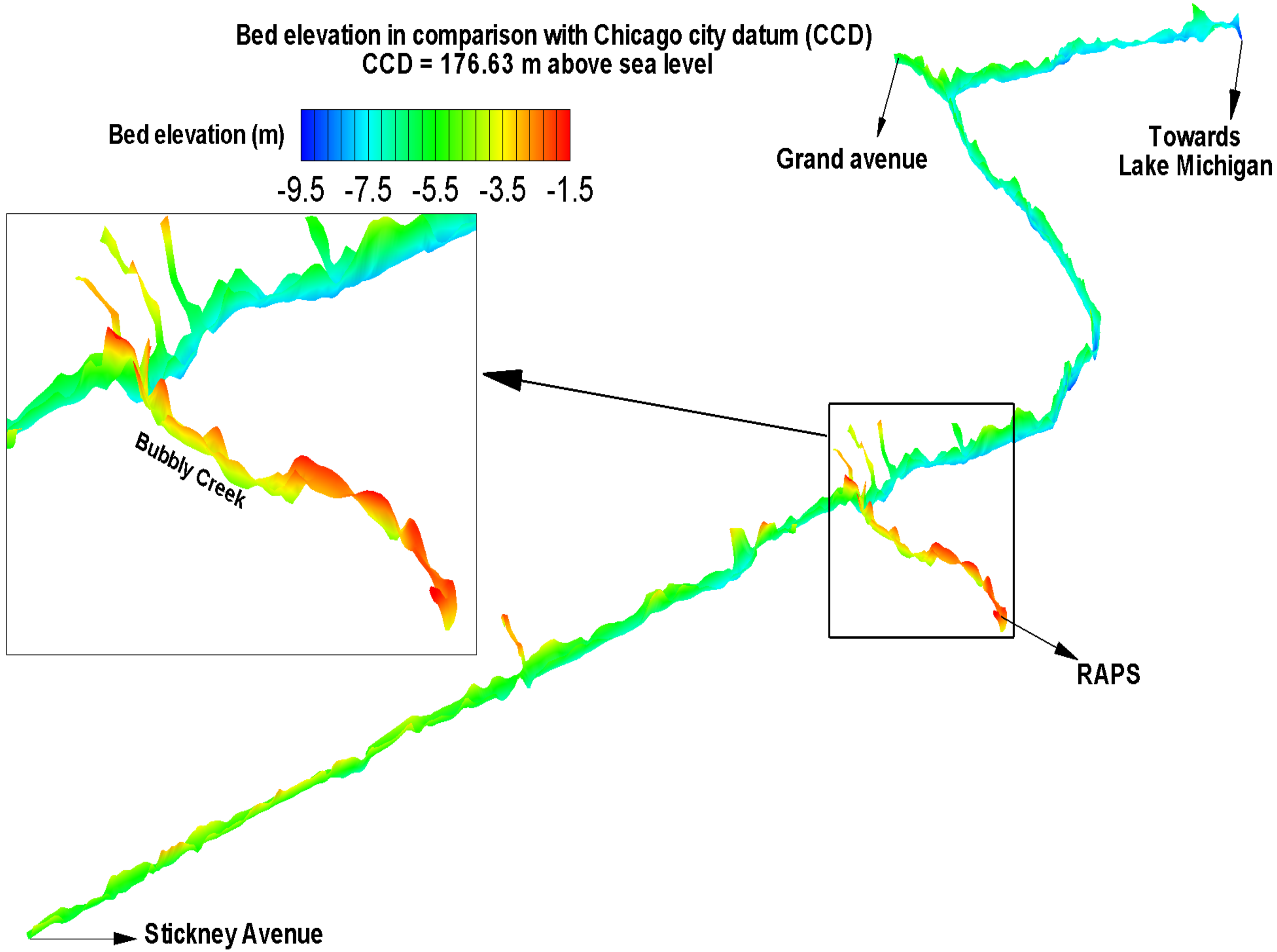
But what is the true value of SOD?

Summary of 2D modeling

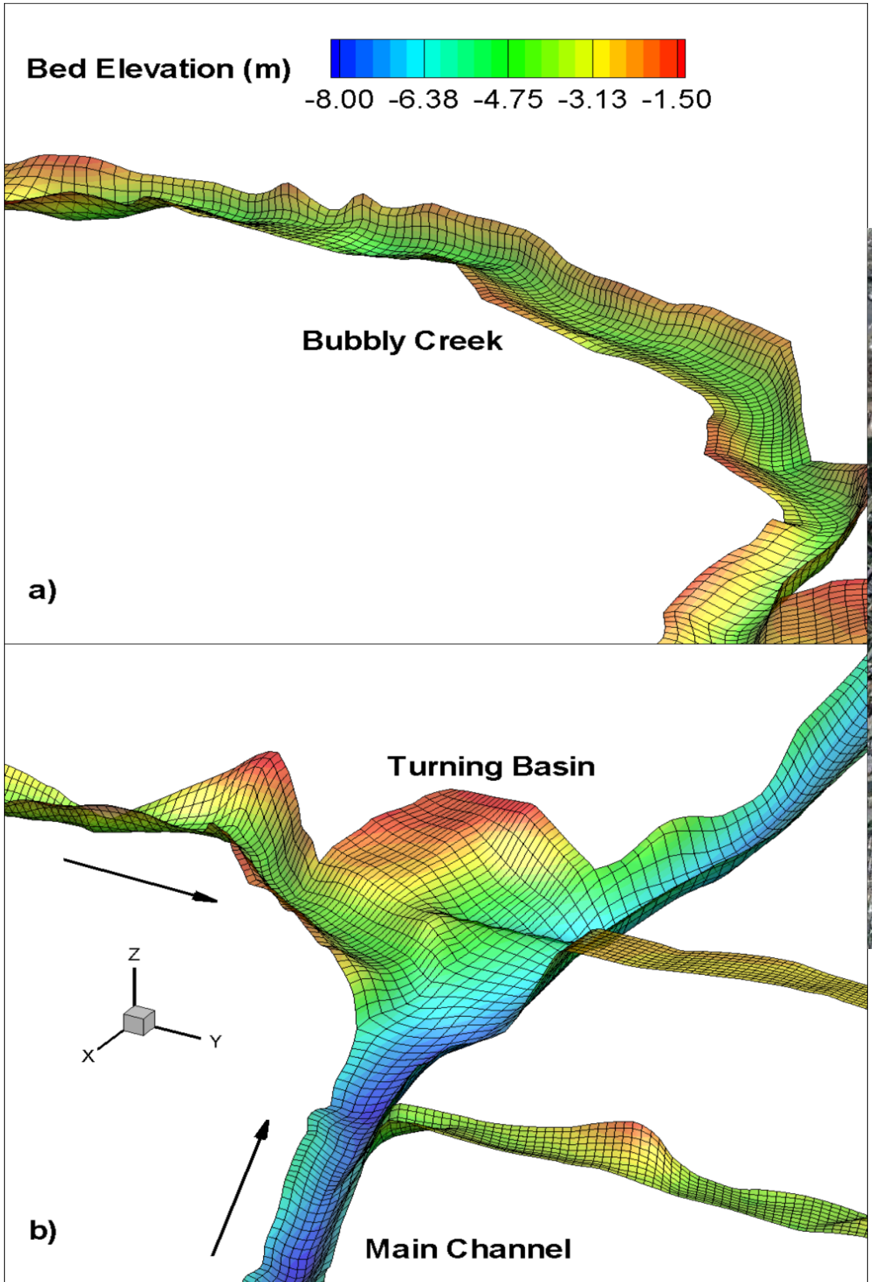
- Two-dimensional depth-averaged water quality BOD-DO model in the numerical code STREMR-HySedWq. Quantitative framework for the evaluation of the BOD transport across the bed/water interface in rivers was derived, in order to capture the additional oxygen demand in the water

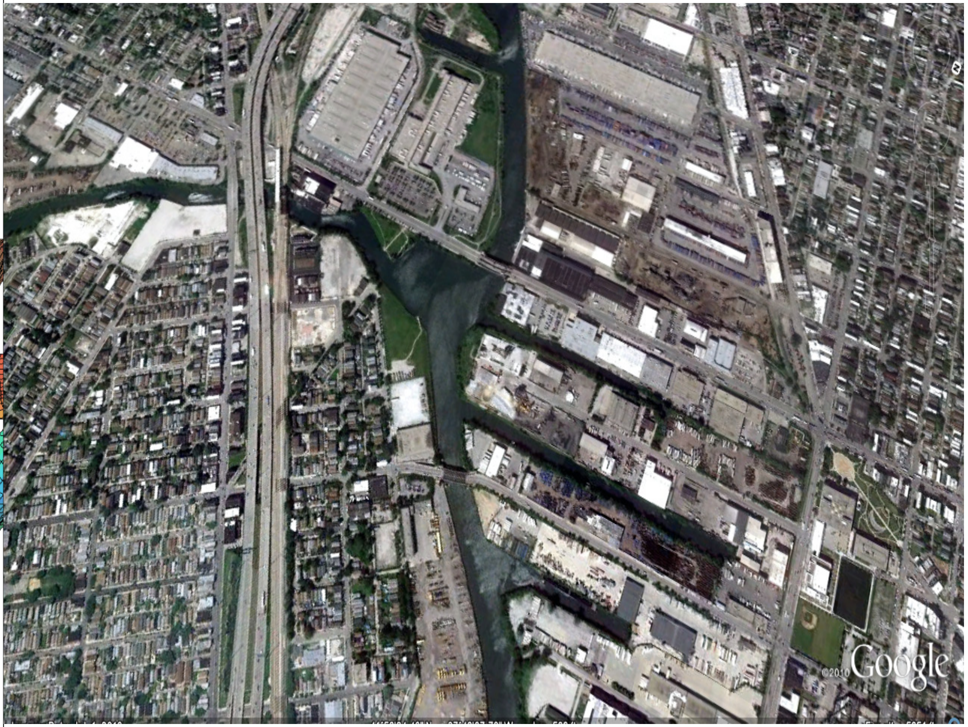
- SOD estimation is important for analysis of purification scenarios

3D modeling of Chicago waterways

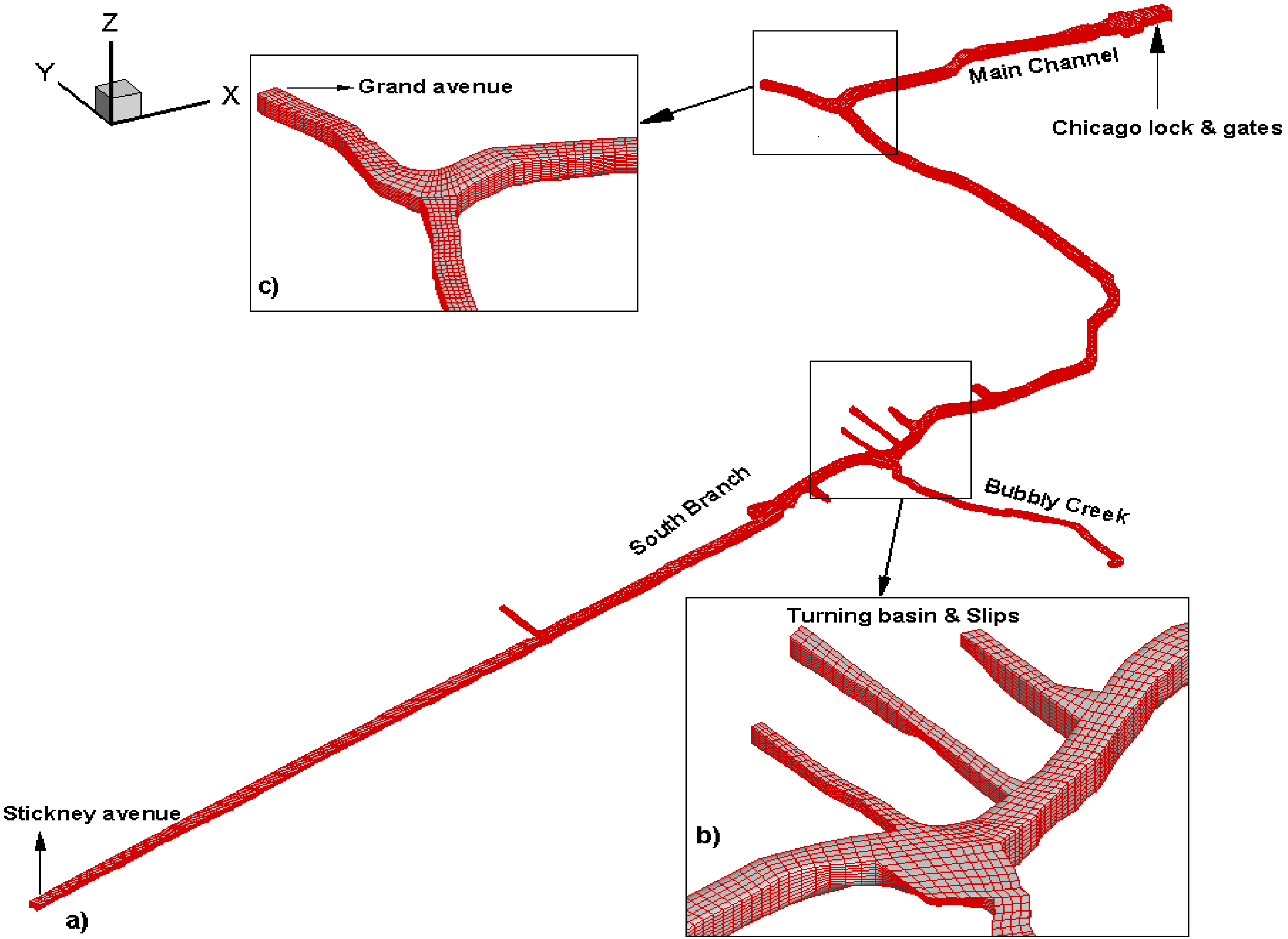


Closer Look at Bathymetry near Turning Basin

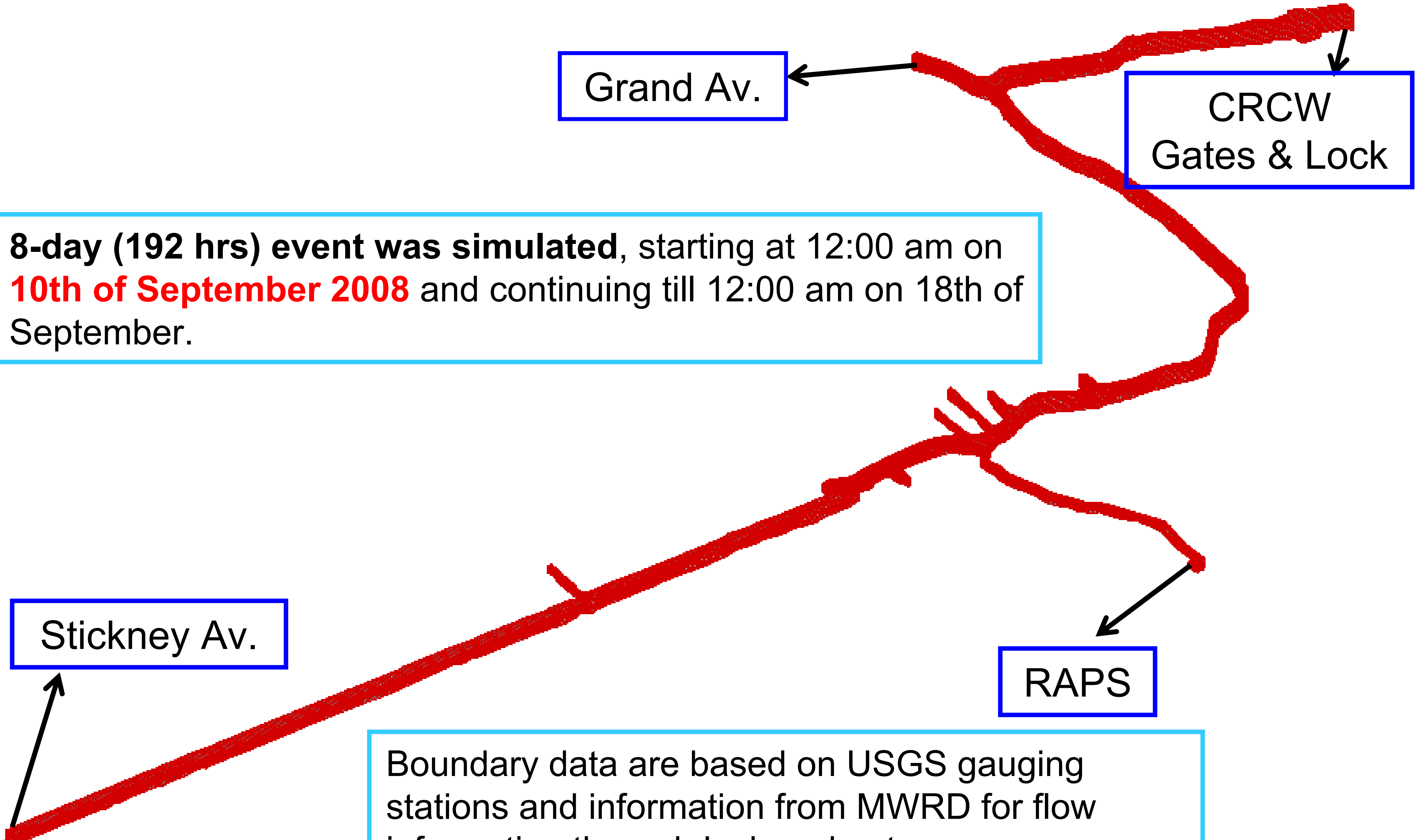




Computational mesh with 4400 cells in horizontal and 8 layers in vertical



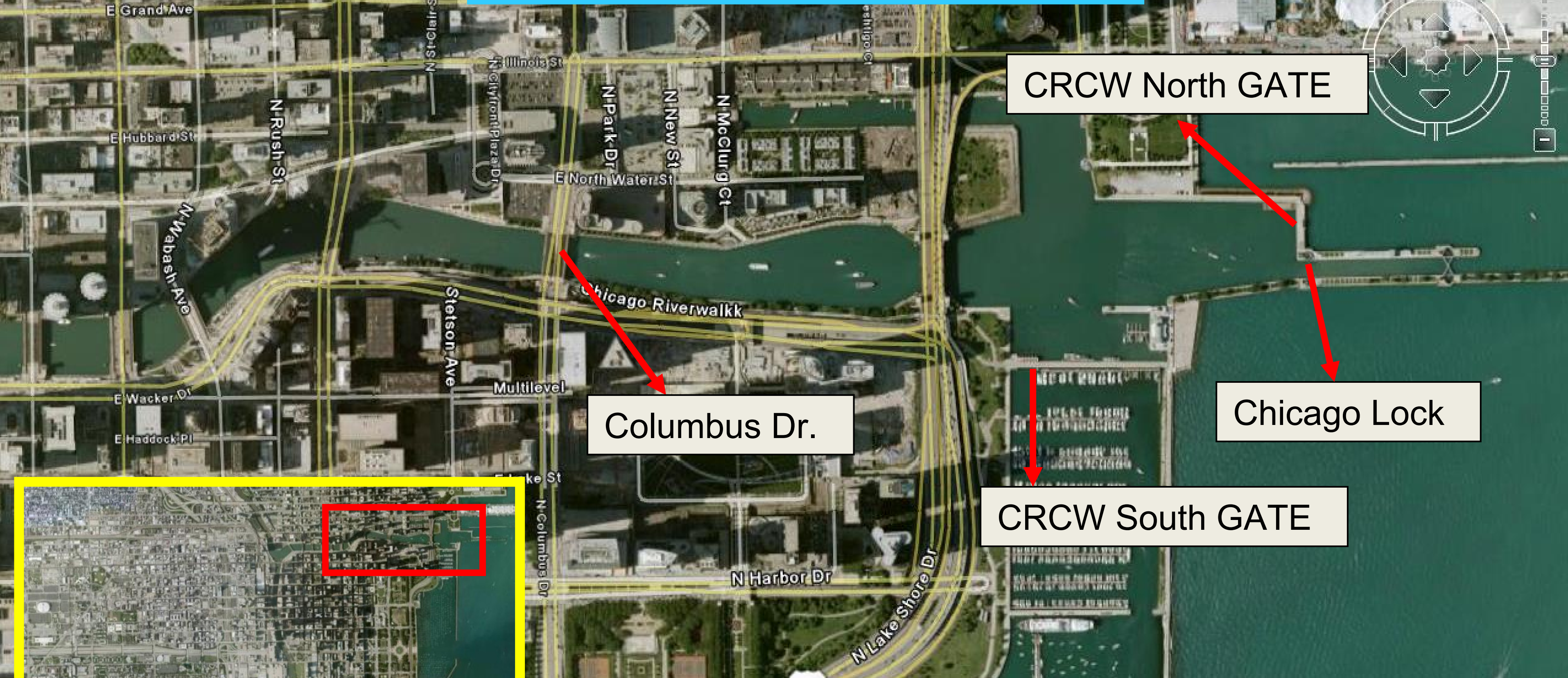
Setting of the 3D Hydrodynamic Simulation

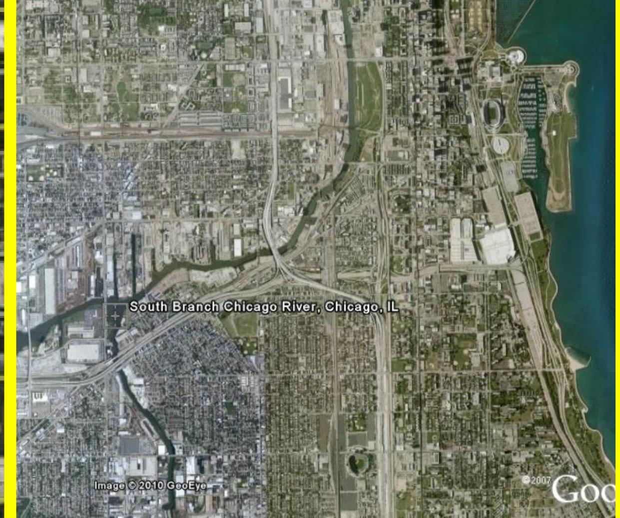


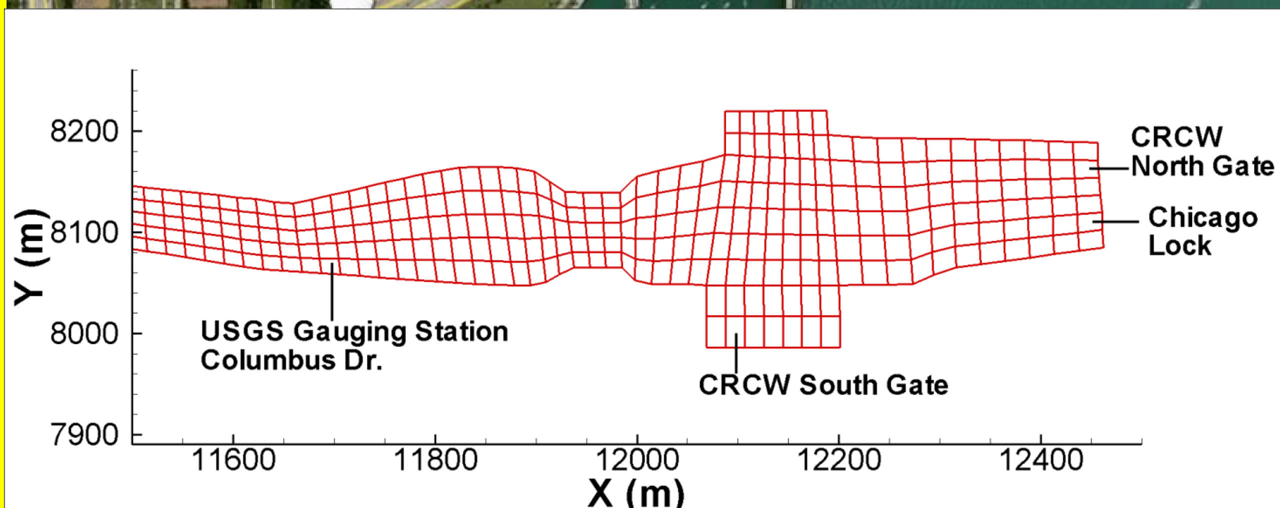
8-day (192 hrs) event was simulated, starting at 12:00 am on **10th of September 2008** and continuing till 12:00 am on 18th of September.

Boundary data are based on USGS gauging stations and information from MWRD for flow information through lock and gates

