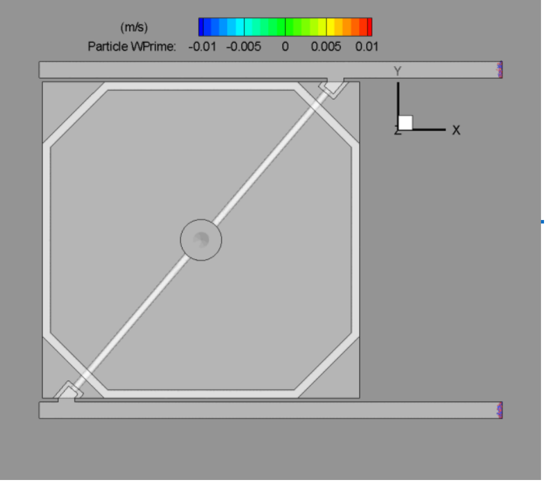
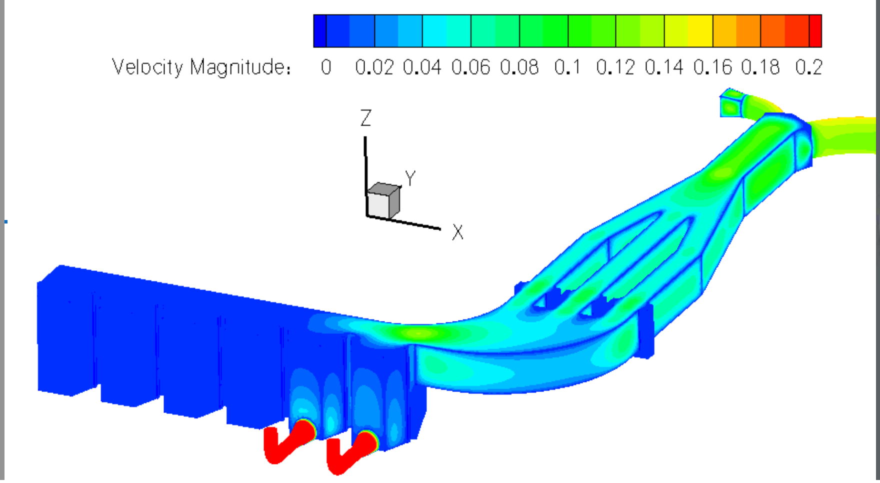
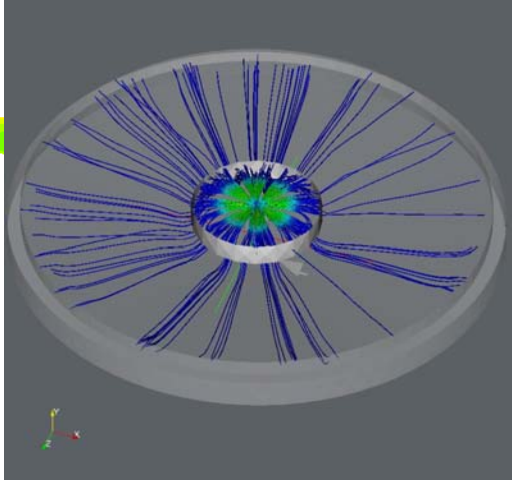






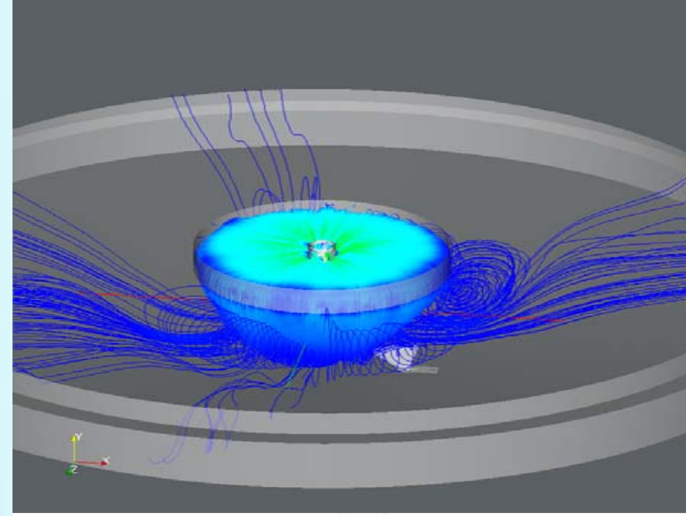
Computer Modeling to Support Process Design at the District

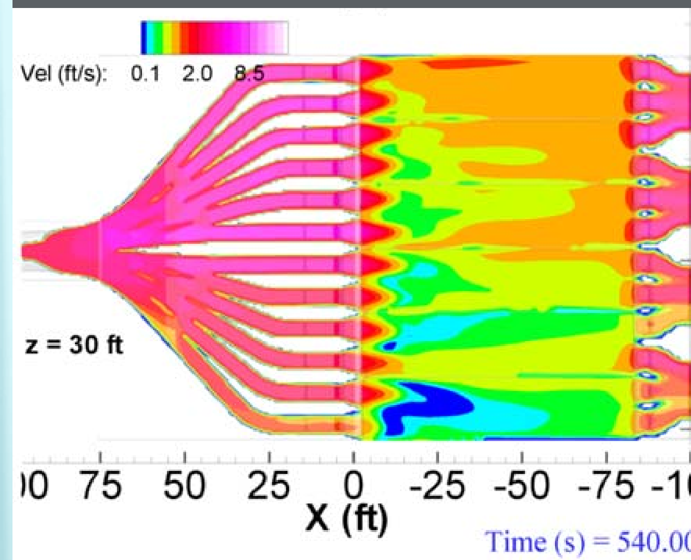
M&R Monthly Seminar, November 18, 2011

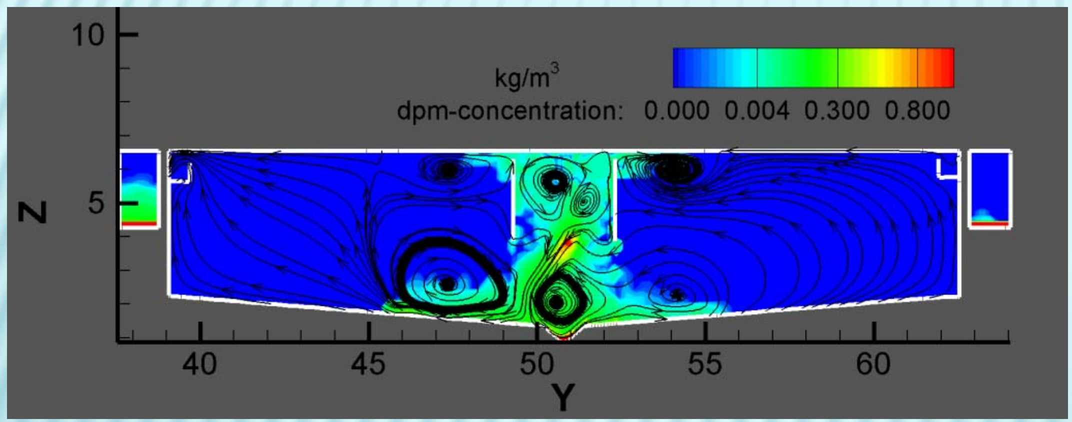
Edward Podczerwinski, PE
Principal Civil Engineer
Plant Design Management

MWRD

COMPUTER MODELING





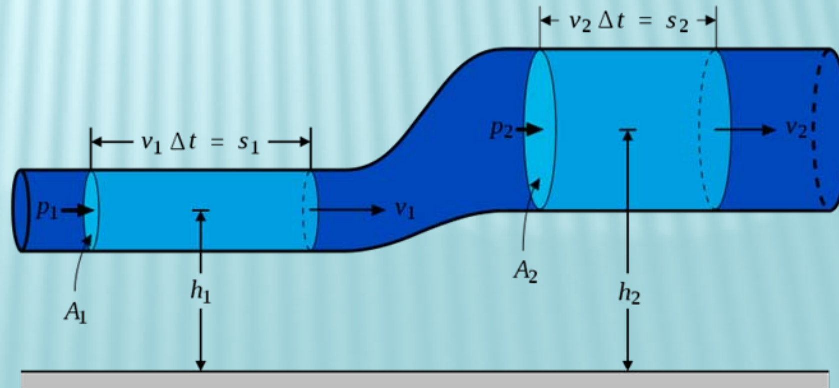


Not just pretty colors and cool visual effects…

$Q = V\,A$ IS THAT ALL

Traditional methods of flow analysis and design have limited accuracy and cannot completely address the fluid flow problems.

Three dimensional flows include numerous variables that are difficult to account for such as turbulence, heat and/or mass transfer, settlement, etc.



WHY COMPUTER MODELING

$$Q = V \cdot A$$

- Used to optimize the new design/geometry
- Can identify operational problems
- Used to solve current operational problems of the existing infrastructure
- Used to simulate fluid behavior in complex applications, for better understanding and visualization
- Simulations are faster and less costly than physical models

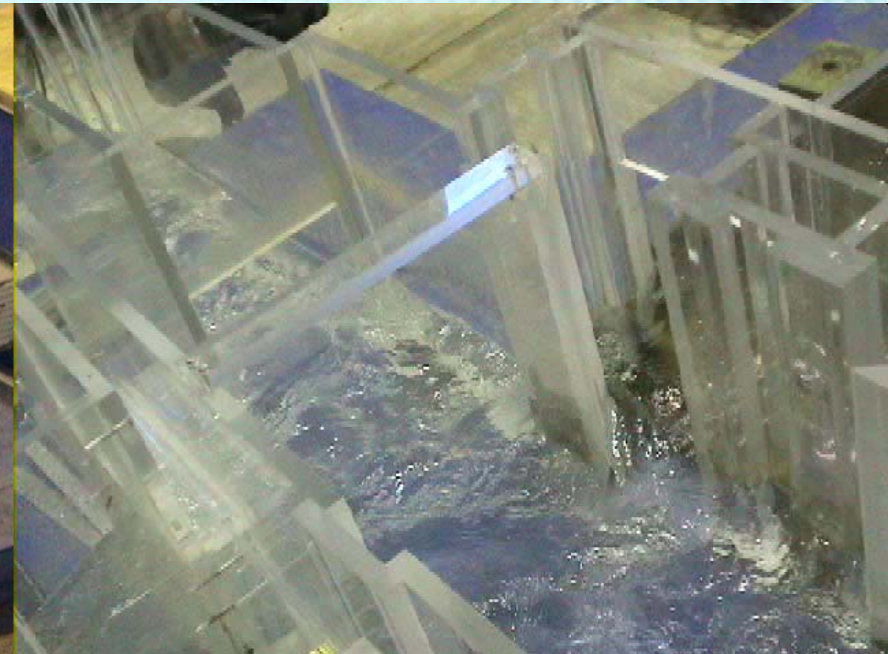
$$\vec{v}_m = \frac{\sum_{k=1}^{N} \alpha_k \rho_k \vec{v}_k}{\rho_m} \qquad \vec{v}_{pq} = \frac{\tau_p}{f_{drag}} \frac{(\rho_p - \rho_m)}{\rho_p} \vec{a}$$

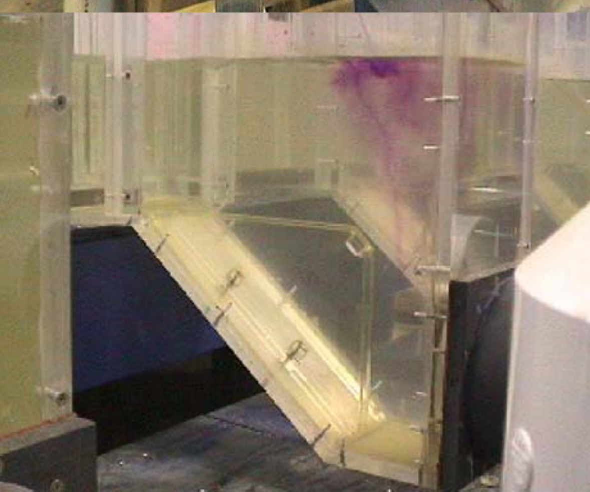
$$\frac{\partial}{\partial t}\left(\alpha_p \rho_p\right) + \nabla \cdot \left(\alpha_p \rho_p \vec{v}_m\right) = -\nabla \cdot \left(\alpha_p \rho_p \vec{v}_{dr,p}\right)$$

$$\frac{\partial}{\partial t}\left(\rho_m \vec{v}_m\right) + \nabla \cdot \left(\rho_m \vec{v}_m \vec{v}_m\right) = -\nabla p + \nabla \cdot \left[\mu_m \left(\nabla \vec{v}_m + \nabla \vec{v}_m^{\,T}\right)\right] + \rho_m \vec{g} + \vec{F} + \nabla \cdot \left(\sum_{k=1}^{n} \alpha_k \rho_k \vec{v}_{dr,k} \vec{v}_{dr,k}\right)$$

CALUMET HLIPS PHYSICAL MODEL

(Video Simulation)

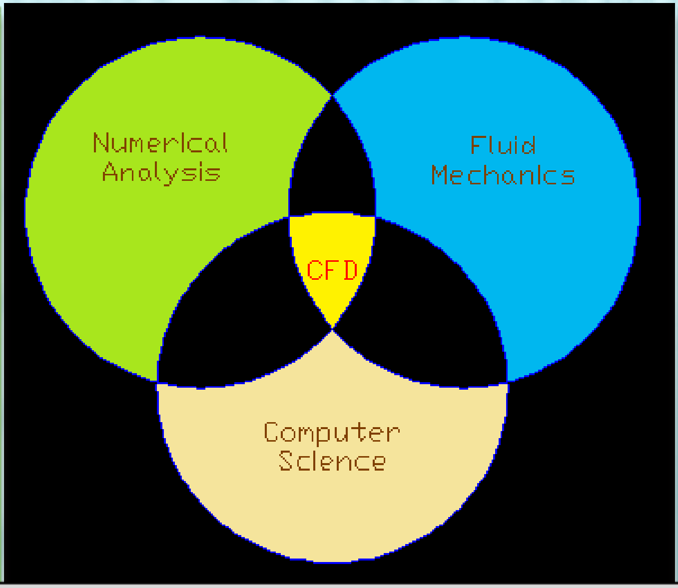




COMPUTATIONAL FLUID DYNAMICS (CFD)

Equations and Algorithms

- Discretization of continuous fluid flow behavior
  - Finite volume method
  - Finite element method
  - Boundary element method
  - Integrals and differential equations
- Algorithms – step-by-step procedure for calculations
  - SIMPLE (Semi-Implicit Method for Pressure Linked Equations)



Fluid Behavior

- Euler Equations (Ideal fluid)
  - Conservation of Mass
  - Conservation of Momentum
  - Conservation of Energy
- Navier-Stokes Equations
  - Introduced viscous forces to Euler equations
  - Describe the changes in momentum of particles in relation to external pressure and internal viscous forces

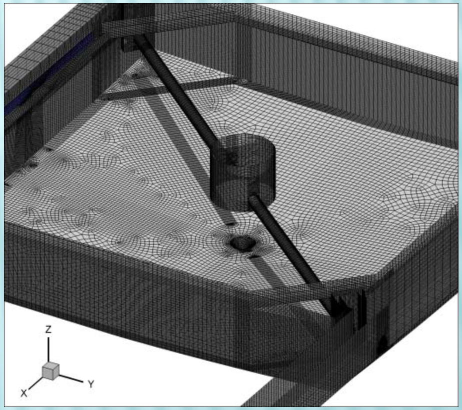
Computerized Aid

- Developing geometrical model (CAD)
- Programmable software codes
  - OpenFOAM
  - Flow 3D
- Supercomputers for simulations

CFD is a technique for the simulation and analysis of fluid flow using a computer model.

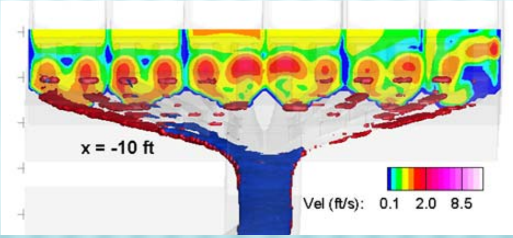
CFD DESIGN PROCESS

- Define the geometry and physical boundary conditions of the system
  - ✓ Use CAD or other graphical interface
  - ✓ Develop a mesh of discrete elements/cells
- Define the equations of fluid motion to be applied in the simulation
- Define the fluid boundary conditions and properties
- Assemble the components in a programmable code or use commercially available software that suits the application
- Perform the simulations using supercomputers yielding measurable results
- Use a postprocessor for visualizing and analyzing the results



Flow Field

Velocities



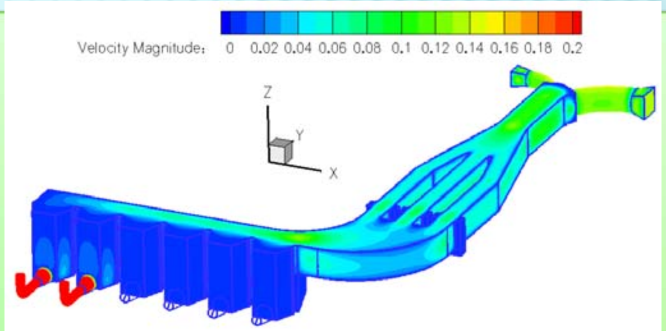
$$\frac{\partial}{\partial t}\left(\alpha_p \rho_p\right) + \nabla \cdot \left(\alpha_p \rho_p \vec{v}_m\right) = -\nabla \cdot \left(\alpha_p \rho_p \vec{v}_{dr,p}\right)$$

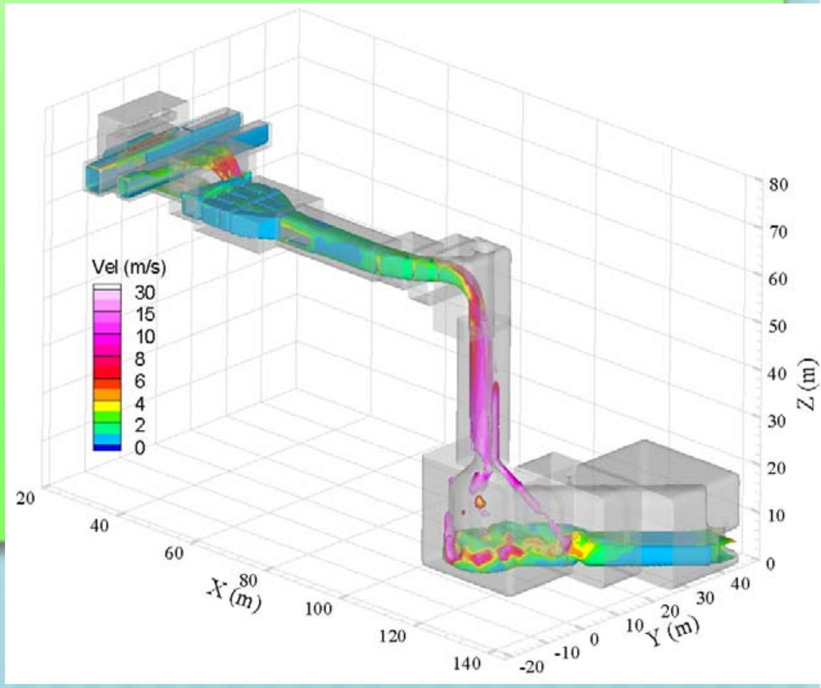
Species Concentration

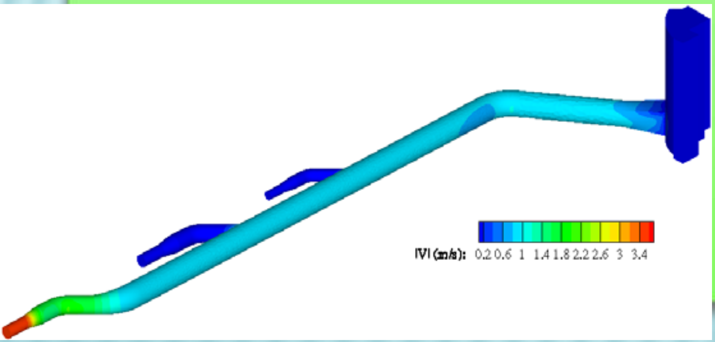
The more accurate the system and fluid are defined, the more accurate are the output results

DISTRICT APPLICATIONS USING COMPUTER MODELING

- Calumet TARP Pumping Station
- TARP Dropshafts
- Calumet Pumping Station
- Egan Pumping Station
- Stickney WS AGT Flow Split
- Calumet Primary Settling Tanks
- North Side Grit Chambers
- North Side Final Settling Tanks



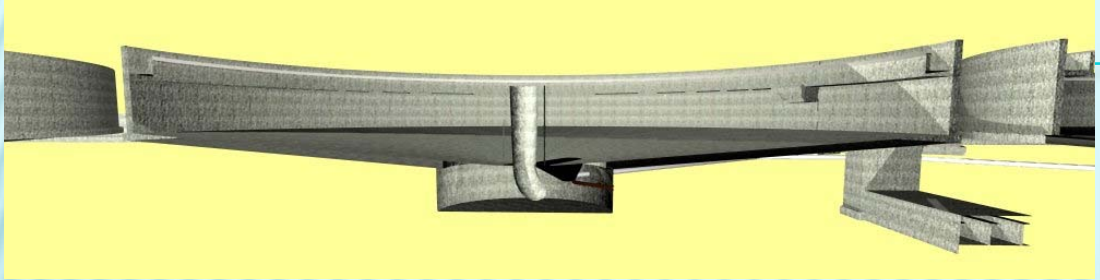


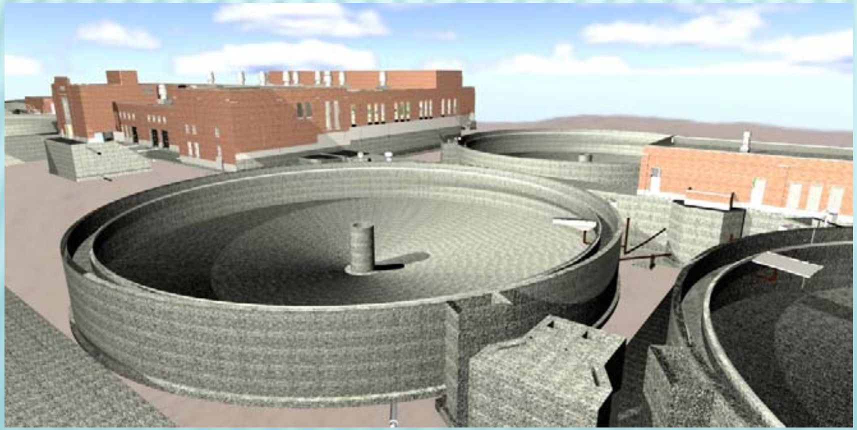


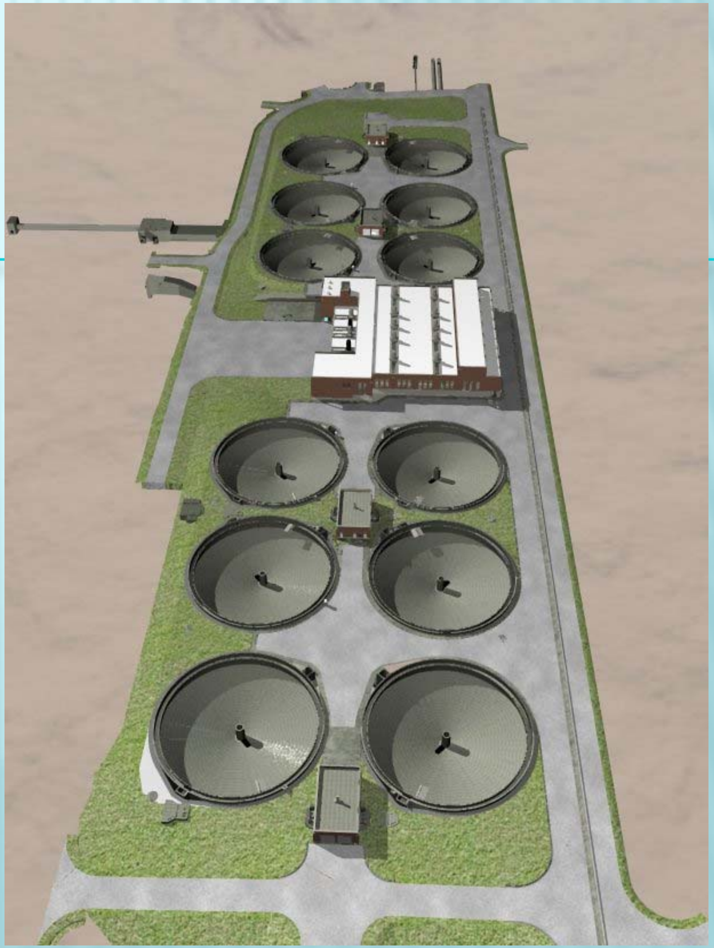
CFD for Primary Settling Tank at CWRP

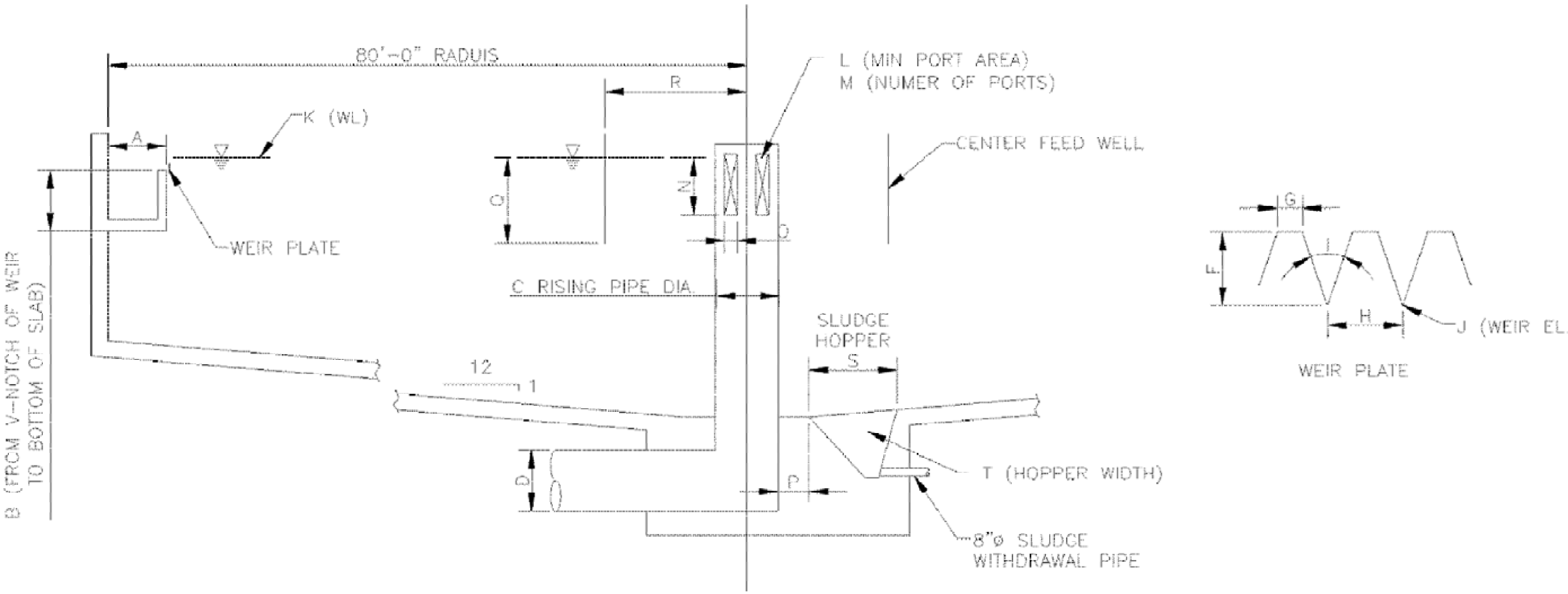
PROJECT OBJECTIVES

- Determine number and size of tanks
- Meet hydraulic and treatment performance criteria
- Optimize variable tank dimension
- Minimize construction costs









PRIMARY SETTLING TANK DIMENSIONS																				
	A	B	C	D COND	D PIPE	F	G	H	I	J	K PEAK	L	M	N	O	P	Q*	R	S	T
UNIT	FT	FT	FT	FT	FT	IN	IN	IN	DEG	FT	FT	FT^2		FT	FT	FT	FT	FT	FT	FT
SWRP	4.67	4.5	6.0	W4.5x H4.25	5.0	3.0	1	4.46	60	21.5	21.74	48.0	6	4.0	2.00	2.0	7.0	25.0	10.0	3.0
CWRP	4.17	4.5	4.5	W3.5x H3.5	4.0	3.0	3/4	6.75	90	21.5	21.75	32.0	6	4.0	1.33	2.0	7.0	21.0	10.0	3.0