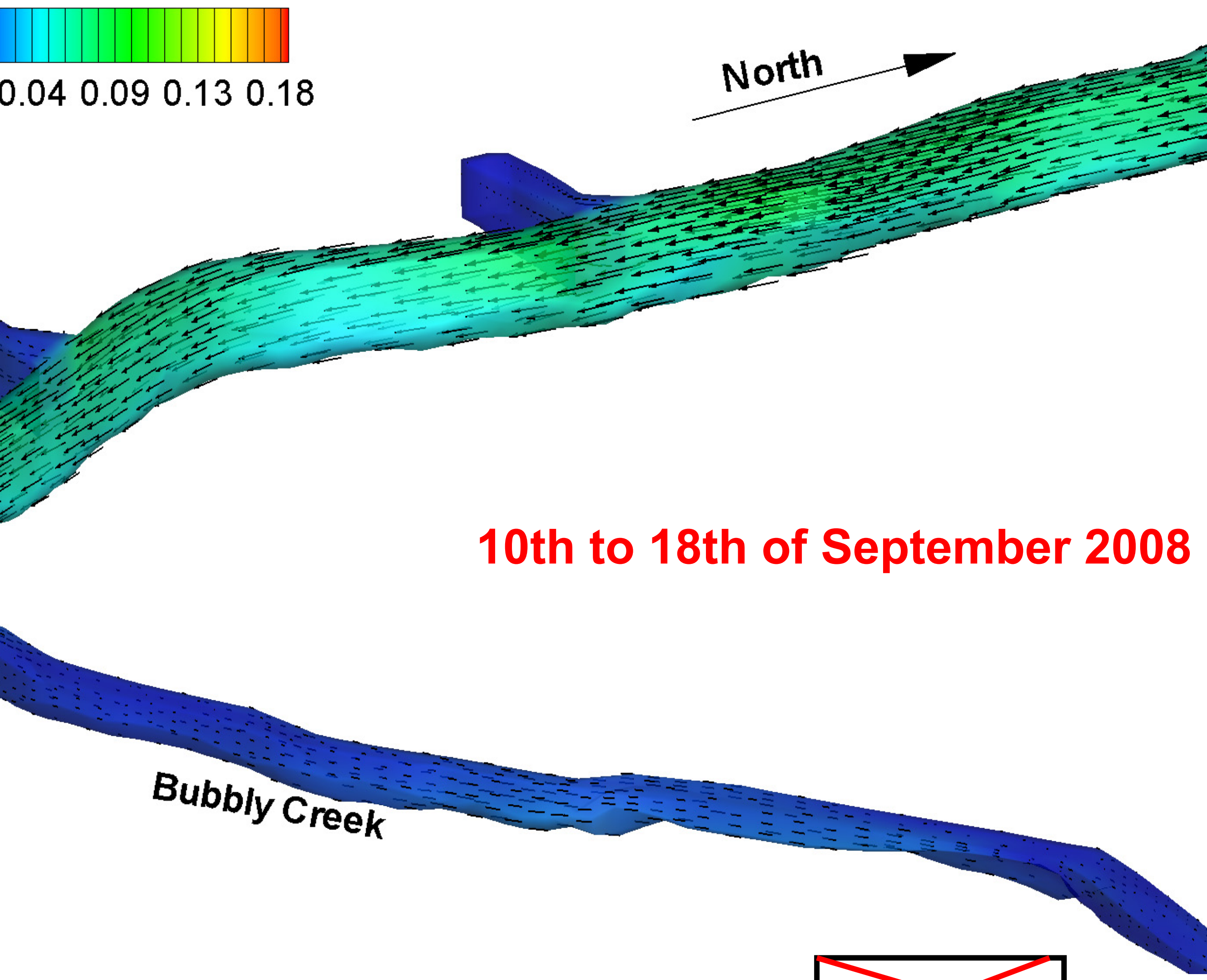
Location of Validation Point



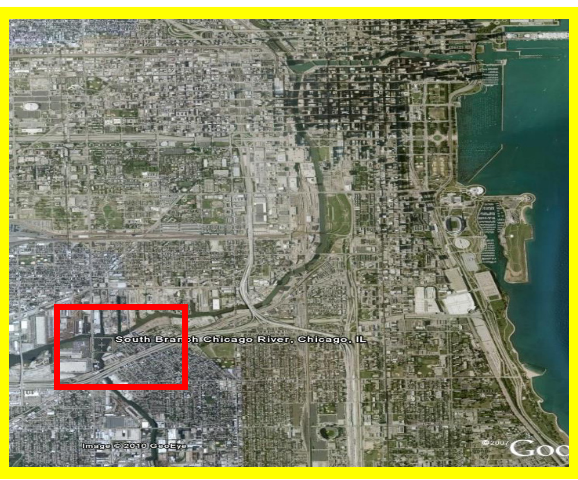




Velocity Magnitude 40 hrs after Start of Simulation



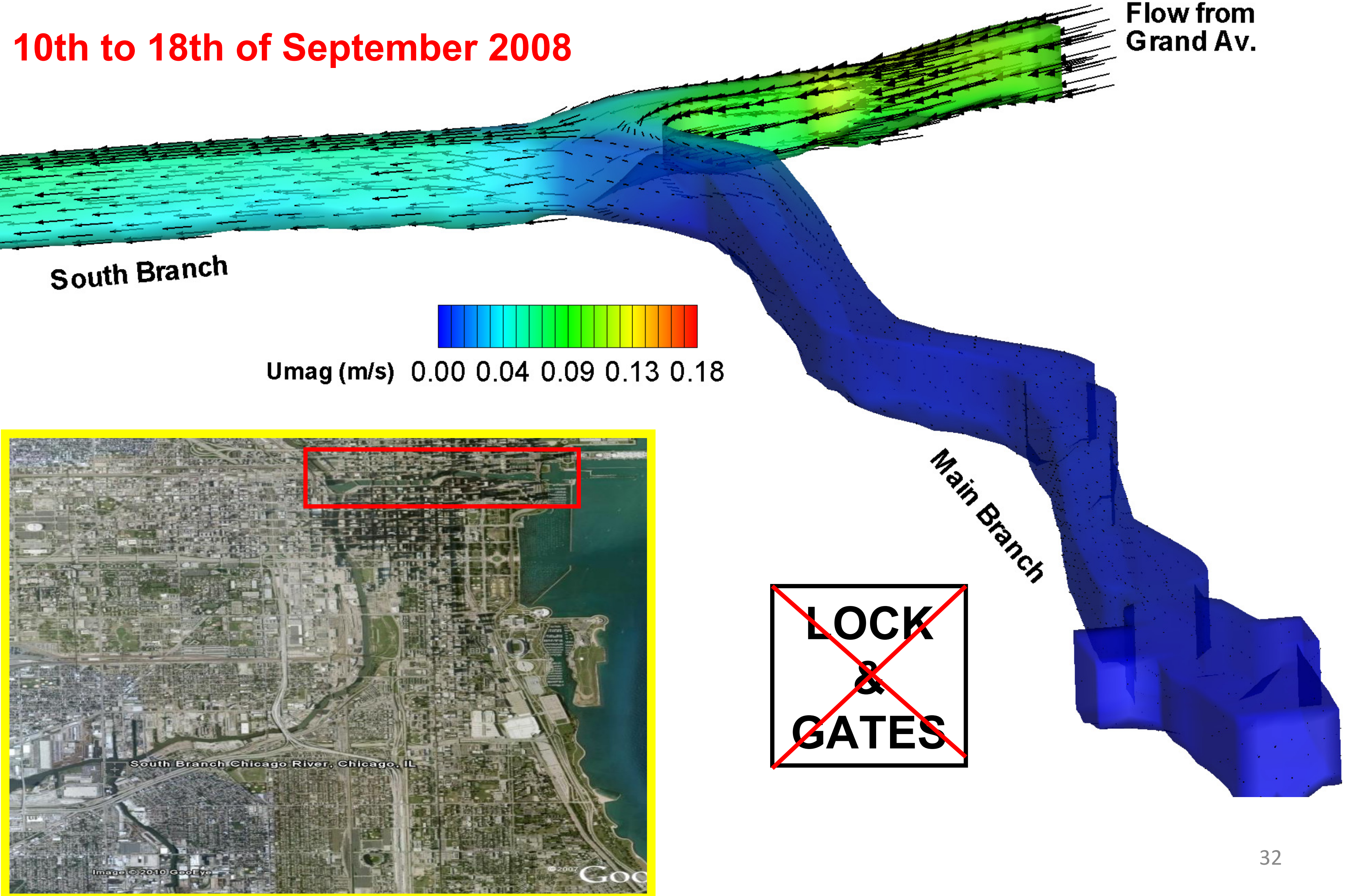
10th to 18th of September 2008



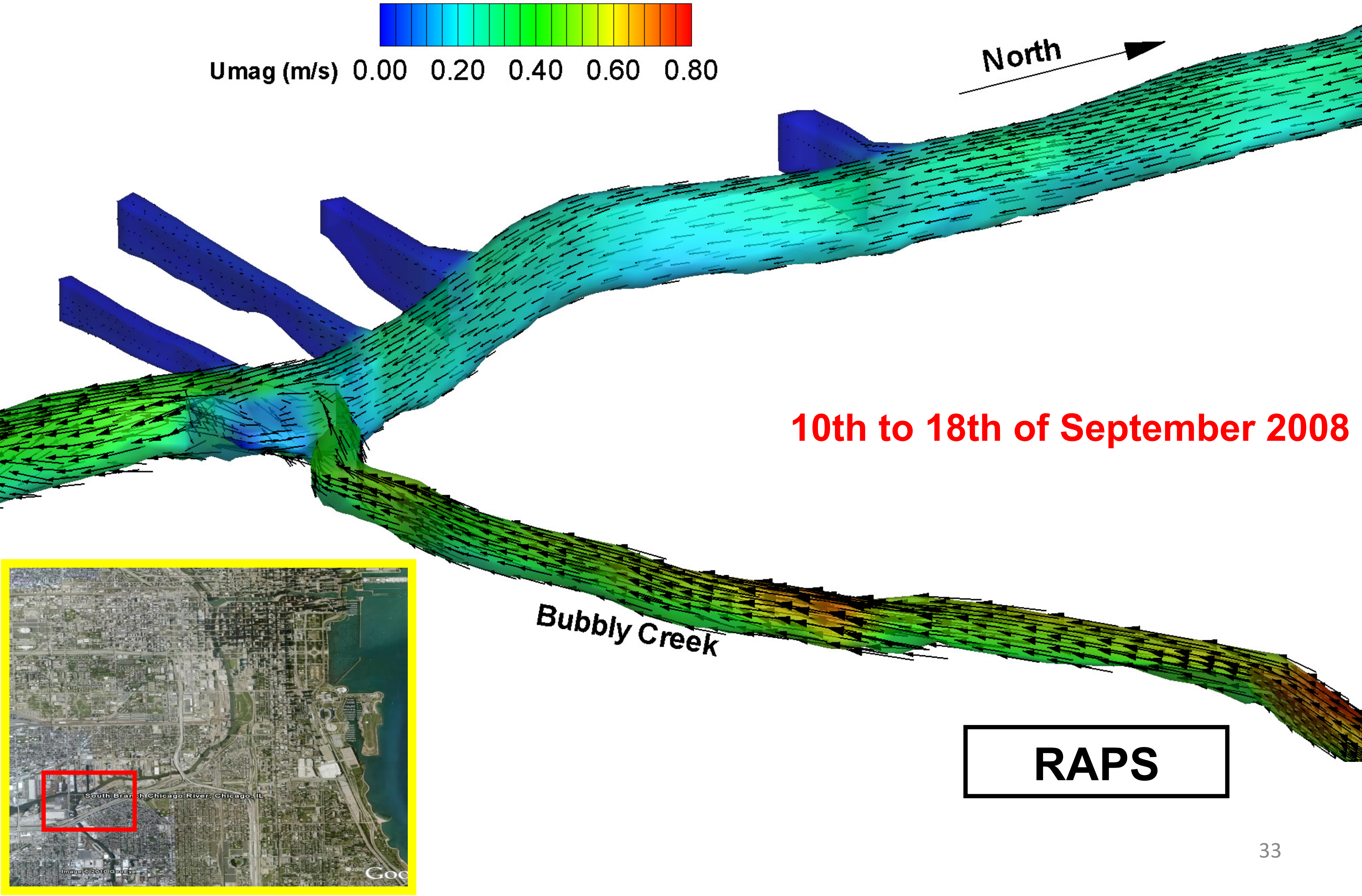
RAPS

Velocity Magnitude 40 hrs after Start of Simulation

10th to 18th of September 2008

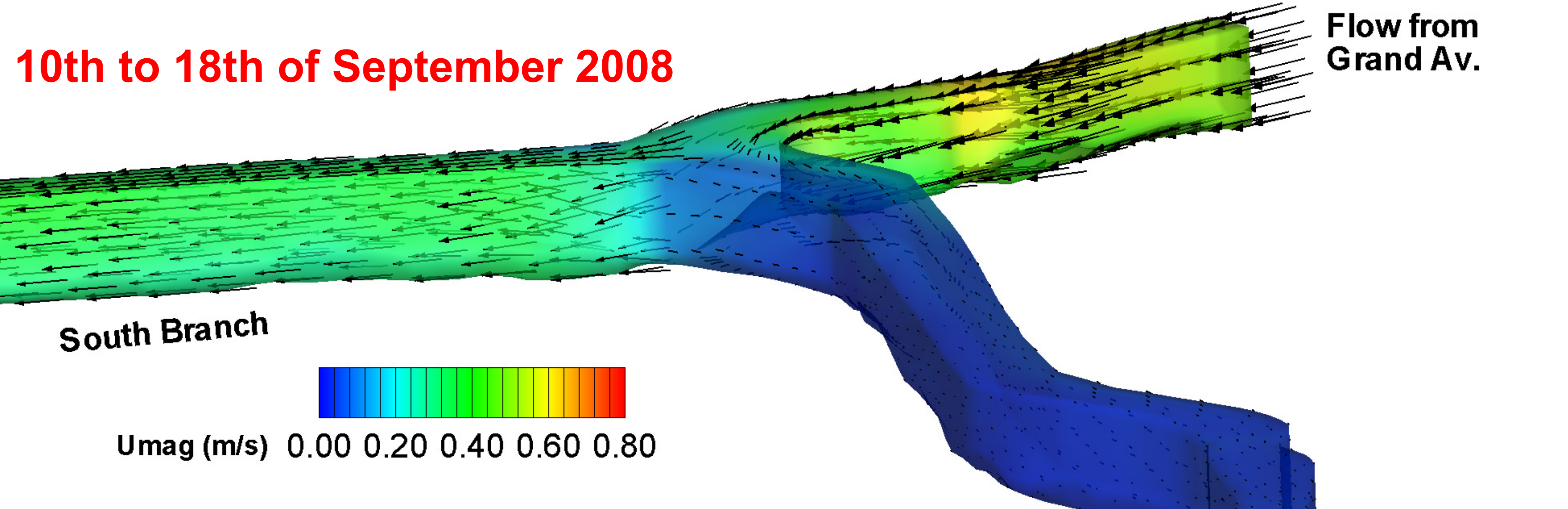


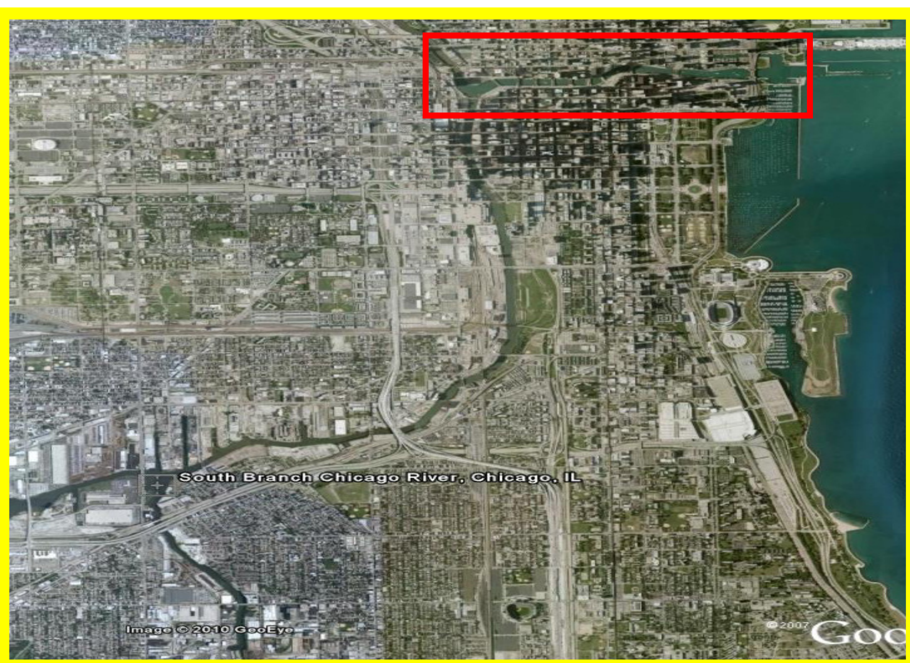
Velocity Magnitude 80 hrs after Start of Simulation



Velocity Magnitude 80 hrs after Start of Simulation

10th to 18th of September 2008

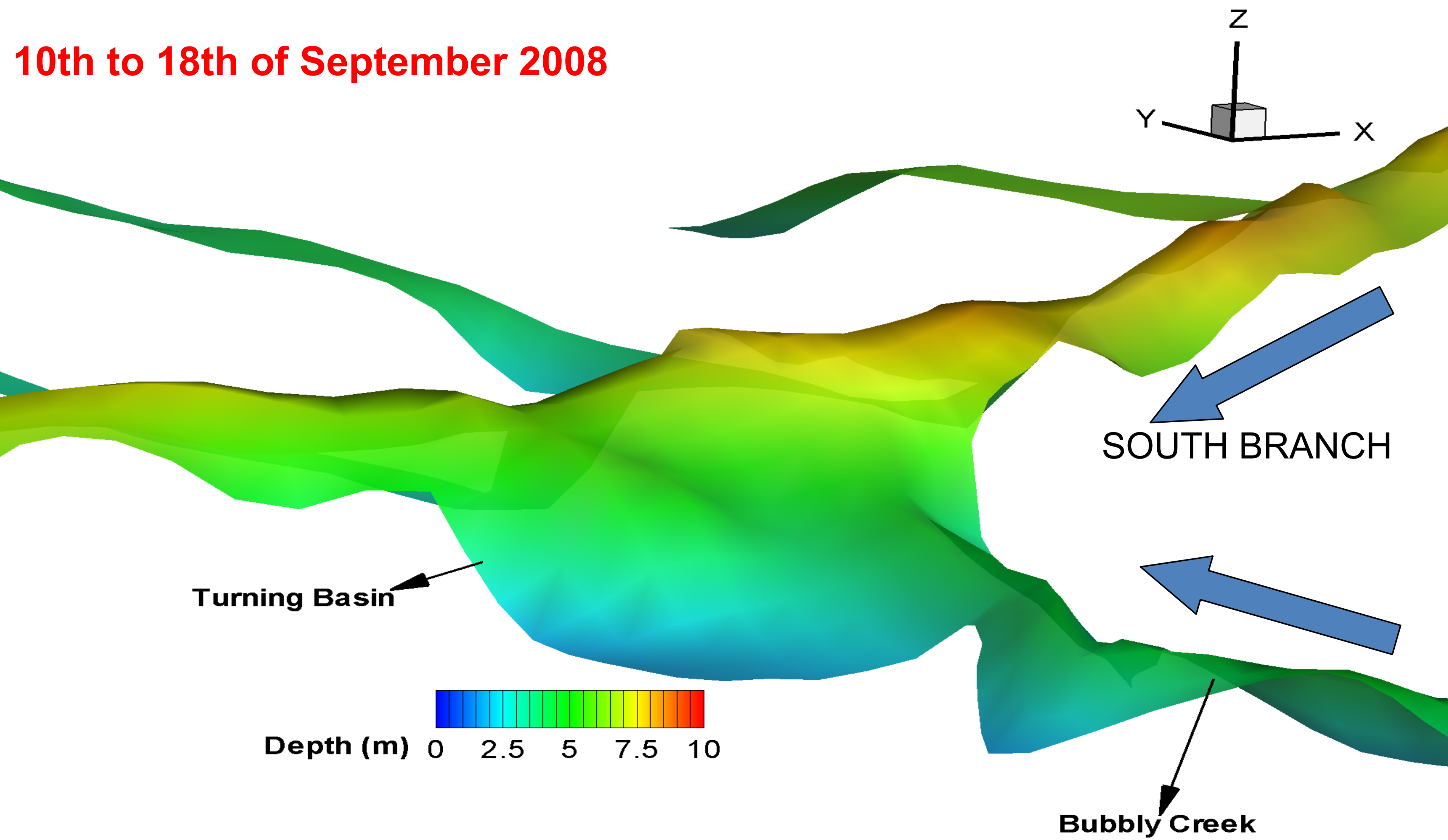




~~LOCK & GATES~~

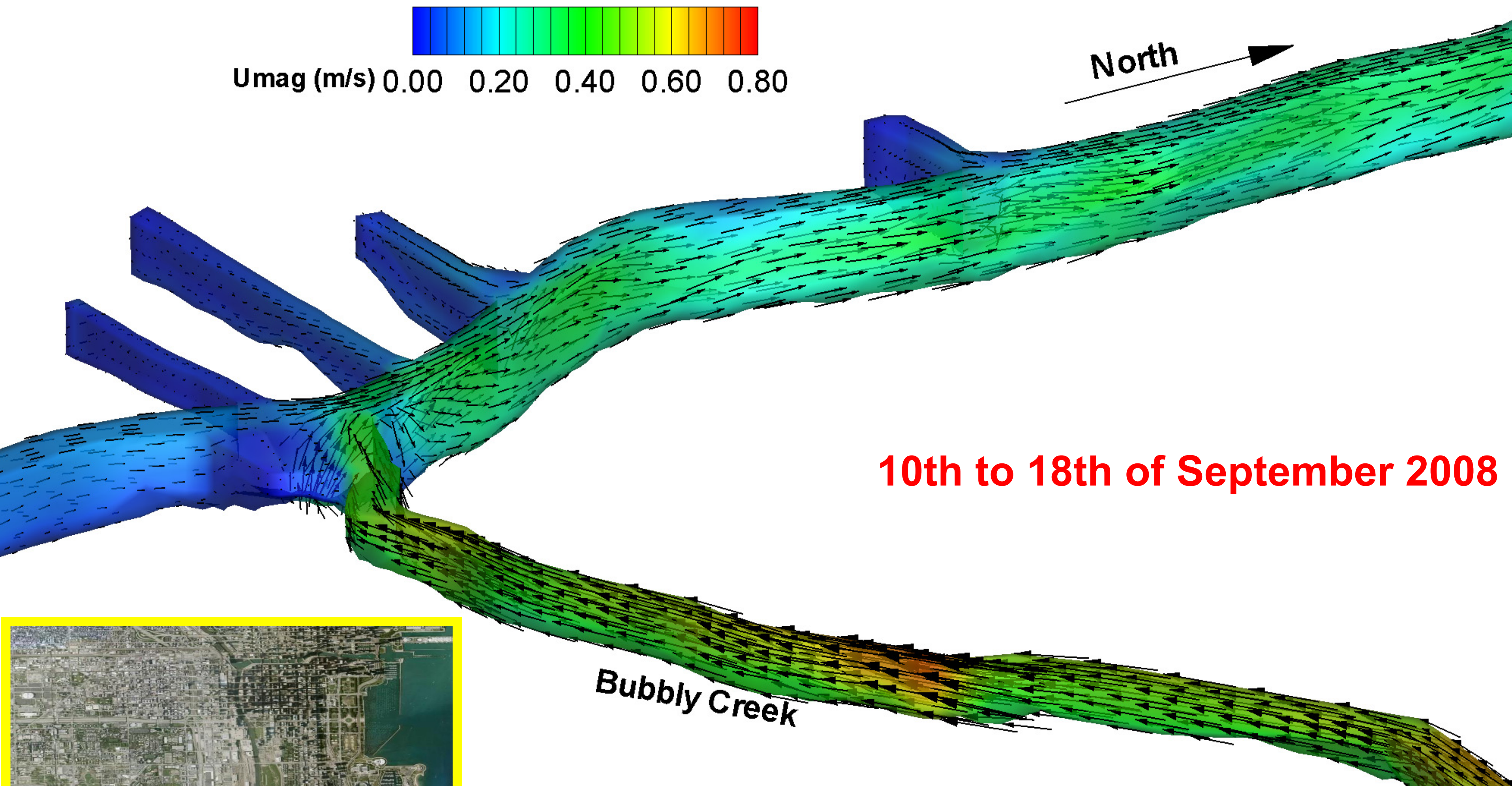
Depth in Turning-Basin 80 hrs after Start of Simulation