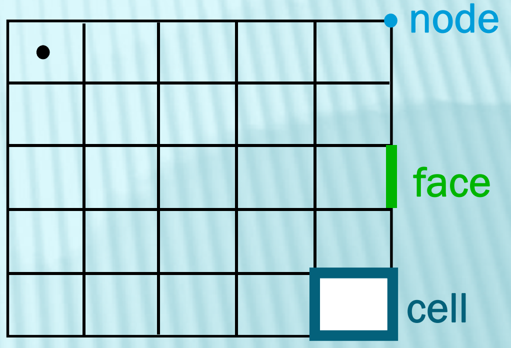
Typical Circular Clarifier (US Filter/Envirex Design)

* NOTE: ALTERNATE 5.0 FT FEEDWELL DEPTH ("Q" DIMENSION)
SHOULD BE INVESTIGATED FOR CFD MODELING

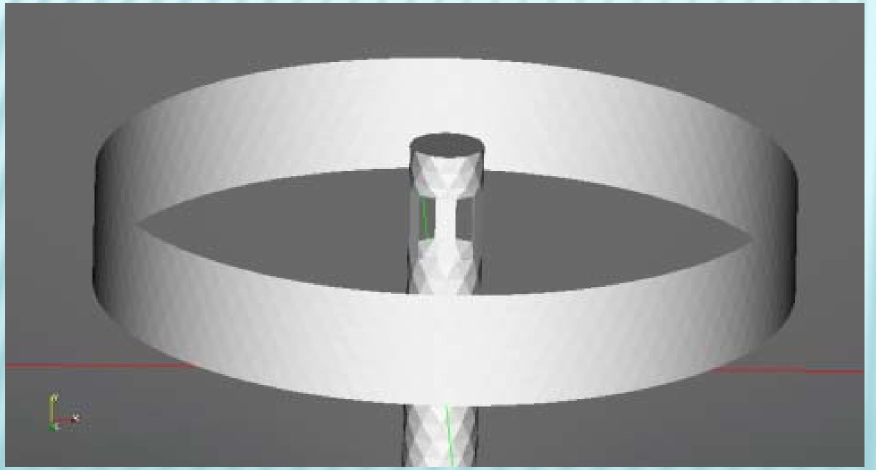
CFD Modeling Objectives

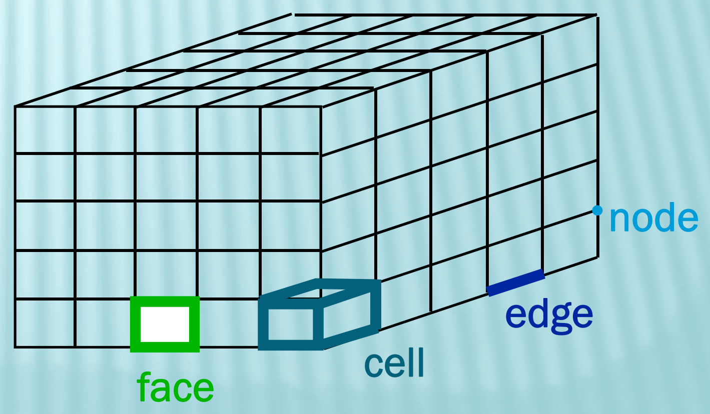
- Use as Tool to Optimize Key Design Parameters
  - Inlet Pipe
  - Feedwell
  - Side Water Depth

- Evaluate TSS removal efficiencies at various flows



2D mesh

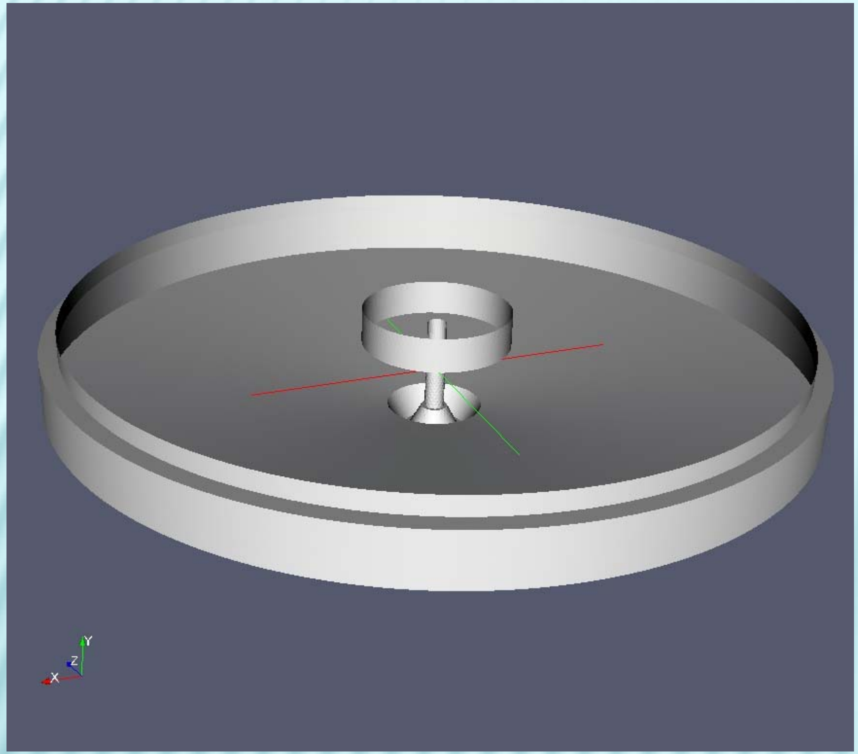




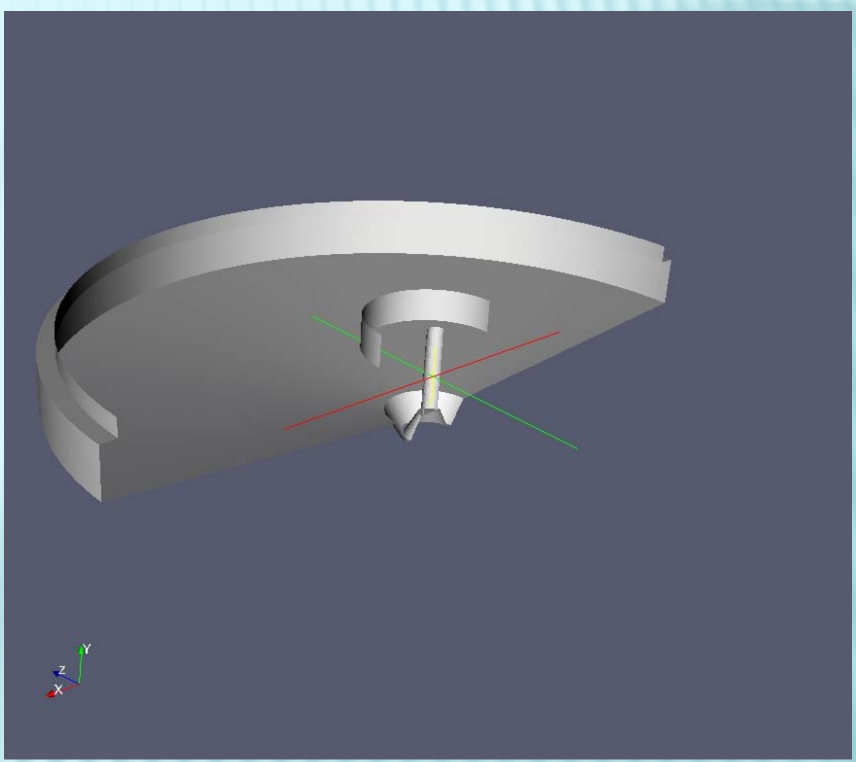
3D mesh

3D Geometry for the Numerical Simulation

3D View of the Tank



Cross Section View

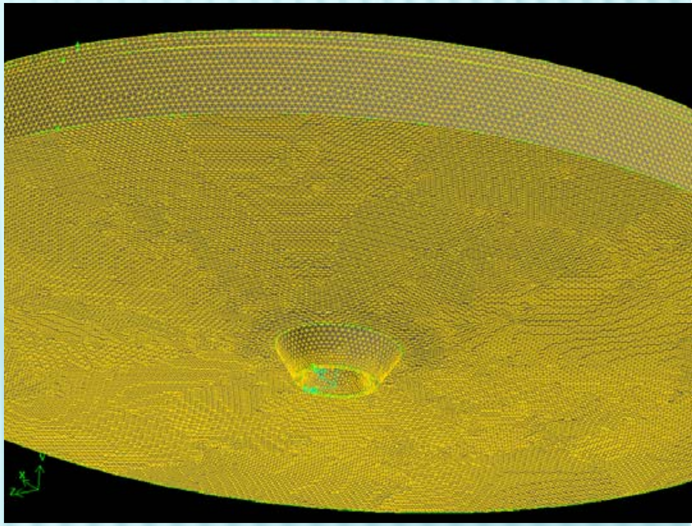


Initial Design: Straight rising inlet pipe
Port Design : Inlet with ports

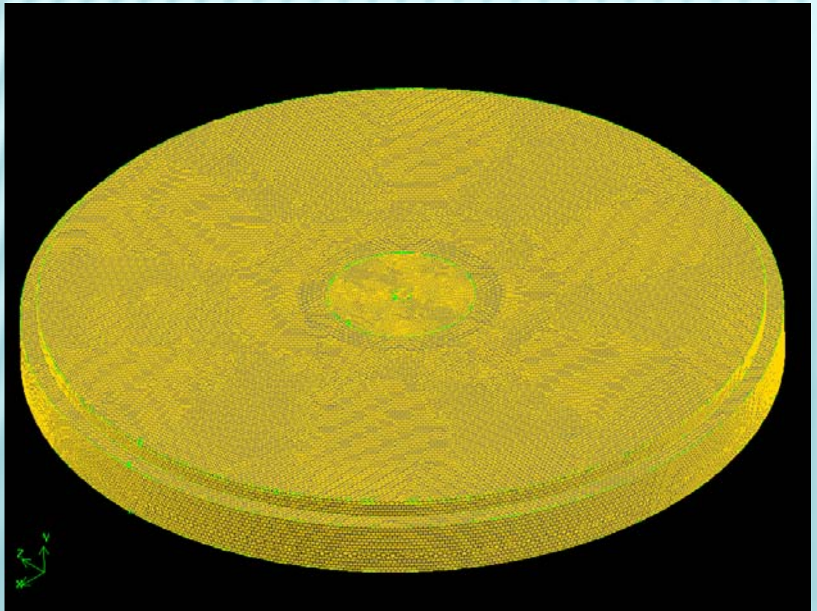
Three Dimensional Model Development

- 1.2 Million Cells
- Simulated on NCSA Supercomputers
  (National Center for Supercomputing Applications)

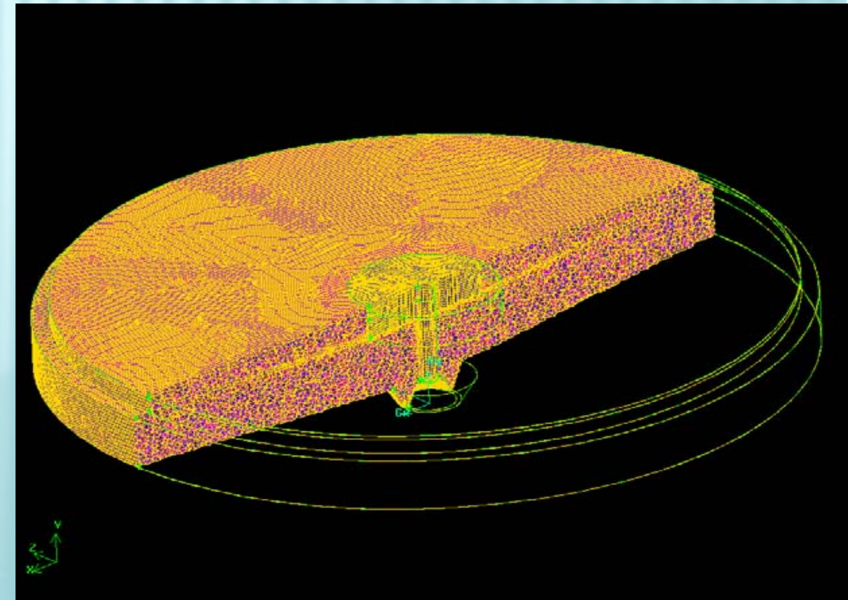
Bottom View



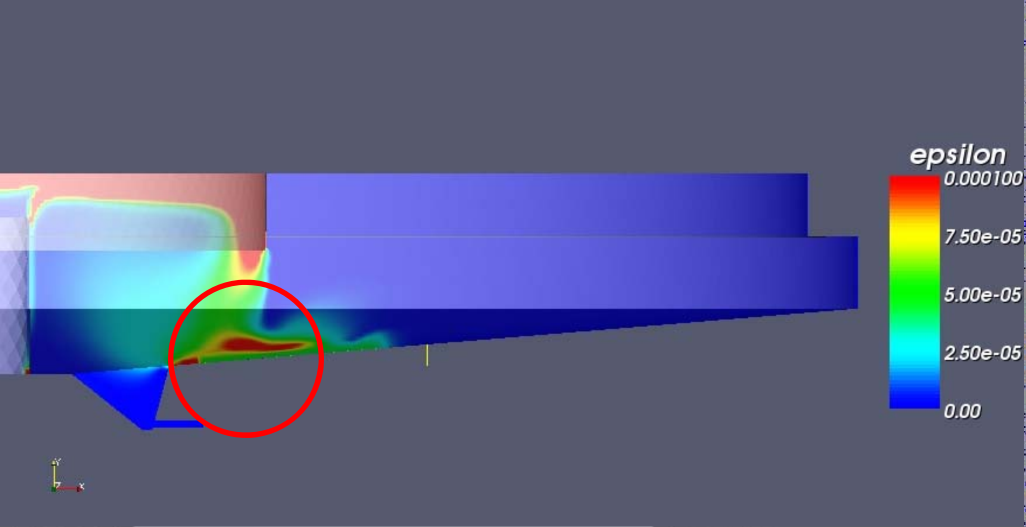
Top View

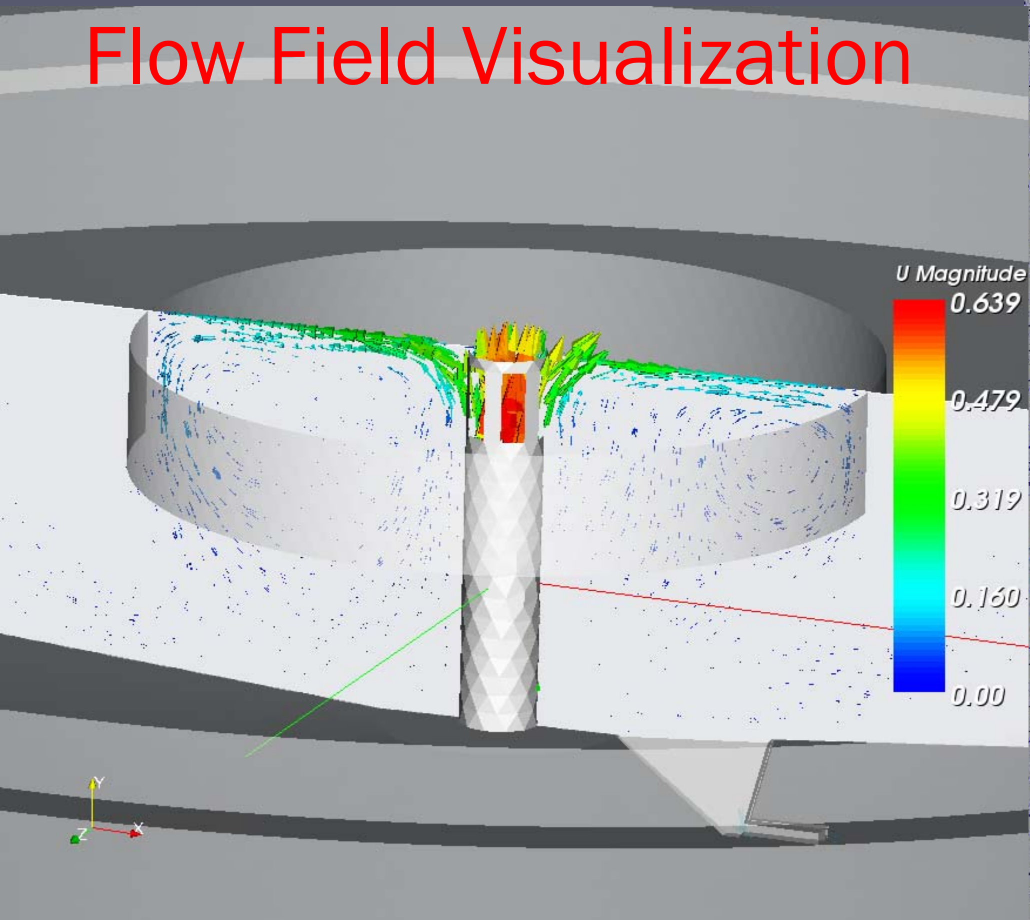


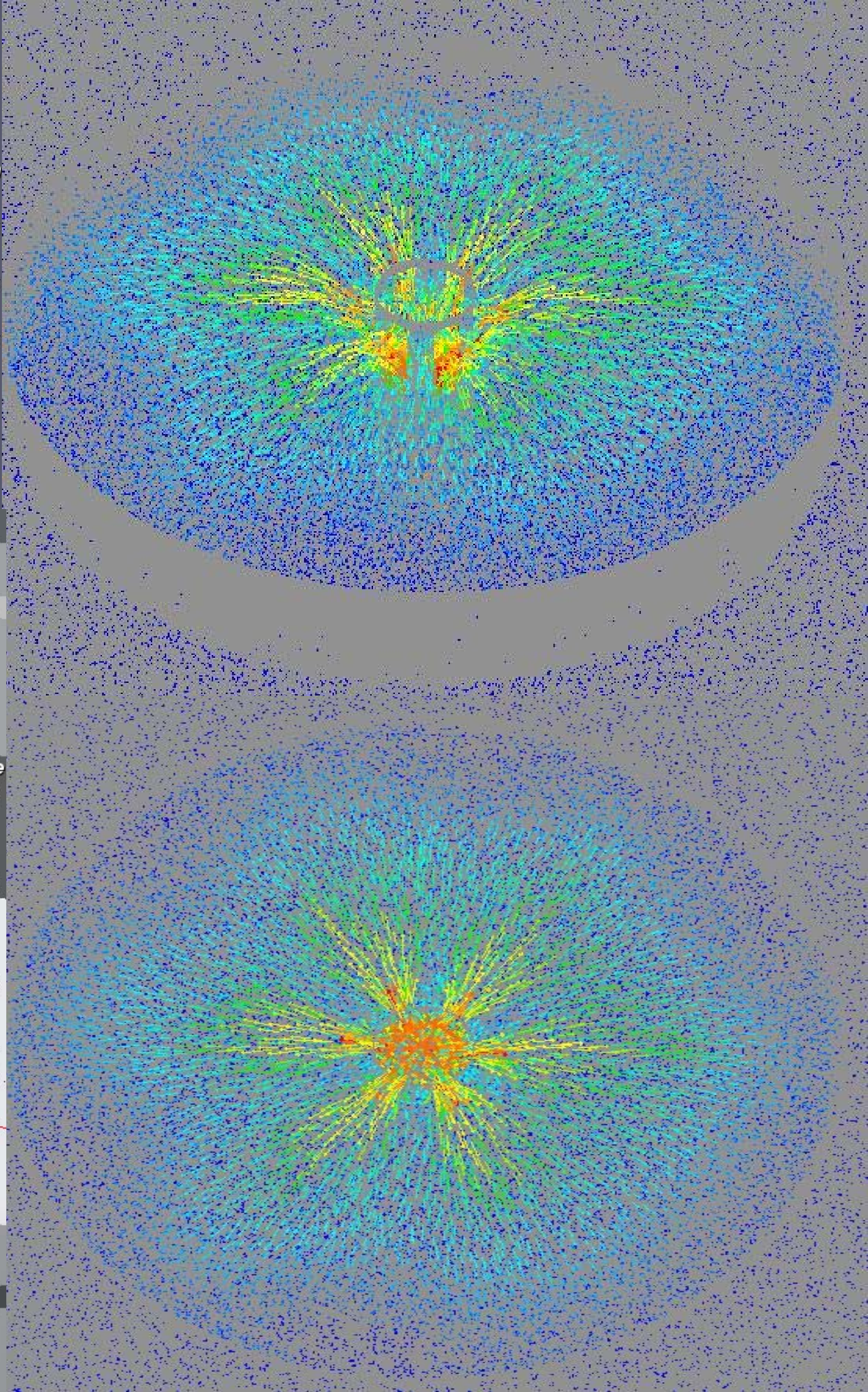
Cross Section



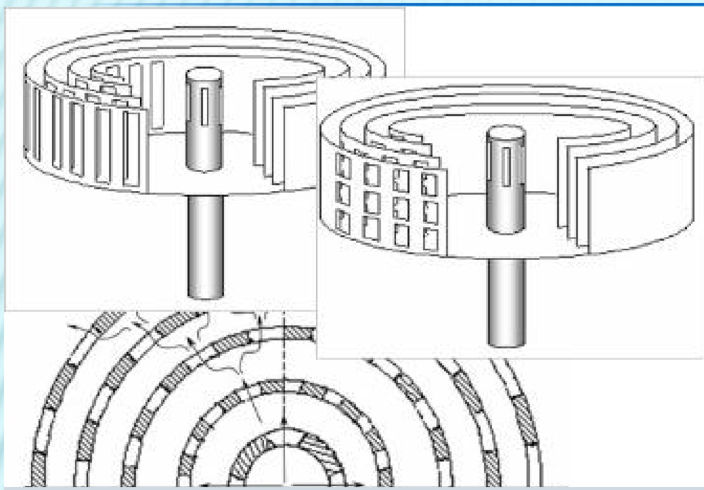
Flow Field Visualization

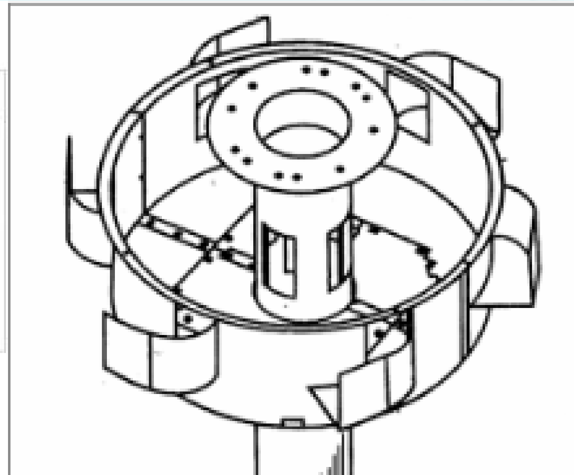


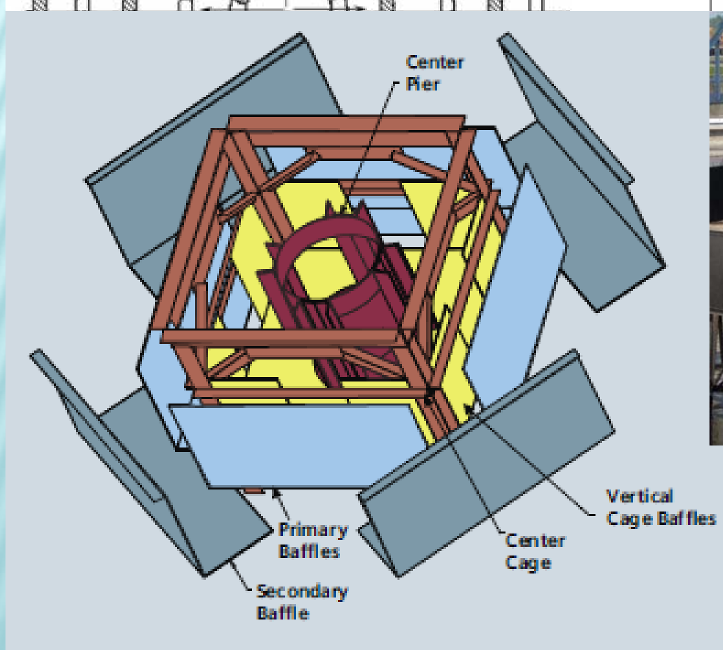


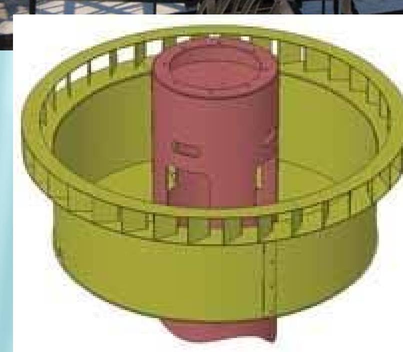


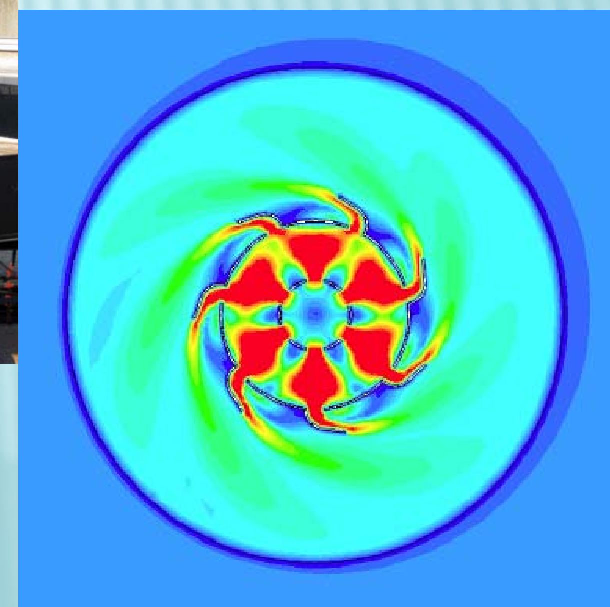
Energy Dissipating Inlet (EDI)