10th to 18th of September 2008

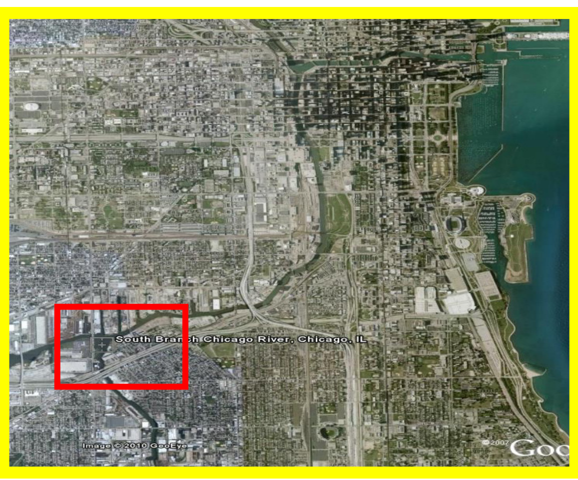


Notice dam/barrier effect

Velocity Magnitude 110 hrs after Start of Simulation



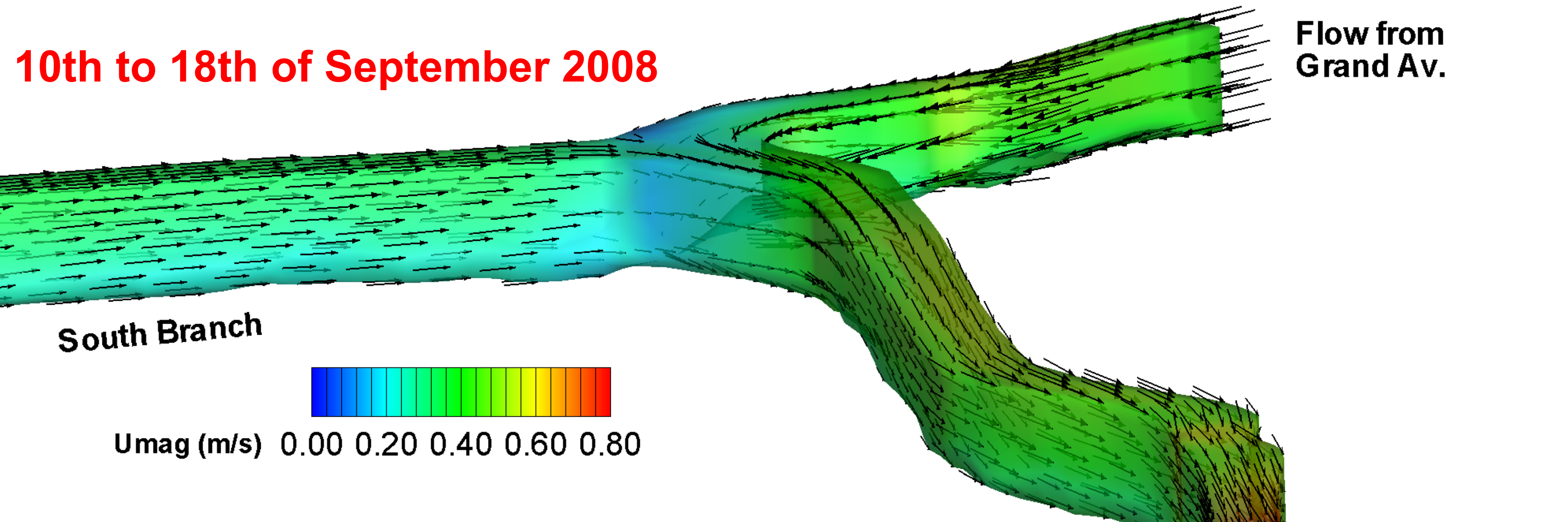
10th to 18th of September 2008

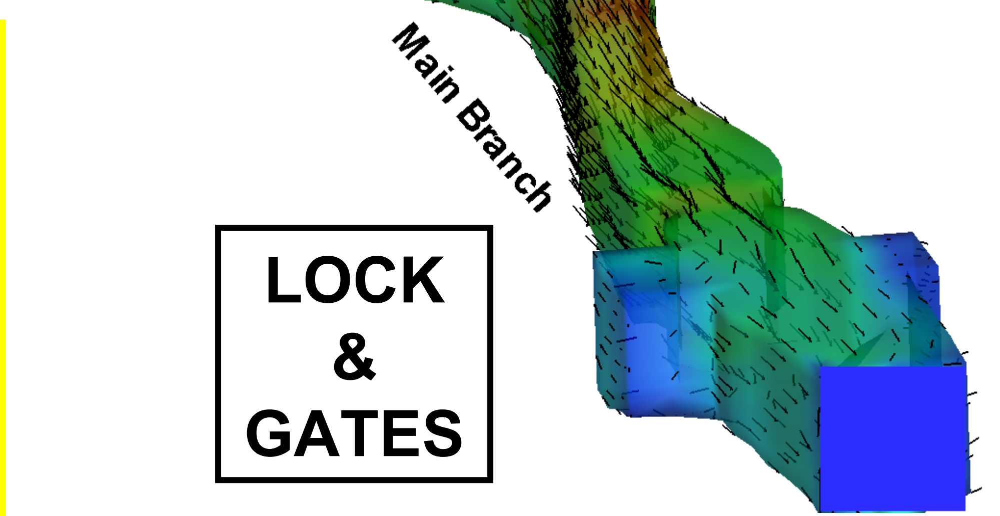


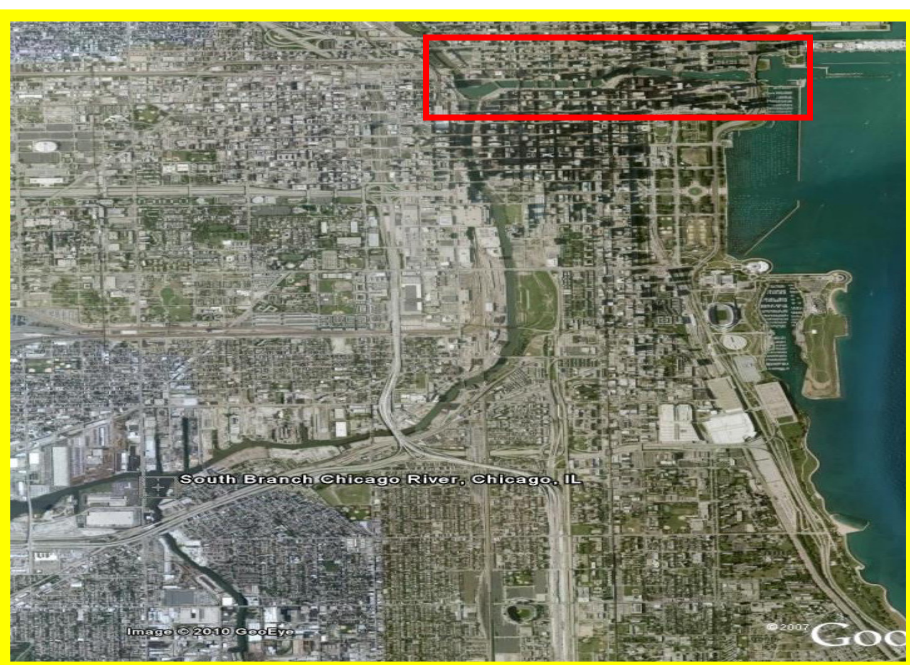
RAPS

Velocity Magnitude 110 hrs after Start of Simulation

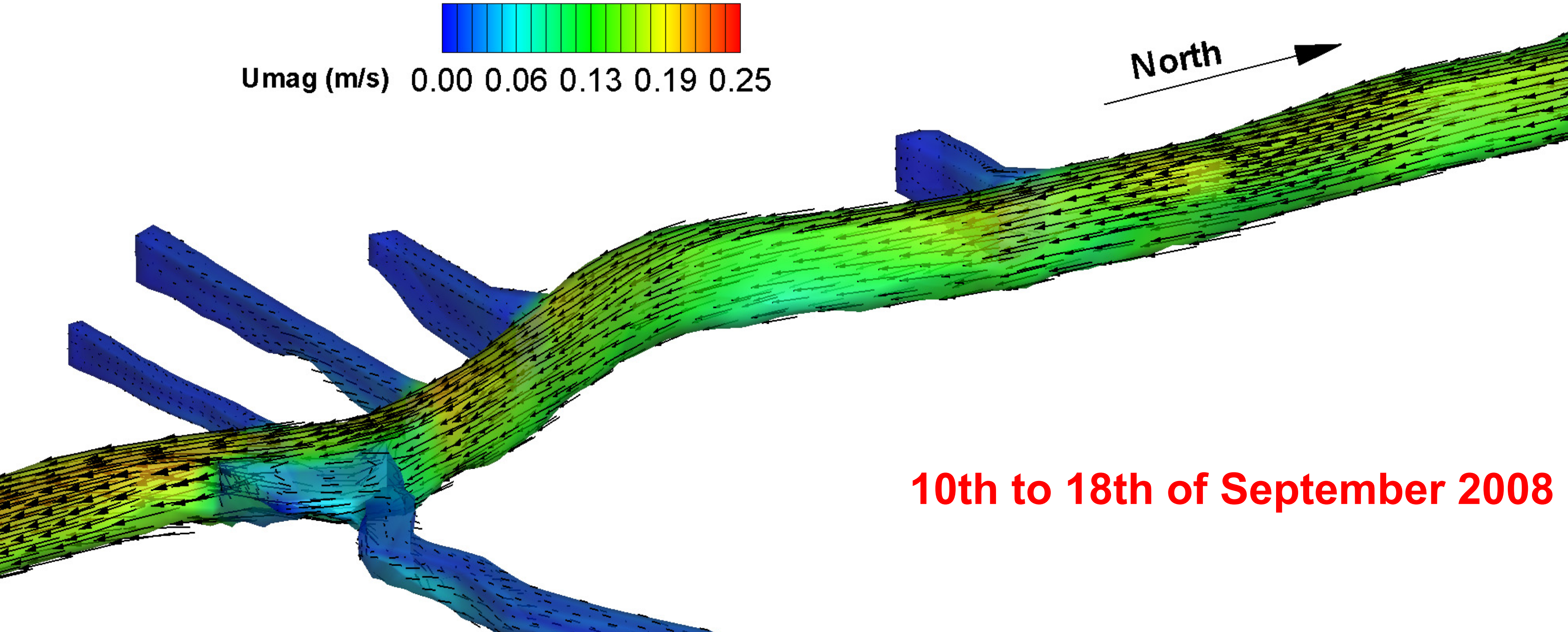
10th to 18th of September 2008

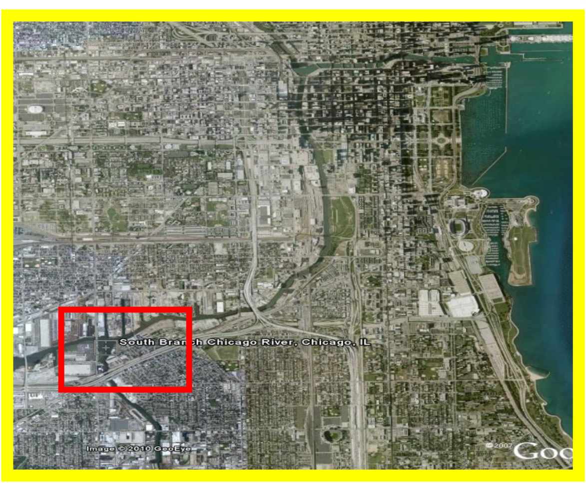






Velocity Magnitude 150 hrs after Start of Simulation

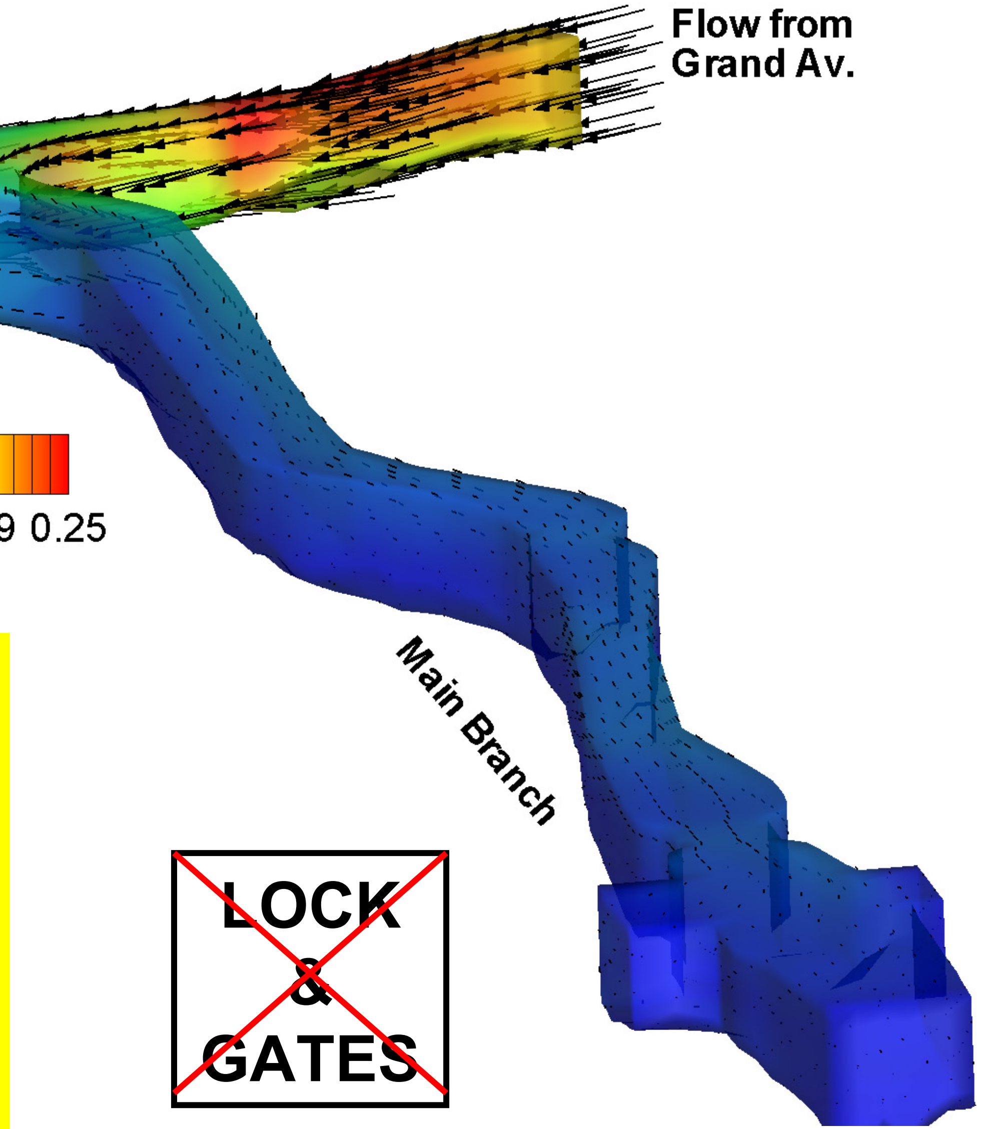


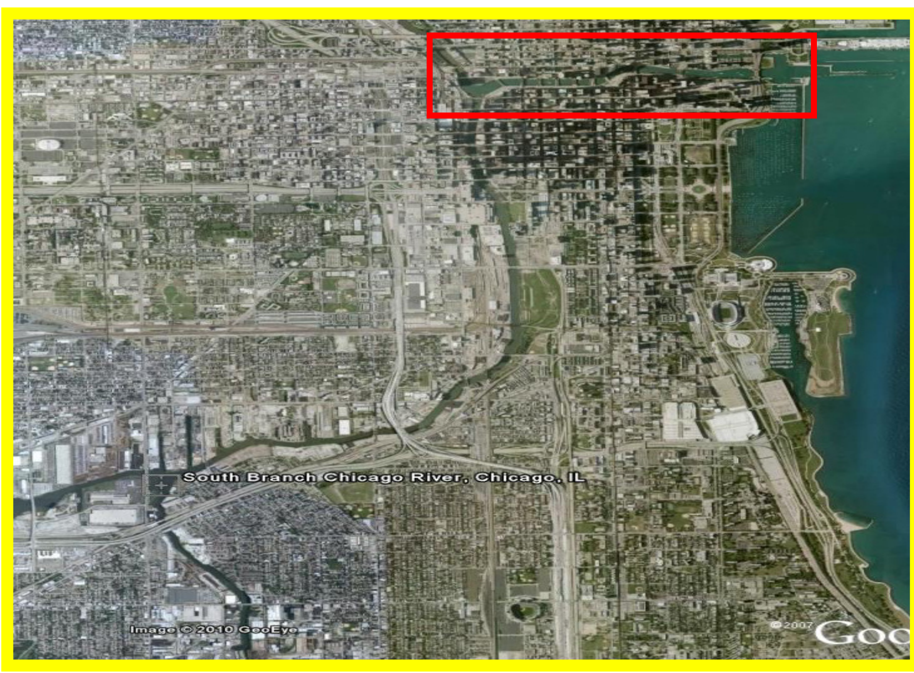


RAPS

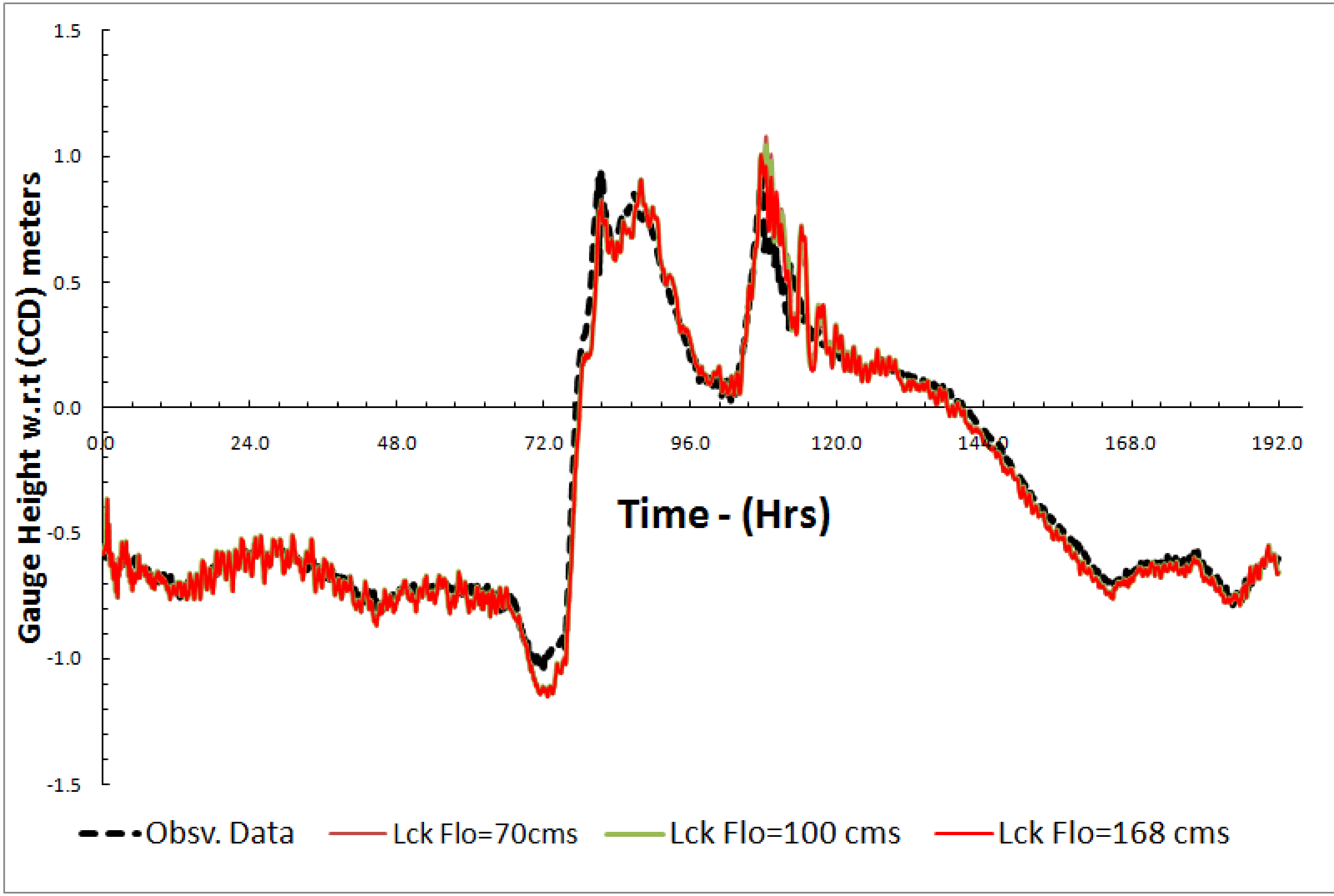
Velocity Magnitude 150 hrs after Start of Simulation

10th to 18th of September 2008





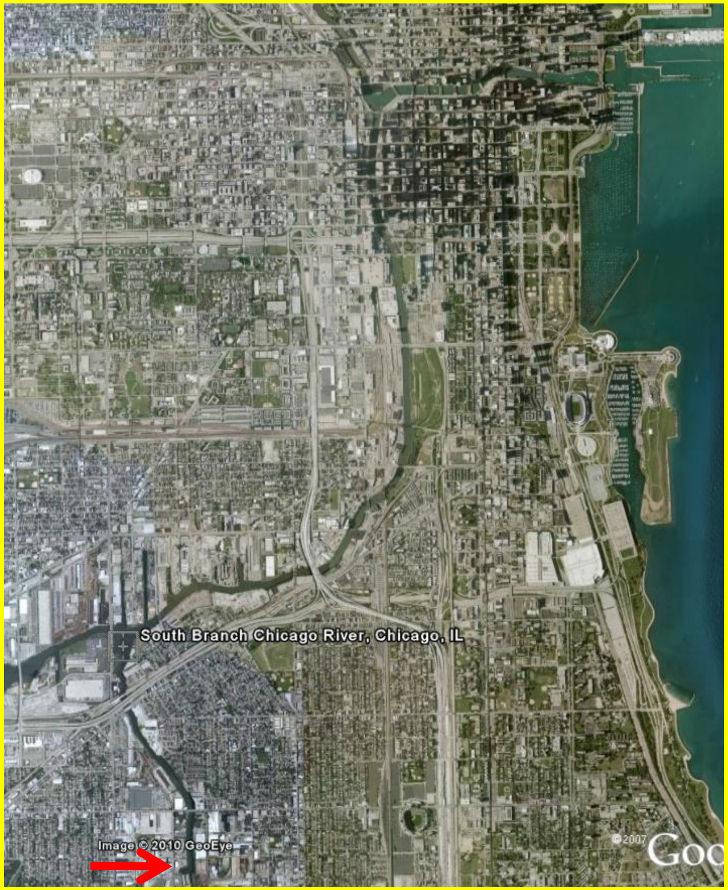
Comparison of Modeled and Observed Stage Values at the Validation Point



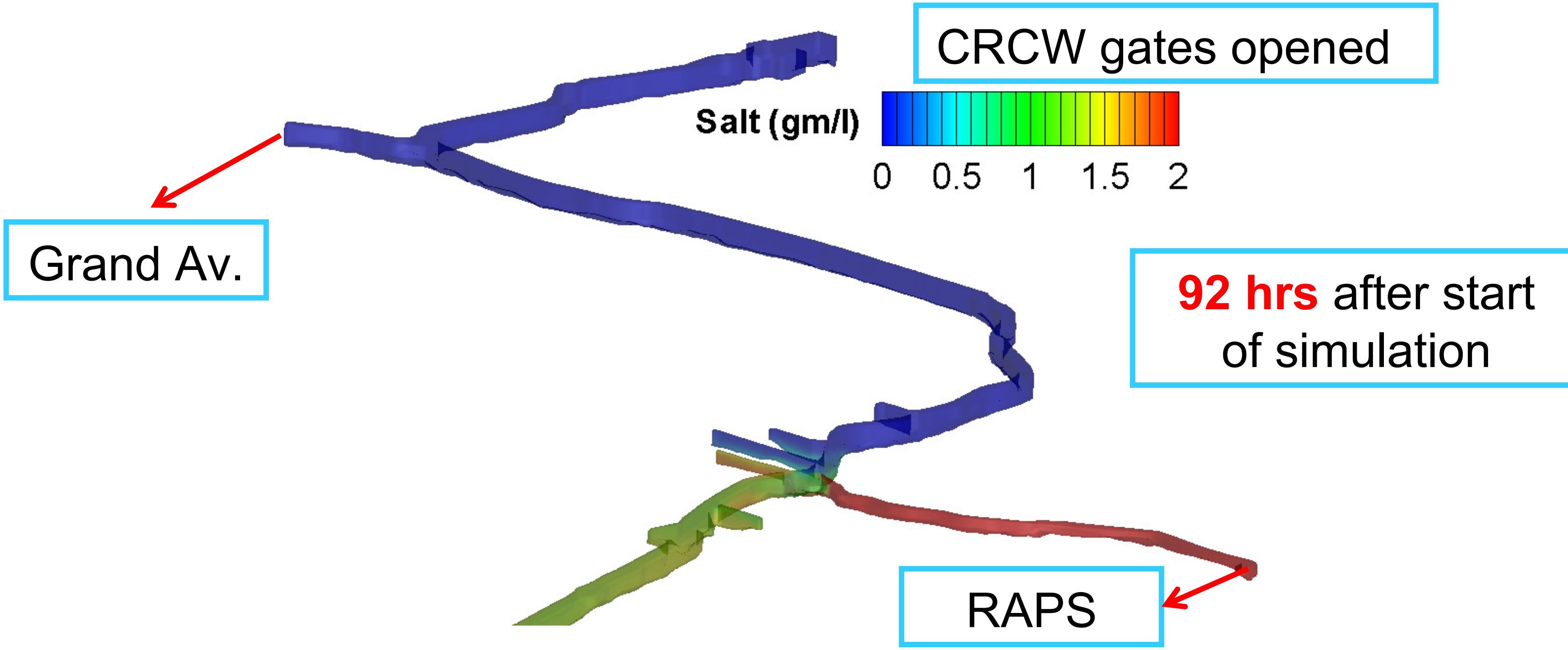
Upstream Flow and Transport

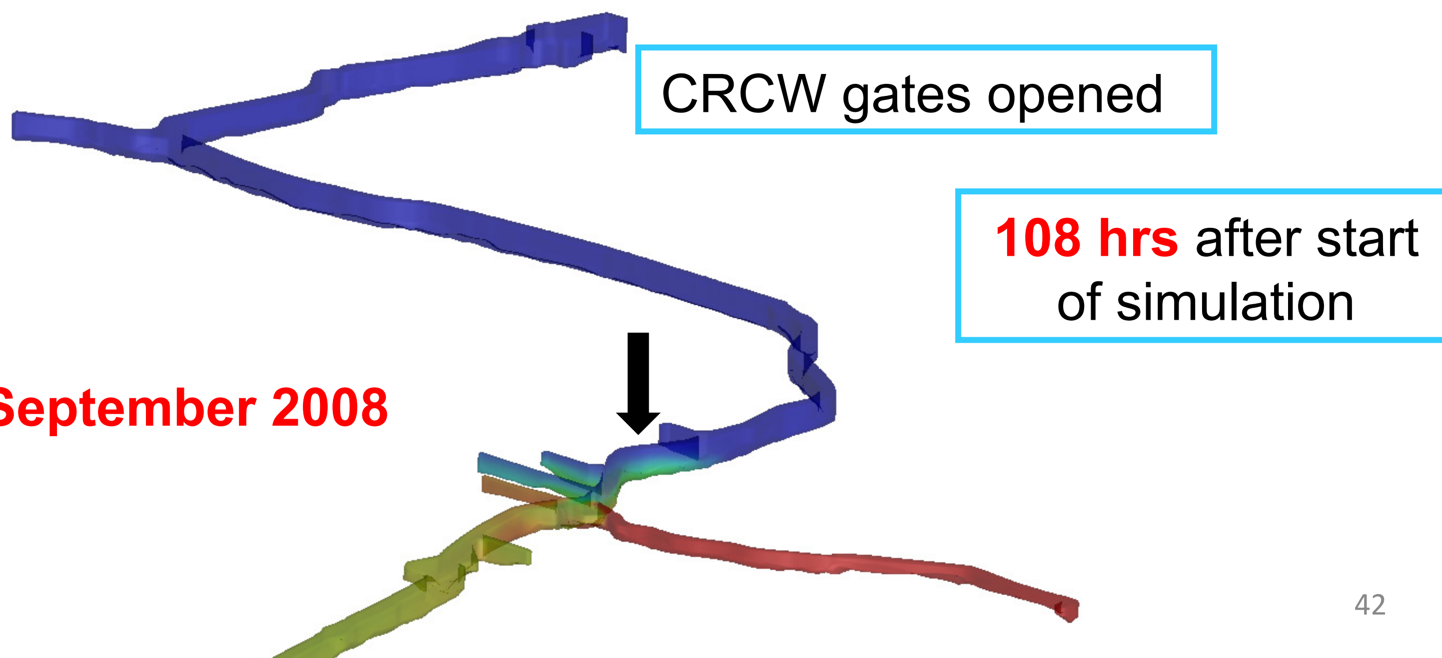
Salt was used as a surrogate for dealing with the problem of upstream intrusion.

In this simulation, as long as the RAPS stayed on 2 gms/l of salt was supplied with the flow.

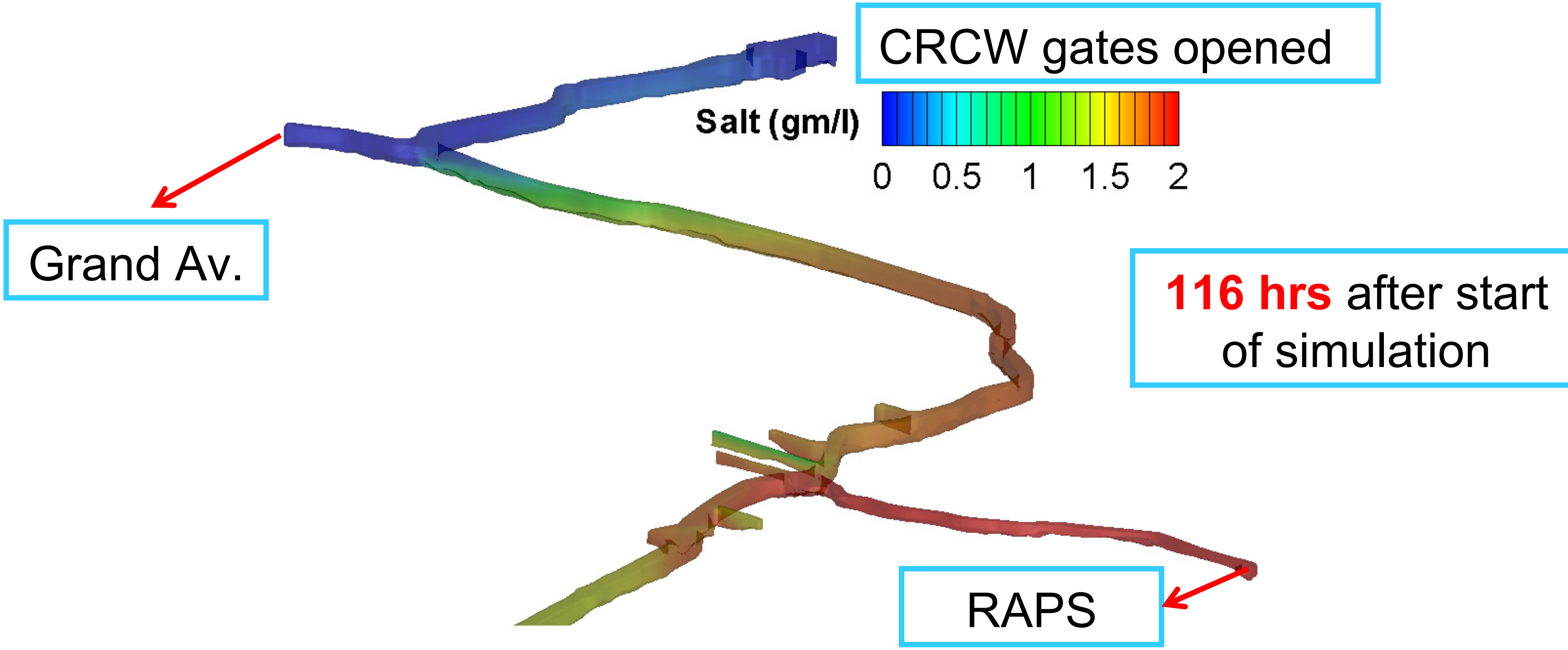


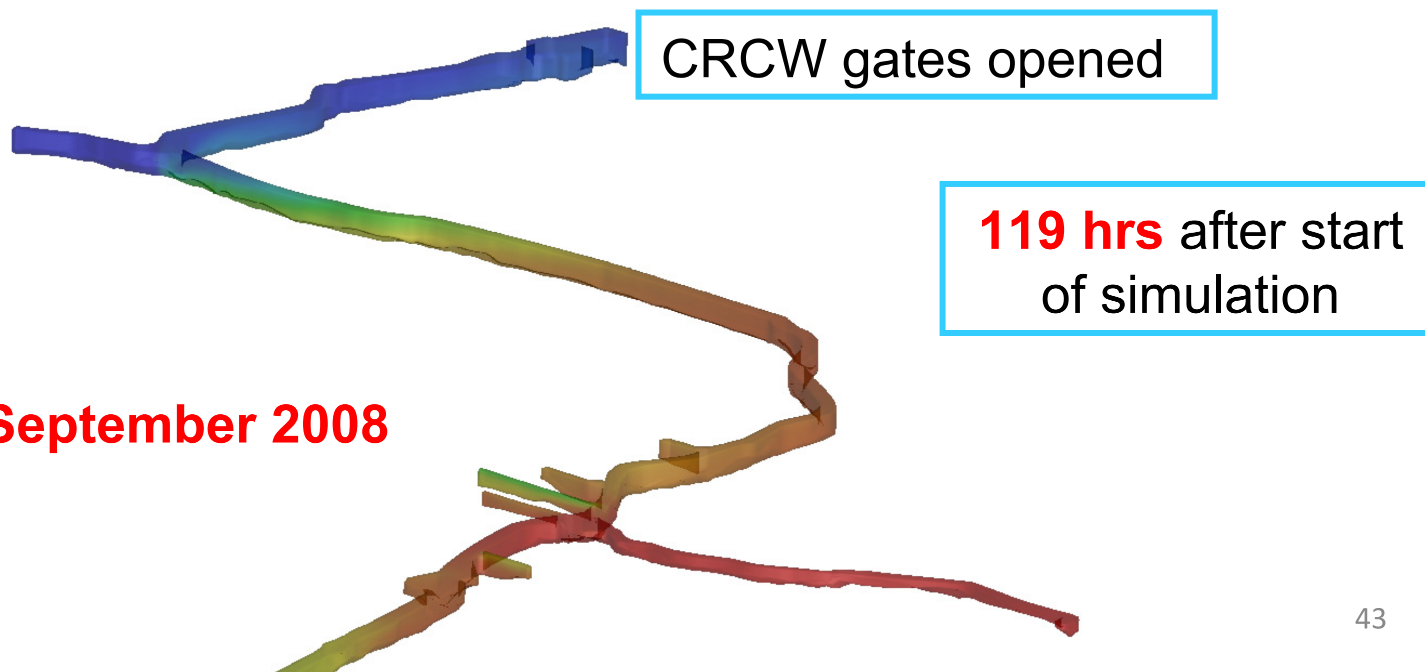
Finally the concentration of salt was recorded in the whole domain and it’s evolution in time was examined.