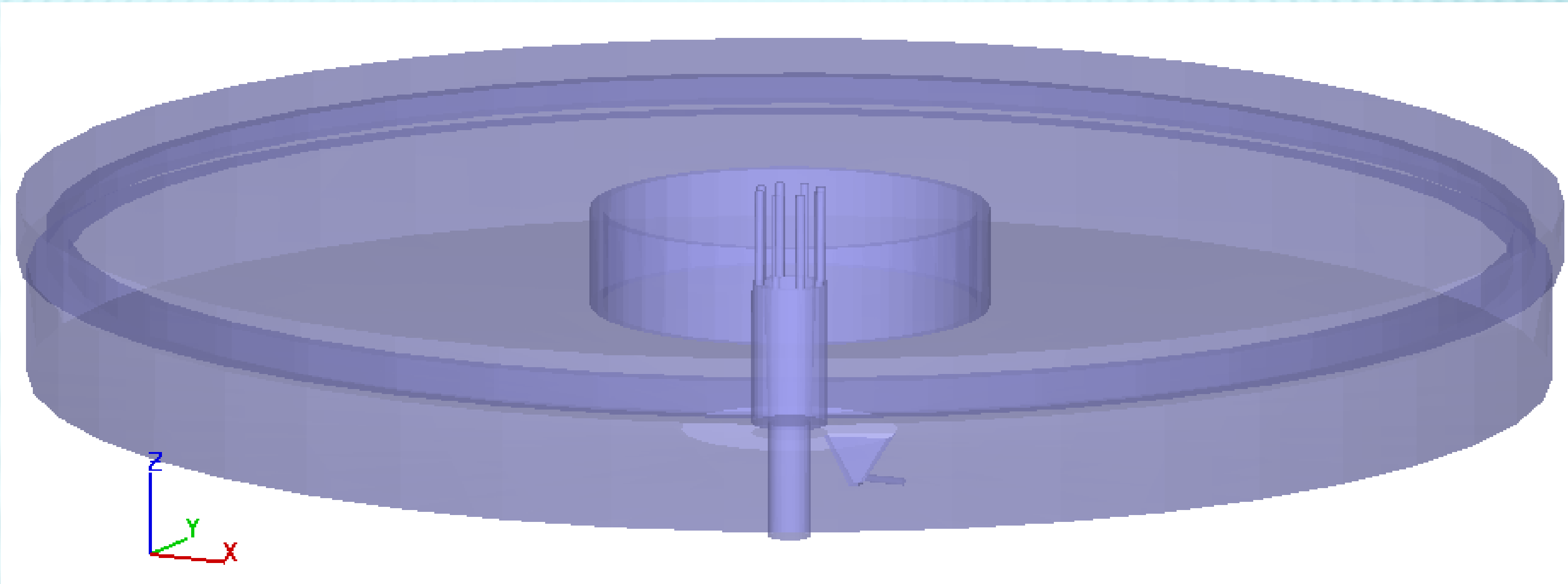


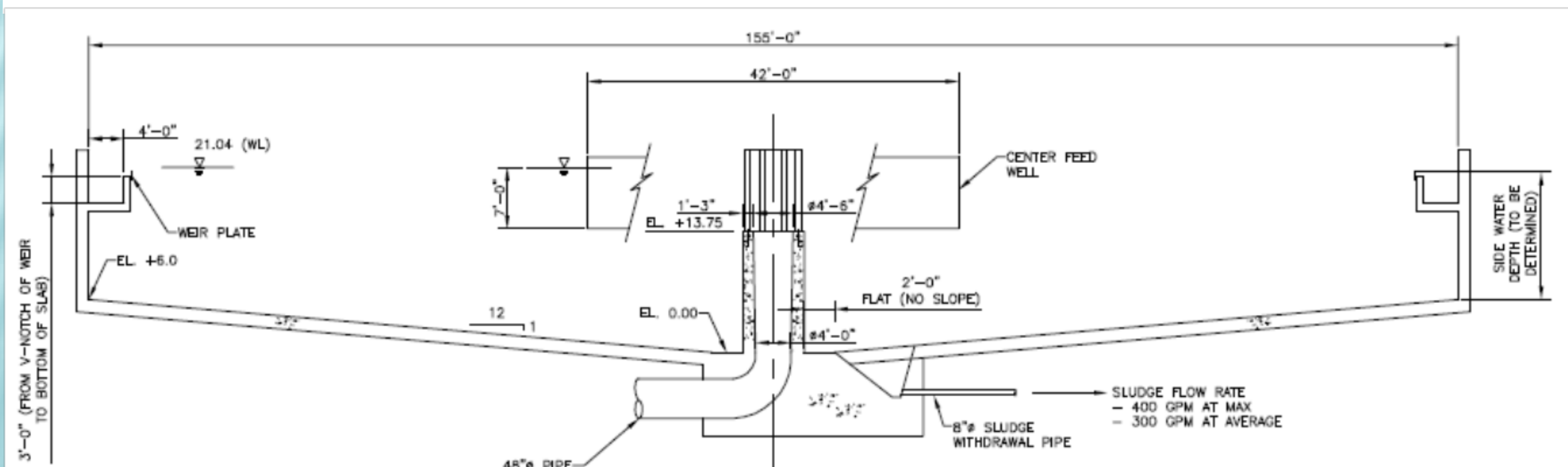




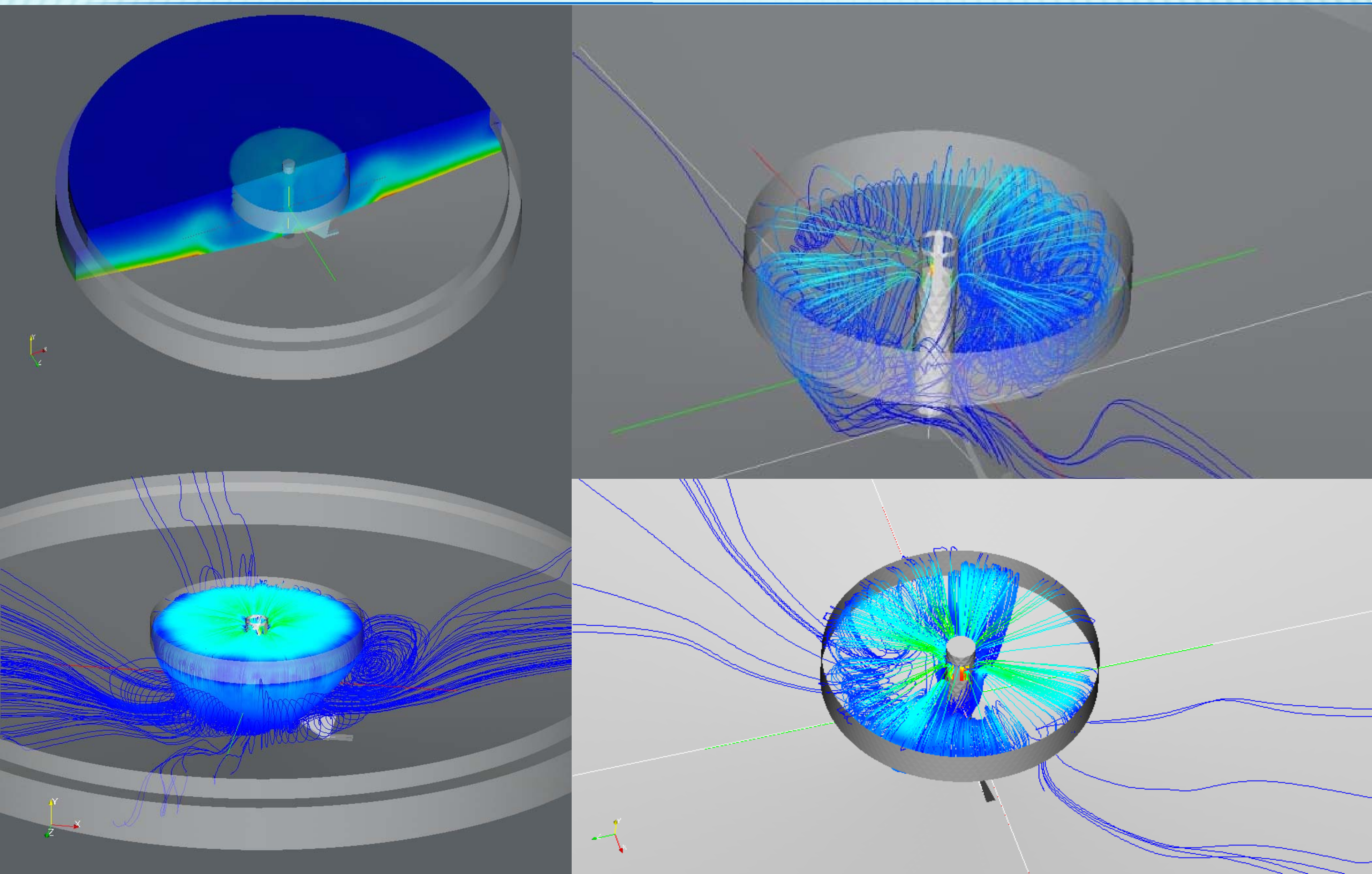
Stickney WRP Circular Clarifiers (1935)

New Design: Inlet pipe with open ‘cage’

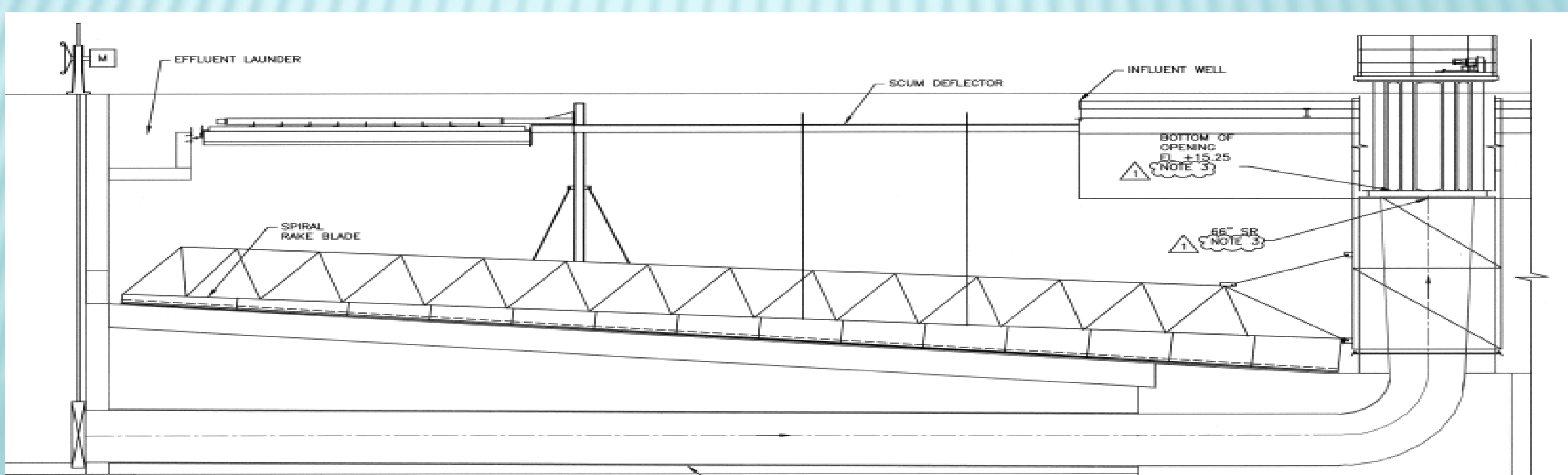




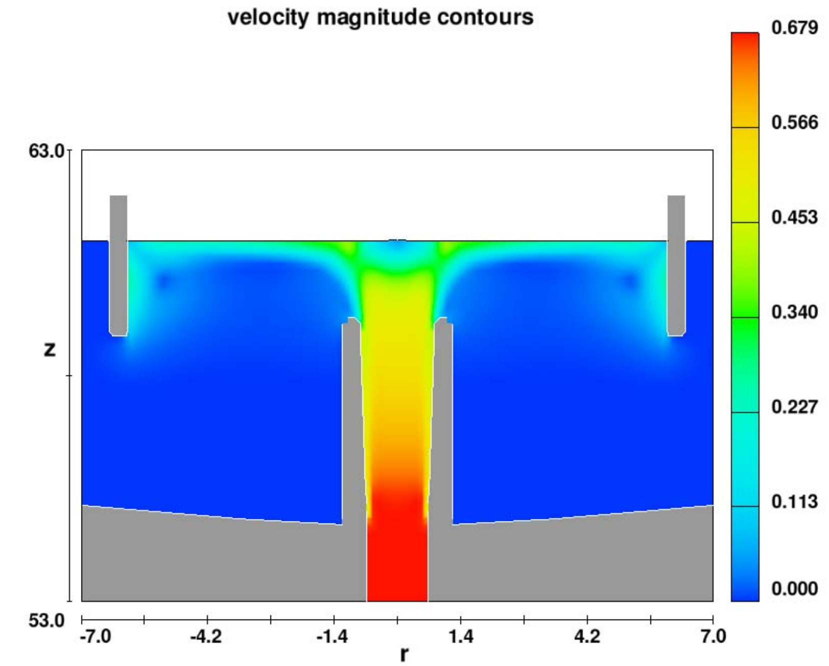
Visualization of Flow Field



MORNING GLORY INLET



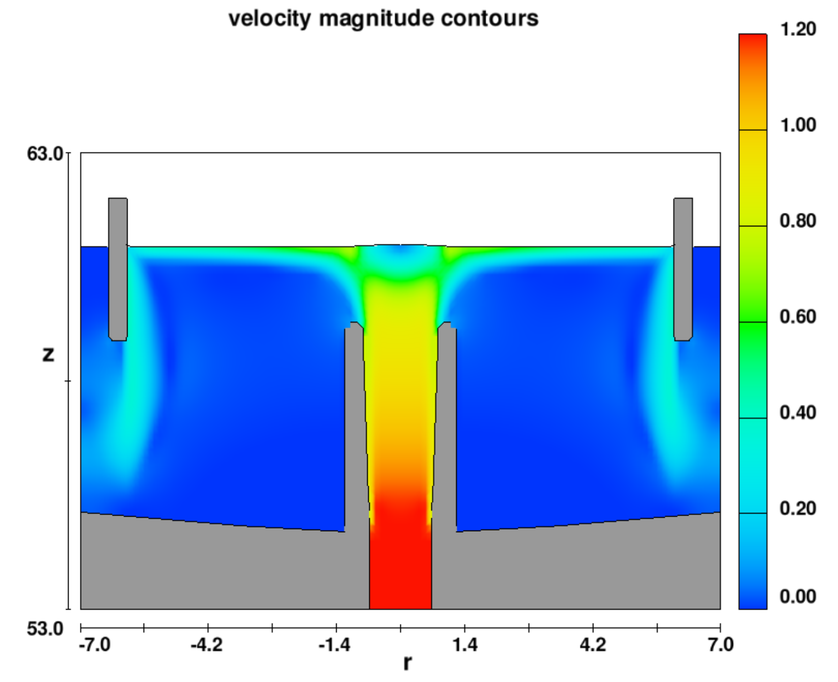
THE TOP ELEVATION OF TAPERED INLET PIPE WAS EVALUATED AT 5, 6, AND 7 FT. BELOW WATER SURFACE



Average Flow

Effect of Free Water Surface

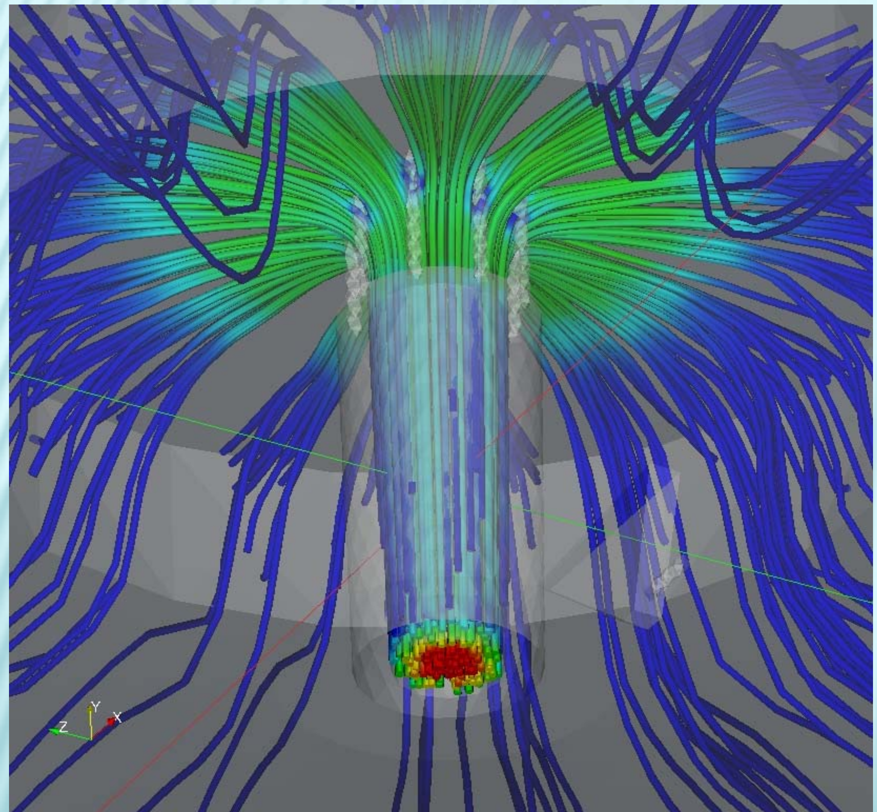
Maximum Flow

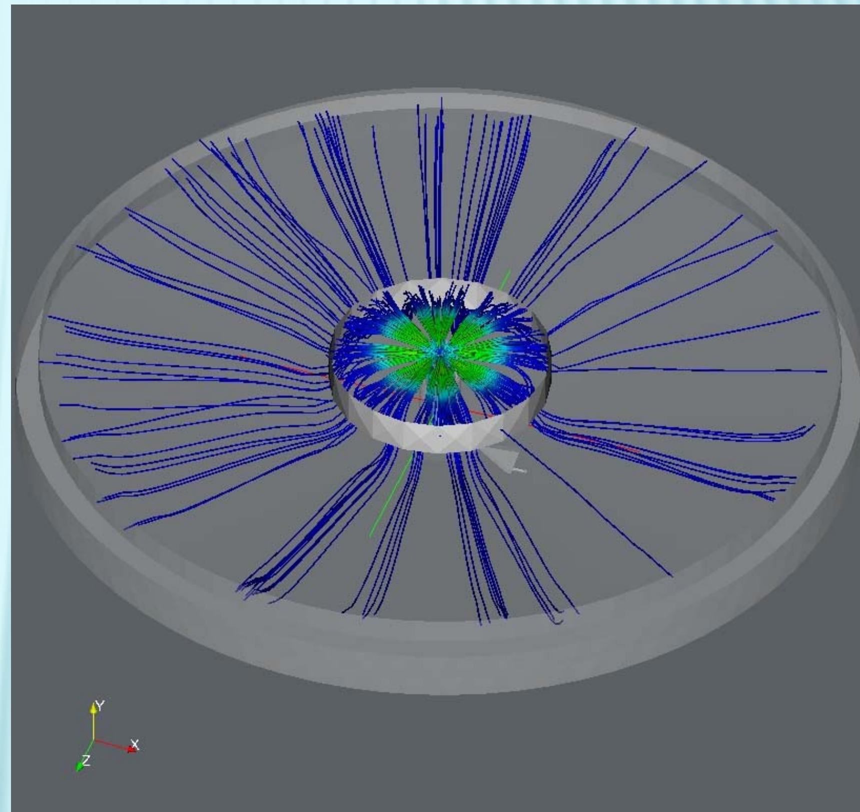


FEEDWELL DESIGN EVALUATION:

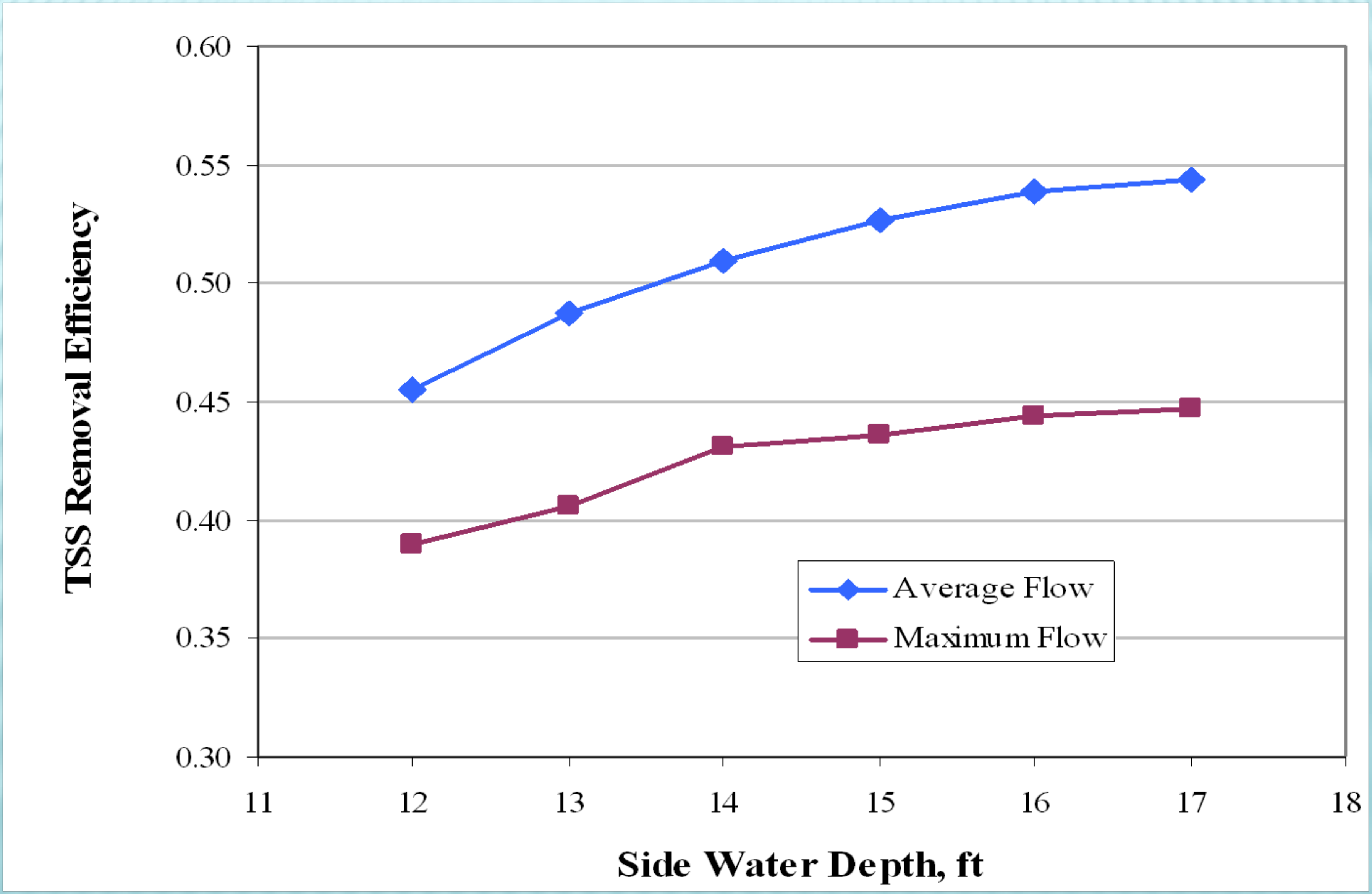
- 40, 41, 42, 43 AND 44 FT. DIAMETER
- 5, 6, AND 7 FT. FEEDWELL DEPTH

Visualization of Flow Field

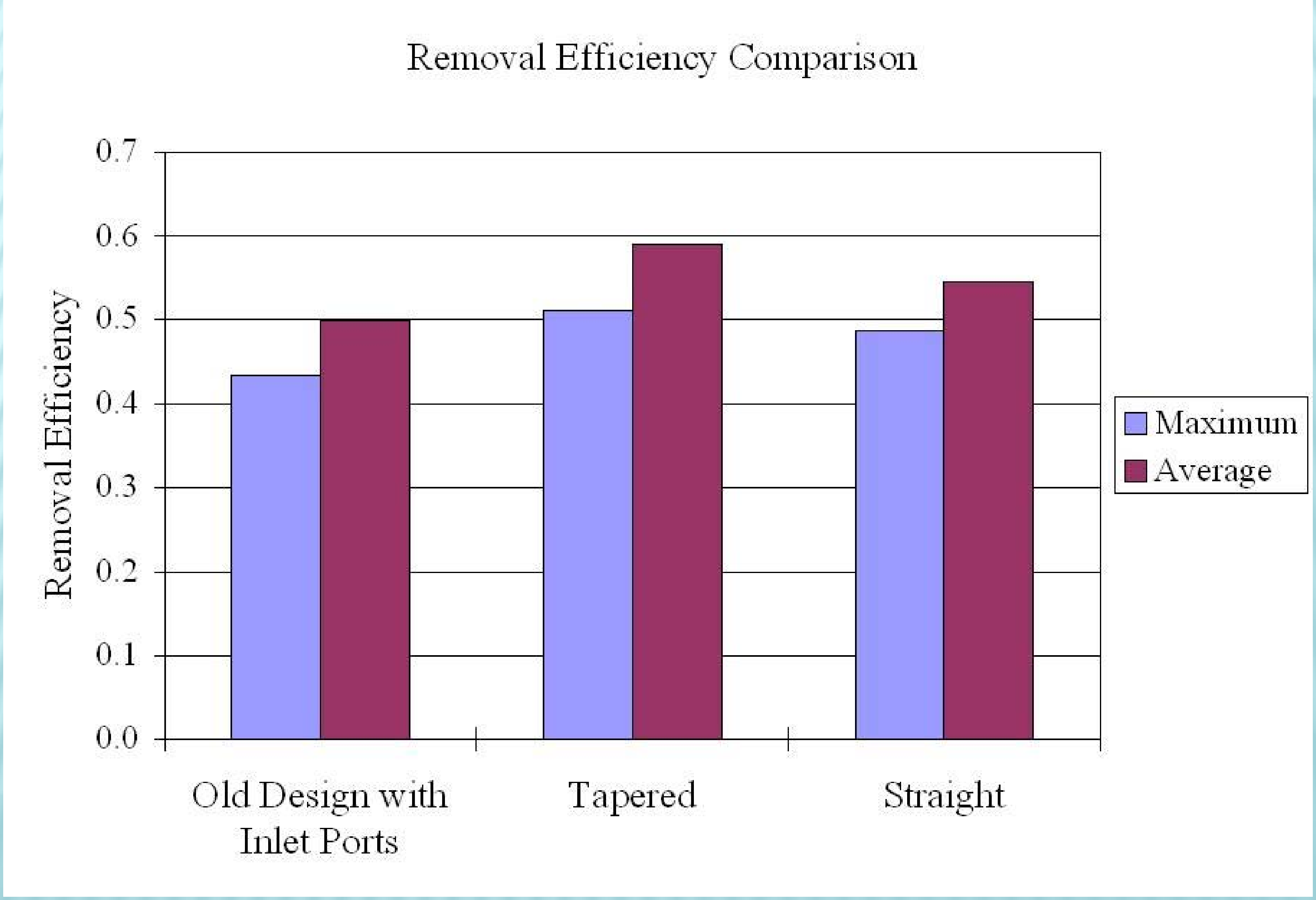




DEEPER IS BETTER BUT ……………….



THE TAPERED INLET REMOVES A HIGHER PERCENTAGE OF TSS



FINAL TANK DESIGN

Diameter:	155’
Side Water Depth:	15’
Inlet Pipe Diameter:	4’ tapered to 5’-6”
Inlet Pipe Elevation:	6’ below water surface
Feedwel Diameter:	41’
Feedwel Depth:	5’
SOR Avg. Day:	1,195 gpd/sf
SOR Peak Hour:	2,486 gpd/sf
Detention Time:	1.24h to 2.75h

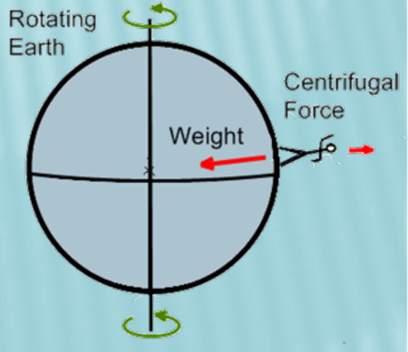
Primary Settling Tank at CWRP

CFD for Aerated Grit Chamber at NSWRP

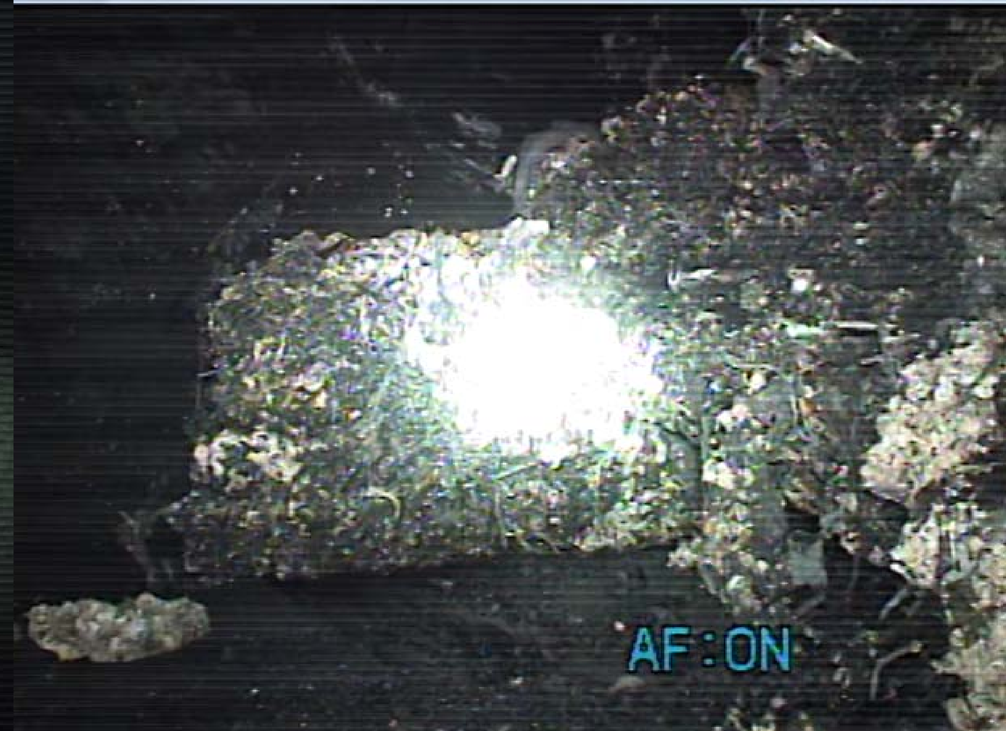
Purpose: To correct uneven grit distribution at conduits and Grit Tanks

CFD Modeling Objectives

- Investigate the non-uniform grit distribution in the aerated grit chambers
- Suggest a method which ensures optimal plant operation.




AF:ON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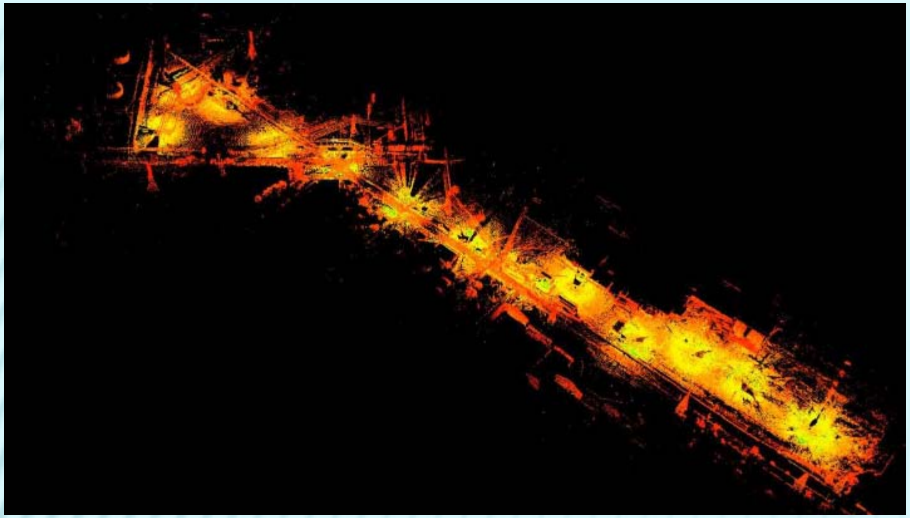
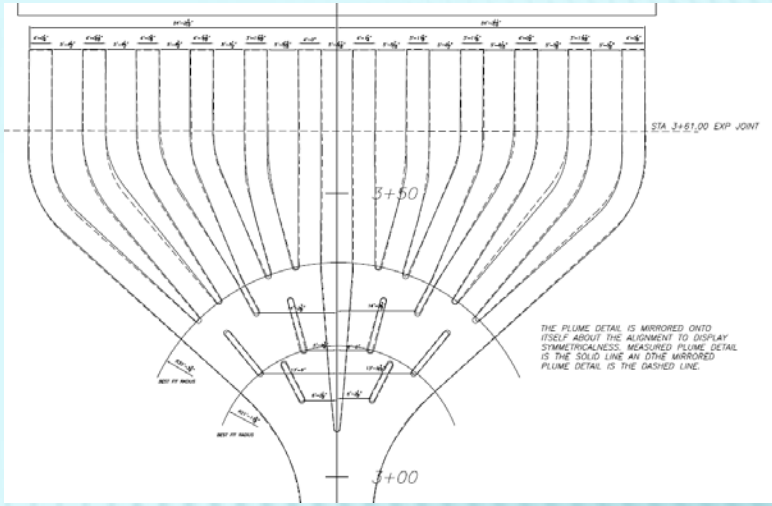
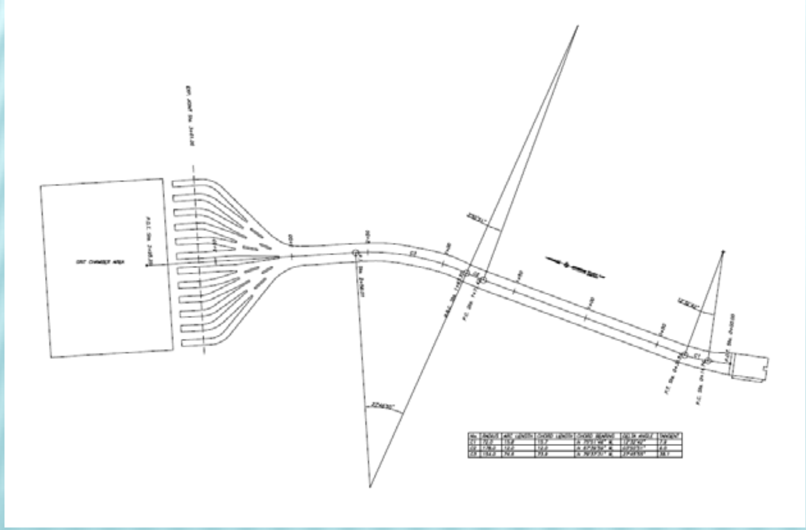
AF:ON

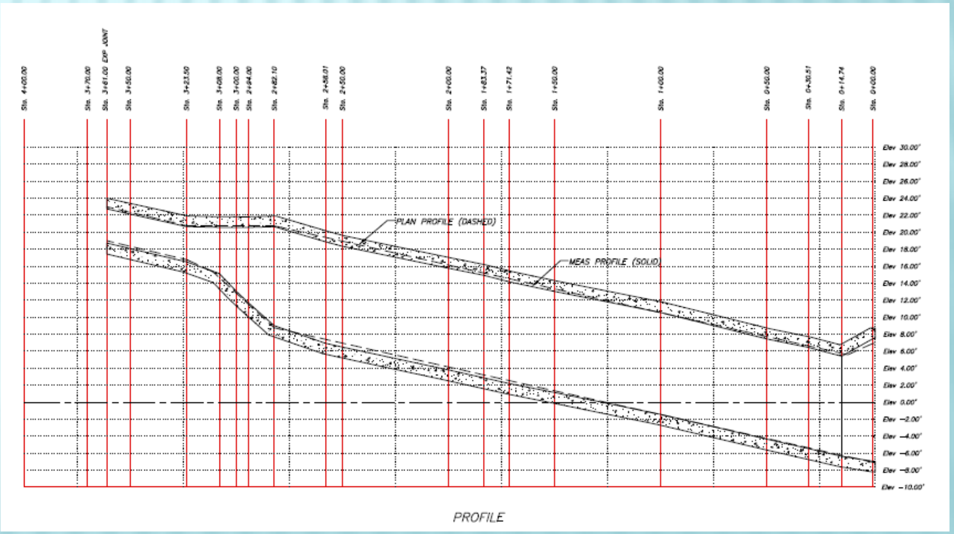

AF:ON



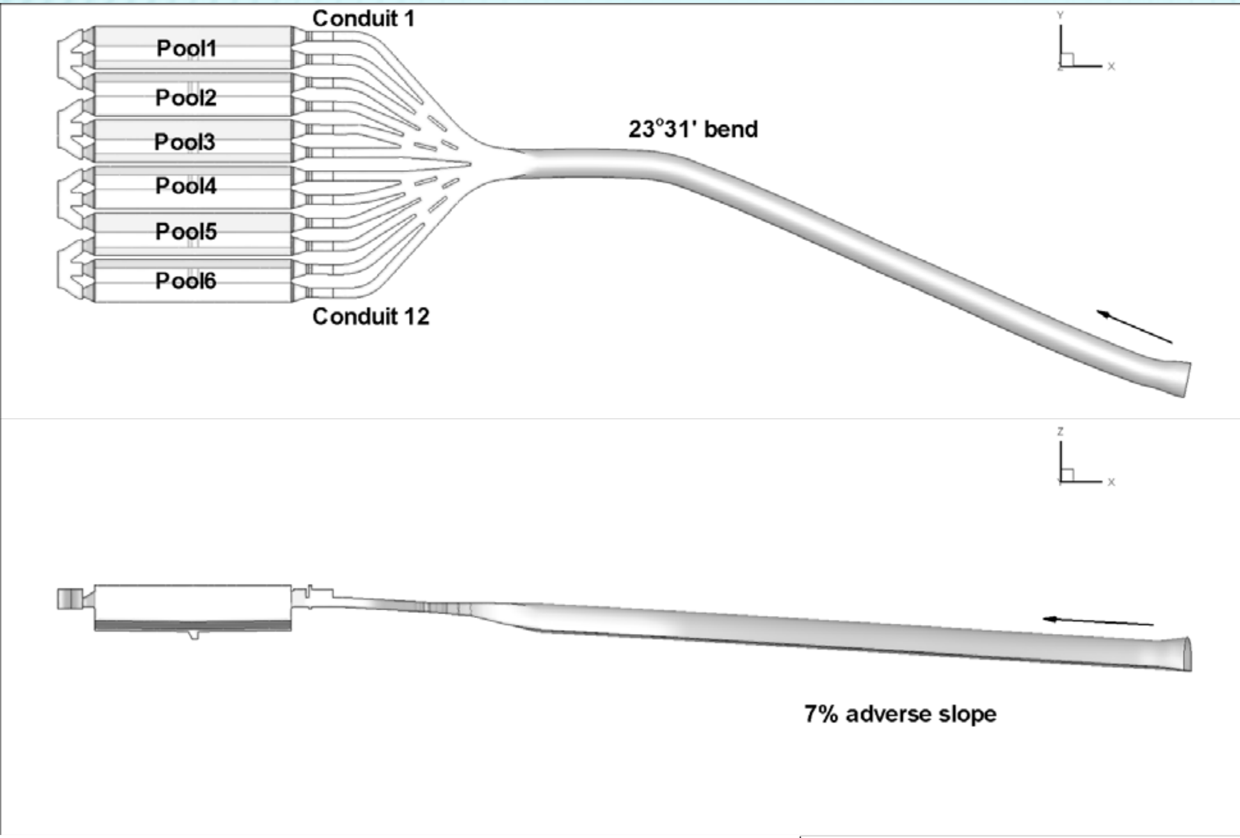


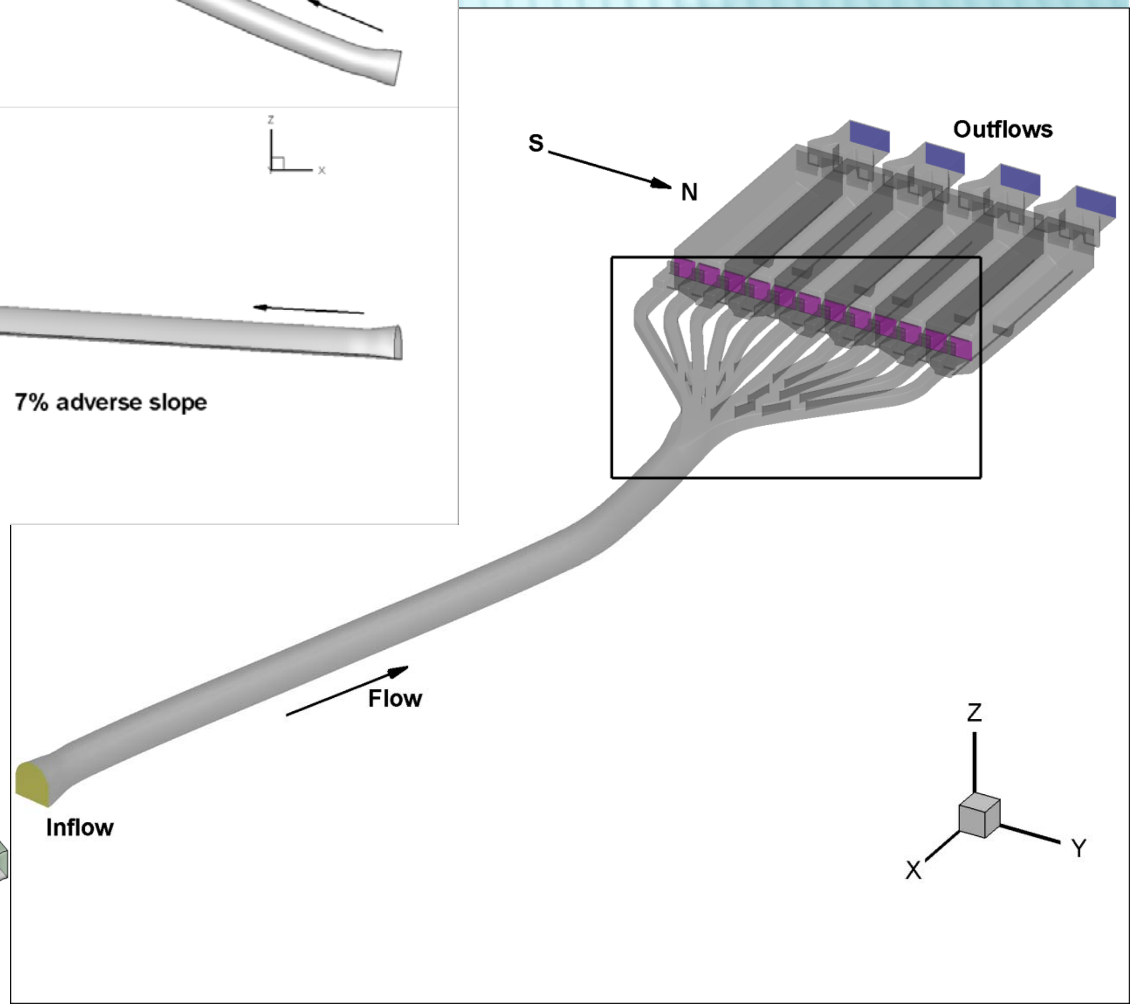
Surveying using state-of-the-art 3-D High-Definition Laser Scanning

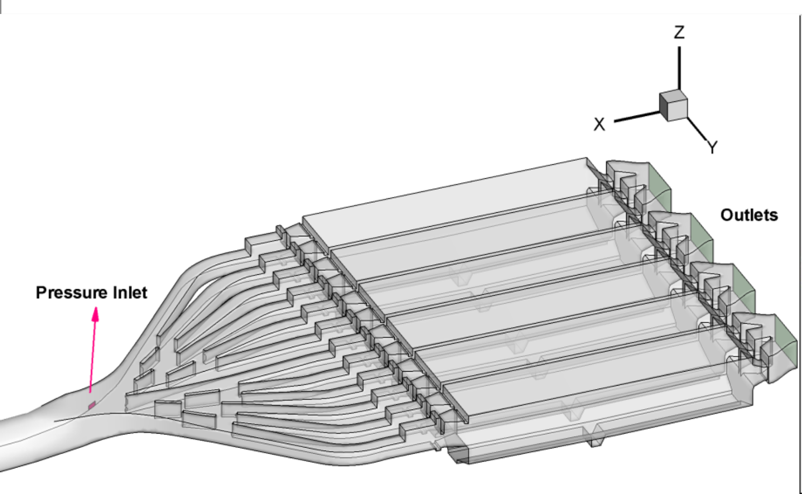




Geometry from Laser Scanning Survey



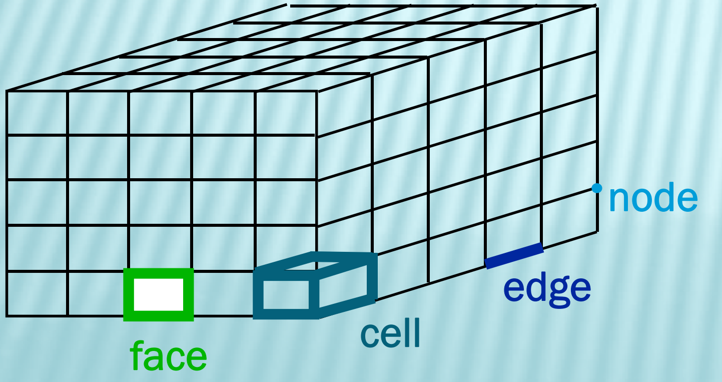




Two different computer systems were used for the 30-min (1800 sec) simulations

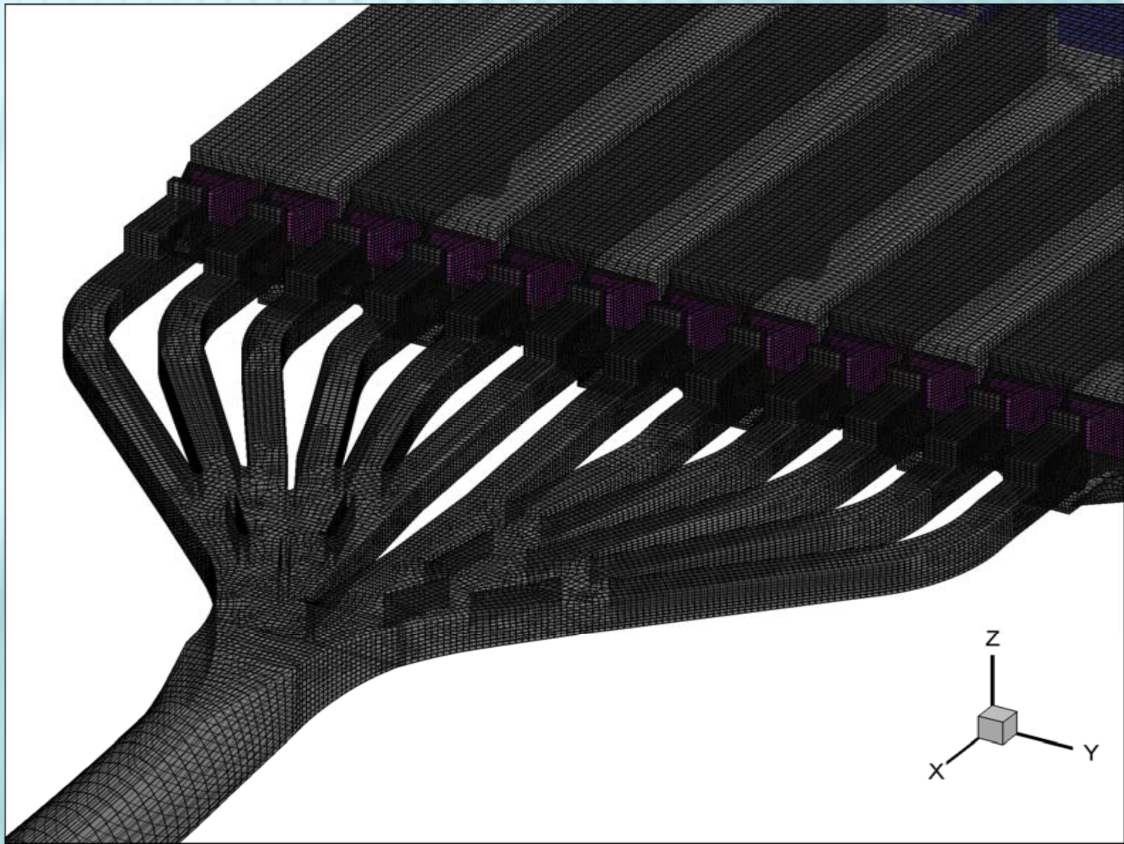
- ❑ FLOW-3D: U of I Hydrosystem Laboratory. 7 node, 56-core Intel Xeon cluster. Each node has 8 cores and 32 GB of RAM. The simulations were conducted using 8 processors. 9-10 days to complete flow simulations.

- ❑ FLUENT: Argonne National Laboratories. 128 compute nodes with total of 1024 cores. The simulations were conducted using 8 processors. 4-7 days to complete flow simulations.

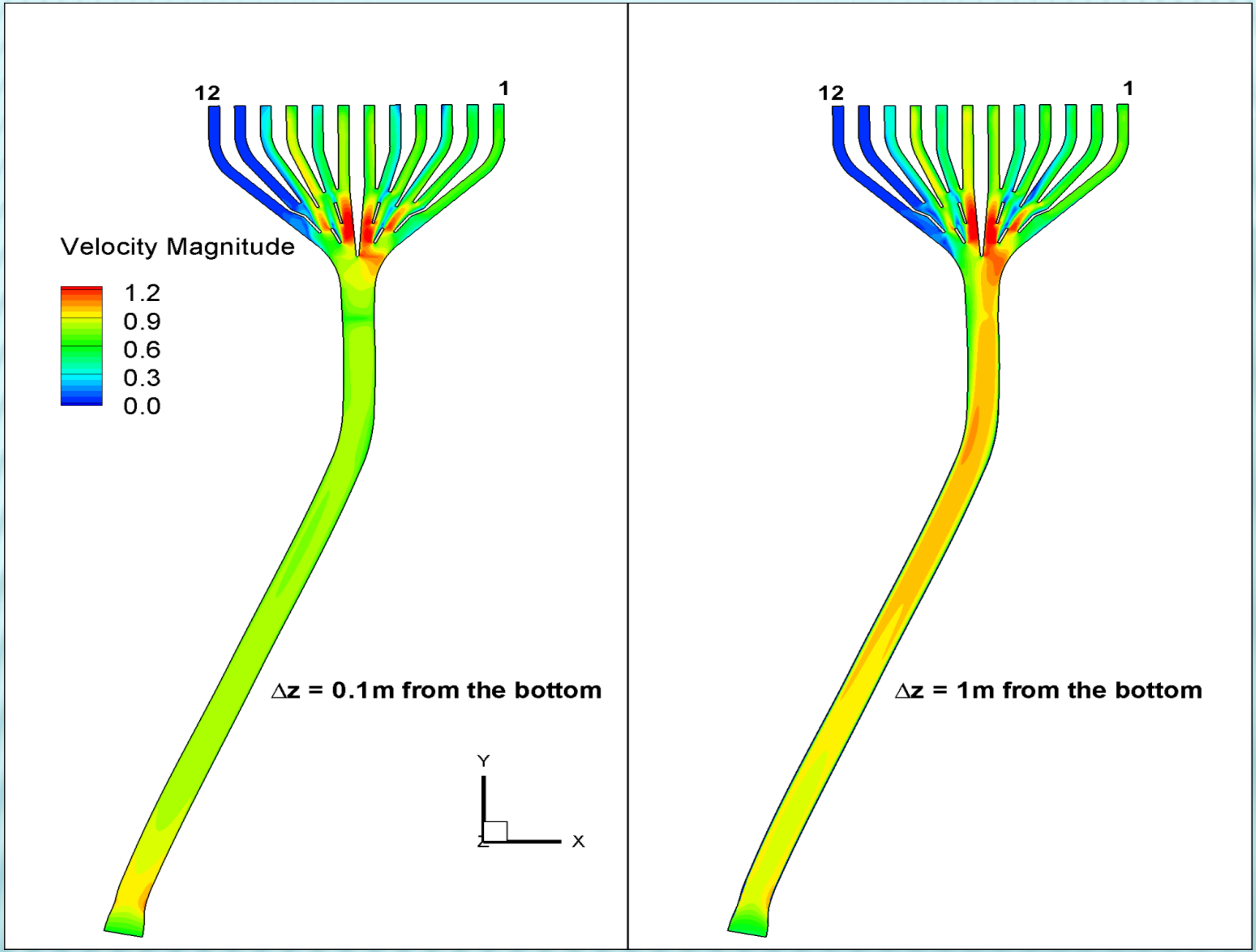


3D mesh

Computational Grid



HYDRODYNAMICS VALIDATION/COMPARISON WITH MEASURED FLOW DISCHARGE



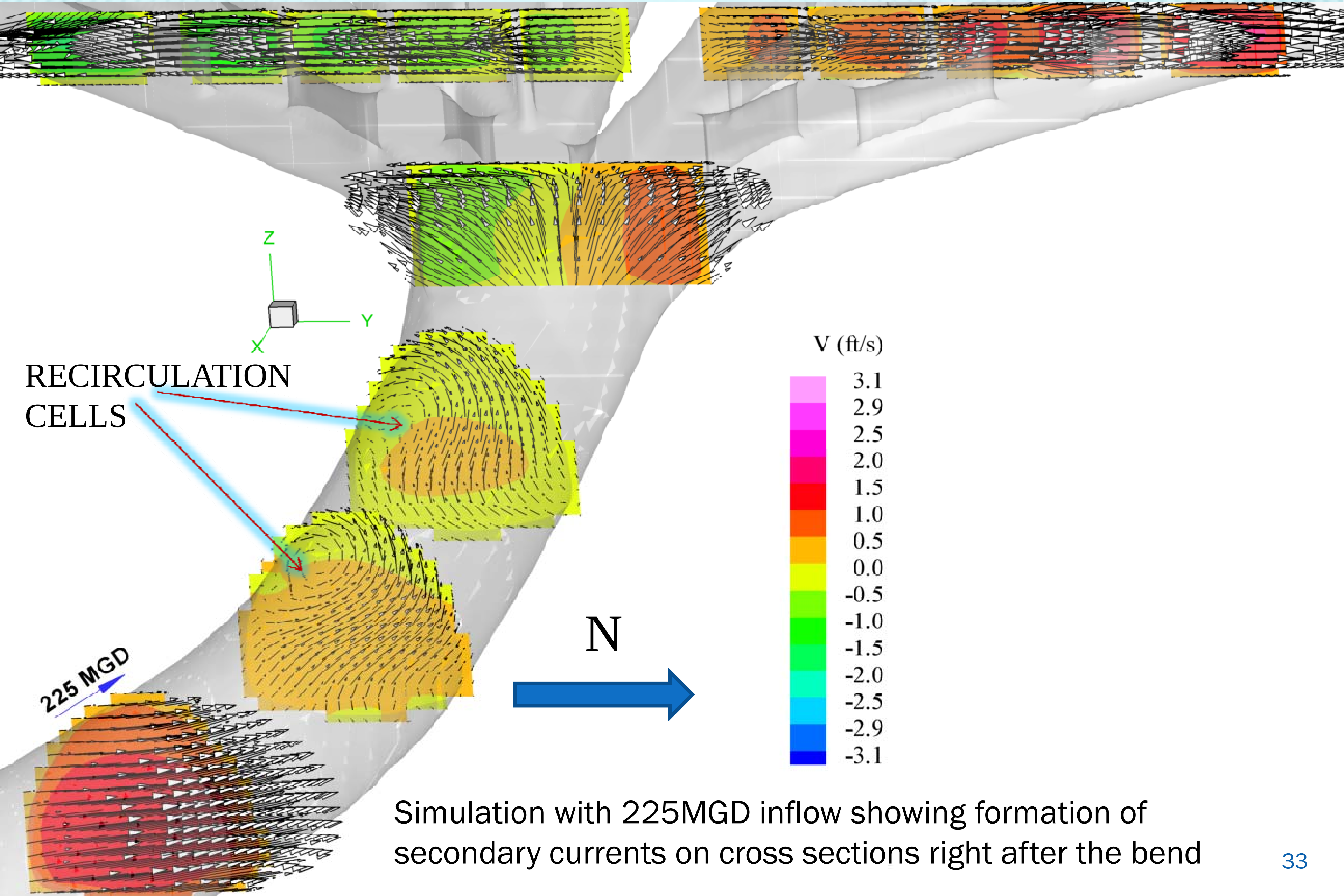
The flow discharge at gates 1-10 are recorded through the simulation and compared to the field measurements.

Based on flow measurements in Grit Chamber while conduits 11 and 12 were closed with low discharge conditions:

Conduit	Q_{fluent} (cfs)	Q_{obs}(cfs)	Q_{fluent} (MGD)	Q_{obs} (MGD)	%ERROR
1	33.8	34.4	21.8	22.3	1.9
2	29.3	29.8	18.9	19.3	2.0
3	24.1	24.4	15.6	15.8	1.4
4	33.2	33.8	21.4	21.9	1.9
5	20.5	20.7	13.3	13.4	1.0
6	37.4	38.0	24.1	24.5	1.6
7	42.2	42.9	27.3	27.8	1.7
8	22.9	23.3	14.8	15.1	1.6
9	40.1	40.9	25.9	26.4	1.9
10	17.6	18.1	11.4	11.7	2.7
11	0.0		0.0		
12	0.0		0.0		
Total	301.0	306.4	194.5	198.0	1.8

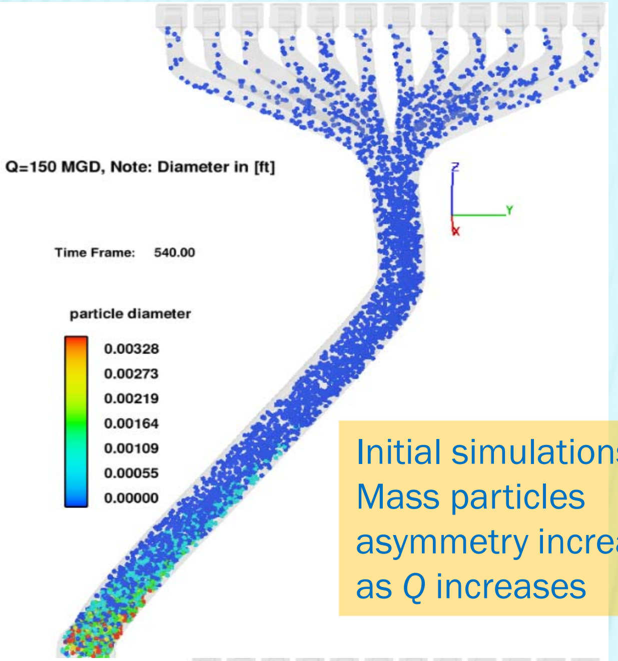
The maximum error between the field measurements and the simulation results is around 2.7%.