10th to 18th of September 2008





10th to 18th of September 2008

SOD field observations

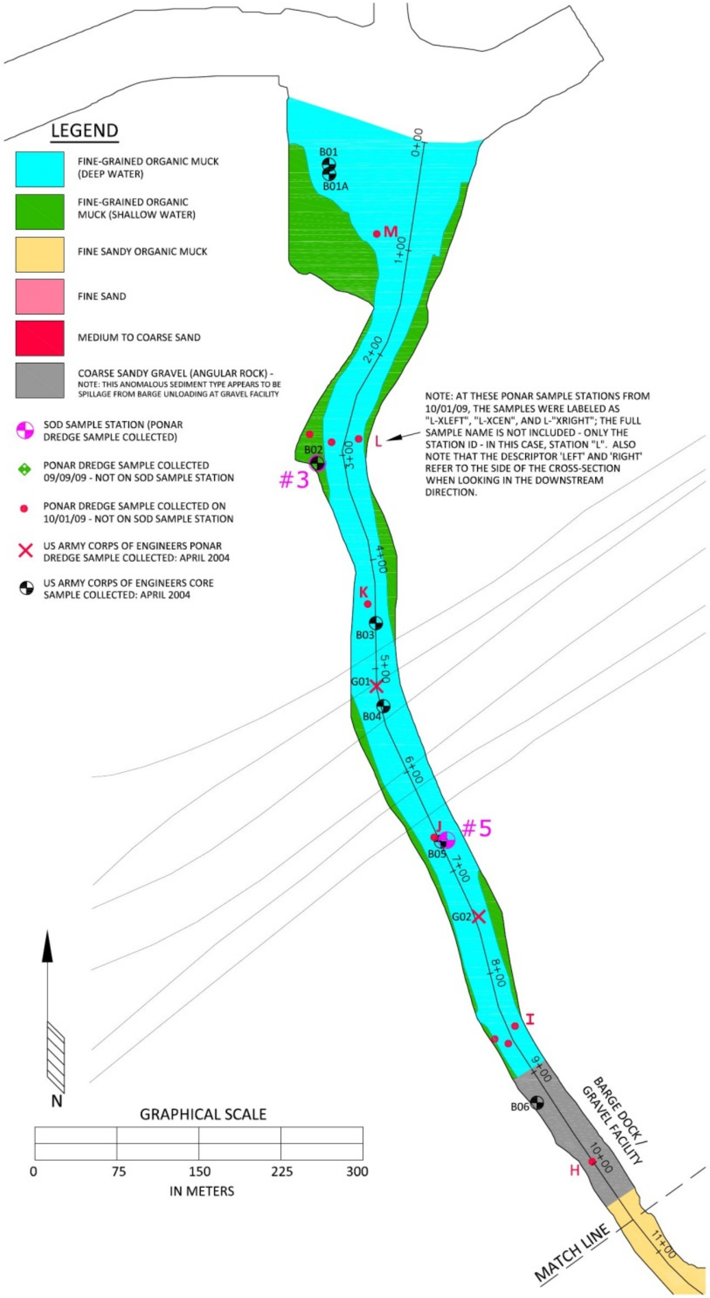
Objectives of the Study:

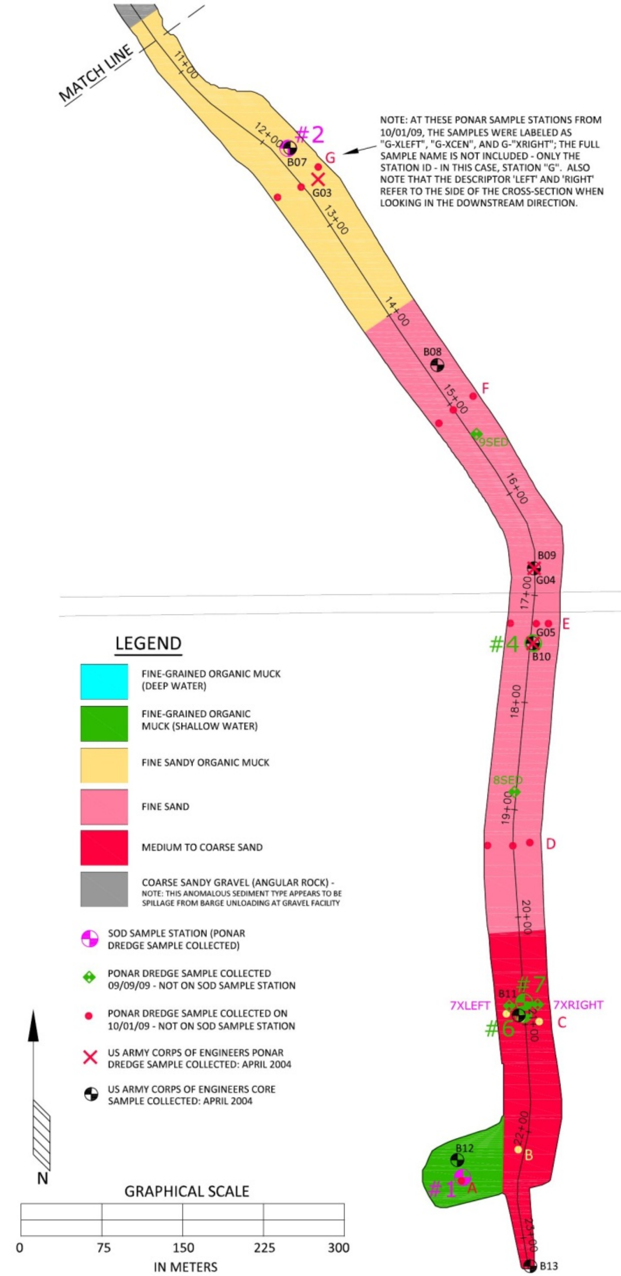
For a non-resuspension condition:

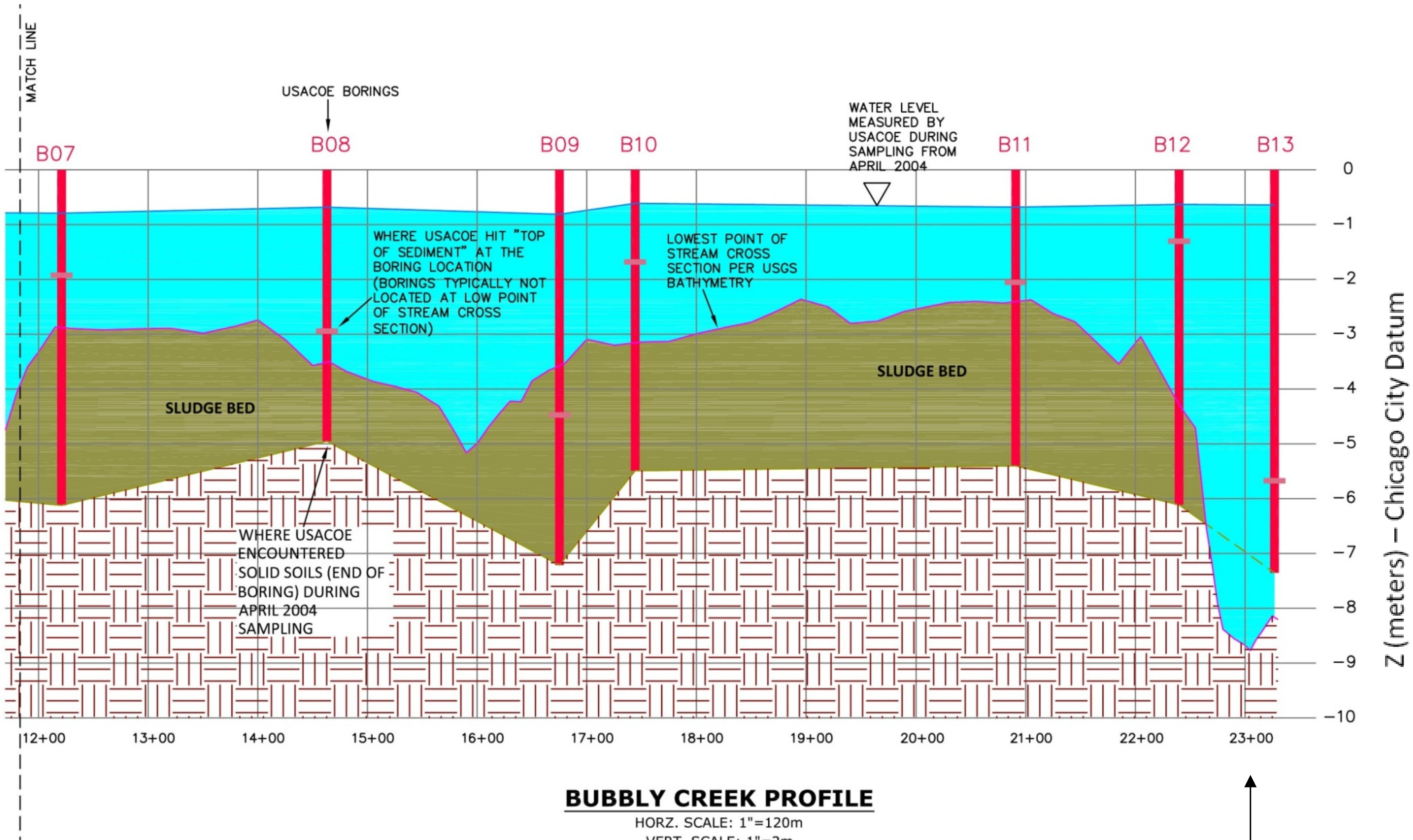
1) What is the background SOD?
2) How does the SOD vary with increasing velocity (up to the point of resuspension)?

For a sediment resuspension condition:

1) At what bed shear stress is sediment resuspension initiated?
2) What is the magnitude of resuspension with increasing bed shear stress?
3) What is the oxygen demand associated with varying degrees of resuspension?


LEGEND
FINE-GRAINED ORGANIC MUCK (DEEP WATER)
FINE-GRAINED ORGANIC MUCK (SHALLOW WATER)
FINE SANDY ORGANIC MUCK
FINE SAND
MEDIUM TO COARSE SAND
COARSE SANDY GRAVEL (ANGULAR ROCK) - NOTE: THIS ANOMALOUS SEDIMENT TYPE APPEARS TO BE SPILLAGE FROM BARGE UNLOADING AT GRAVEL FACILITY
SOD SAMPLE STATION (PONAR DREDGE SAMPLE COLLECTED)
PONAR DREDGE SAMPLE COLLECTED 09/09/09 - NOT ON SOD SAMPLE STATION
PONAR DREDGE SAMPLE COLLECTED ON 10/01/09 - NOT ON SOD SAMPLE STATION
US ARMY CORPS OF ENGINEERS PONAR DREDGE SAMPLE COLLECTED: APRIL 2004
US ARMY CORPS OF ENGINEERS CORE SAMPLE COLLECTED: APRIL 2004
NOTE: AT THESE PONAR SAMPLE STATIONS FROM 10/01/09, THE SAMPLES WERE LABELED AS "L-XLEFT", "L-XCEN", AND L-"XRIGHT"; THE FULL SAMPLE NAME IS NOT INCLUDED - ONLY THE STATION ID - IN THIS CASE, STATION "L". ALSO NOTE THAT THE DESCRIPTOR 'LEFT' AND 'RIGHT' REFER TO THE SIDE OF THE CROSS-SECTION WHEN LOOKING IN THE DOWNSTREAM DIRECTION.
B01
B01A
M
L
B02
#3
K
B03
G01
B04
J
#5
B05
G02
I
B06
H
BARGE DOCK / GRAVEL FACILITY
MATCH LINE
N
GRAPHICAL SCALE
0 75 150 225 300
IN METERS


MATCH LINE
NOTE: AT THESE PONAR SAMPLE STATIONS FROM 10/01/09, THE SAMPLES WERE LABELED AS "G-XLEFT", "G-XCEN", AND G-"XRIGHT"; THE FULL SAMPLE NAME IS NOT INCLUDED - ONLY THE STATION ID - IN THIS CASE, STATION "G". ALSO NOTE THAT THE DESCRIPTOR 'LEFT' AND 'RIGHT' REFER TO THE SIDE OF THE CROSS-SECTION WHEN LOOKING IN THE DOWNSTREAM DIRECTION.
#2
B07
G
G03
B08
F
9SED
B09
G04
E
#4
G05
B10
8SED
D
#7
B11
7XLEFT
7XRIGHT
#6
C
B12
B
#1
A
B13
LEGEND
FINE-GRAINED ORGANIC MUCK (DEEP WATER)
FINE-GRAINED ORGANIC MUCK (SHALLOW WATER)
FINE SANDY ORGANIC MUCK
FINE SAND
MEDIUM TO COARSE SAND
COARSE SANDY GRAVEL (ANGULAR ROCK) - NOTE: THIS ANOMALOUS SEDIMENT TYPE APPEARS TO BE SPILLAGE FROM BARGE UNLOADING AT GRAVEL FACILITY
SOD SAMPLE STATION (PONAR DREDGE SAMPLE COLLECTED)
PONAR DREDGE SAMPLE COLLECTED 09/09/09 - NOT ON SOD SAMPLE STATION
PONAR DREDGE SAMPLE COLLECTED ON 10/01/09 - NOT ON SOD SAMPLE STATION
US ARMY CORPS OF ENGINEERS PONAR DREDGE SAMPLE COLLECTED: APRIL 2004
US ARMY CORPS OF ENGINEERS CORE SAMPLE COLLECTED: APRIL 2004
N
GRAPHICAL SCALE
0 75 150 225 300
IN METERS



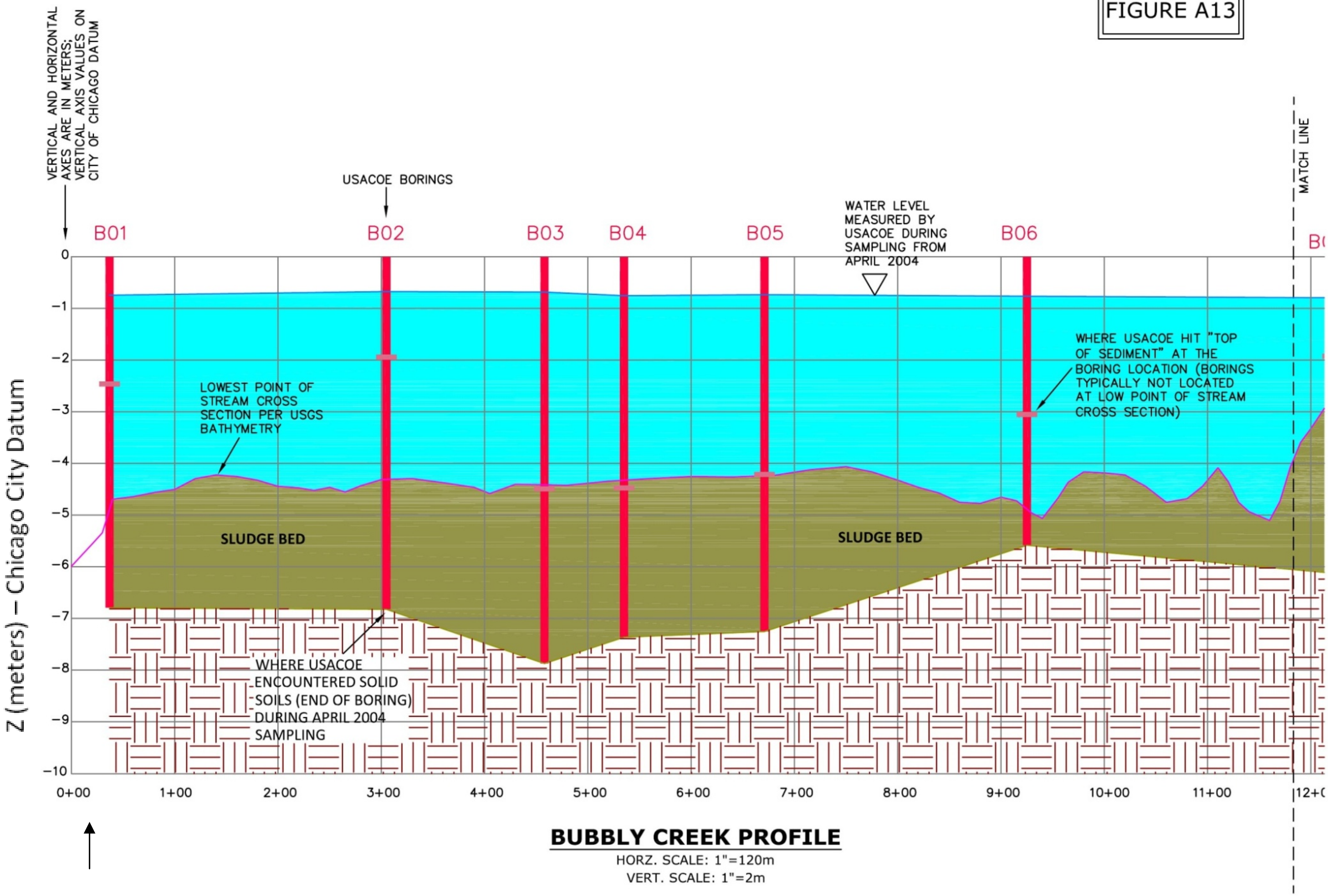
BUBBLY CREEK PROFILE

HORZ. SCALE: 1"=120m

VERT. SCALE: 1"=2m

RAPS

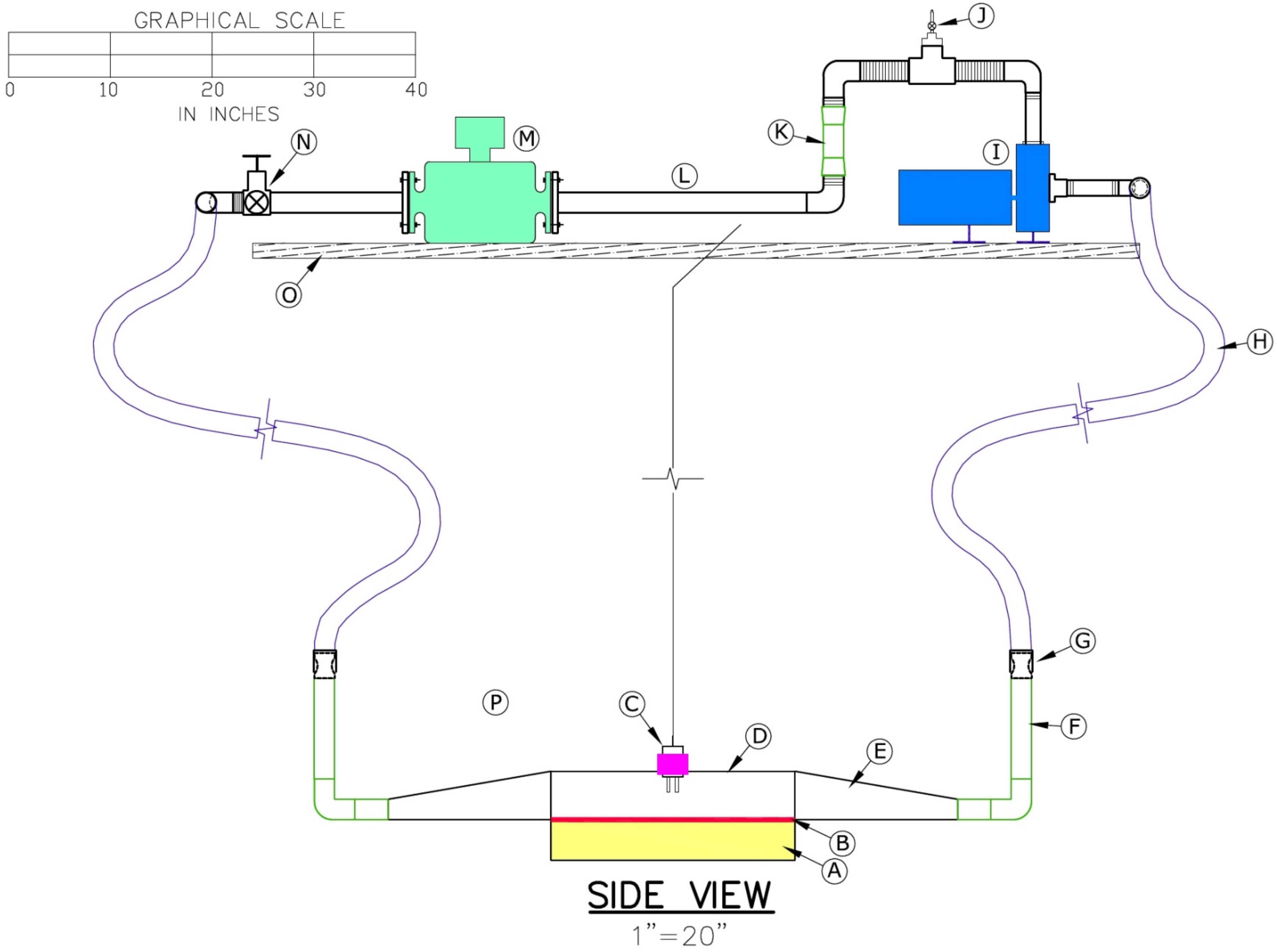
FIGURE A13



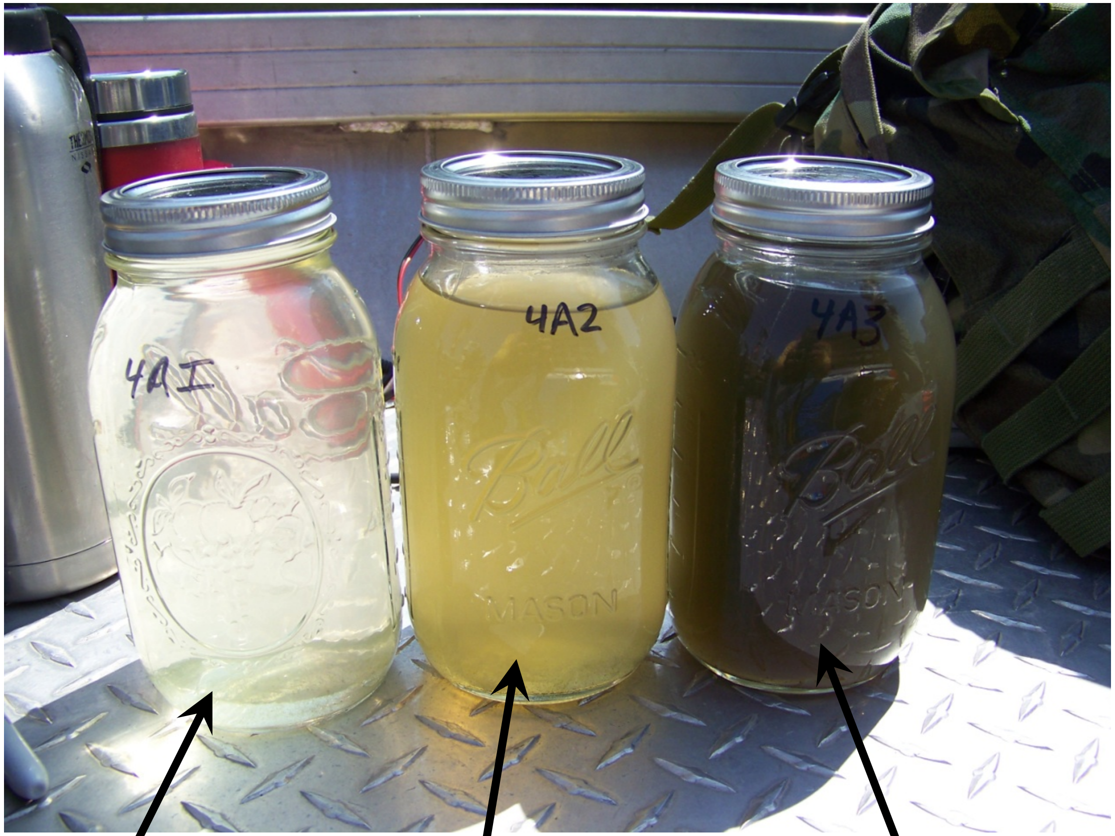
BUBBLY CREEK PROFILE
HORZ. SCALE: 1"=120m
VERT. SCALE: 1"=2m

South Branch

The U of I Hydrodynamic SOD Sampler



FIELD OBSERVATIONS AND RESULTS



No resuspension

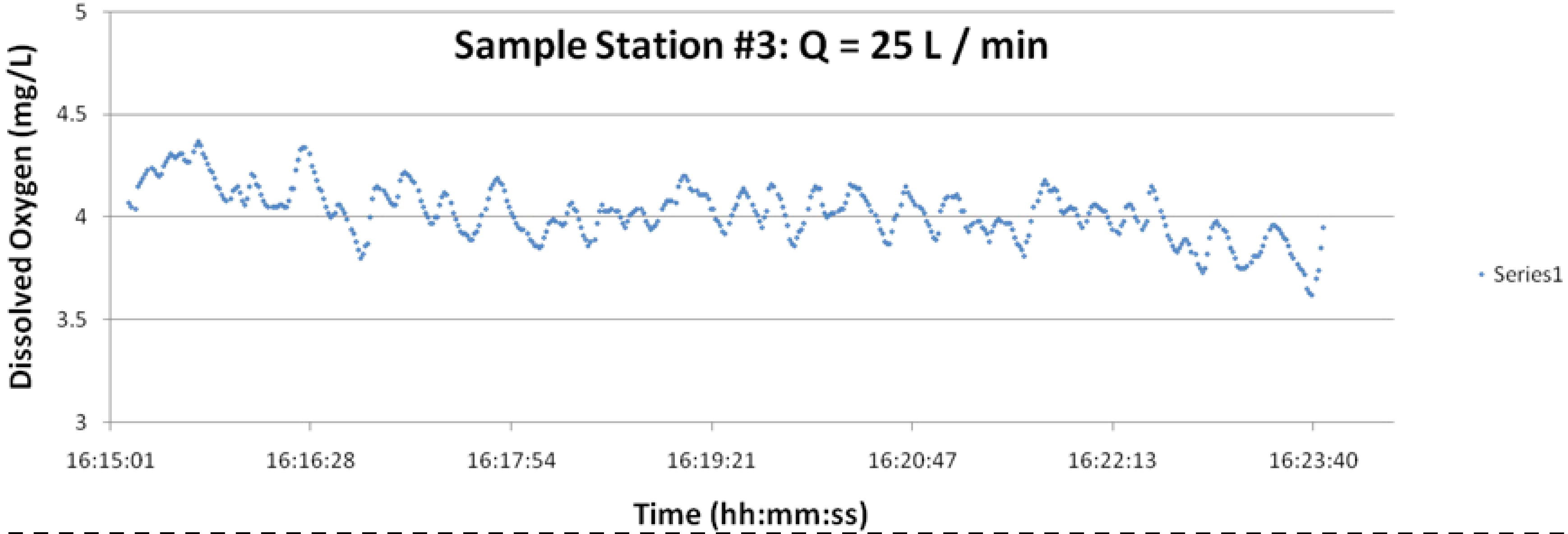
"Flaking" phase

"Slurry" phase

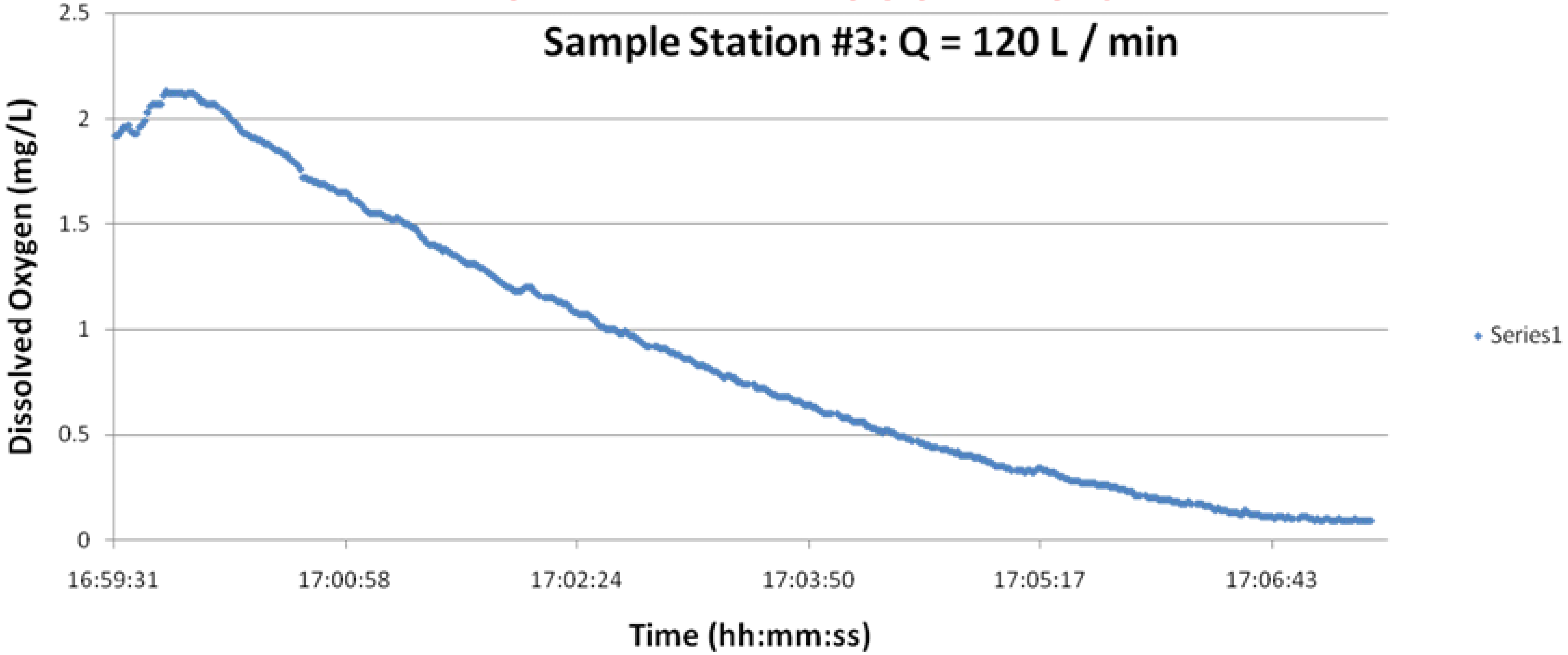
(Note: an intermediate "Bedload" phase in coarse-grained sediment.)