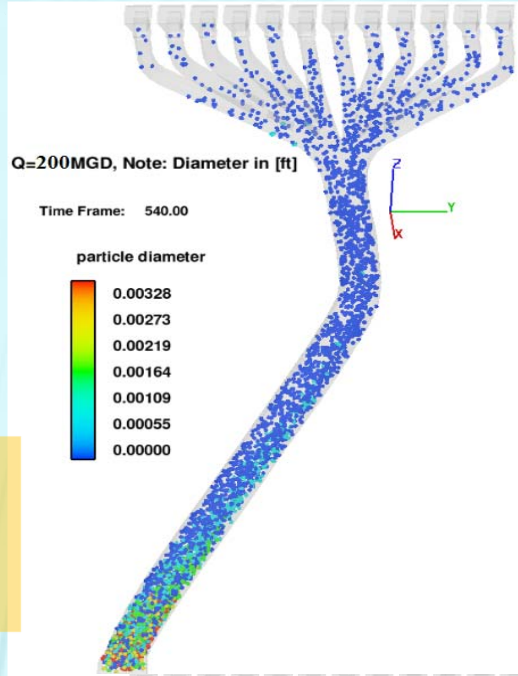
FLOW DYNAMICS AT THE BEND

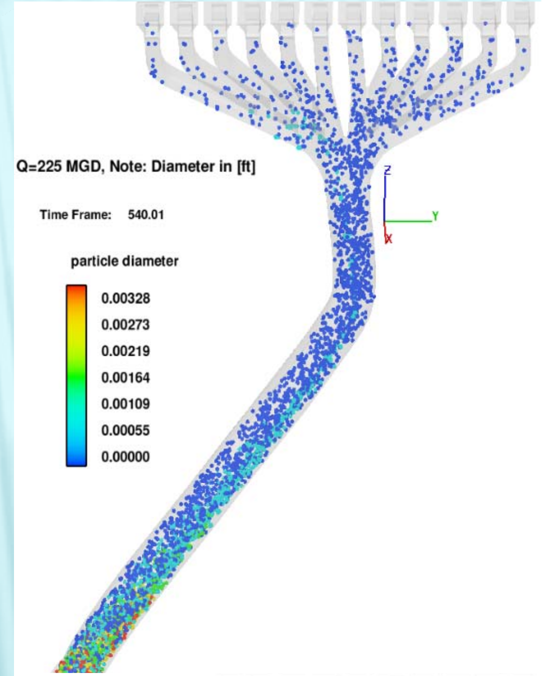


Simulation with 225MGD inflow showing formation of secondary currents on cross sections right after the bend

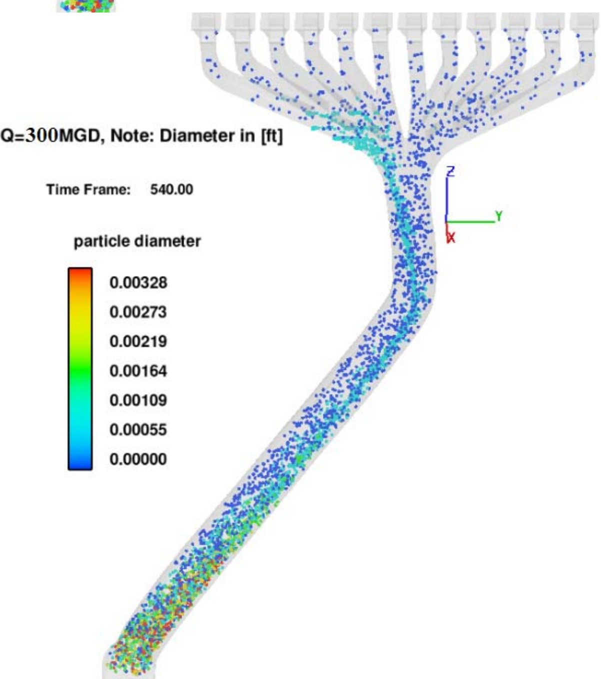
SEDIMENT TRANSPORT SIMULATION-SUMMARY

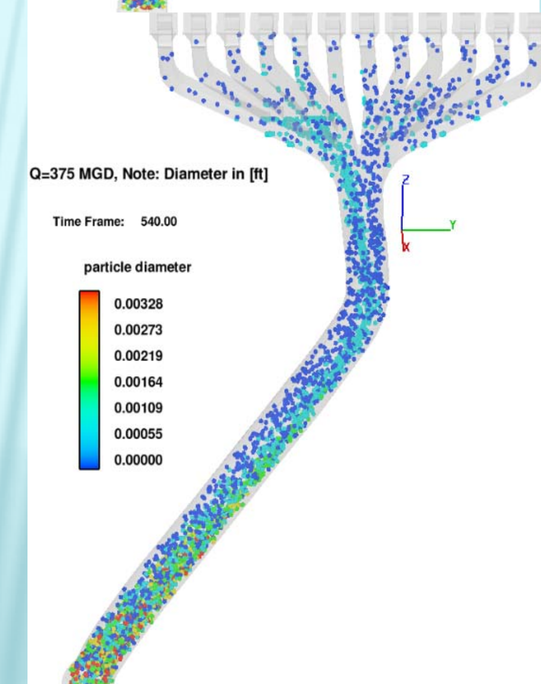


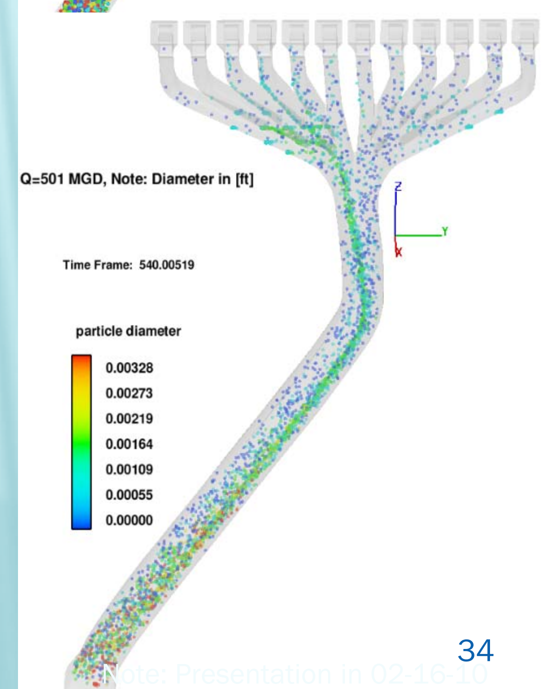




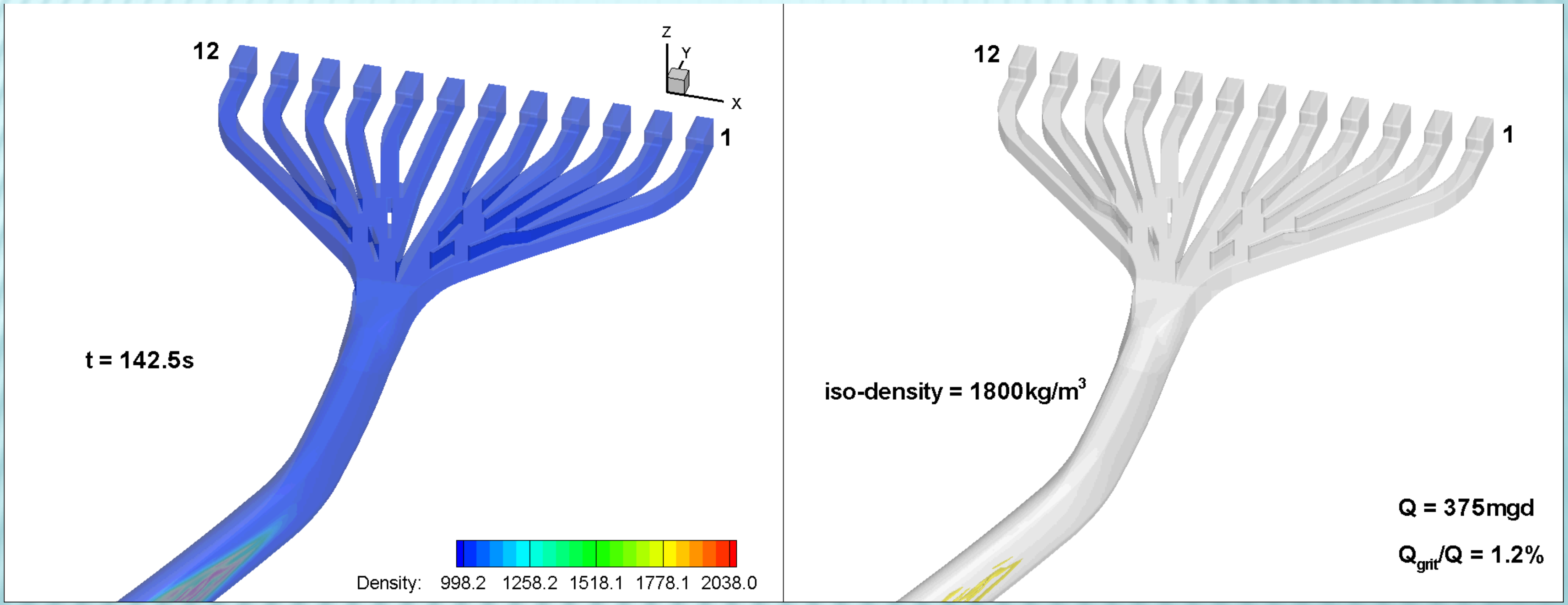
Initial simulations: Mass particles asymmetry increases as *Q* increases







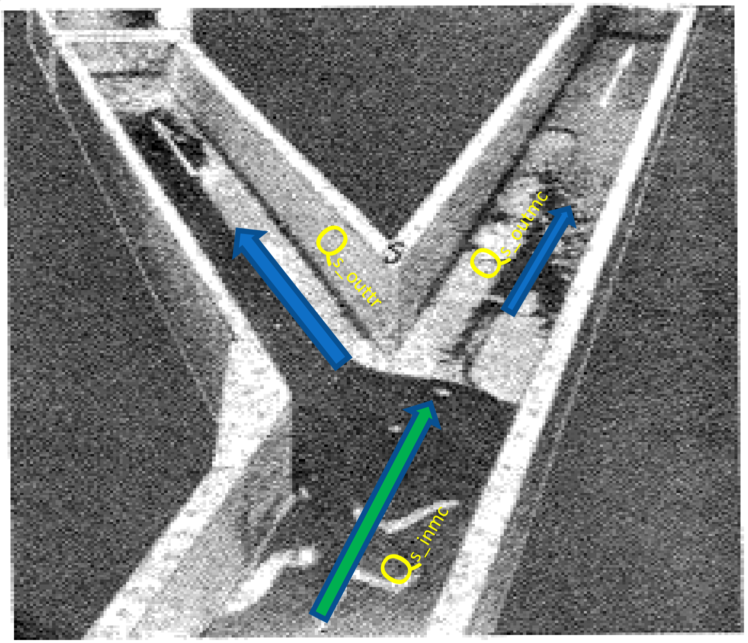
FLOW WITH GRIT MATERIAL INTRODUCED TO DOMAIN



(Video Simulation)

BULLE'S EFFECT (1926)

Uneven sediment distribution due to bifurcation

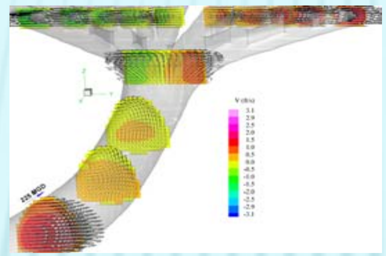


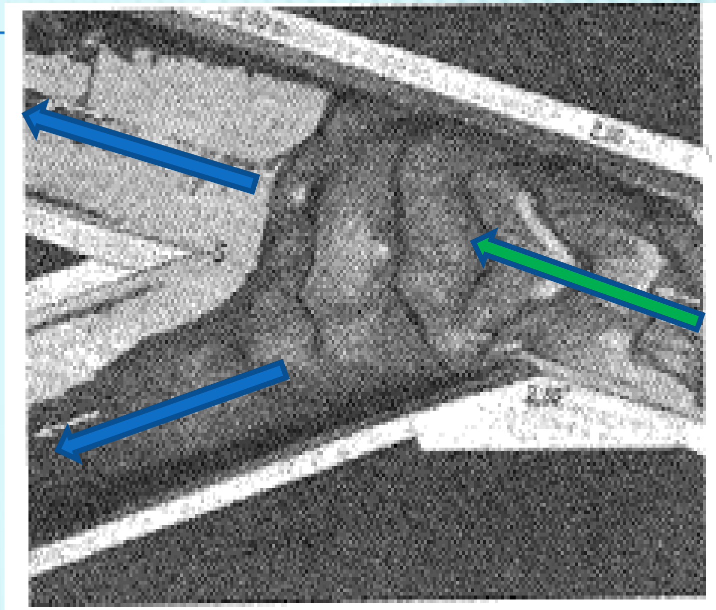
$Q_{s\_in\text{-}mc} = Q_{s\_out\text{-}mc} + Q_{s\_out\text{-}tr}$

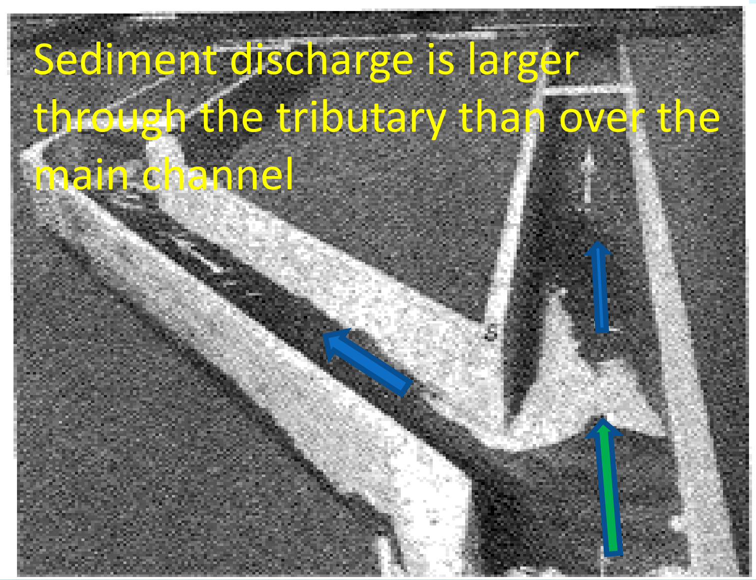
$Q_{s\_out\text{-}mc} < Q_{s\_out\text{-}tr}$

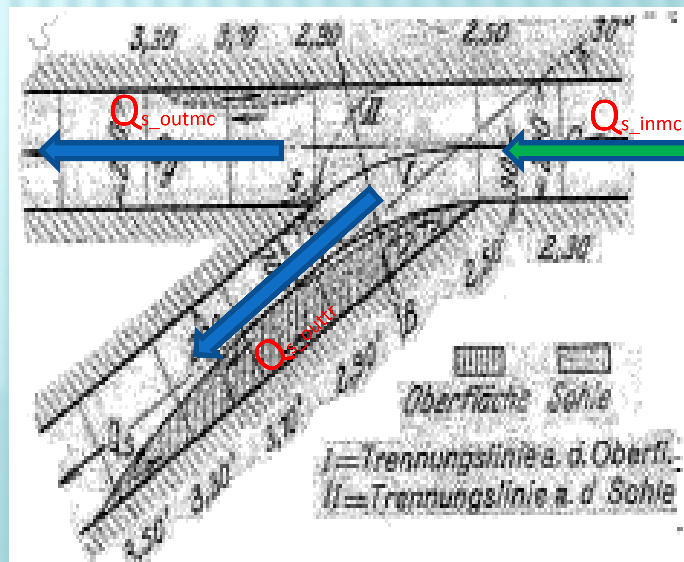
Although,

$Q_{out\text{-}mc} > Q_{out\text{-}tr}$

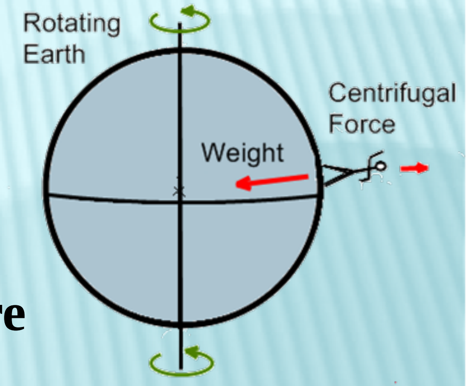








PRELIMINARY CONCLUSIONS



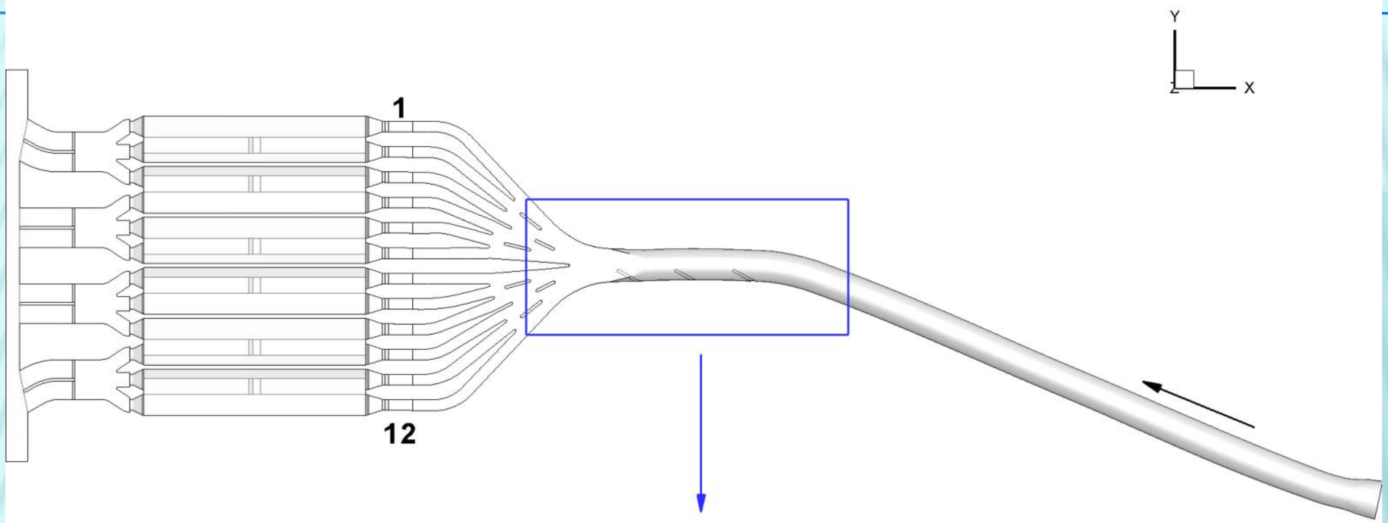
- There is a clear Proof of Secondary current generation and recirculation due the 23º 31’ Bend.

- The simulations show the existence of a non-uniform flow distribution across the 12 distribution conduits which is **more pronounced** as Q increases.

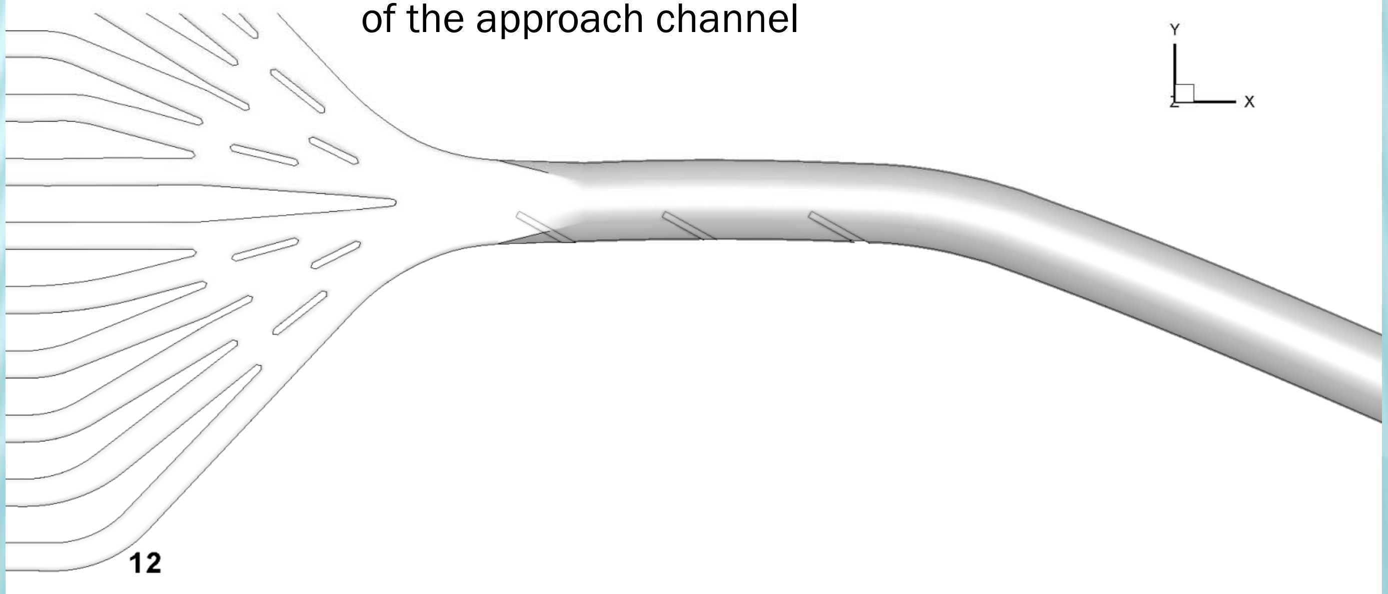
- Non-Uniform distribution of sediment due to the Bulle’s effect, enhanced by the secondary current at the bend, has been observed for larger flow discharges.

- Sediment transport simulations show that sediment distribution is symmetric for lower discharges (e.g. Q=150 MGD) but becomes asymmetric for higher flow discharges (e.g. Q => 300 MGD). As Q increases sediment particles (simulated in the range of 75 and 1000 microns) tend to increase in conduits on the south side (11 and 12).

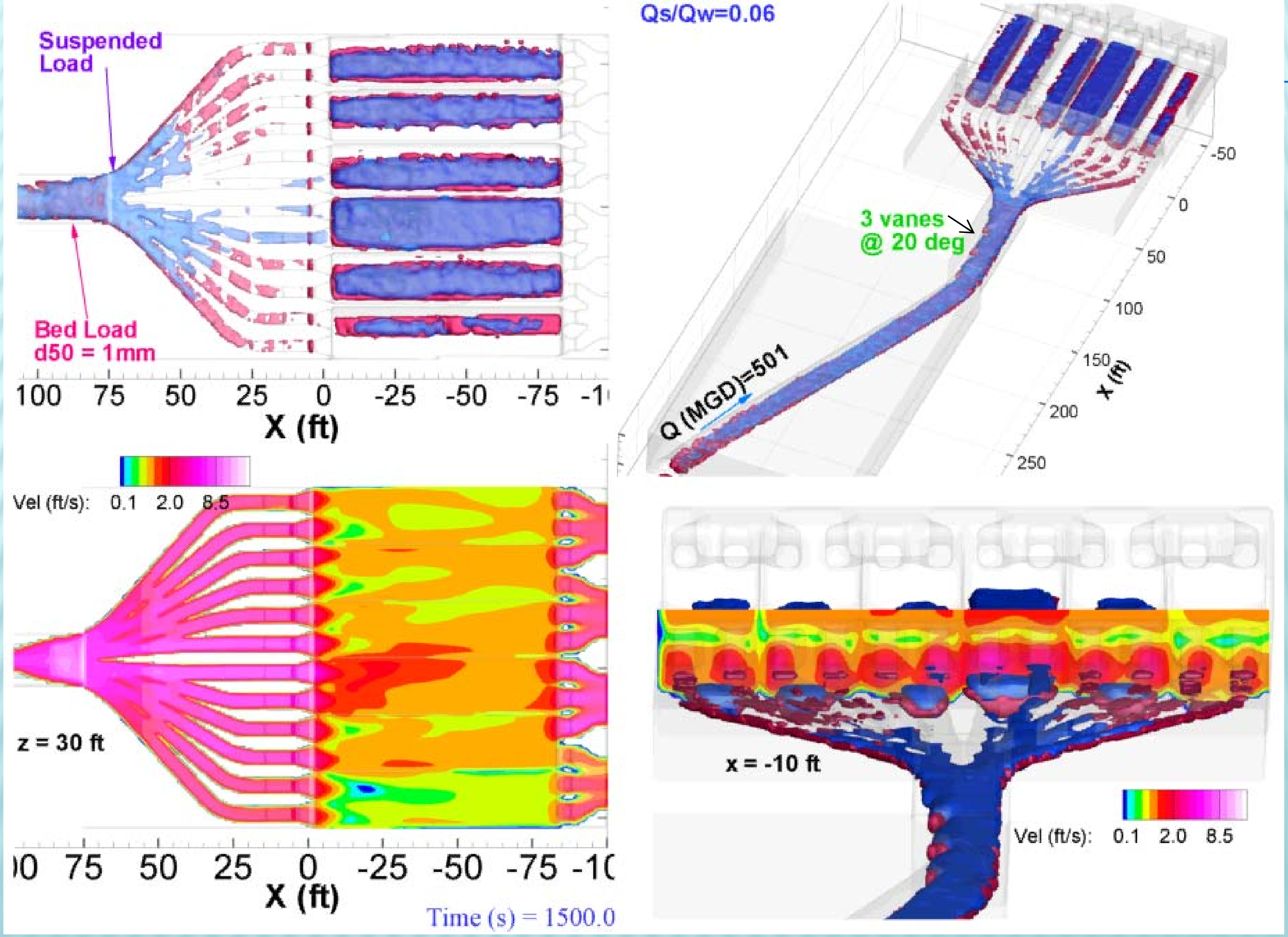
PROPOSED SOLUTIONS TO CONSIDER…



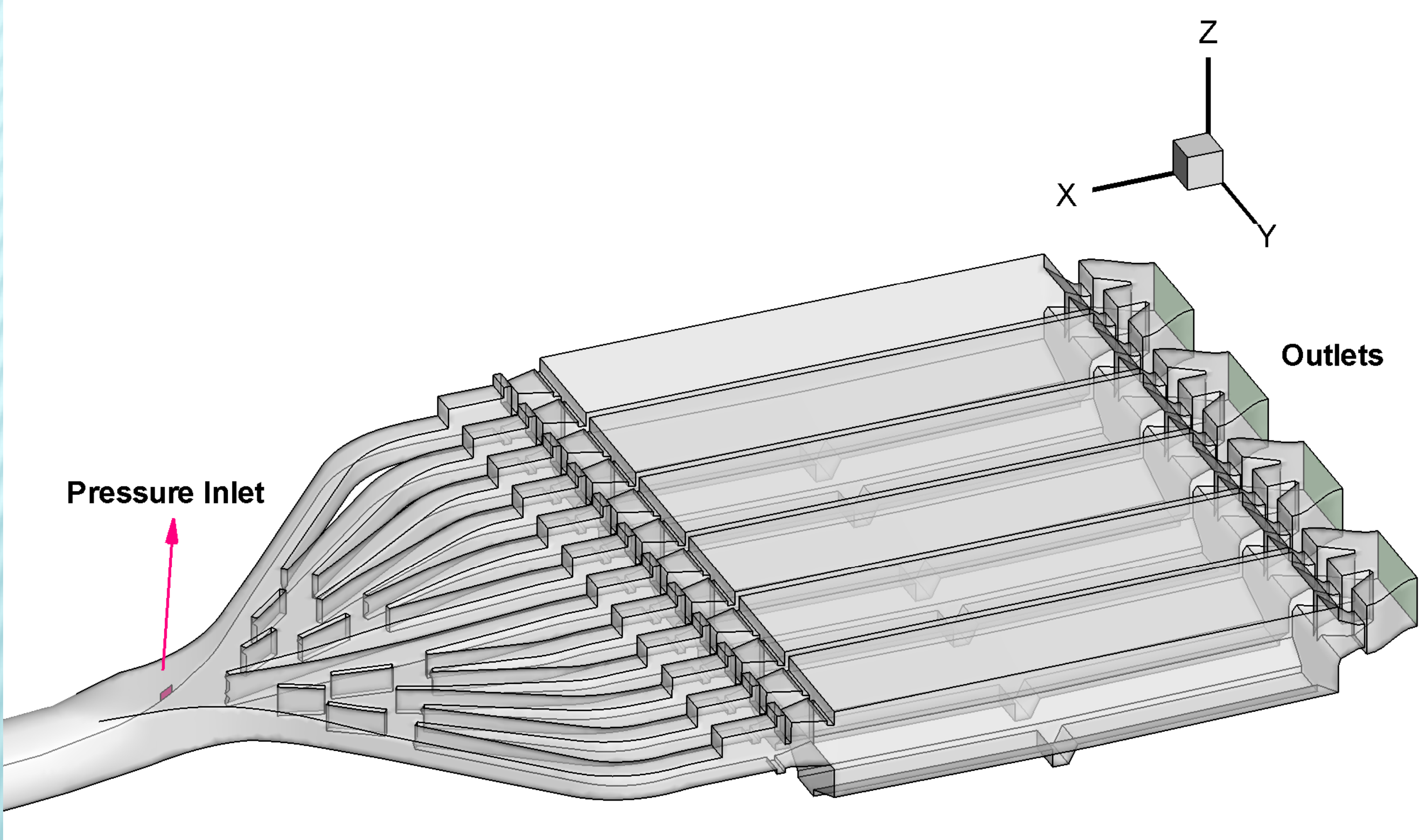
Vanes making 20^{o} angle with the side wall of the approach channel



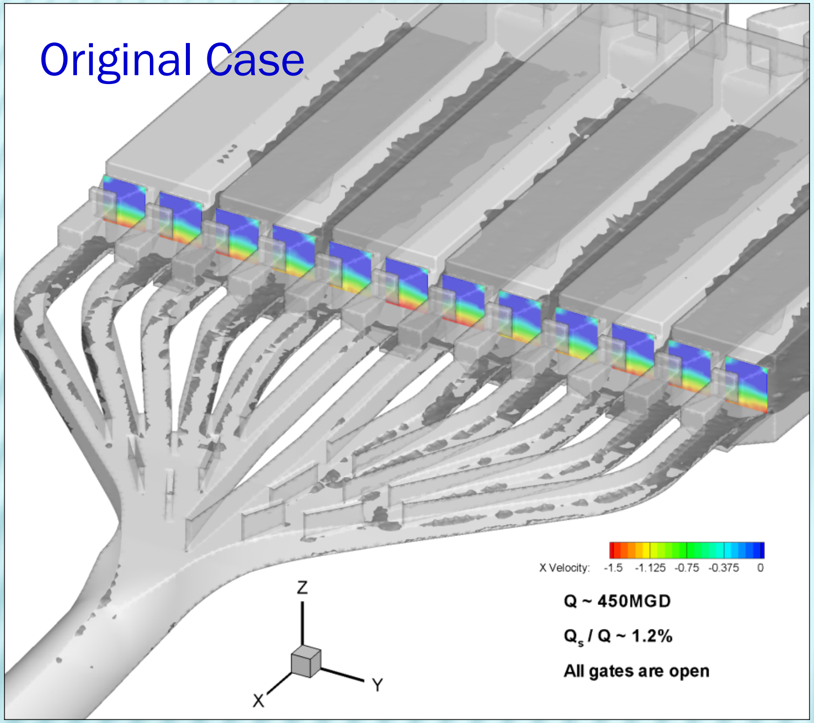
FLOW PATTERN FOR SUSPENDED SEDIMENT AND BEDLOAD MATERIAL WITH VANES PRESENT IN THE SYSTEM

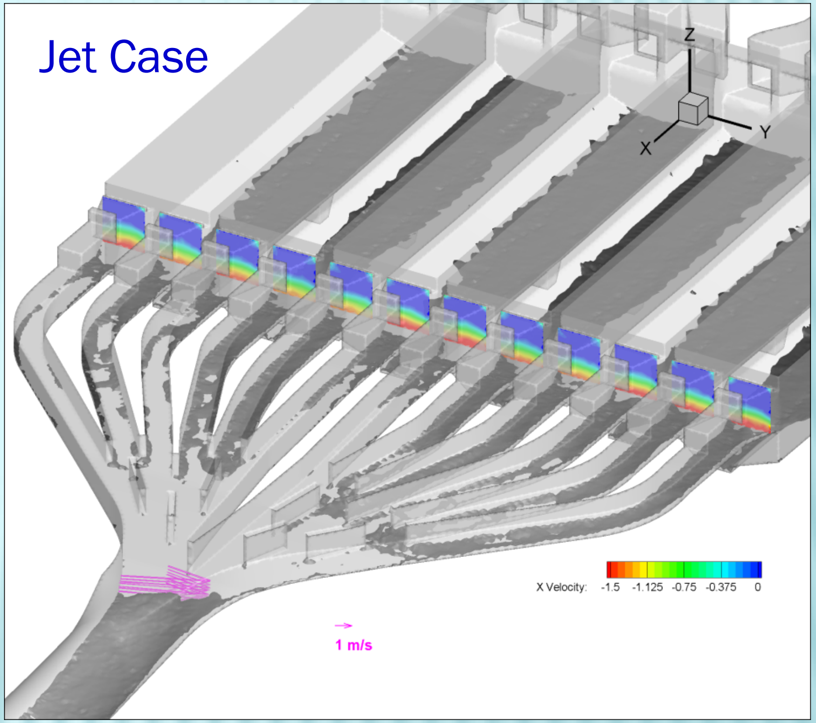


PROPOSED SOLUTIONS TO CONSIDER…



SINGLE JET LOCATED ON THE LATERAL WALL DIVERTS THE SOLIDS TO NORTH SIDE CONDUITS, HOWEVER CAUSES SOME ACCUMULATION AT THE "WRIST" AND CONDUITS 1-5.