3 or 4 Phases of Sediment Resuspension

NO SEDIMENT RESUSPENSION



WITH SEDIMENT RESUSPENSION

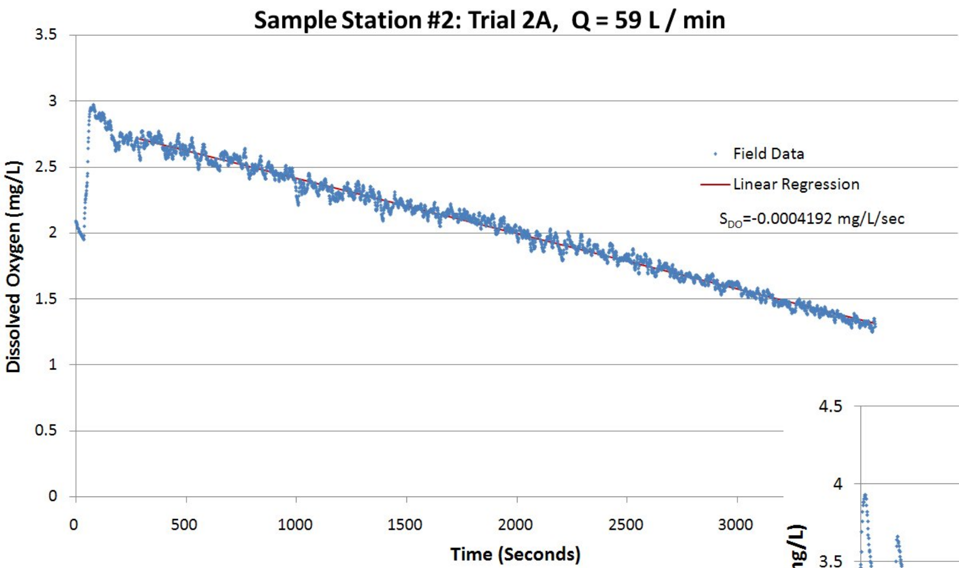


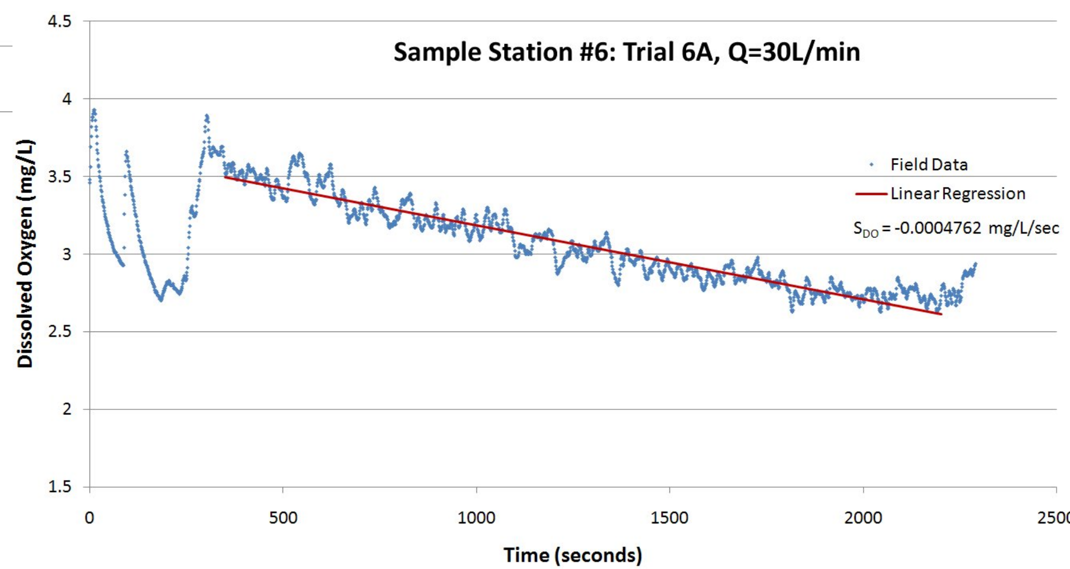
SOD_{NR20} RESULTS

Sediment Type	SOD_{NR20} ($g/m^2/day$)
Fine-grained organic muck	12.1
Fine sandy organic muck	6.7
Fine sand	6.8
Medium to coarse sand	9.2

(All values normalized to 20°C)

$$SOD_{20} = SOD_T * 1.065^{(20-T)}$$



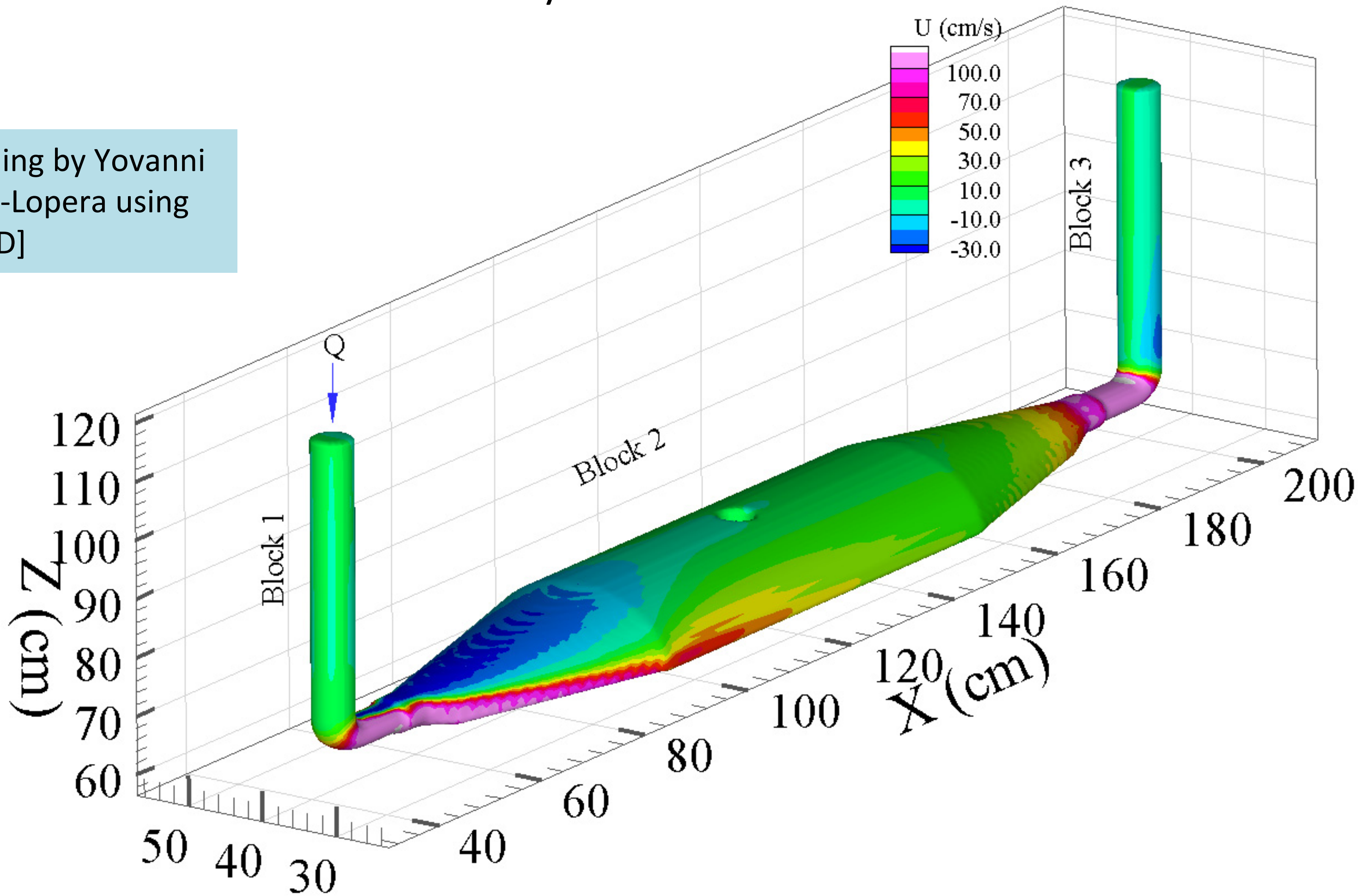


$$SOD_{NR} = \frac{V}{A} * \left(\frac{dC}{dt} - \text{BOD}\right)$$

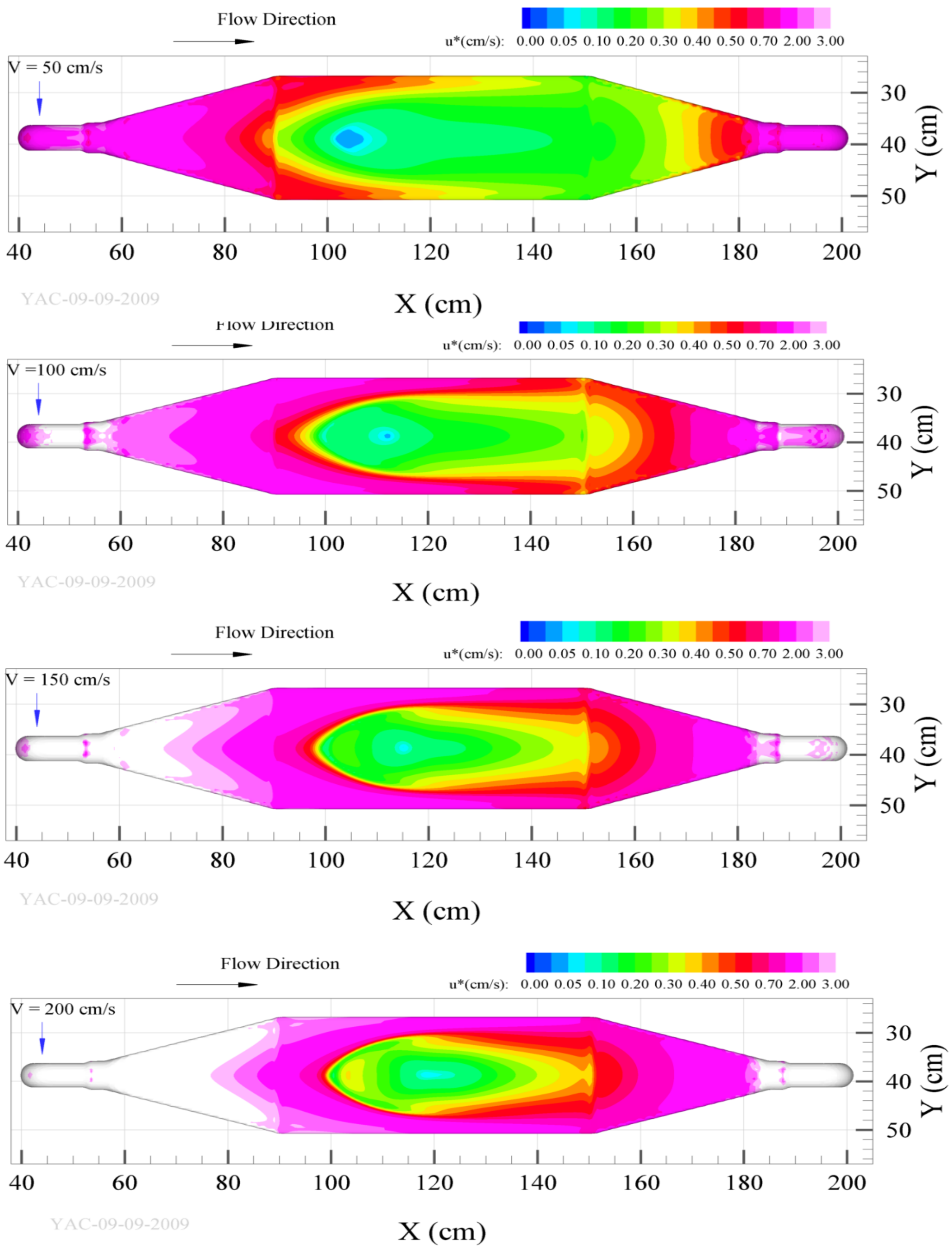
BED SHEAR STRESS AND EROSION ANALYSIS

During Field Measurements, Q was recorded. But we need to analyze in terms of bed shear stress or shear velocity. So we turn to CFD.

[Modeling by Yovanni Cataño-Lopera using Flow-3D]



3-D rendering of the Horizontal Velocity u (cm/s) using Flow-3D's FAVOR



Shear Velocity (u_*) is often used as a surrogate for Bed Shear Stress (τ_B):

$$u_* = \sqrt{\frac{\tau_B}{\rho}} \quad \frac{\left[\frac{kg \cdot m}{s^2 \cdot m^2}\right]}{\left[\frac{kg}{m^3}\right]}$$

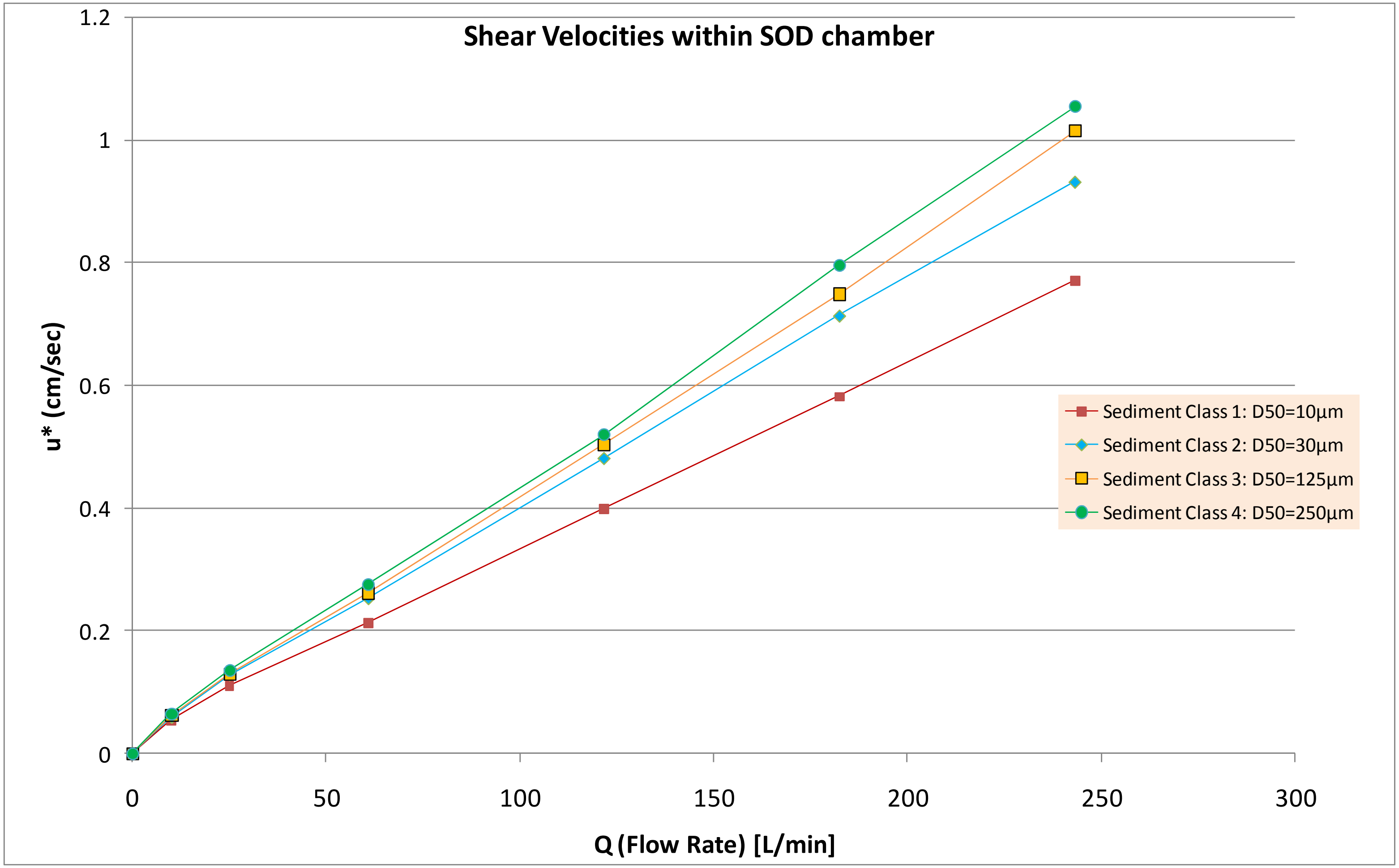
Where:

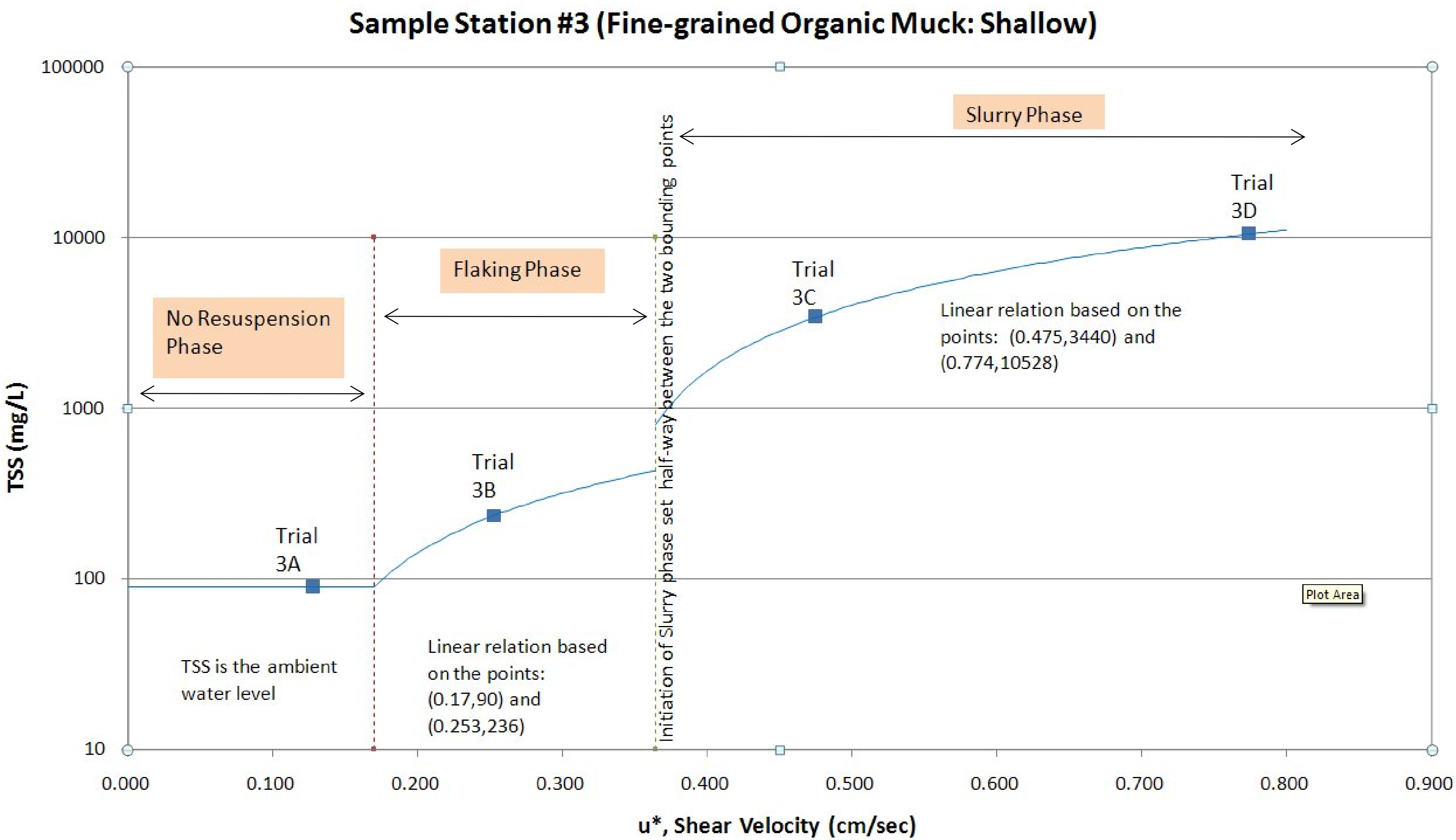
τ_B : Bed Shear Stress (N/m^2)

u_*: Shear Velocity (m/s)

ρ: Fluid Density (kg/m^3)

Field tests were performed under:
$0.13 \leq u^* \leq 0.93$ cm/s

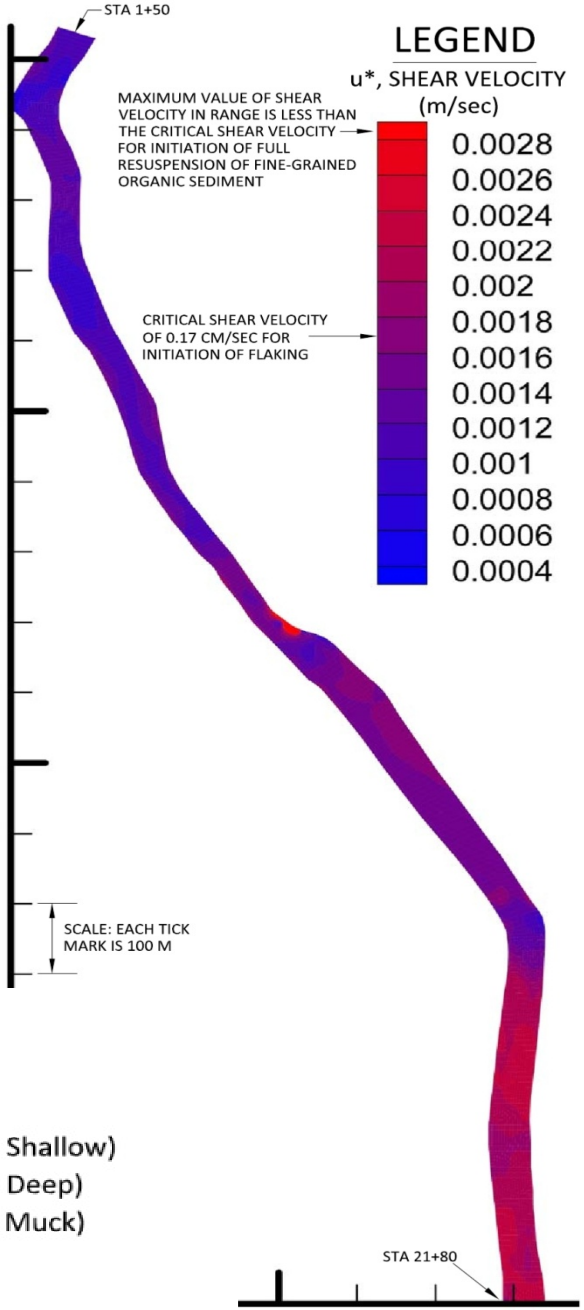

Shear Velocities within SOD chamber
u* (cm/sec)
Q (Flow Rate) [L/min]
1.2
1
0.8
0.6
0.4
0.2
0
0
50
100
150
200
250
300
Sediment Class 1: D50=10μm
Sediment Class 2: D50=30μm
Sediment Class 3: D50=125μm
Sediment Class 4: D50=250μm

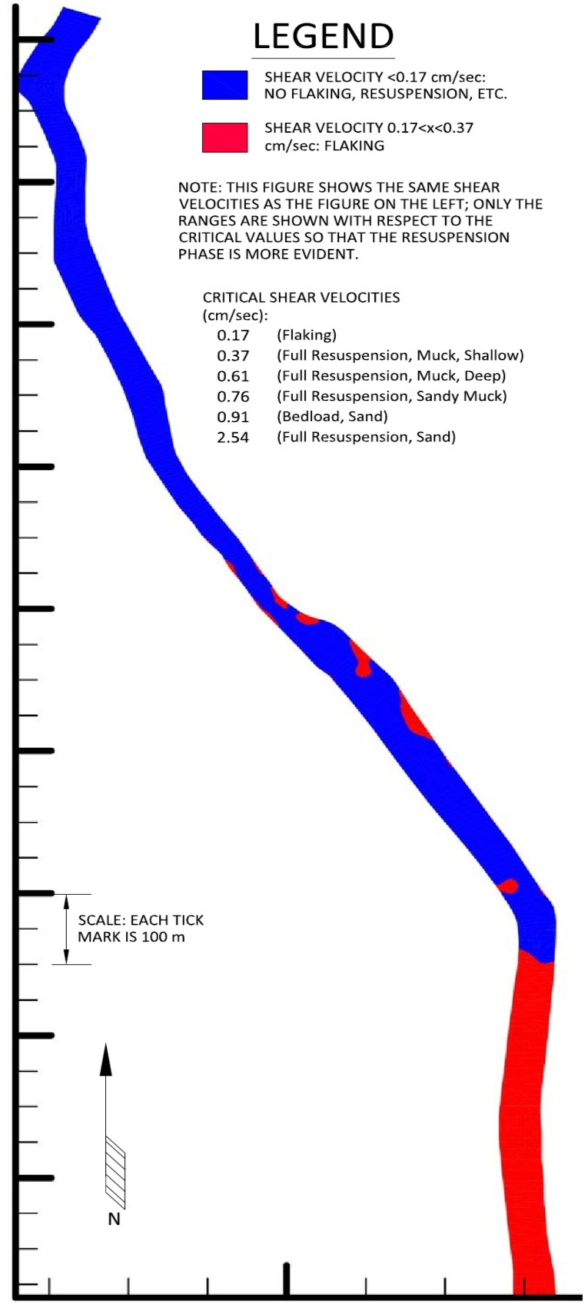


Sample Station #3 (Fine-grained Organic Muck: Shallow)
TSS (mg/L)
100000
10000
1000
100
10
u*, Shear Velocity (cm/sec)
0.000
0.100
0.200
0.300
0.400
0.500
0.600
0.700
0.800
0.900
No Resuspension Phase
Flaking Phase
Slurry Phase
Trial 3A
Trial 3B
Trial 3C
Trial 3D
Initiation of Slurry phase set half-way between the two bounding points
TSS is the ambient water level
Linear relation based on the points: (0.17,90) and (0.253,236)
Linear relation based on the points: (0.475,3440) and (0.774,10528)
Plot Area

From 2D model

For Q=2.19 m^3/sec

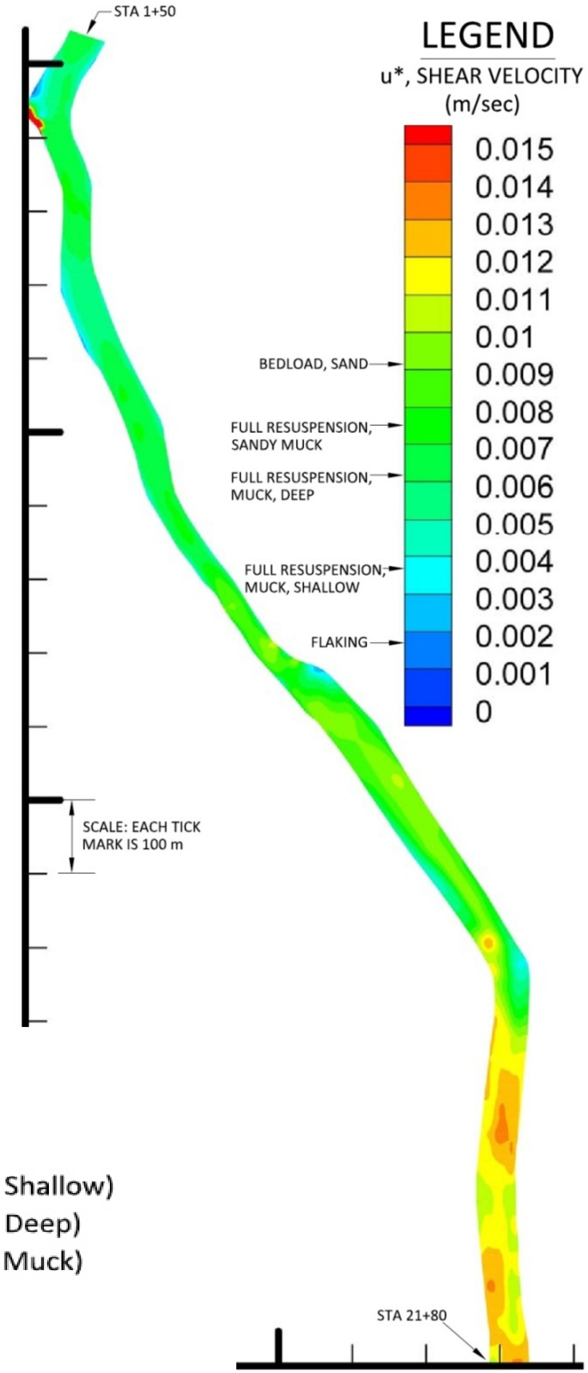


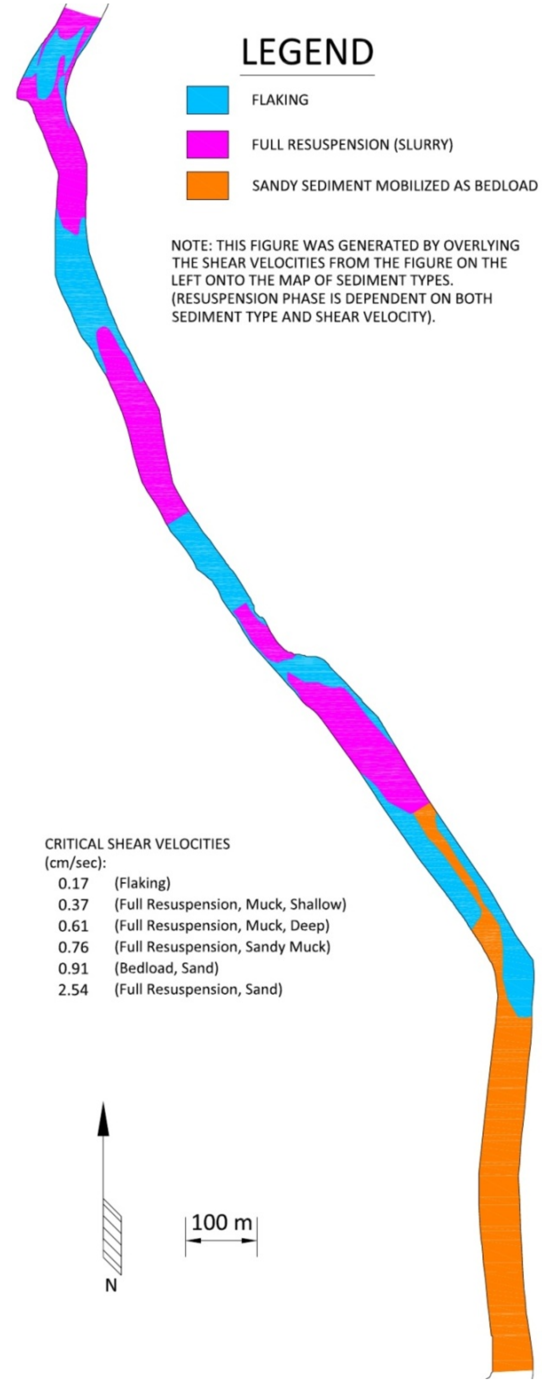


CRITICAL SHEAR VELOCITIES (cm/sec):

0.17	(Flaking)
0.37	(Full Resuspension, Muck, Shallow)
0.61	(Full Resuspension, Muck, Deep)
0.76	(Full Resuspension, Sandy Muck)
0.91	(Bedload, Sand)
2.54	(Full Resuspension, Sand)