Grit Collected	Original	Pressure Jet
North Side	747.85	733.03
South Side	753.63	691.05
North/South	0.99	1.06
Total (m3)	1501.48	1424.08
Total (million gallons)	0.40	0.38

SEVERAL FLOW TRAINING STRATEGIES WERE CONSIDERED:

- **Triangular steps** of height 1.5-1.6ft (50cm) are placed in checkerboard pattern starting from bend until the “wrist” of the approach channel. (OPTION 1)

- Several variations in terms of location and length of these triangular steps were considered. (OPTION 2, 3)

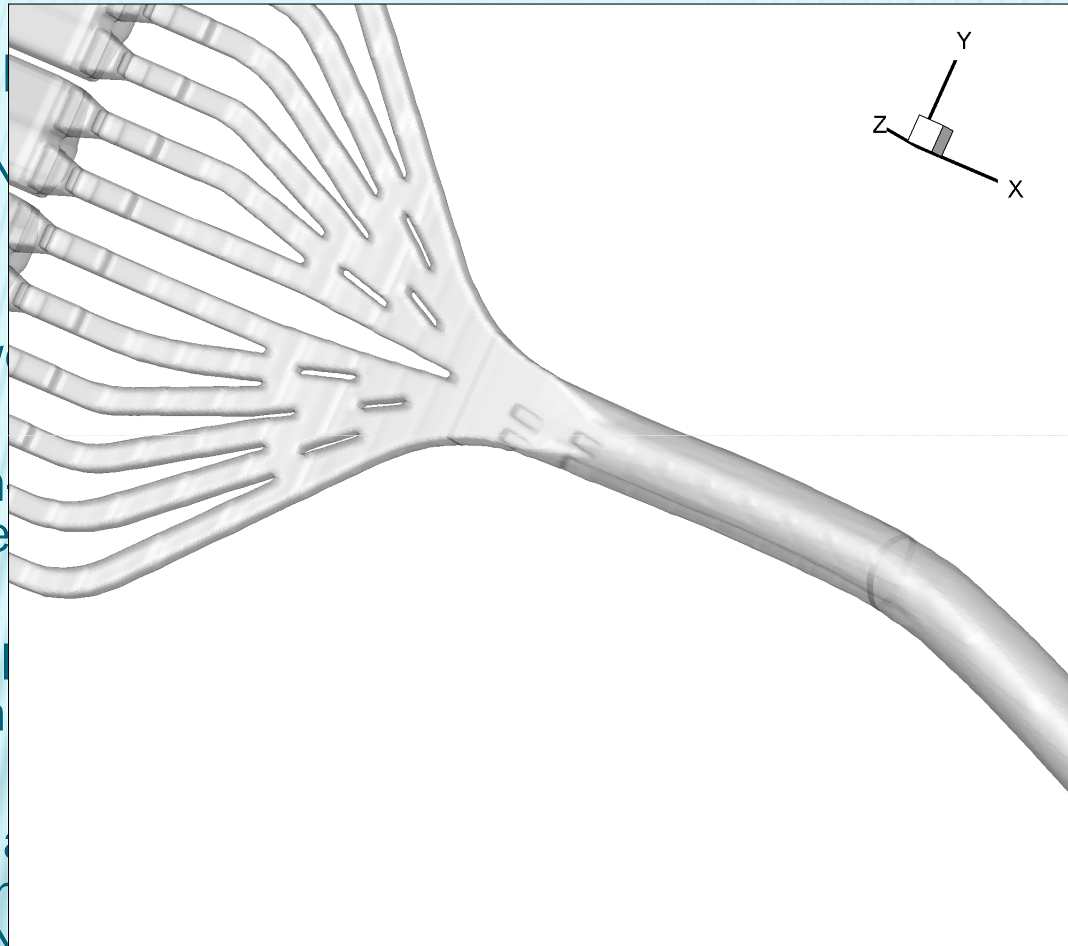
- An **arch-shaped perforated wall** at the wrist of the approach channel was considered. (OPTION 6)

- Triangular steps were placed near the south side lateral wall starting from the bend until the wrist of the approach channel. (OPTION 4)

- Finally, a **guide wall** following the south side lateral wall starting from the bend until the wrist with 3 triangular steps at the wrist was considered. (OPTION 5: variation of Option 4)

SEVERAL FLOW TRAINING STRATEGIES WERE CONSIDERED:

- Triangul… n checkerboard pattern … ach channel. (OPTION…
- Several … se triangular steps w…
- An arch… ach channel was conside…
- Triangul… wall starting from the ben… ON 4)
- Finally, … starting from the bend ur… was considered. (OPTION 5: variation of option 4)



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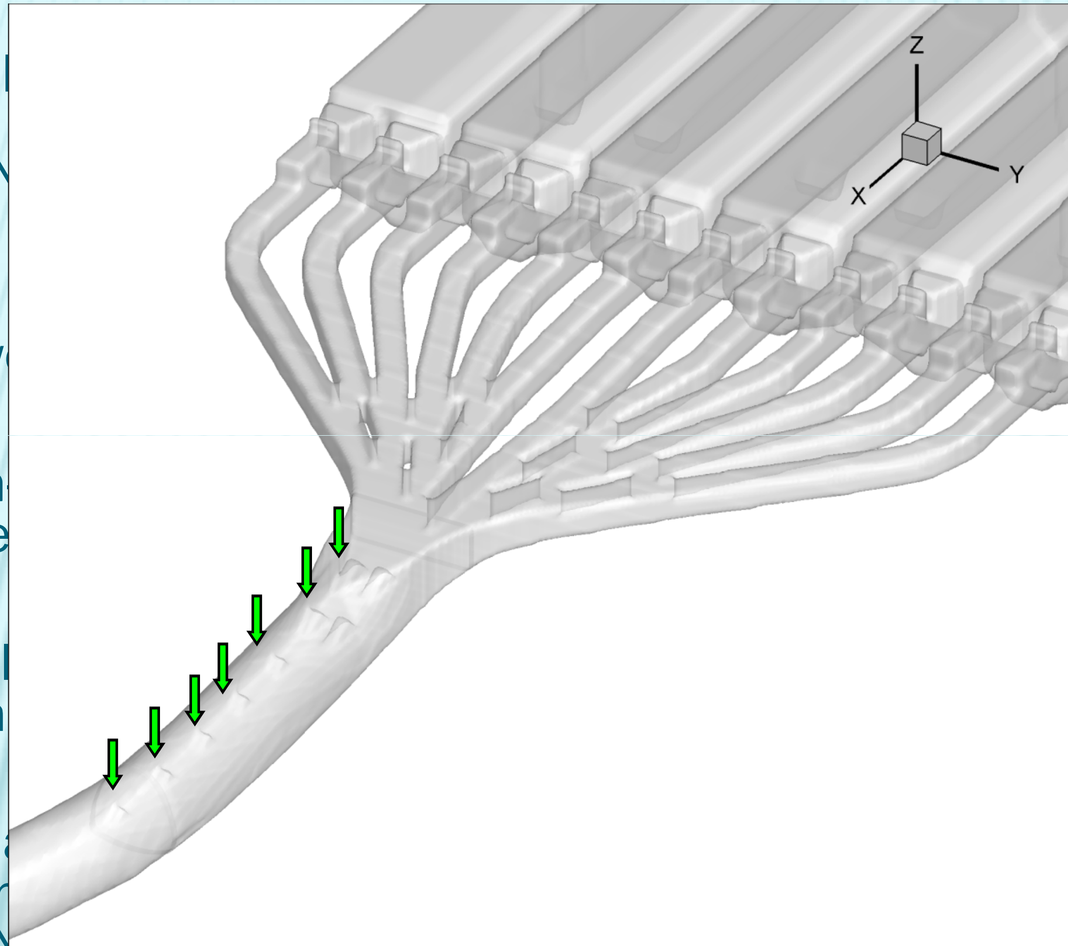

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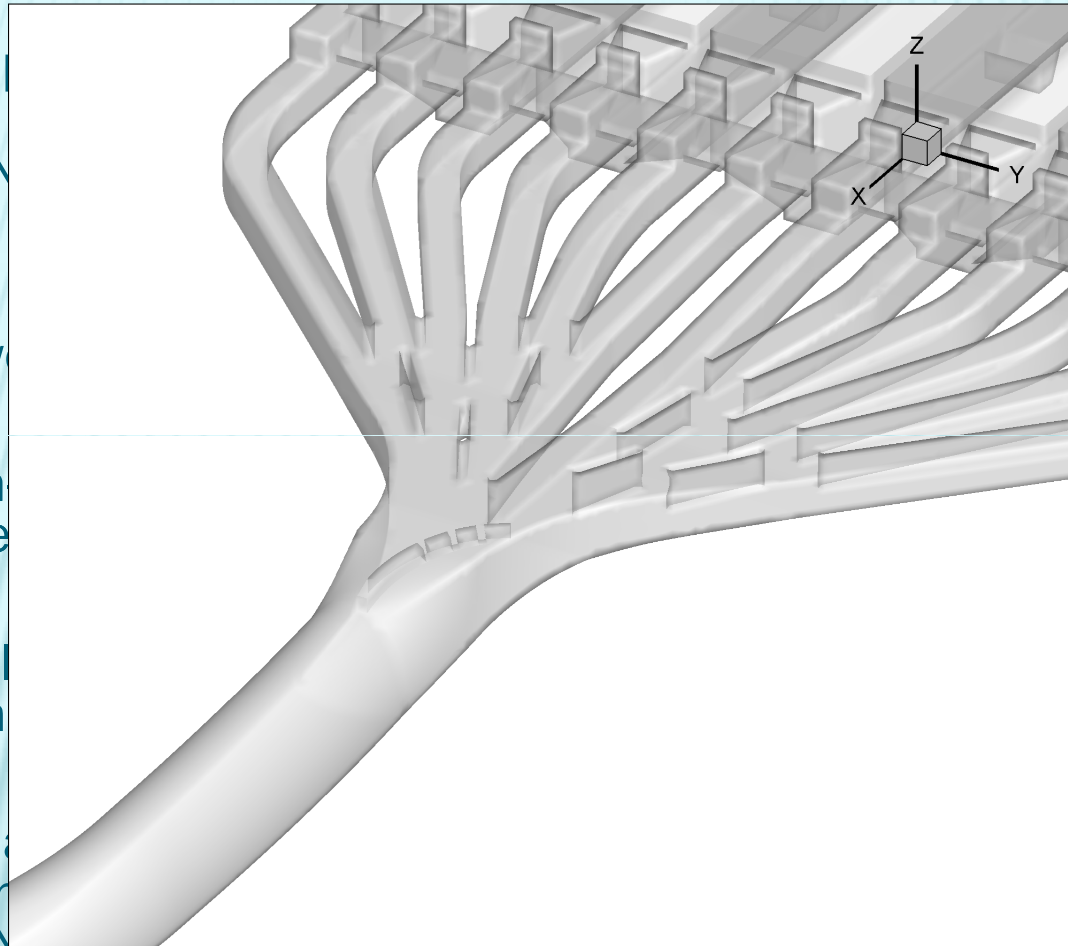

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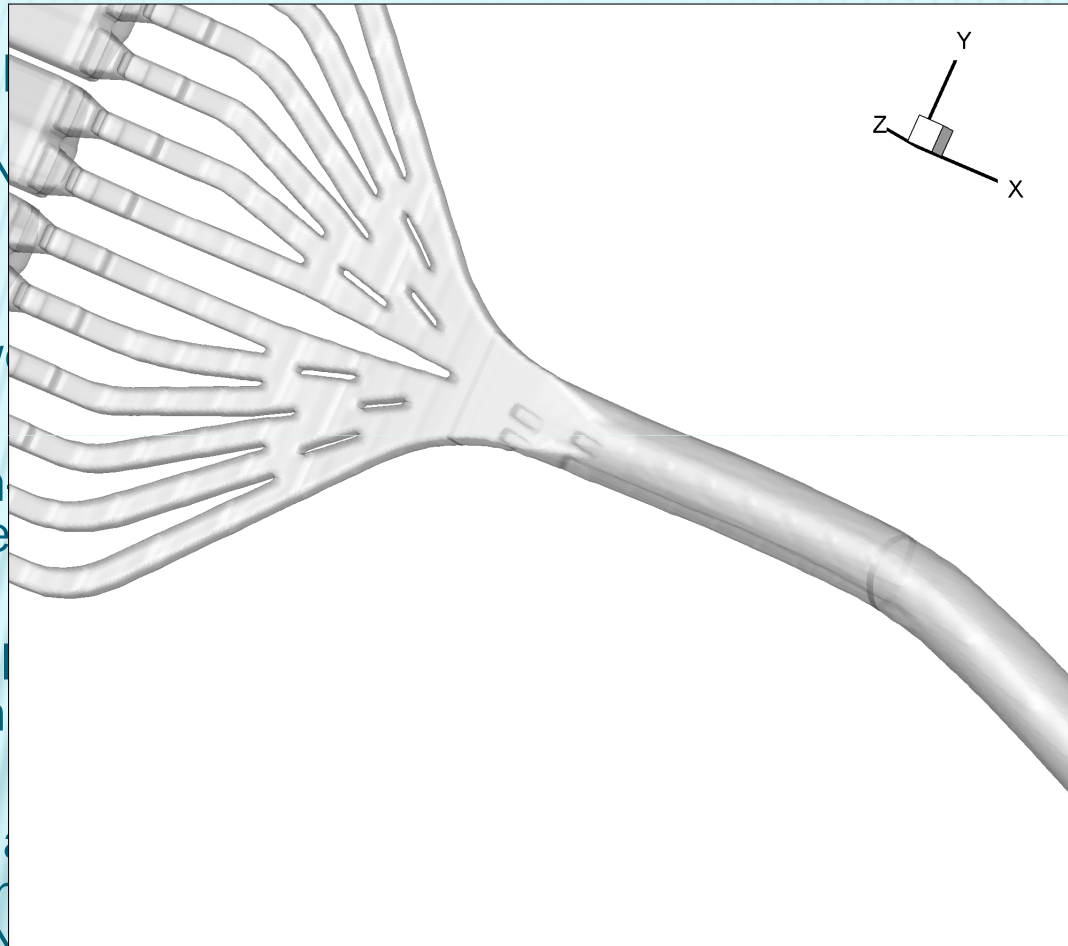

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- Triangul … wall starting from the ben … N 4)

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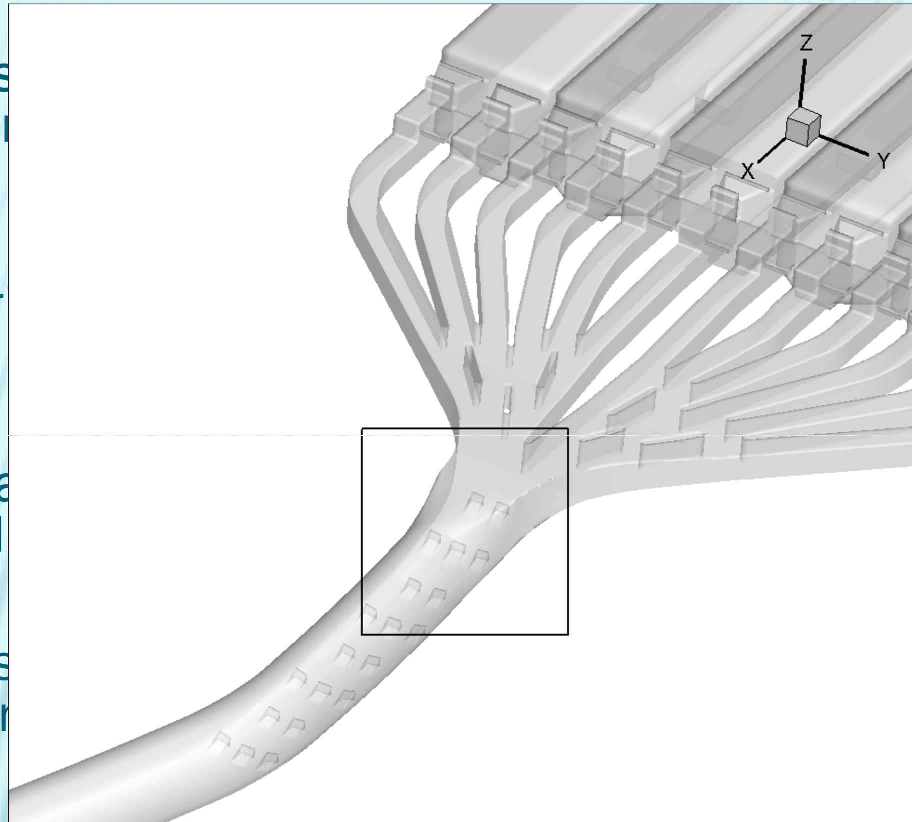
- Several variations in terms of location and length of these triangular steps were considered. (OPTION 2, 3)
- An **arch-shaped perforated wall** at the wrist of the approach channel was considered. (OPTION 6)
- Triangular steps were placed near the south side lateral wall starting from the bend until the wrist of the approach channel. (OPTION 4)
- Finally, a **guide wall** following the south side lateral wall starting from the bend until the wrist with 3 triangular steps at the wrist was considered. (OPTION 5: variation of Option 4)

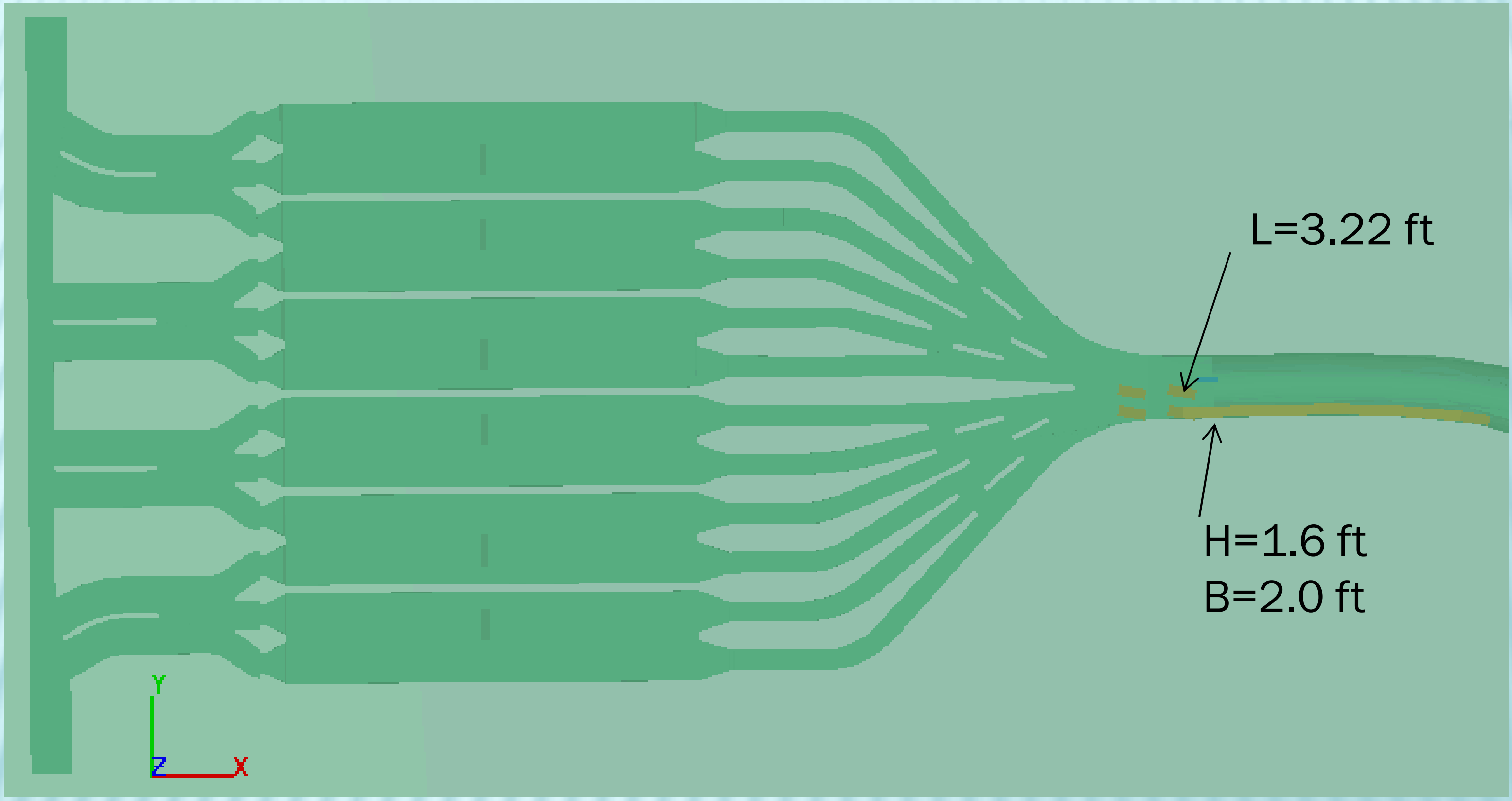
SEVERAL FLOW TRAINING STRATEGIES WERE CONSIDERED:

- **Triangular s**… …ed in checkerboard pattern star… …proach channel. (OPTION 1)



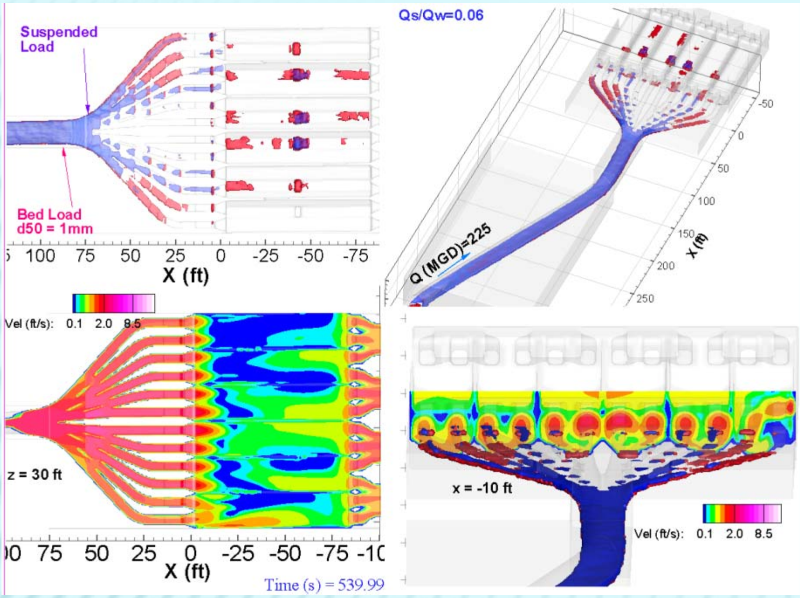
- Several var… …these triangular steps were …
- An **arch-sha**… …proach channel was considered…
- Triangular s… …eral wall starting from the bend ur… …PTION 4)
- Finally, a **guide wall** following the south side lateral wall starting from the bend until the wrist with 3 triangular steps at the wrist was considered. (OPTION 5: variation of Option 4)

OPTION 5-VARIATION OF OPTION 4 CONSIDER A CONTINUOUS GUIDING BAFFLE

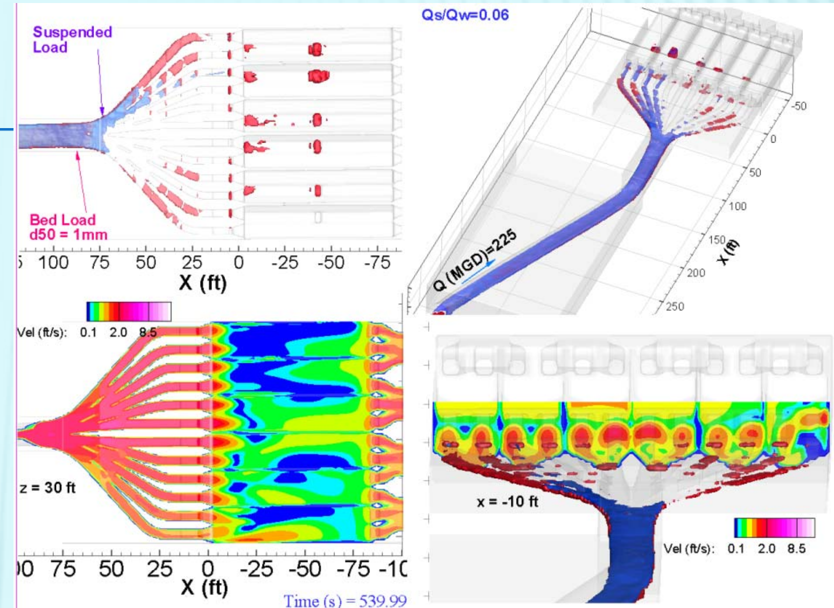


Option 5, continuous guiding baffle following the south-side lateral wall of approach channel with triangular steps at the wrist