For Q=12 m^3/sec

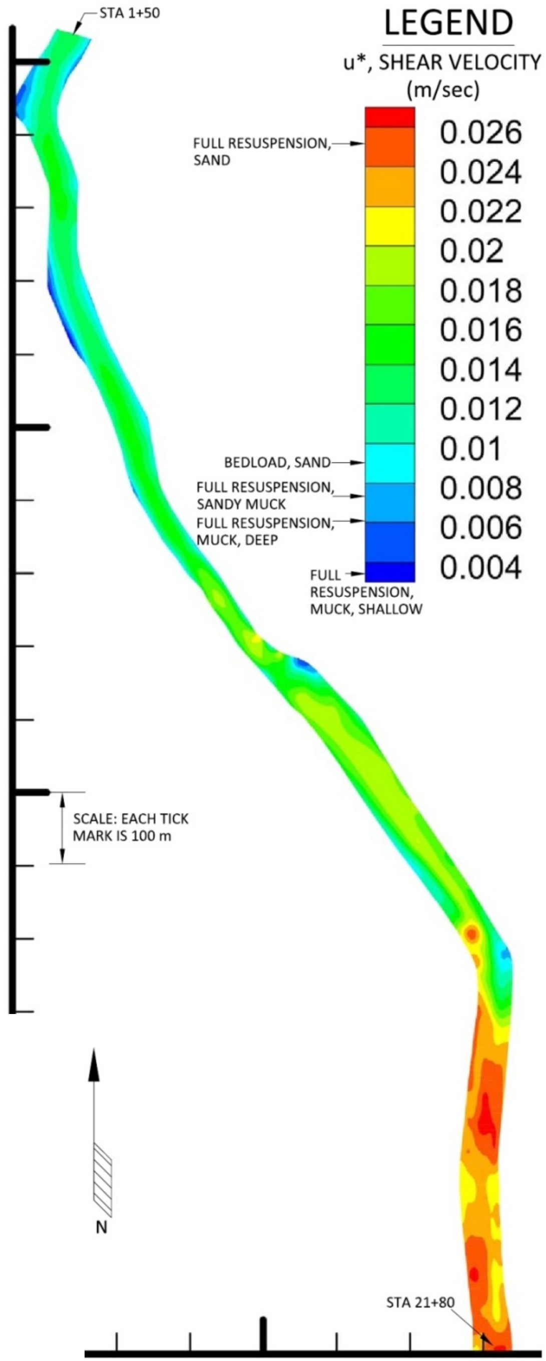


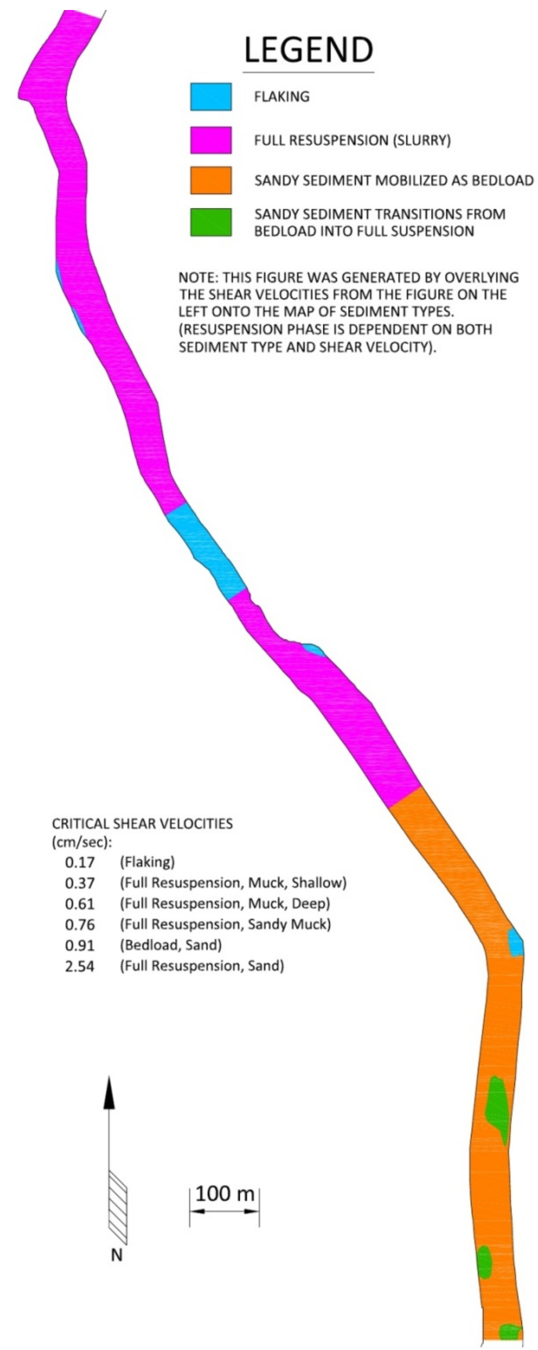


CRITICAL SHEAR VELOCITIES
(cm/sec):

0.17	(Flaking)
0.37	(Full Resuspension, Muck, Shallow)
0.61	(Full Resuspension, Muck, Deep)
0.76	(Full Resuspension, Sandy Muck)
0.91	(Bedload, Sand)
2.54	(Full Resuspension, Sand)

For Q=24 m^3/sec





CRITICAL SHEAR VELOCITIES (cm/sec):

0.17	(Flaking)
0.37	(Full Resuspension, Muck, Shallow)
0.61	(Full Resuspension, Muck, Deep)
0.76	(Full Resuspension, Sandy Muck)
0.91	(Bedload, Sand)
2.54	(Full Resuspension, Sand)

OXYGEN DEMAND ANALYSIS FOR RESUSPENDED SEDIMENT

Standard Equation for DO sink exerted by BOD

$$\frac{dC_{DO}}{dt} = -K_D \Theta_D^{T-20} \left(\frac{C_{DO}}{K_{BOD} + C_{DO}} \right) C_{BOD}$$

- K_D is the deoxygenation (oxidation) rate coefficient at 20 °C (1/day)
- $\Theta_D^{(T-20)}$ is the temperature correction factor, whose standard value is 1.047
- C_{DO} is the concentration of dissolved oxygen (mg/L)
- C_{BOD} is the concentration of oxidizable material remaining in terms of how much oxygen it will require to oxidize it (mg/L)
- K_{BOD} is a half-saturation constant for BOD oxidation (mg/L)

Proposed Parallel Equation for TSS

$$\frac{dC_{DO}}{dt} = -K_D \Theta_D^{T-20} \left(\frac{C_{DO}}{K_{BOD} + C_{DO}} \right) C_{BOD}$$

Replace C_{BOD} with C_{TSS}

Assumptions:

1. $C_{TSS} \propto C_{\%\ Organic} \propto C_{BOD}$
2. Depletion of C_{BOD} was negligible for the time scale of the field tests

Rate constant: Establish using the relation between oxygen demand and C_{TSS} at a set concentration of DO

Temperature constant: This term characterizes oxygen demand as a function of temperature. This term will not change

DO dependent term: This term dictates how oxygen demand decreases as a function of the DO present. Establish an appropriate function to substitute for this term.

Calibrate these parameters using field data

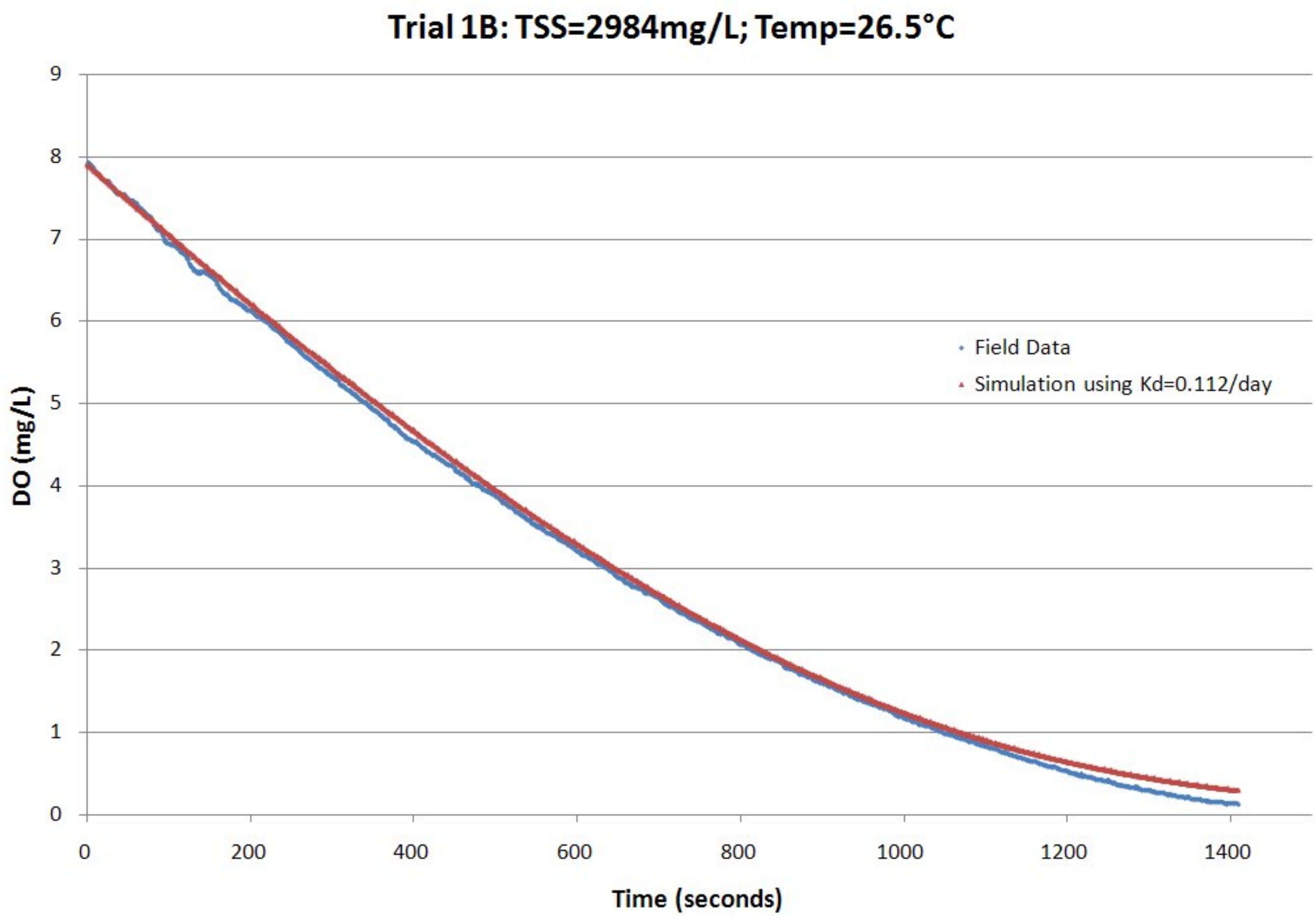
The Final Formulation for Oxygen Sink term associated with Resuspended Sediment:

$$S_{O2} = 0.112\frac{1}{day} * 1.047^{(T-20)} * \left[2.22 * \frac{C_{DO}}{(C_{DO}+2.44)}\right] * C_{TSS}$$

(SOD_R)

Simulations of the Oxygen Sink term on Field Experiments:

$$C_{DO}(t+1) = C_{DO}(t) - SOD_R(t)*\Delta t$$

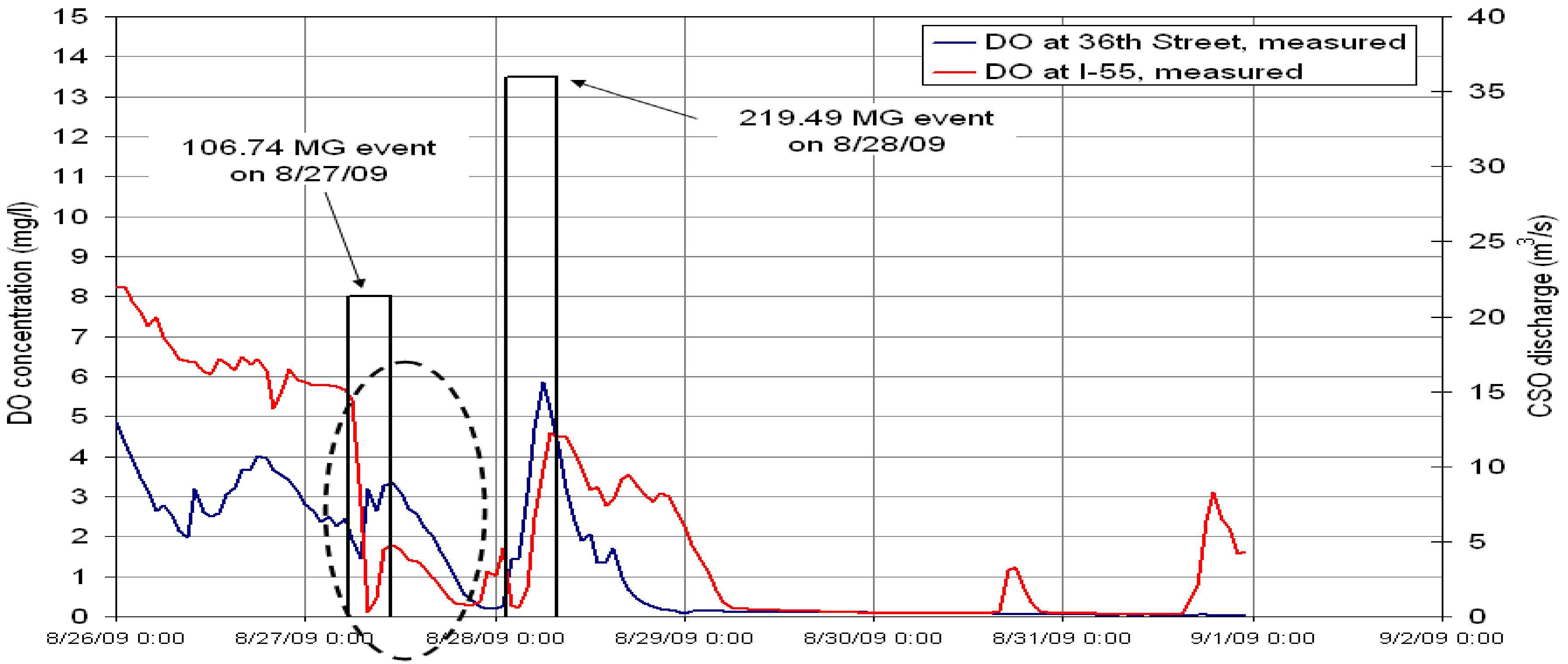


3D modeling with SOD from field observations

I-55 observation point

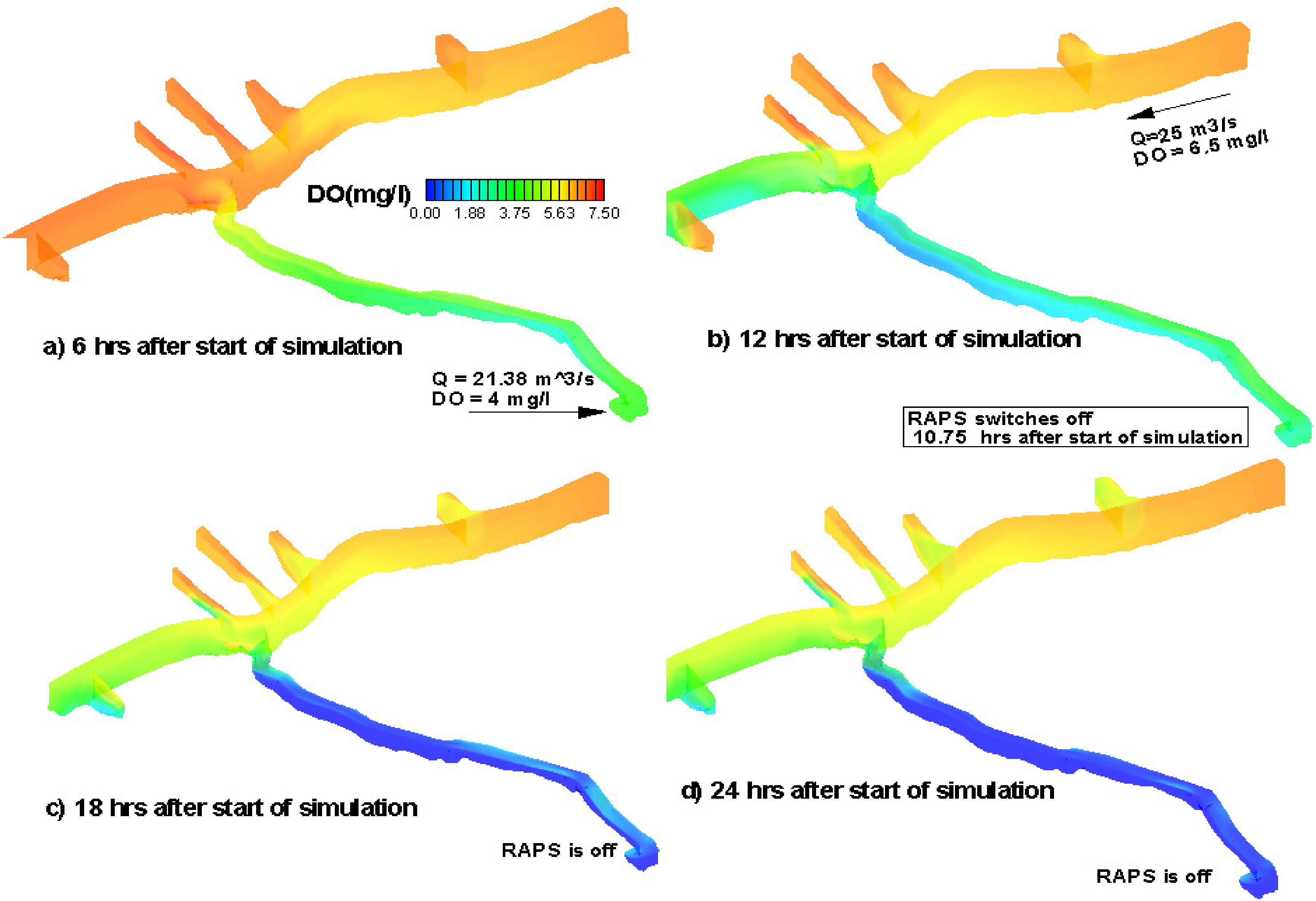
36 Street observation point

Simulation Parameter for DO-BOD model with field – SOD for Aug-27-28,2009

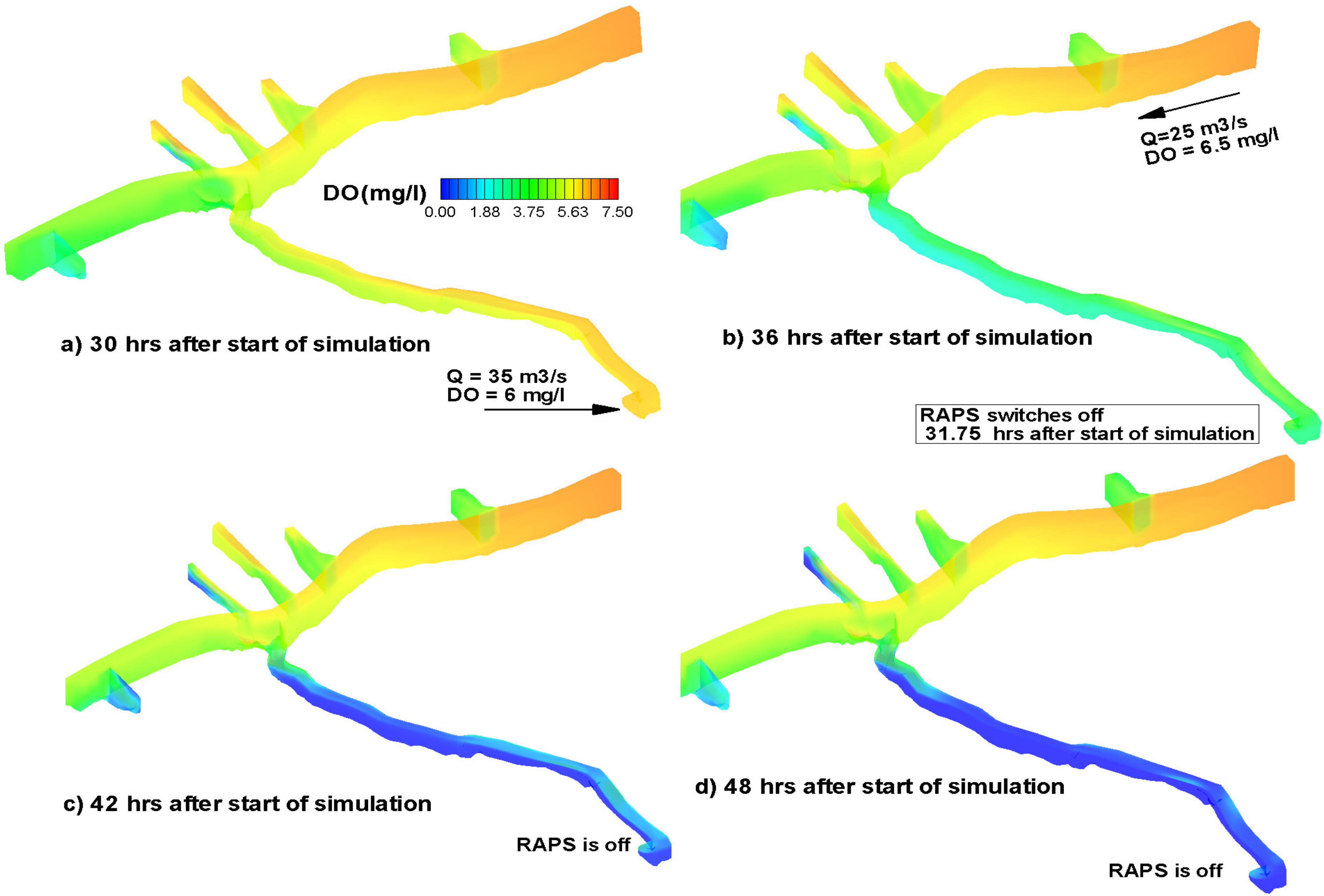


- Incoming BOD from RAPS for event-1 and event-2, 108.79 mg/l and 92.15 mg/l respectively.
- Incoming SS from RAPS for event-1 and event-2, 384.92 mg/l and 379.49 mg/l respectively.
- Incoming DO from RAPS for event-1 and even-2, 4 mg/l and 6.73 mg/l respectively.
- Settling velocity for particle 4.5 m/day. **SOD = 8.7 $g/m^2/day$**

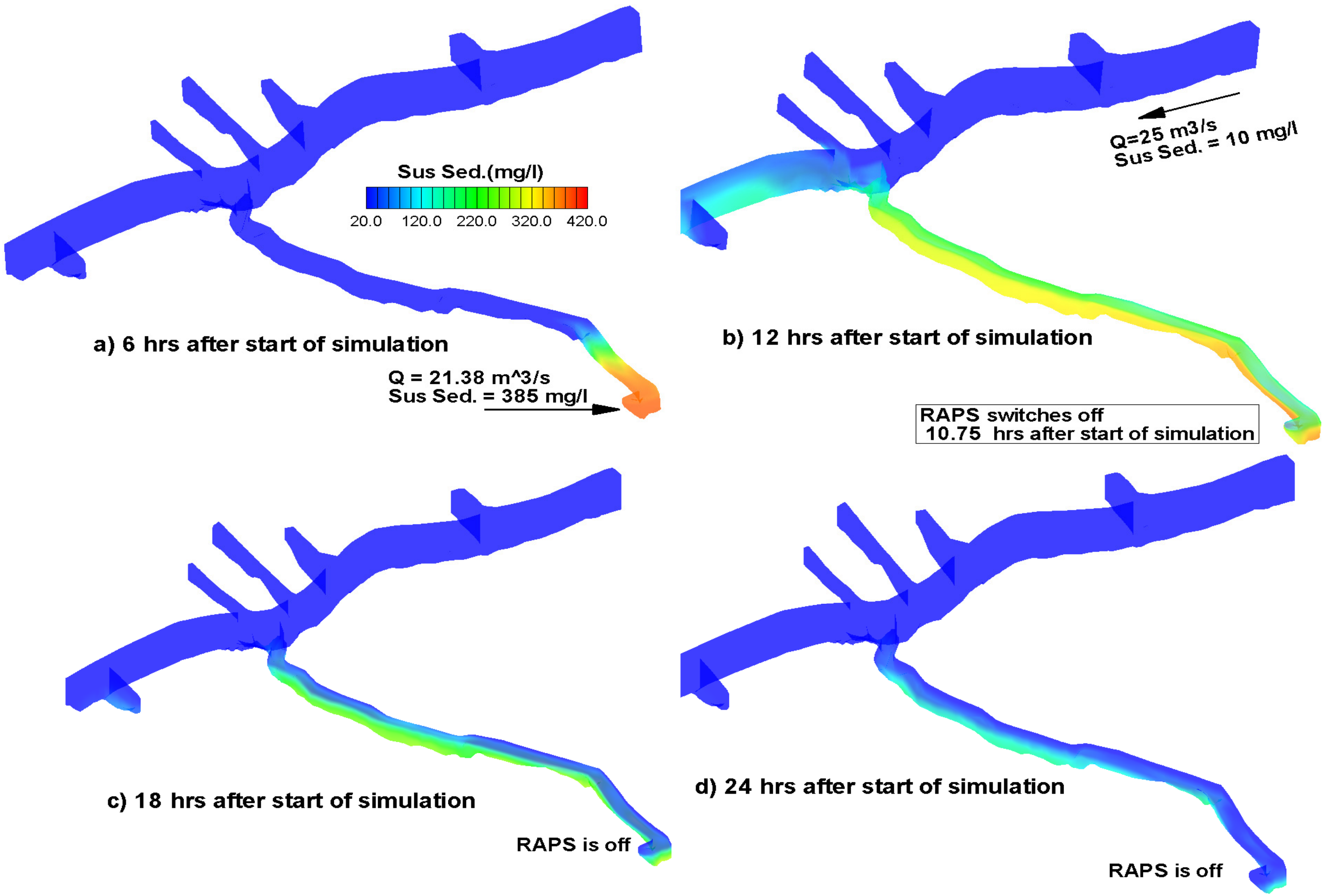
Simulation results starting from 12:00 am Aug-27,2009



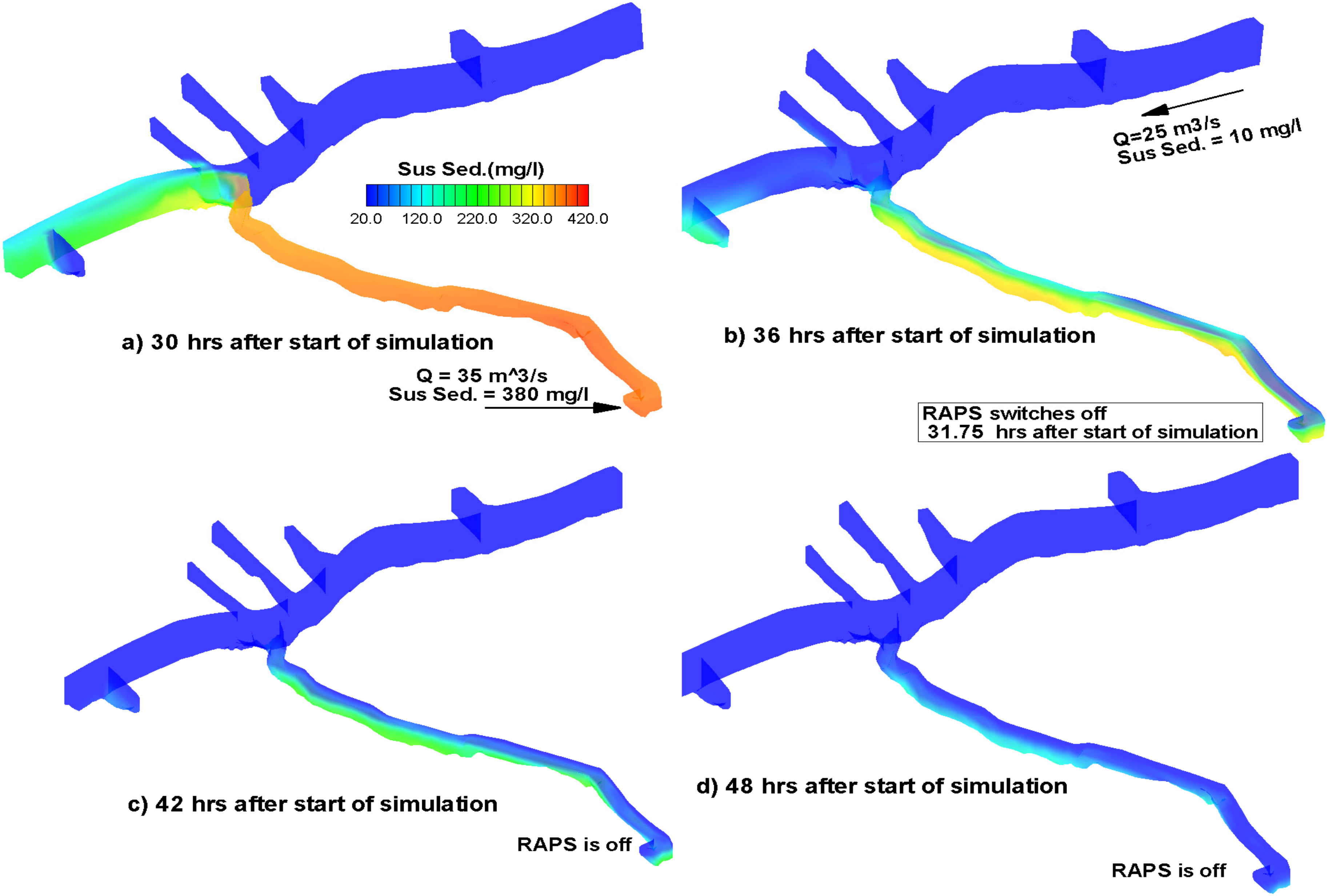
Simulation results starting from 12:00 am Aug-27,2009