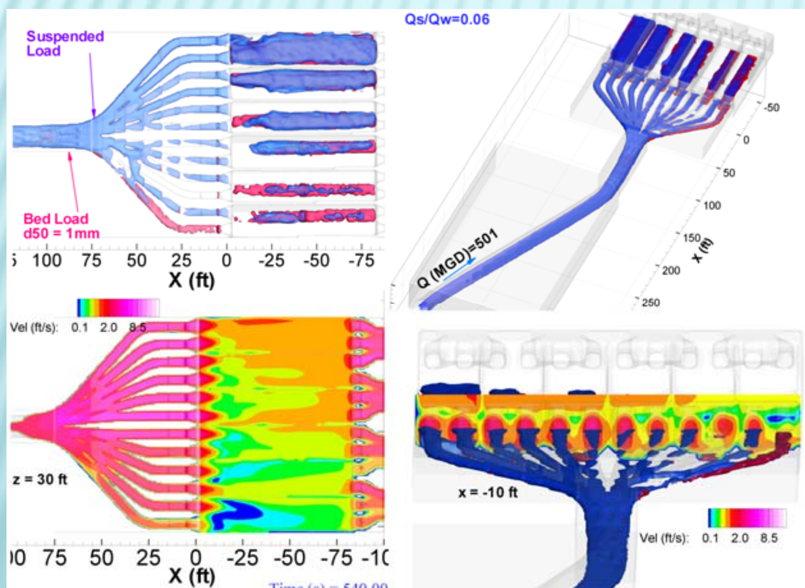
Original Domain



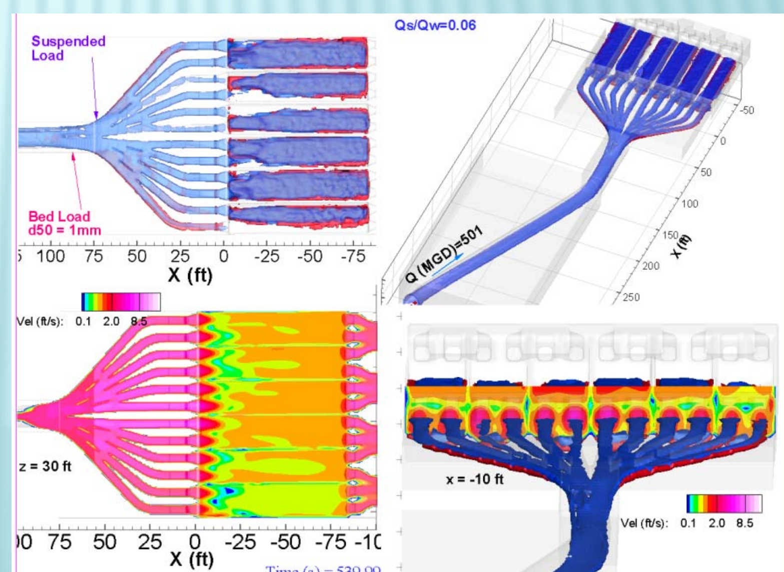
Q = 225 MGD



Original Domain

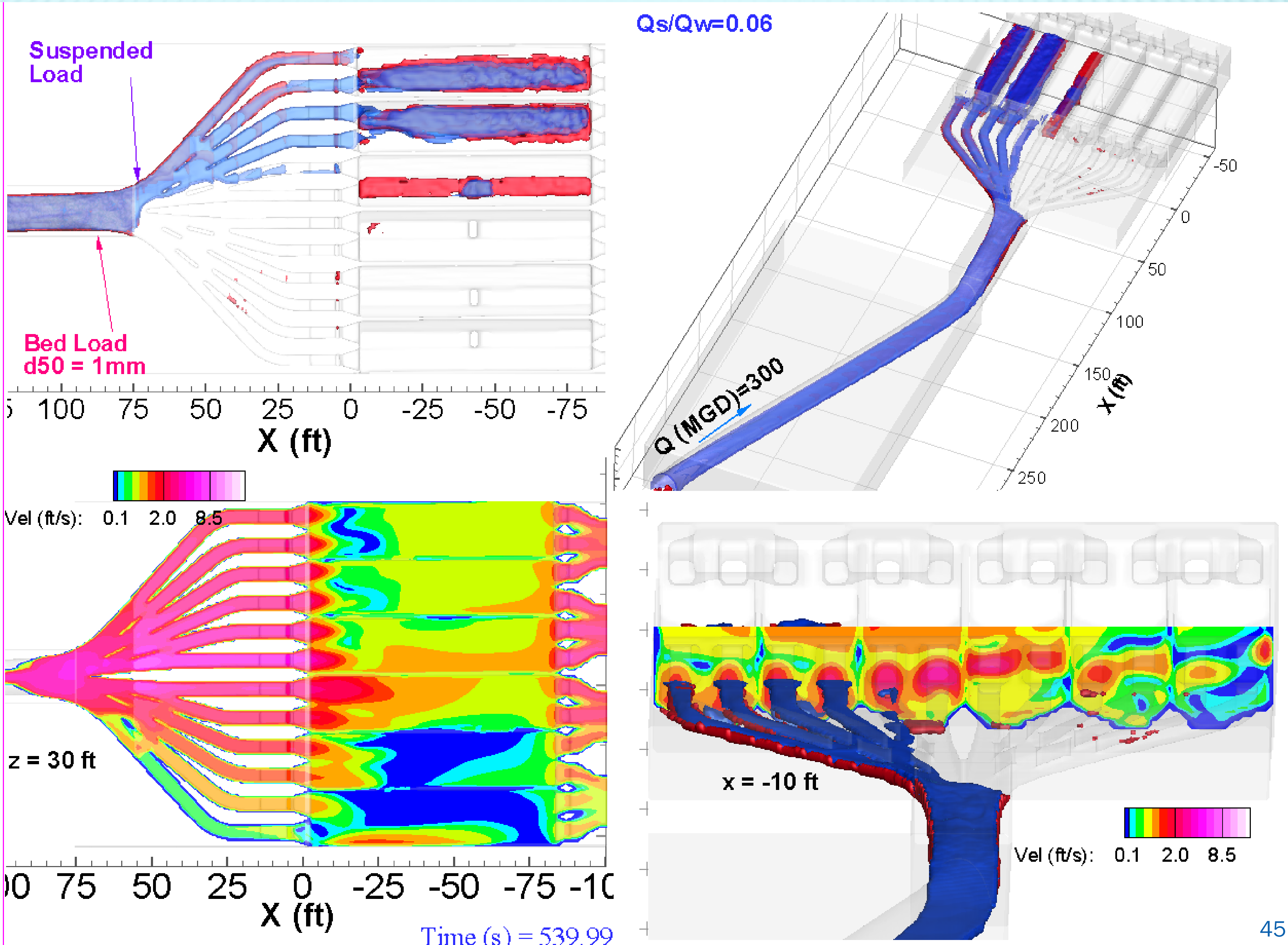


Q = 501 MGD

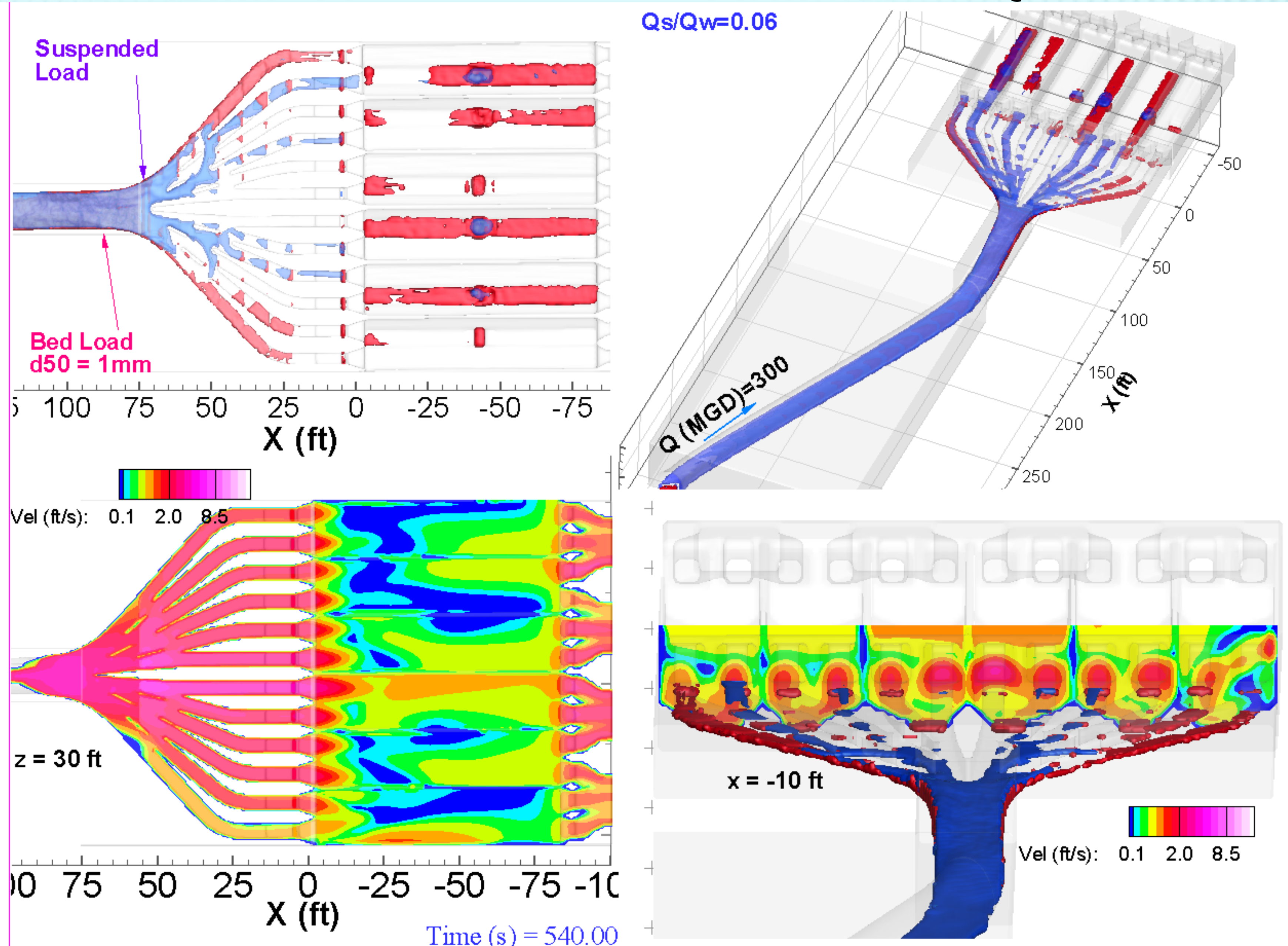


Original Domain

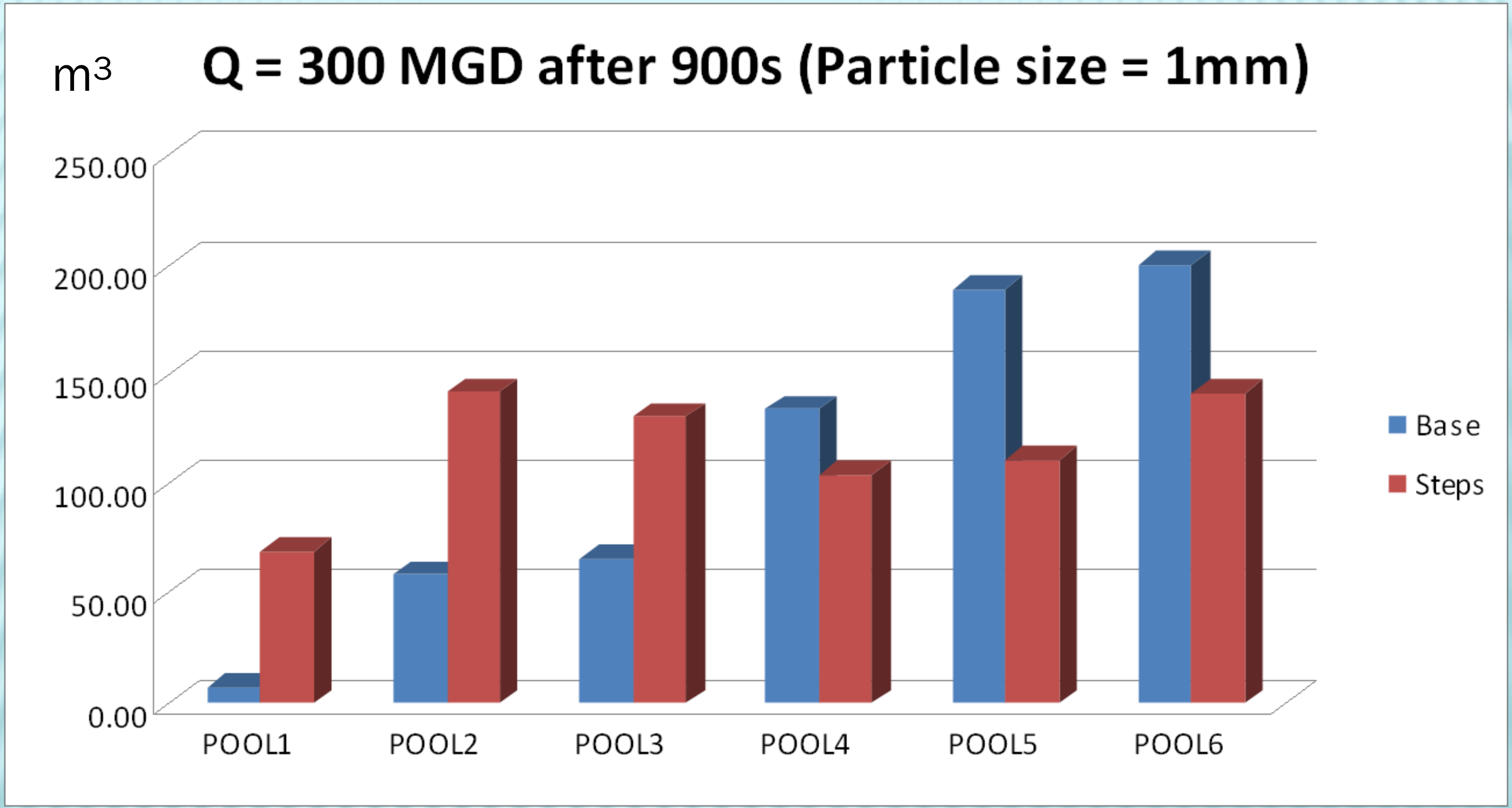
Q = 300 MGD



Option 5 Q = 300 MGD



OPTION 5: Q = 300 MGD FLOW

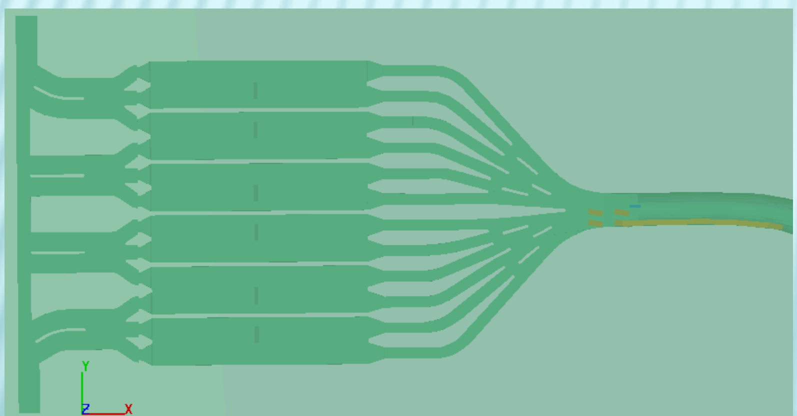


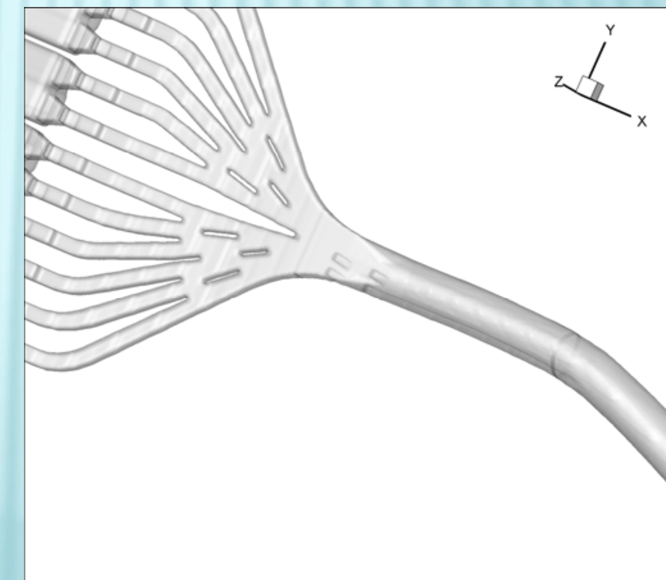
%Change in Amount	Pool1	Pool2	Pool3	Pool4	Pool5	Pool6
t=900s	518	20.19	13.36	-34.65	-42.73	-48.24

CONCLUSIONS:

- Out of all the flow training devices tested, Option 5, continuous guiding baffle following the south-side lateral wall of approach channel with triangular steps at the wrist, shows the most improvement in terms of grit distribution in each pool for most of the discharges considered.

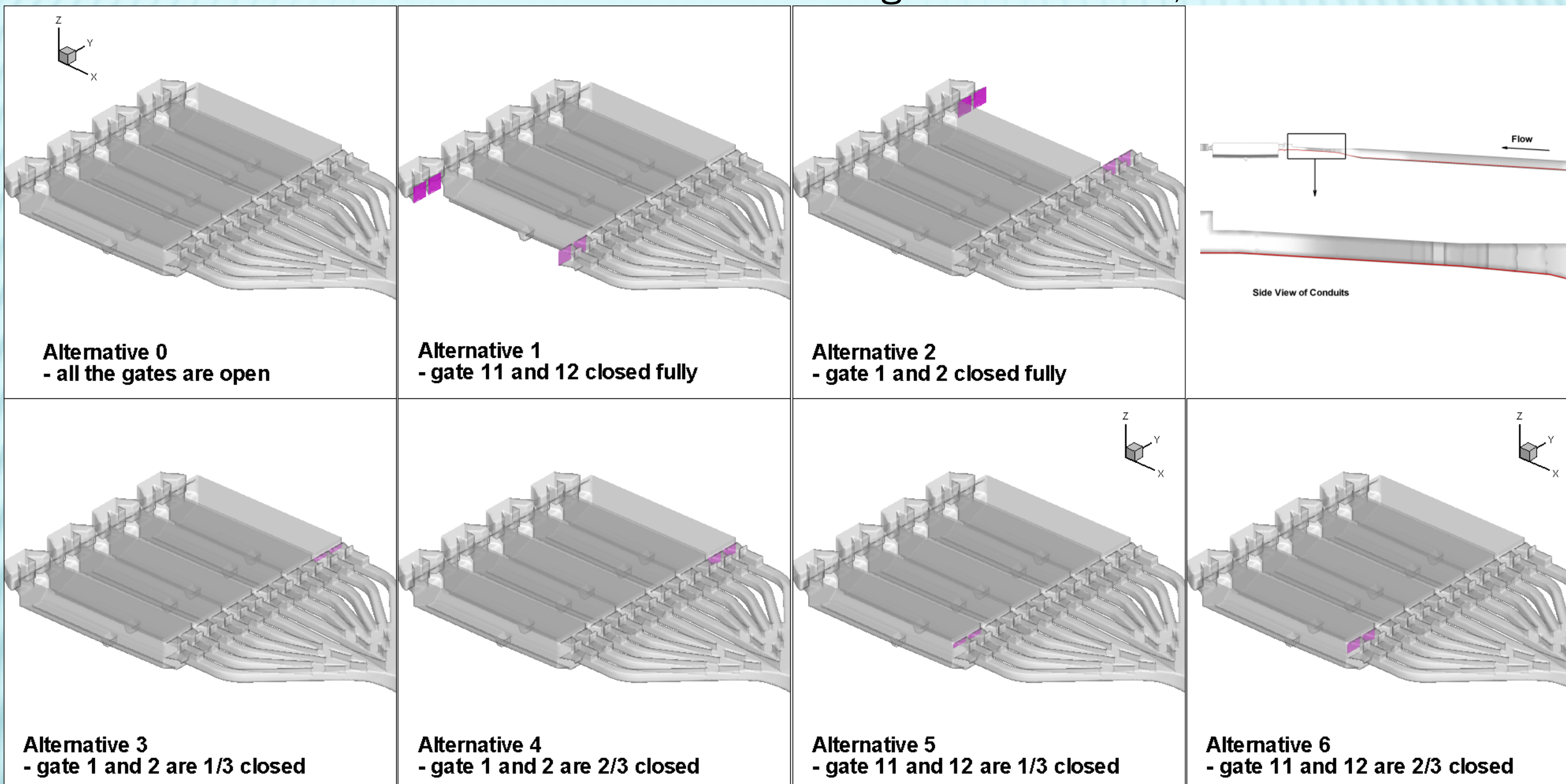
- This is an easily applicable option in terms of structure geometry considered.





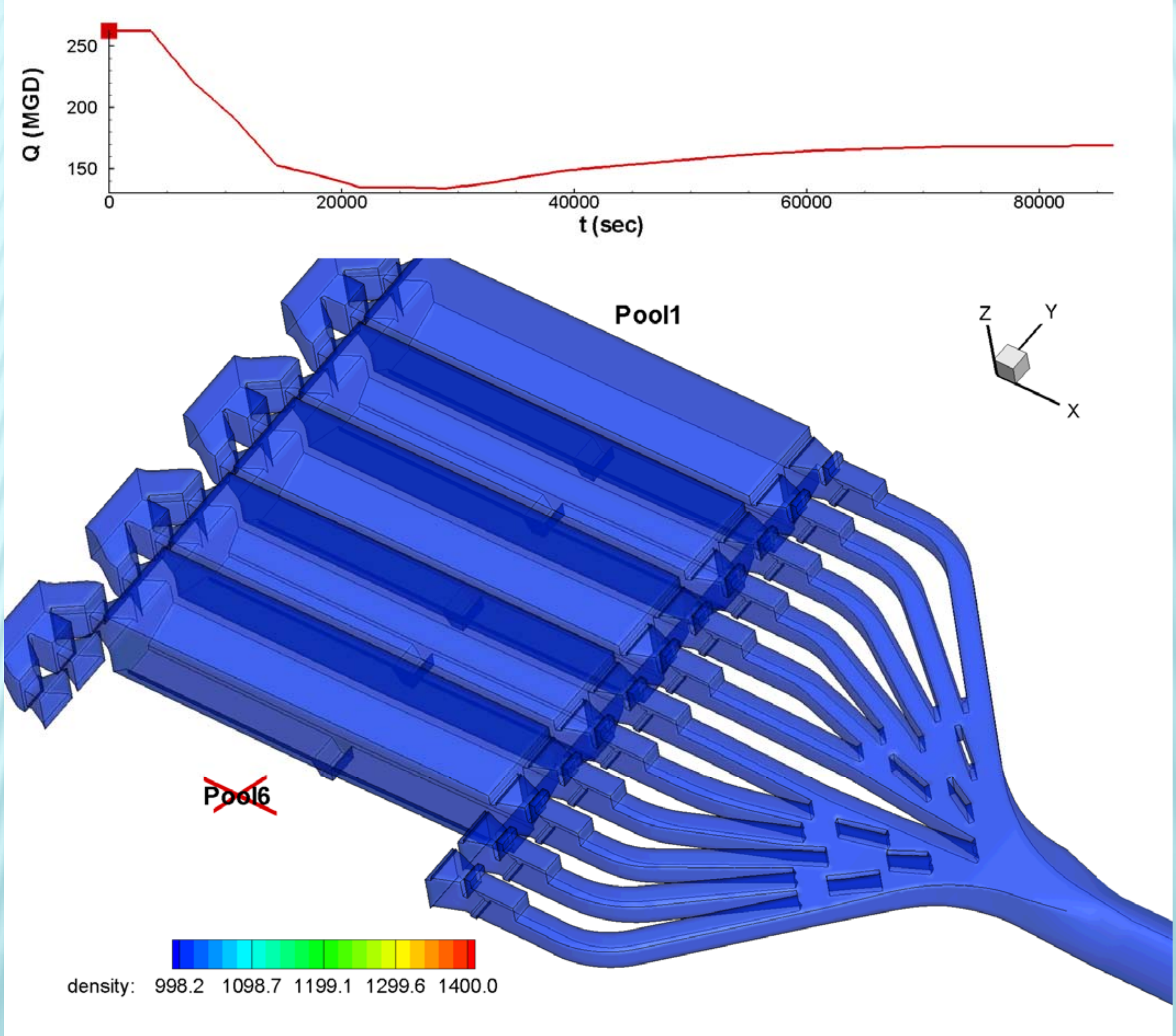
GATE OPENING SOLUTION SCENARIOS…

The different cases were tested for three discharge values of 250, 350 and 450 MGD



- Alternative 0 (A0) considers the case in which all the gates are open.
- Alternative 1 (A1) considers the case in which gates 11 and 12 are fully closed.
- Alternative 2 (A2) considers the case in which gates 1 and 2 are fully closed.
- Alternative 3 (A3) considers the case in which gates 1 and 2 are 2/3 open.
- Alternative 4 (A4) considers the case in which gates 1 and 2 are 1/3 open.
- Alternative 5 (A5) considers the case in which gates 11 and 12 are 2/3 open.
- Alternative 6 (A6) considers the case in which gates 11 and 12 are 1/3 open.

ALTERNATIVE 1: GATE 11 & 12 FULLY CLOSED



(Video Simulation)

CONCLUSIONS AND RECOMMENDATIONS FROM GATE OPERATION SIMULATIONS

- Changing the openings on north side extreme for gates 1 and 2 does not affect the flow distribution to conduits 7 to 12 significantly.

- Similarly changing openings of gates 11 and 12 does not affect the flow distribution to conduits 1 to 6.

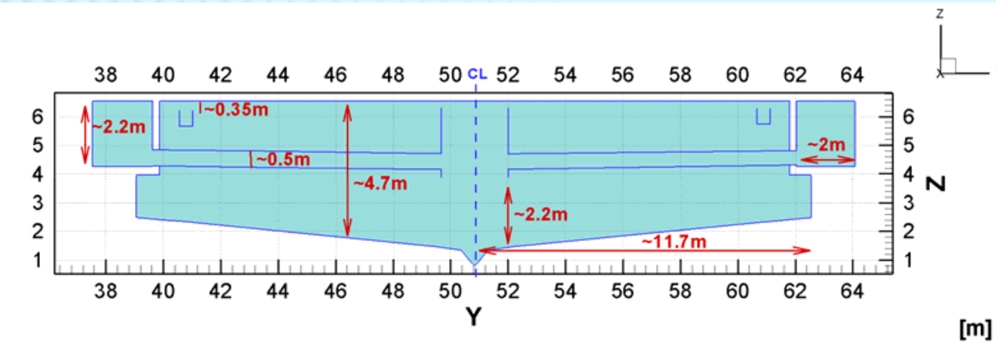
- **Shutting the gates 11 and 12 fully, causes formation of a dead zone considerably large, almost over the full length of distribution conduits 11 and 12.** This dead zone is prone to accumulate solid material of all sizes since the flow velocity in the region is much slower than the fall velocity of grit sizes that are observed in the system (75μm to 1mm).

- **Fully shutting gates 11 and 12 could also overload gates 9 and 10 in high inflow times.**

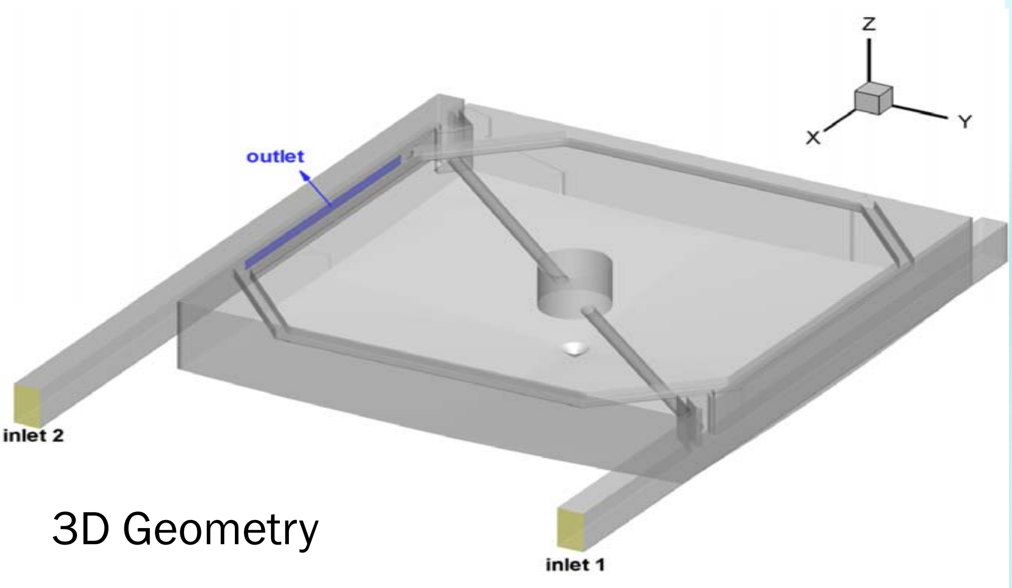
- **In the high flow times** (Q~450MGD) **keeping the gates 11 and 12 2/3 open** instead of fully shut and **at the low flow times** (Q~250MGD) **keeping the gates 1/3 open** will prevent accumulation of solid material in the distribution conduit 11 and 12 while reducing the loading to Pool 6.