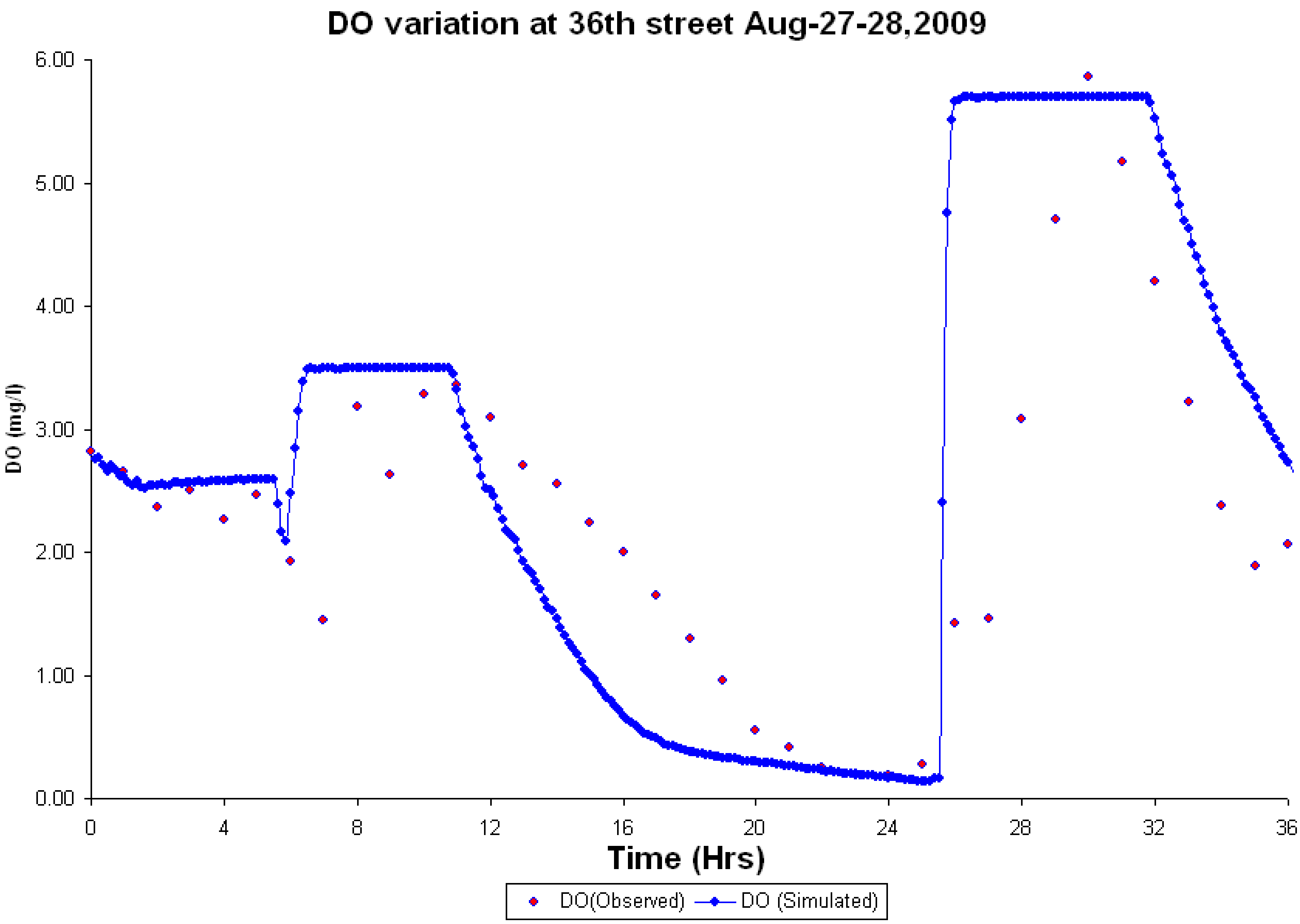
Simulation results starting from 12:00 am Aug-27,2009



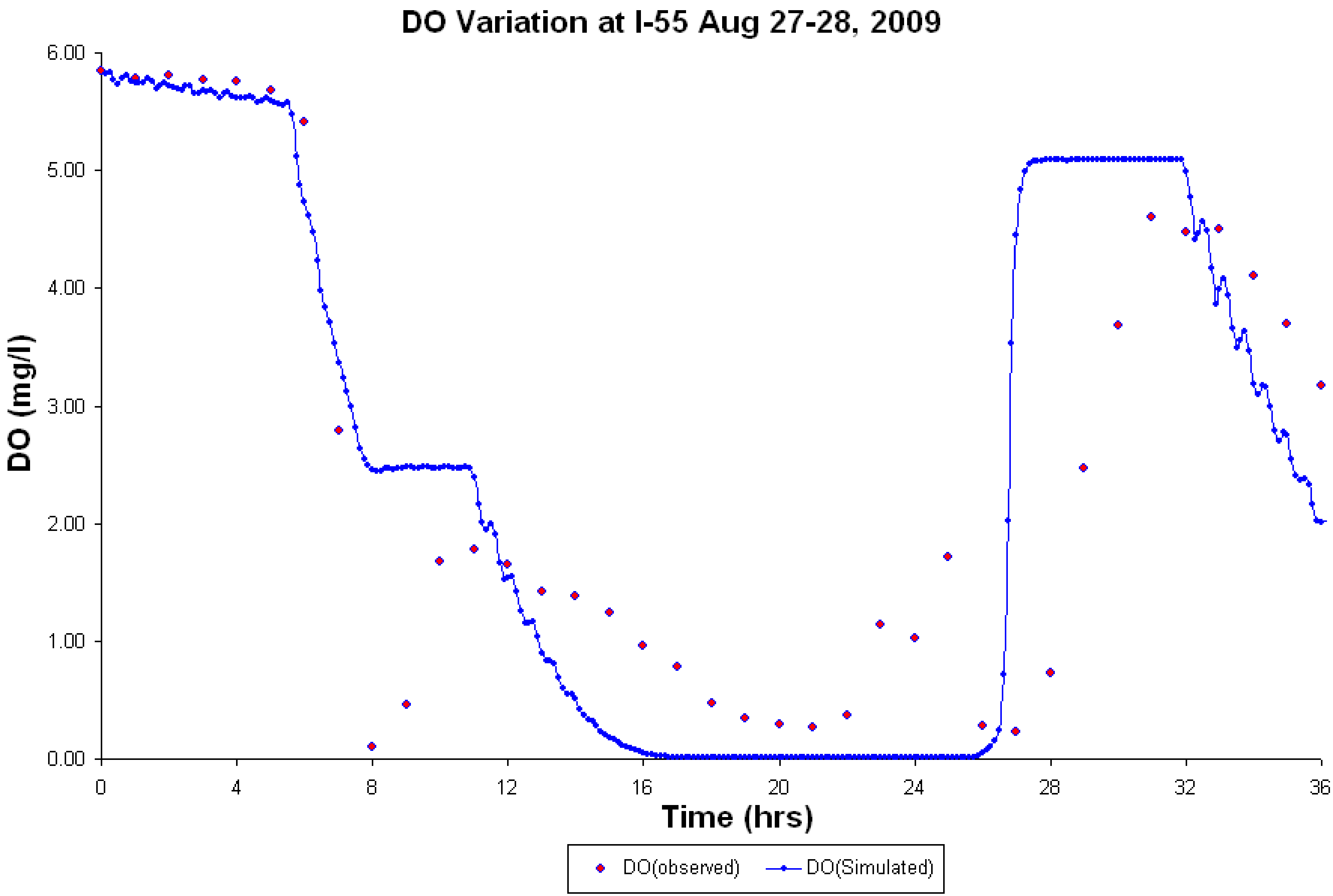
Simulation results starting from 12:00 am Aug-27,2009



Simulation results from DO-BOD model covering two CSO events between Aug 27-28,2009



Simulation results from DO-BOD model covering two CSO events between Aug 27-28,2009



Remediation alternatives in light of SOD studies

Zero-th order analysis of "purification" scenarios based on flow augmentation

→ in absence of sediment resuspension
→ in presence of sediment resuspension

1D analysis of "purification" scenarios based on flow augmentation and supplemental aeration

---

- All the analyses are based on a **balance** between:

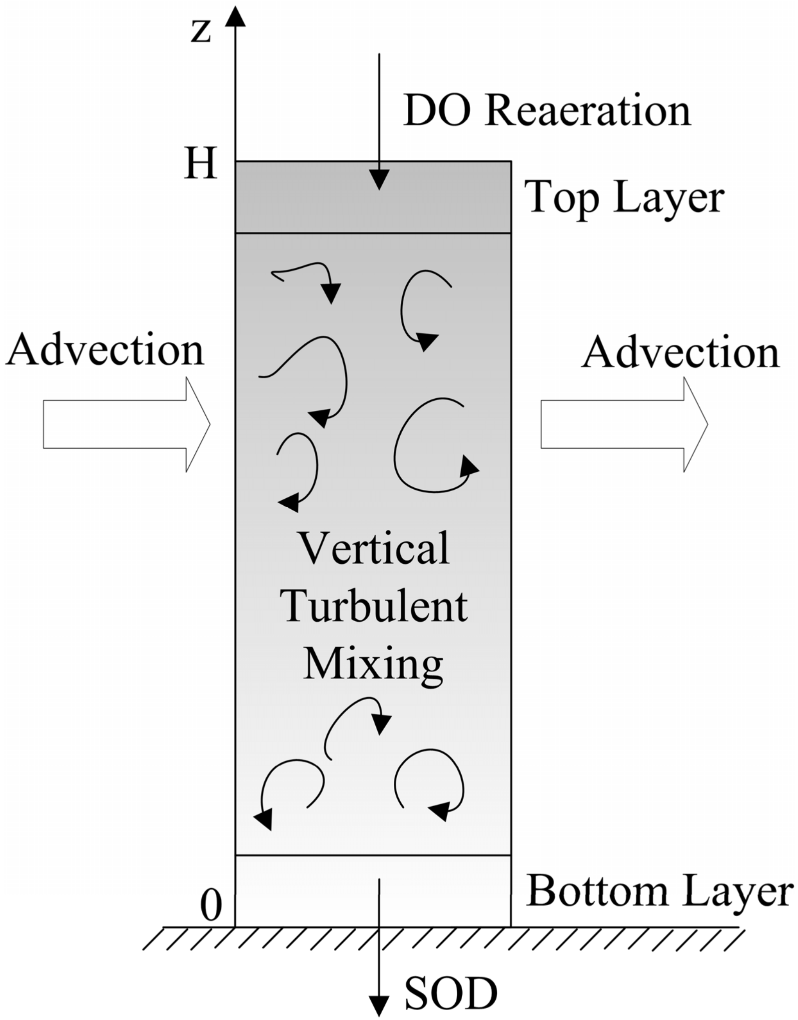
flow reaeration → source term for Dissolved Oxygen
bed and suspended sediment oxygen demand → sink terms for Dissolved Oxygen

Zero-th order analysis

Analytical Solution for DO Dynamics in the Water Column

Assumptions for the water column:

- steady state
- BOD has settled or been oxidized
- net advection effect is zero ($\partial/\partial x = \partial/\partial y = 0$)
- **balance between reaeration on the top and SOD on the bottom**



Zero-th order analysis (contd.)

- The water column is taken as control volume.
- At steady state, the reaeration flux is balanced by the SOD flux.
- We solve for the control volume-averaged equilibrium concentration of Dissolved Oxygen

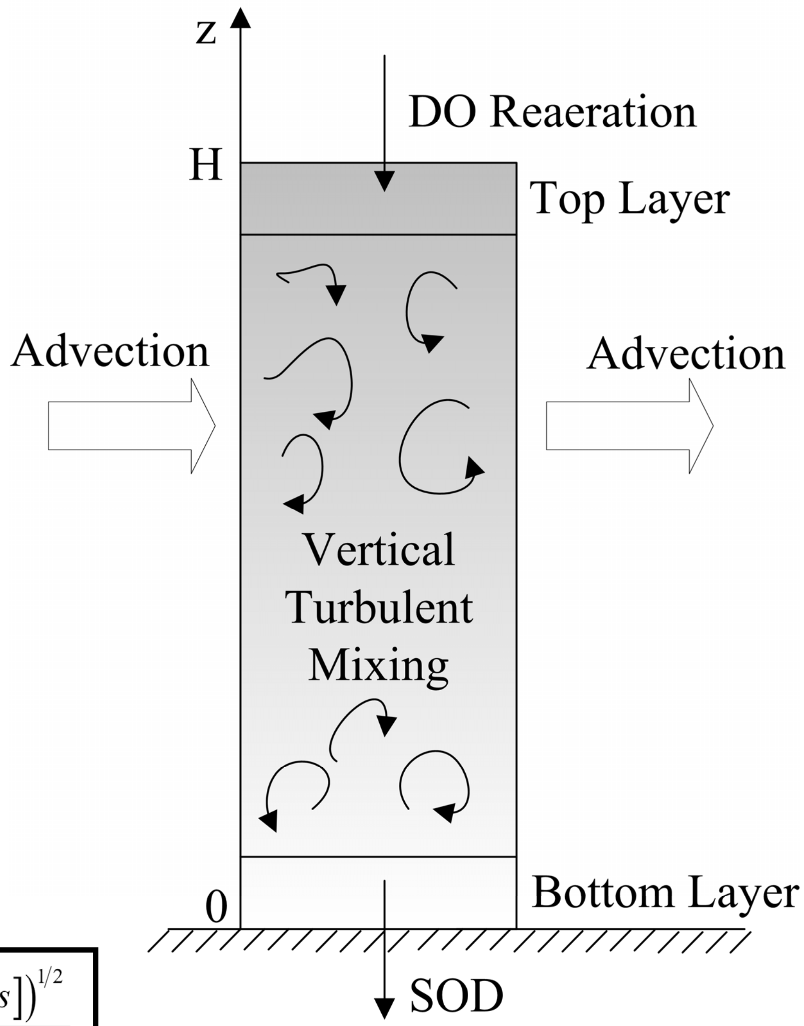
$$k_a \theta_a^{T-20} \left(C_s - C_{DO} \right) = \frac{SOD}{H} \theta_s^{T-20}$$

$$\Rightarrow C_{DO} = C_s - \frac{SOD}{Hk_a} \frac{\theta_s^{T-20}}{\theta_a^{T-20}}$$

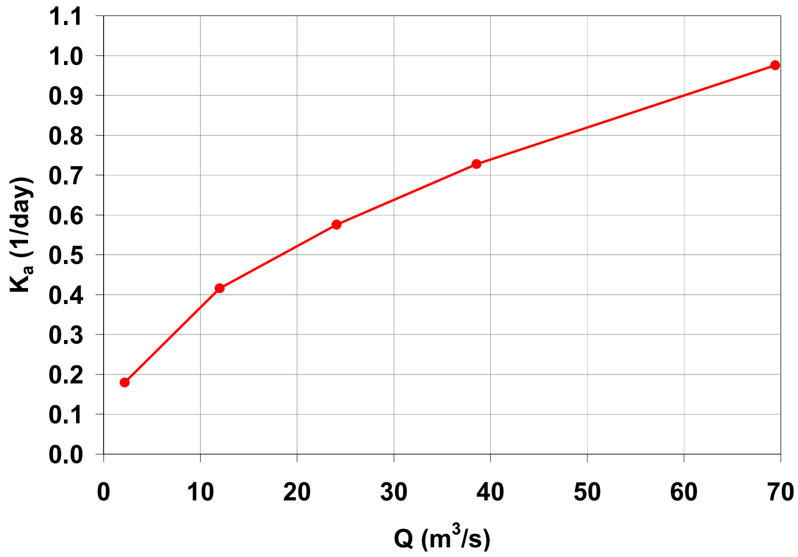
with

$$C_s = \exp\left[7.71 - 1.31 \ln\left(T + 45.93\right)\right]$$

$$K_a[day^{-1}] = \frac{3.93\left(U\left[m/s\right]\right)^{1/2}}{\left(H\left[m\right]\right)^{3/2}}$$

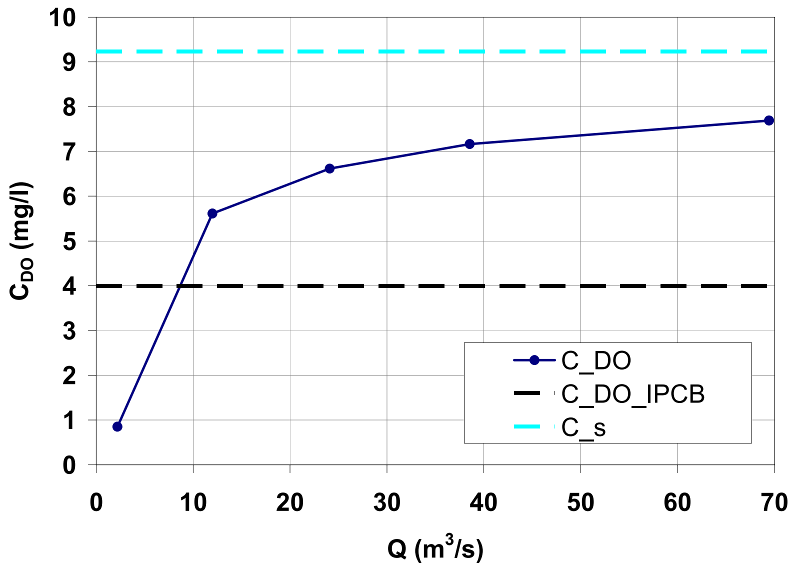


Zero-th order analysis (contd.)



Reaeration coefficient
as function of the discharge

Reaeration coefficient increases as discharge increases



Equilibrium Dissolved Oxygen concentration
as function of the discharge
with SOD = 3.30 g/m^2/day

Equilibrium Dissolved Oxygen concentration increases as discharge increases

Zero-th order analysis (contd.)

Sensitivity to SOD

MWRDGC measurements (2006)

Average value (g/m^2/day)	**2.32**

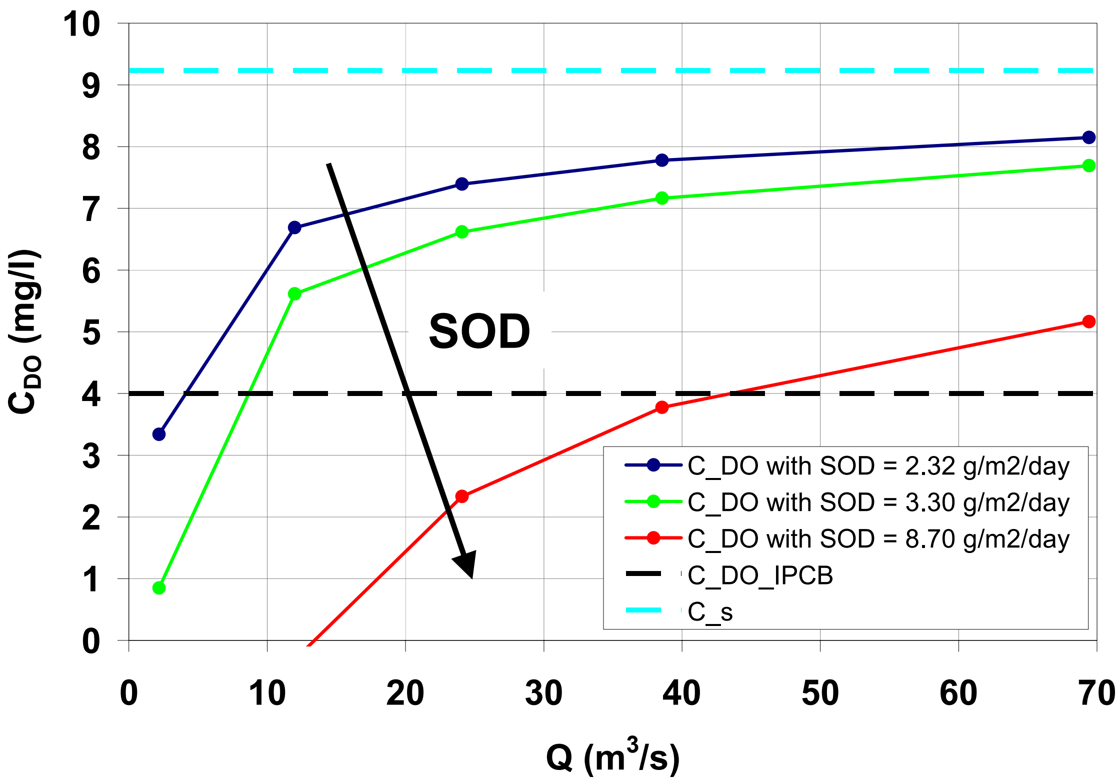
MWRDGC measurements (2007)

Average value (g/m^2/day)	**3.30**

Waterman et al. (2009)

Sediment Type	SOD (g/m^2/day)
Fine-grained organic muck	12.1
Fine sandy organic muck	6.7
Fine sand	6.8
Medium to coarse sand	9.2
Average	**8.7**

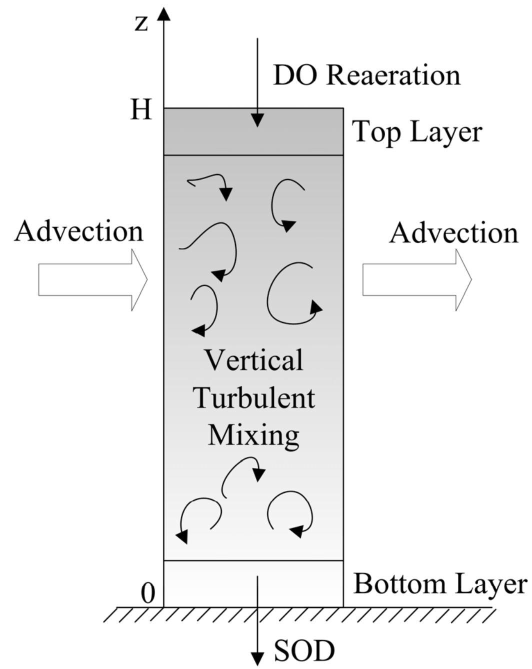
Effect of velocity on SOD even in absence of resuspension (increased mixing)



The higher the SOD,
the lower the Dissolved Oxygen
concentration at equilibrium

Zero-th order analysis (contd.)

- The water column is taken as control volume.
- At steady state, the reaeration flux is balanced by the SOD flux **and the oxygen demand by the suspended sediment (SSOD).**
- We solve for the control volume-averaged equilibrium concentration of dissolved oxygen

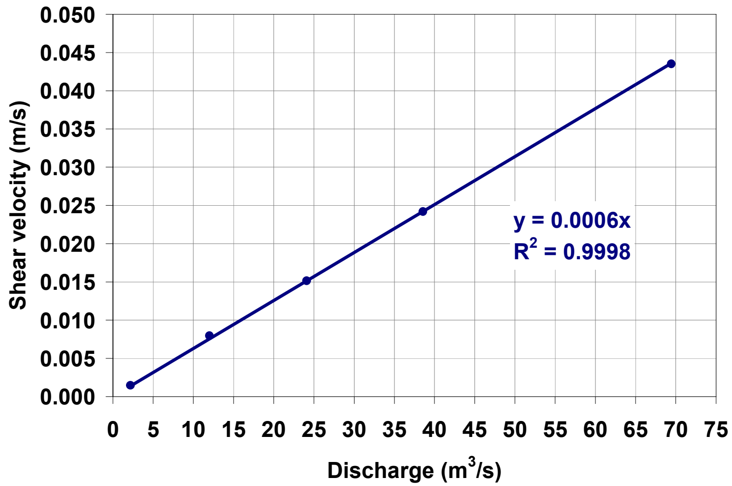


$$k_a \theta_a^{T-20}\left(C_s - C_{DO}\right) = \frac{SOD}{H}\theta_s^{T-20} + \underbrace{0.112 \cdot 1.047^{T-20}\left[2.22\frac{C_{DO}}{C_{DO}+2.44}\right]C_{ss}}_{SSOD}$$

This is a relation that links Suspended Sediment and Dissolved Oxygen

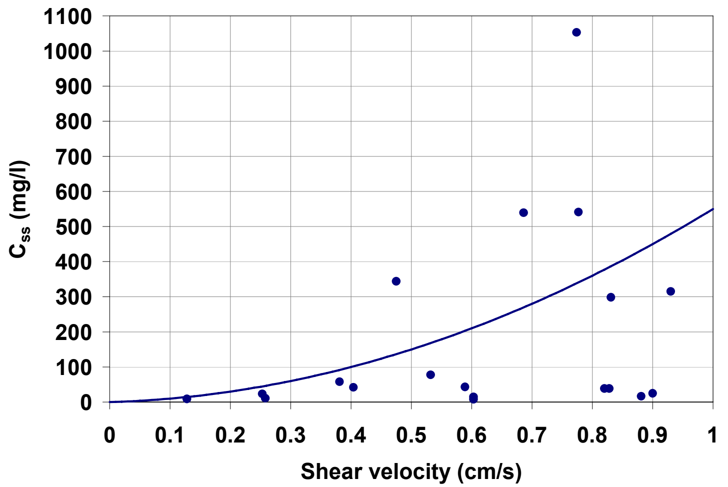
Zero-th order analysis (contd.)

An expression which links suspended sediment concentration and discharge was derived for Bubbly Creek



Average values of shear velocity in Bubbly Creek, obtained with 2D hydrodynamic simulation

$$\left.\begin{array}{l} \dfrac{u_*}{U} = \sqrt{C_f} \quad \Rightarrow \quad u_* \propto U \\ Q = UA \quad \Rightarrow \quad Q \propto U \end{array}\right\} u_* \propto Q$$



Relation between shear velocity and Suspended Sediment concentration, from in situ data by Waterman et al. (2009)

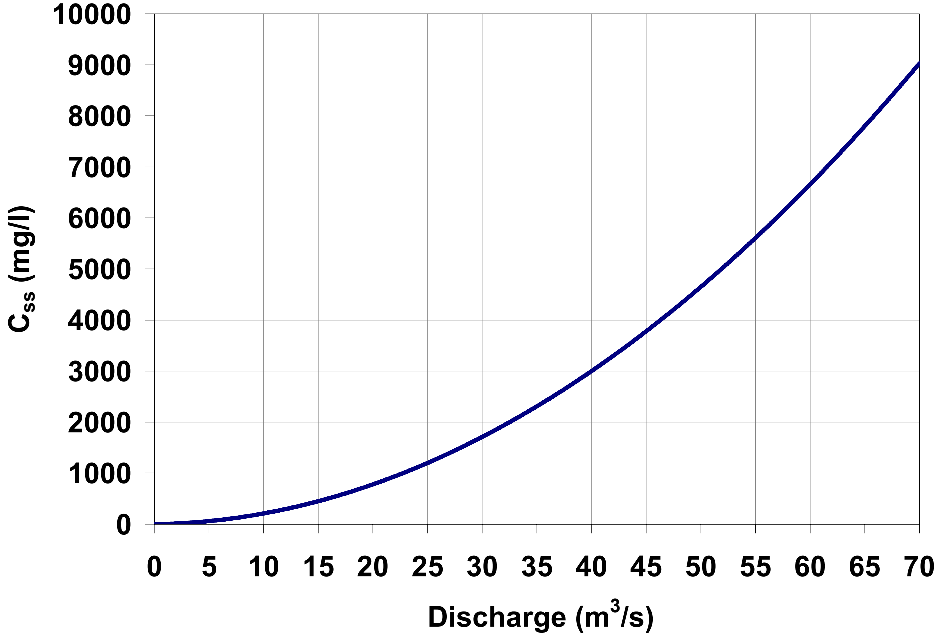
$$C_{ss} = a_1 u_*^2 + a_2 u_*$$

Recall

$$u_* = \sqrt{\frac{\tau_b}{\rho}}$$

Zero-th order analysis (contd.)

Therefore the expression which links suspended sediment concentration and discharge for Bubbly Creek is



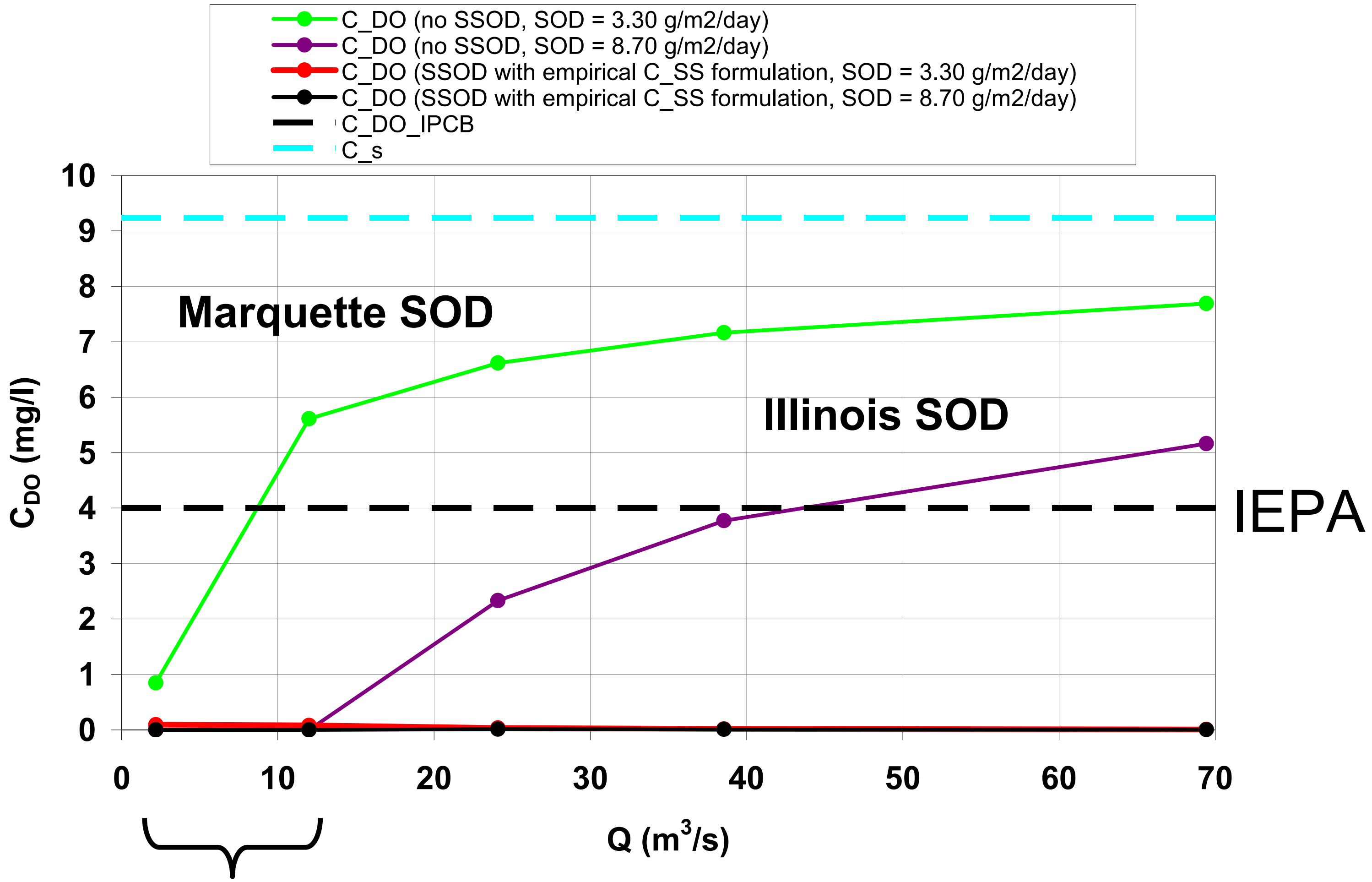
For high flow rates, the curve needs a "cap", since the concentration cannot increase indefinitely

Summary of the hydrodynamics quantities for different discharge values

Q	**2.19**	**12.00**	**24.09**	**38.55**	**69.43**	m^3/s
H	2.19	2.19	2.19	2.19	2.19	m
U	0.02	0.12	0.23	0.36	0.65	m/s
u_star	0.001	0.01	0.02	0.02	0.04	m/s
Tau_bed	0.002	0.06	0.23	0.59	1.89	Pa

Zero-th order analysis (contd.)

The oxygen demand exerted by the Suspended Sediments causes a decrease of Dissolved Oxygen at equilibrium for high values of discharge



Possible Q range for "purification", but supplemental aeration is needed

1D analysis

In absence of suspended sediment

$$\frac{dC_{DO}}{dt} = k_a \theta_a^{T-20}\left(C_s - C_{DO}\right) - \frac{SOD}{H}\theta_s^{T-20}$$

With $u = \frac{dx}{dt}$

$$u\frac{dC_{DO}}{dx} = k_a \theta_a^{T-20}\left(C_s - C_{DO}\right) - \frac{SOD}{H}\theta_s^{T-20}$$

In presence of suspended sediment

$$\frac{dC_{DO}}{dt} = k_a \theta_a^{T-20}\left(C_s - C_{DO}\right) - \frac{SOD}{H}\theta_s^{T-20} \underbrace{- 0.112 \cdot 1.047^{T-20}\left[2.22\frac{C_{DO}}{C_{DO}+2.44}\right]C_{ss}}_{SSOD}$$

With $u = \frac{dx}{dt}$

$$u\frac{dC_{DO}}{dx} = k_a \theta_a^{T-20}\left(C_s - C_{DO}\right) - \frac{SOD}{H}\theta_s^{T-20} \underbrace{- 0.112 \cdot 1.047^{T-20}\left[2.22\frac{C_{DO}}{C_{DO}+2.44}\right]C_{ss}}_{SSOD}$$

Recall $$C_{ss}\left[mg/l\right] = 500\left(0.0006 \cdot 100Q\left[m^3/s\right]\right)^2 + 50\left(0.0006 \cdot 100Q\left[m^3/s\right]\right)$$

→ 1D profiles of Dissolved Oxygen concentration can be obtained, for the evaluation of “purification” scenarios based on flow recirculation and supplemental aeration

1D analysis (contd.)

Considering a recirculation discharge of 2.19 m^3/s (50 MGD), characterized by

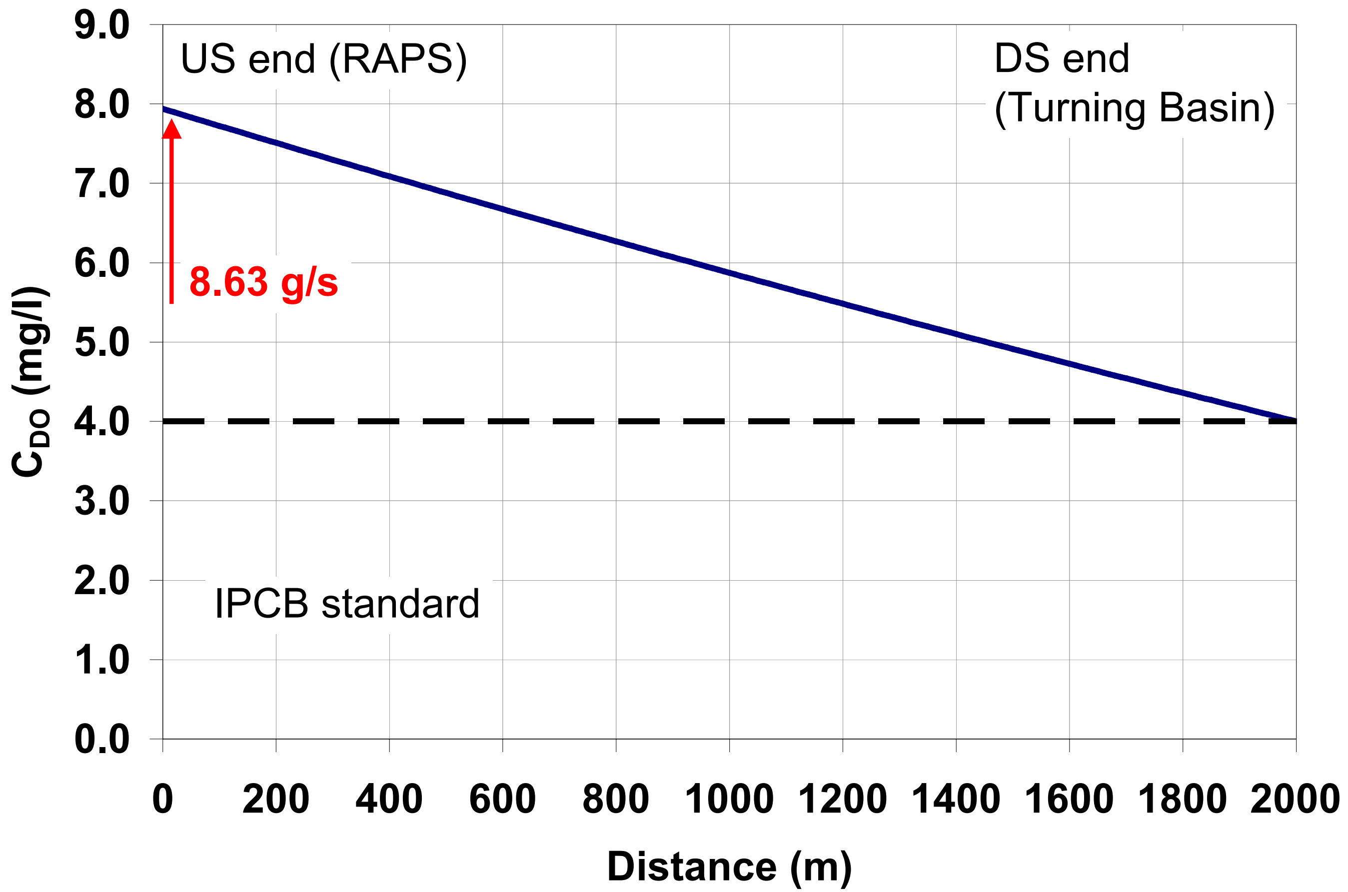
- Average flow velocity = 0.02 m/s
- Average depth = 2.19 m

we analyze a “purification” scenario of this type.
Oxygen demand from the sediments in the bed and in suspension compete with the flow reaeration

1D analysis (contd.)

If sediment resuspension is not considered

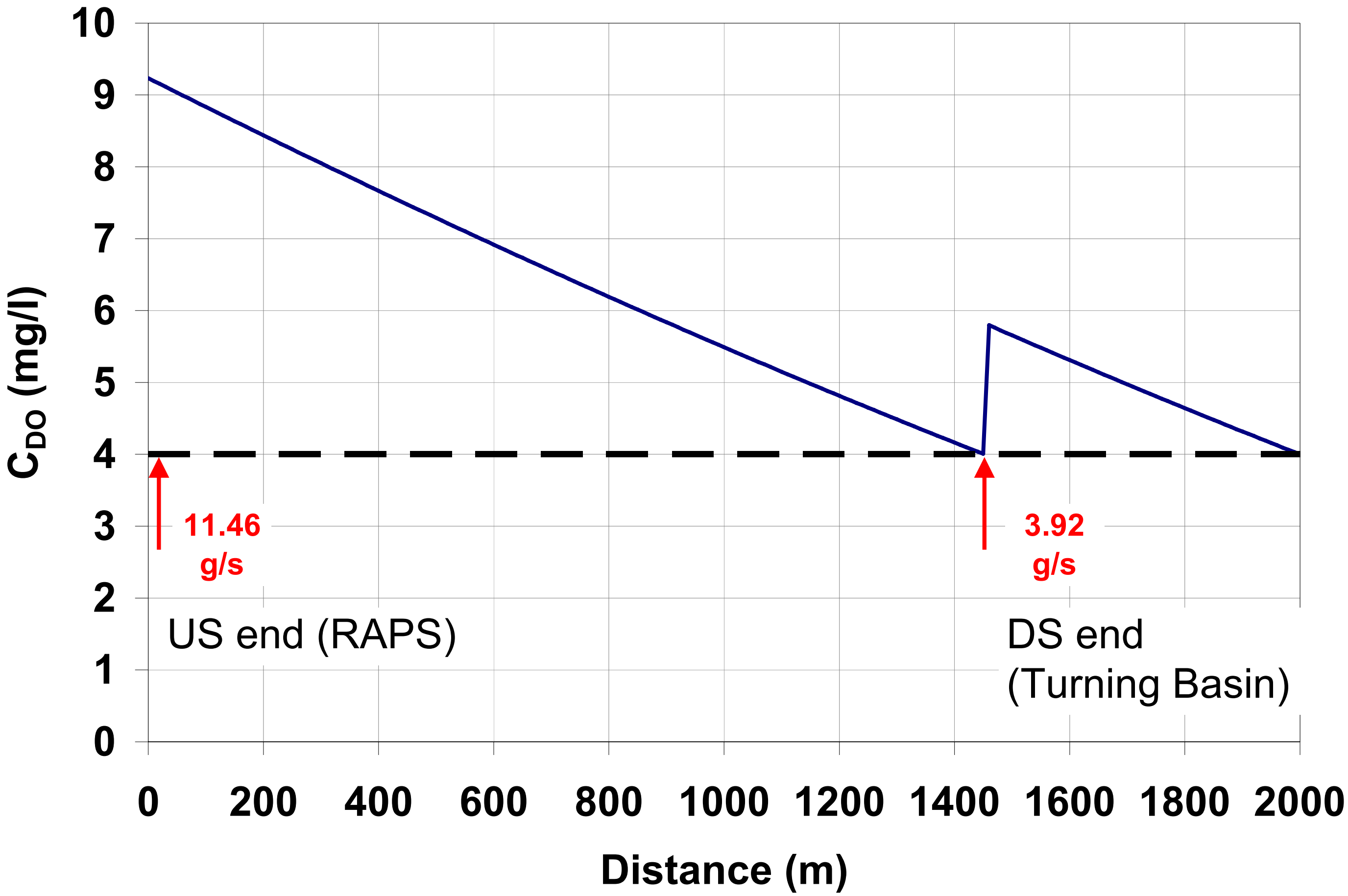
only **one location** is needed for supplemental aeration, in **the pipe**, with reaeration rate = **8.63 g/s**, with a **bottom SOD of 8.7 g/m²/day**
to get a Dissolved Oxygen concentration of at least 4 mg/l in the creek



1D analysis (contd.)

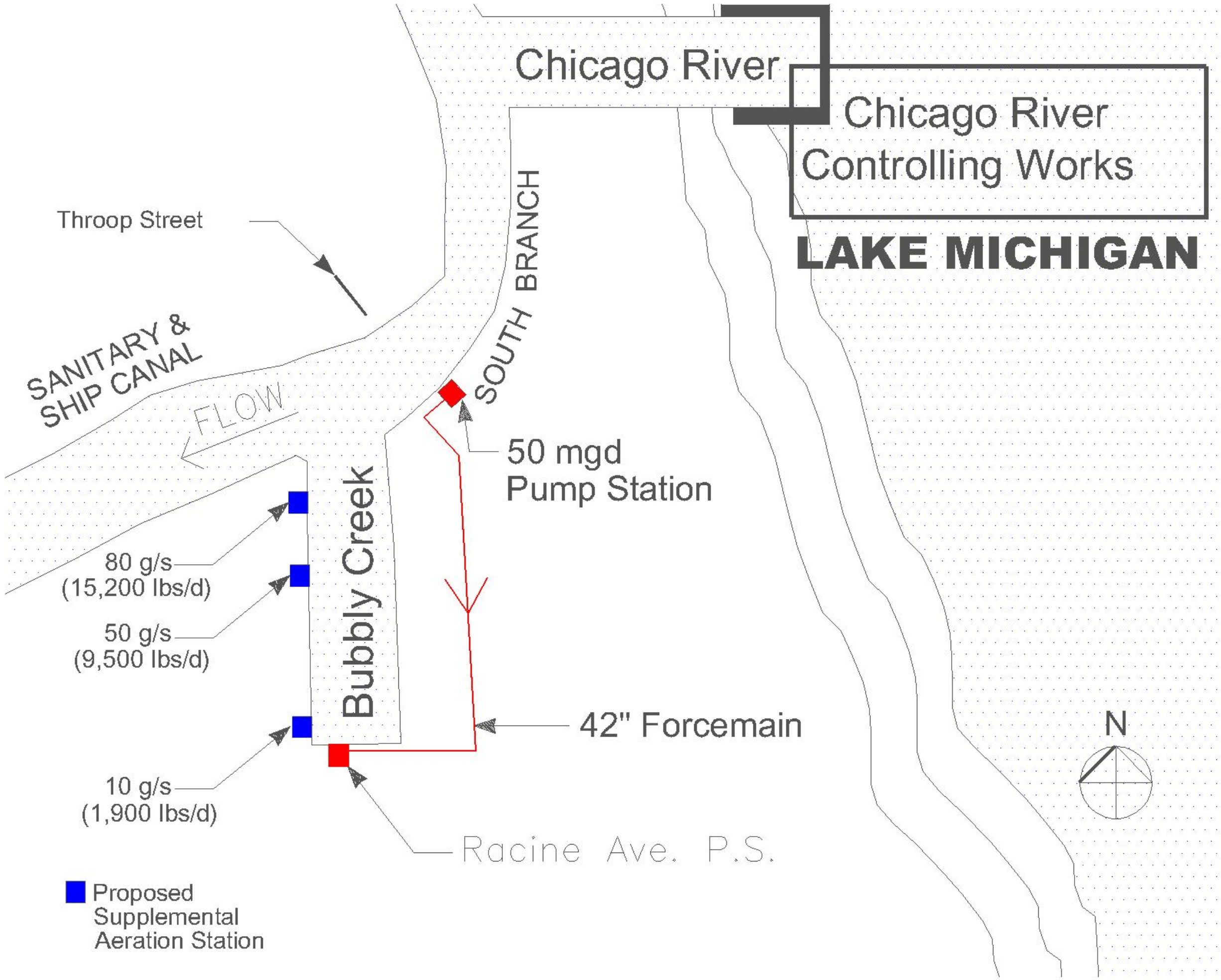
If sediment resuspension is considered (C_{ss} = 15 mg/l)

two locations are needed for supplemental aeration, in **the pipe and in the creek**, with a **total** reaeration rate = **15.38 g/s**, with a **bottom SOD of 8.7 g/m²/day** to get a Dissolved Oxygen concentration of at least 4 mg/l in the creek



IEPA DO = 4 mg/l

Flow Augmentation & Supplemental Aeration of Bubbly Creek

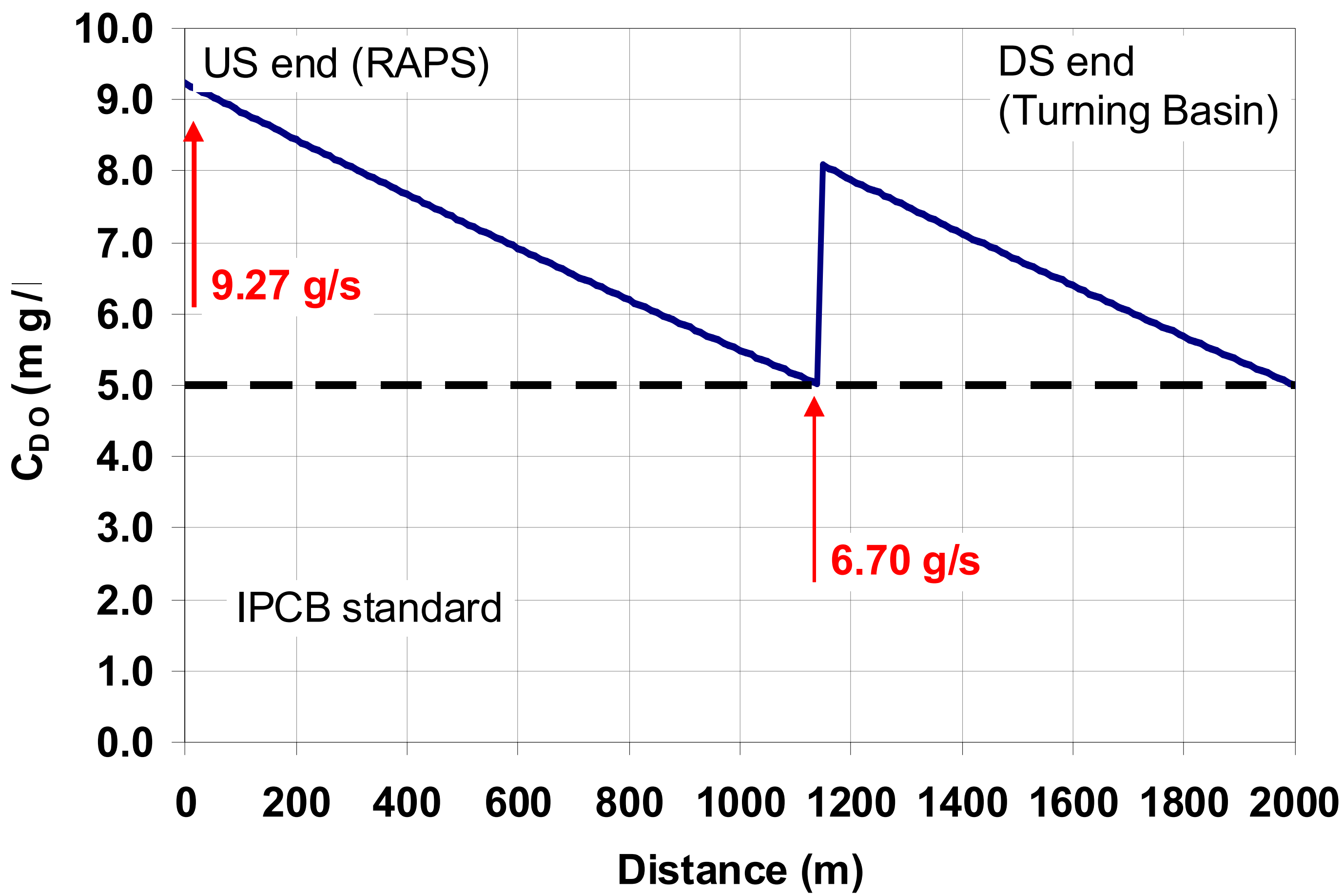


From CTE, Zenz (2007)

1D analysis (contd.)

If sediment resuspension is considered (C_{ss} = 15 mg/l)

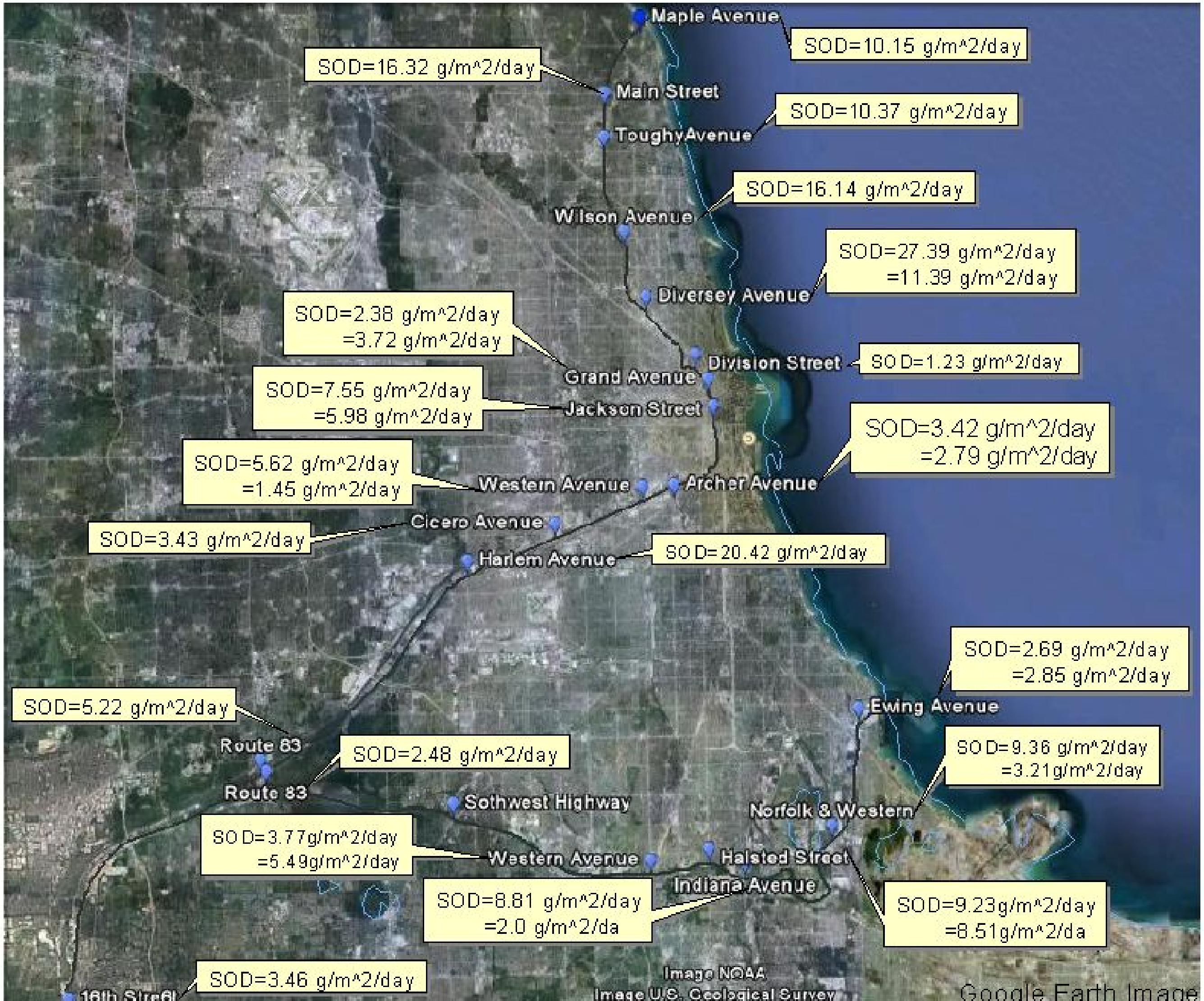
two locations are needed for supplemental aeration, in **the pipe and in the creek**, with a **total** reaeration rate = **15.97 g/s**, with a **bottom SOD of 8.7 g/m²/day** to get a Dissolved Oxygen concentration of at least 4 mg/l in the creek



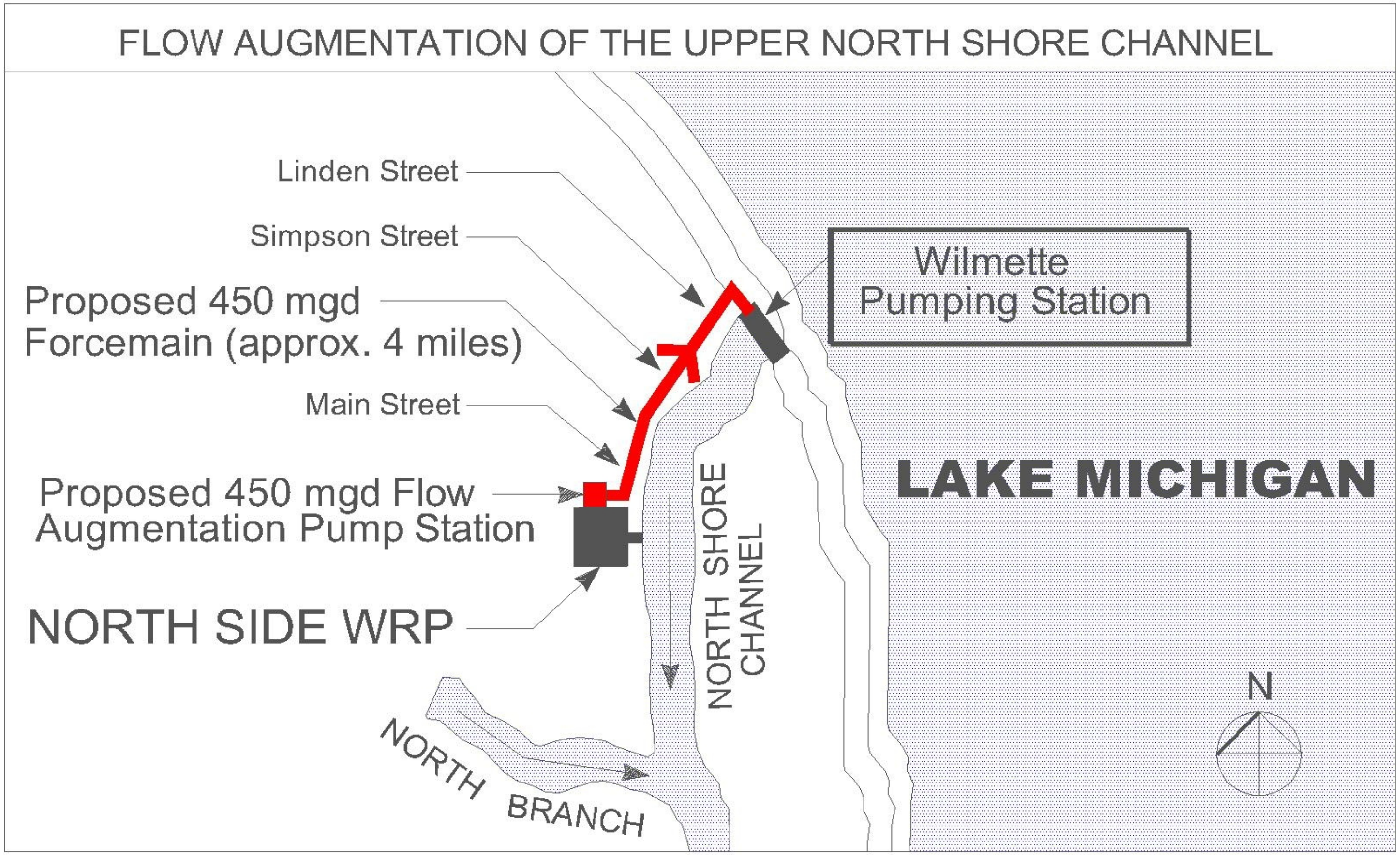
IEPA DO = 5 mg/l

Implications for water quality management

Sediment Oxygen Demand - Chicago Area Waterways



Adapted from: Polls,I., and Spielman, C. 1977. Sedement Oxygen Demand of Bottom Deposits In Deep Draft Waterways in Cook County.



From CTE, Zenz (2007)

Conclusions

- ✓ Strategies to improve water quality in the waterways have to take into account benthic sediment oxygen demand (SOD)
- ✓ Sediment oxygen demand due to resuspension of bottom material can result in very low oxygen levels in the water column
- ✓ Correct modeling of the impact of sediment resuspension and transport on oxygen demand is crucial to assess the effectiveness of different alternatives for water quality improvement and the impact of CSO events on Bubbly Creek and the South Branch of the Chicago River.

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