CFD for Final Settling Tank at NSWRP

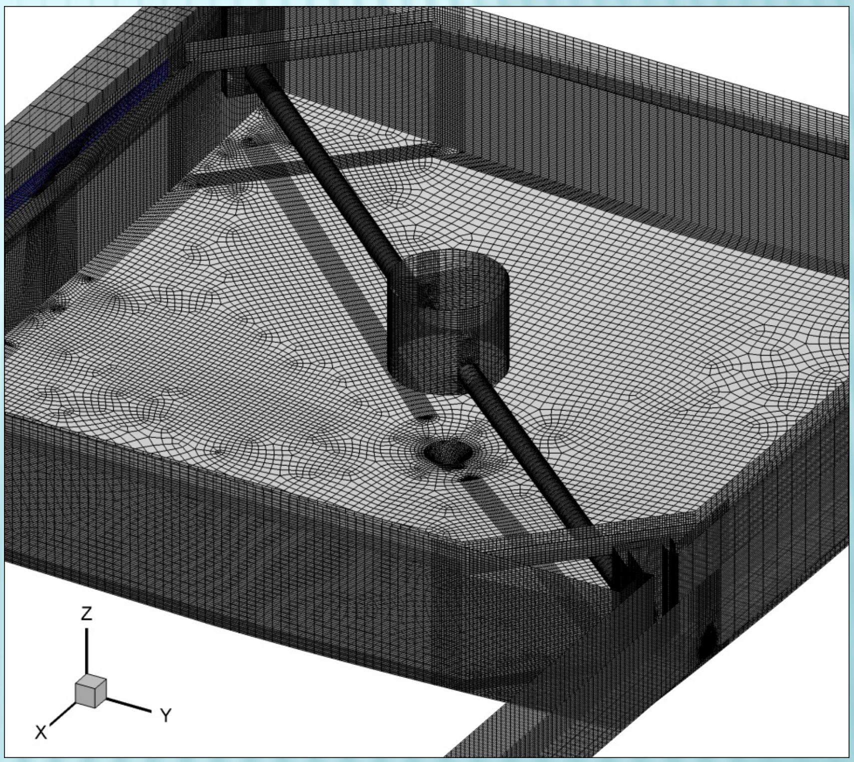
Purpose: To improve settling of suspended solids



Grid Consist of 1.3 million cells.

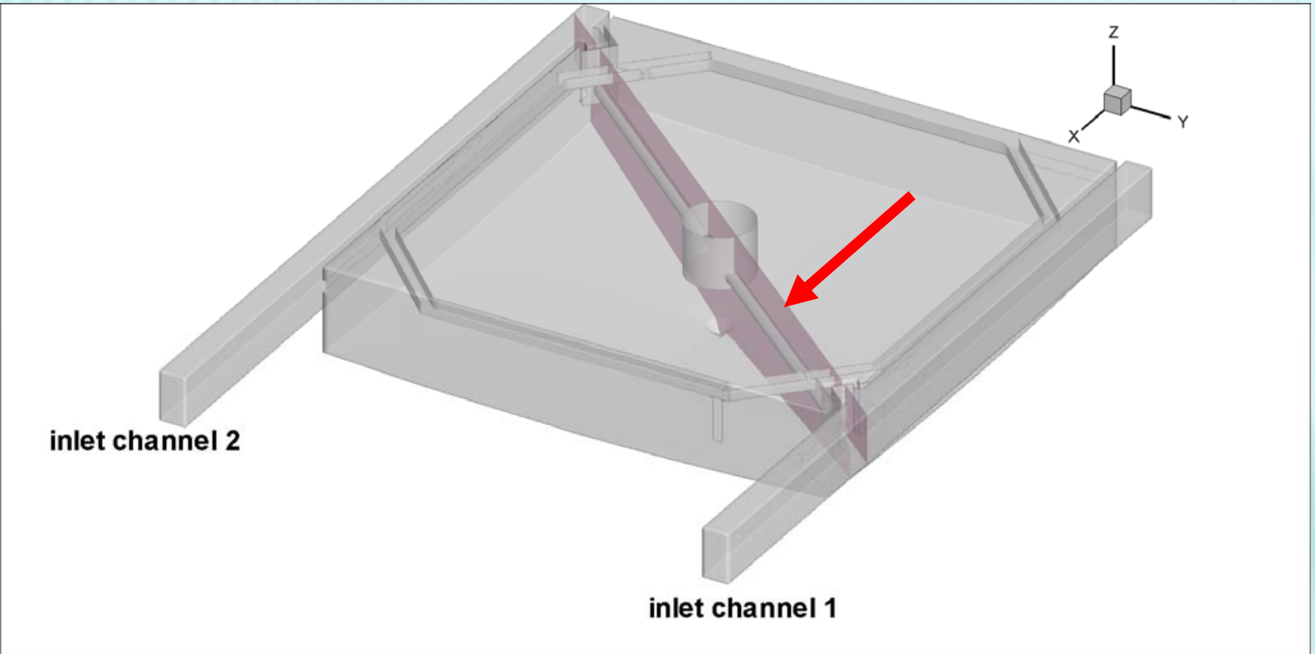


3D Geometry

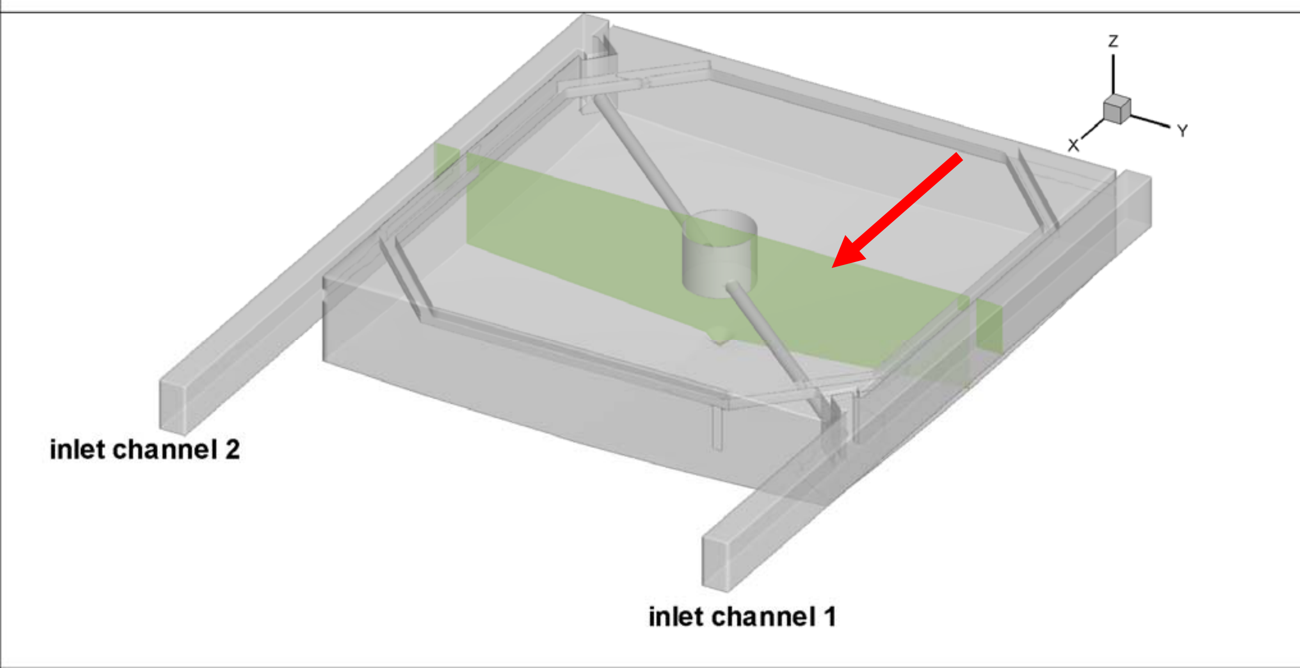


CFD goal of the preliminary simulations is to reproduce the hydrodynamics of a final settling tank for two different discharge conditions so that the mechanics of sedimentation can be observed. Two preliminary simulations are conducted with 2-MGD (low flow) and 6-MGD (high flow) inflow discharges.

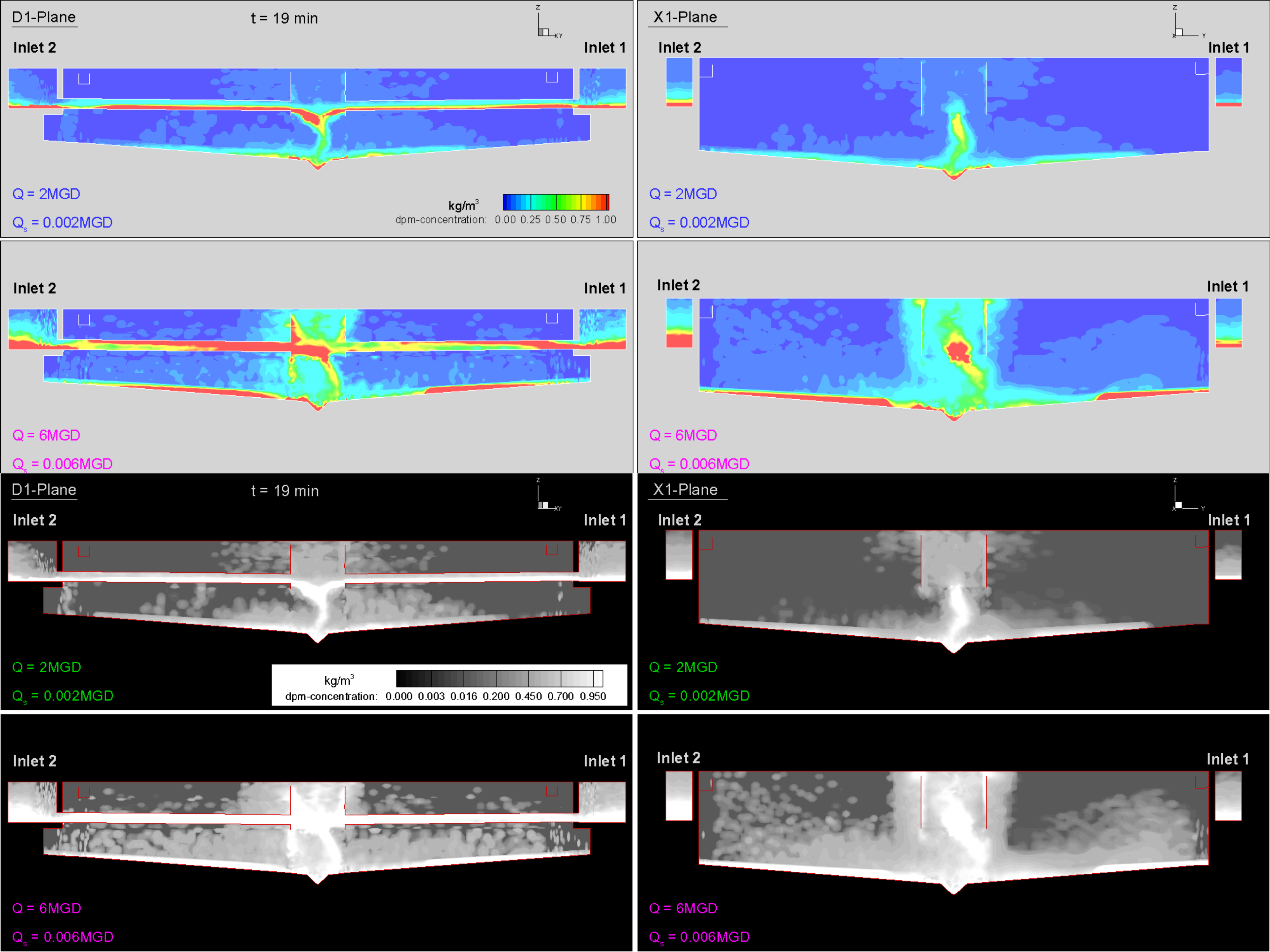
3D Simulation results are presented in two planes cutting through the middle of the tank.



Plane, D1, Cutting Diagonally Through Settling Tank

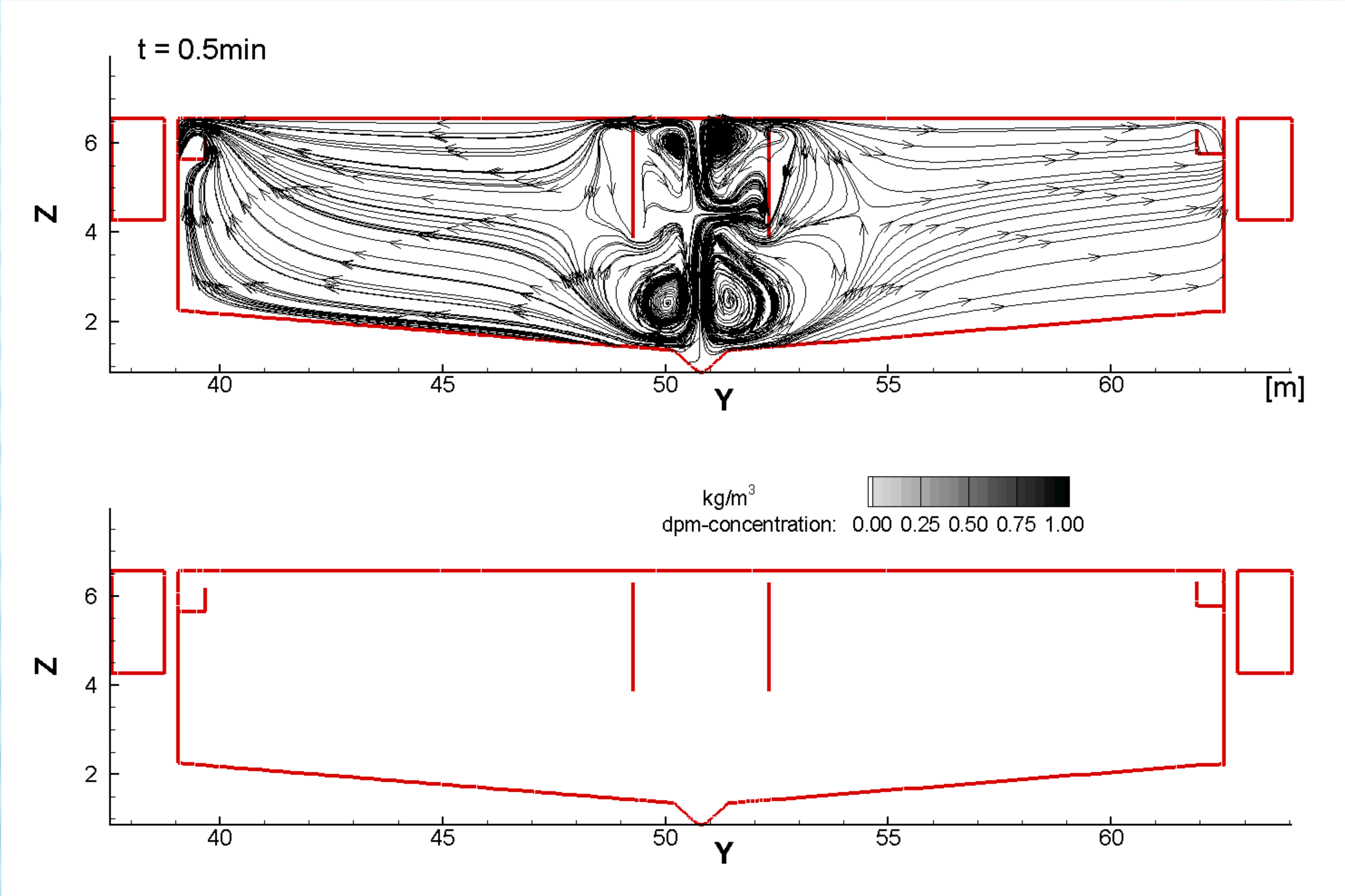


Plane, X1, Cutting Through Middle of the Settling Tank



D1-Plane
t = 19 min
Inlet 2
Inlet 1
Q = 2MGD
Q_s = 0.002MGD
kg/m^3
dpm-concentration: 0.00 0.25 0.50 0.75 1.00
X1-Plane
Inlet 2
Inlet 1
Q = 2MGD
Q_s = 0.002MGD
Inlet 2
Inlet 1
Q = 6MGD
Q_s = 0.006MGD
Inlet 2
Inlet 1
Q = 6MGD
Q_s = 0.006MGD
D1-Plane
t = 19 min
Inlet 2
Inlet 1
Q = 2MGD
Q_s = 0.002MGD
kg/m^3
dpm-concentration: 0.000 0.003 0.016 0.200 0.450 0.700 0.950
X1-Plane
Inlet 2
Inlet 1
Q = 2MGD
Q_s = 0.002MGD
Inlet 2
Inlet 1
Q = 6MGD
Q_s = 0.006MGD
Inlet 2
Inlet 1
Q = 6MGD
Q_s = 0.006MGD

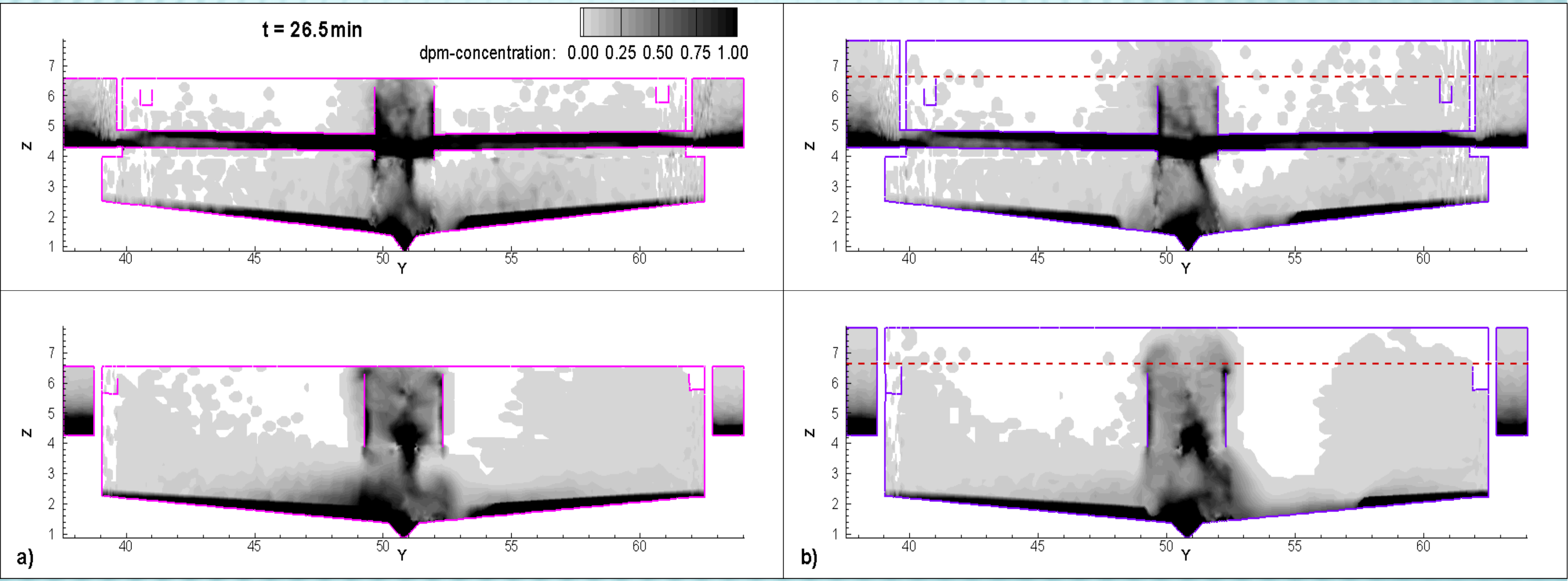
STREAMLINES ON PLANE X1 FROM SIMULATION WITH 6-MGD INFLOW (Video Simulation)



The streamlines show recirculation zones near the tank bottom. The suspended material plunges towards the tank bottom and should settle there. However these strong recirculation zones may re-suspend the solids, promoting their transport towards the outlet of the tank.

POSSIBLE SOLUTION SCENARIOS

- Increasing the depth of the settling tanks (Solution Scenario 1)



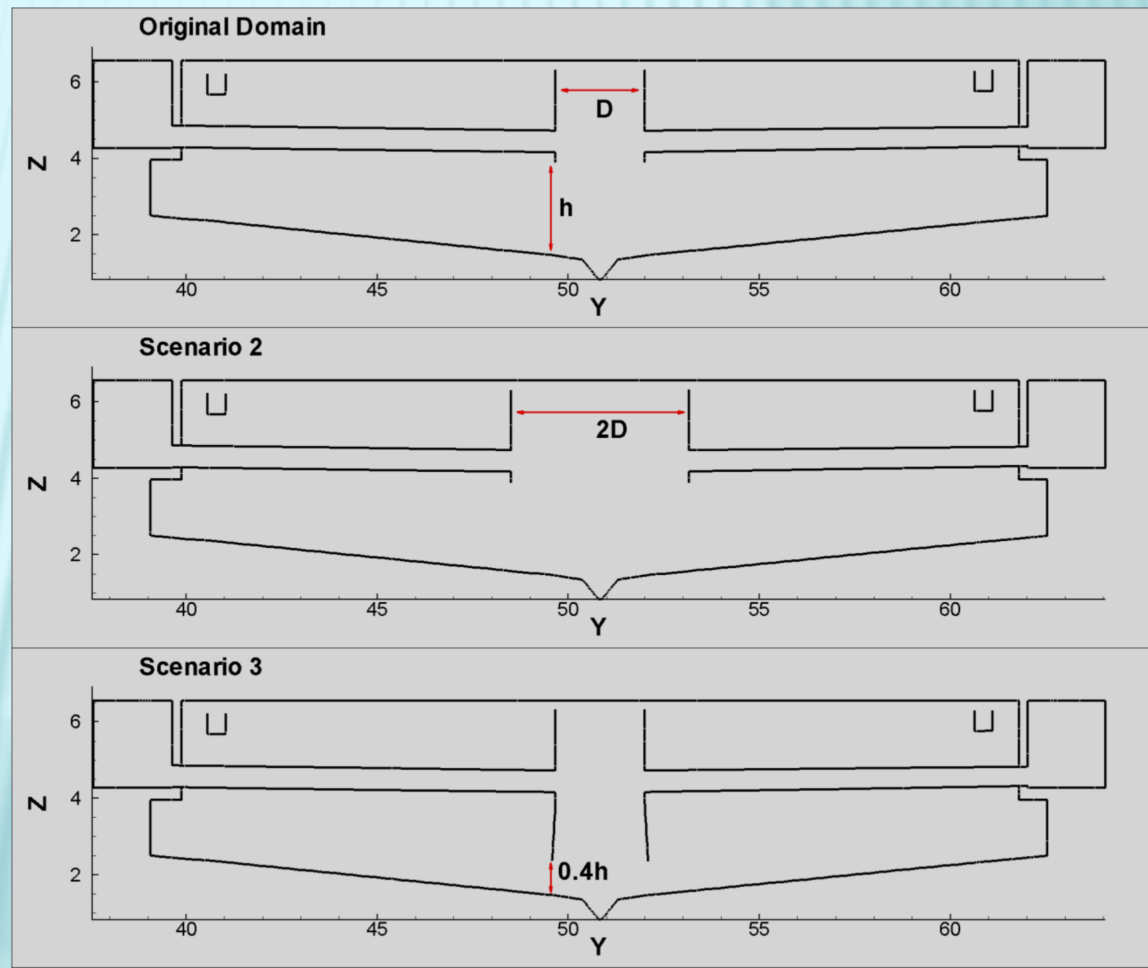
POSSIBLE SOLUTION SCENARIOS

- Increasing the diameter of the central skirt might reduce the amount of interaction between two jets entering the domain. (Solution Scenario 2)
- Decreasing the clearance of central skirt from the tank bottom (bringing the mouth of the ring closer to the tank bottom). (Solution Scenario 3)

Original Domain
$D_r = D = 2.25m$ *(7'-4 1/2")*
$h = 2.2m$ *(7'-2")*

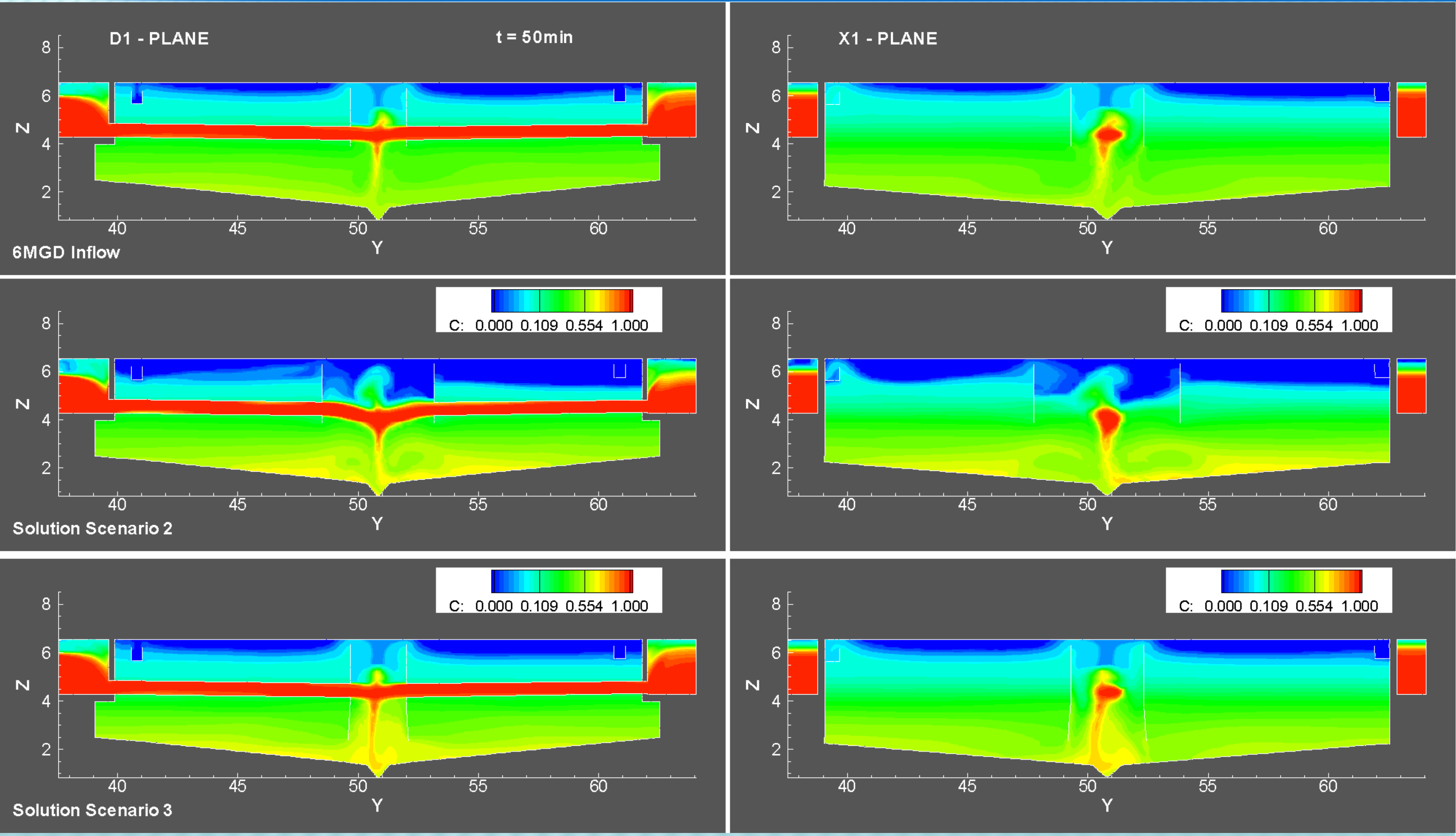
Scenario 2
$D_r = 2D = 4.5m$ *(14'-9")*
$h = 2.2m$ *(7'-2")*

Scenario 3
$D_r \sim D = 2.25m$ *(7'-4 1/2")*
$h = 0.9m$ *(2'-11")*

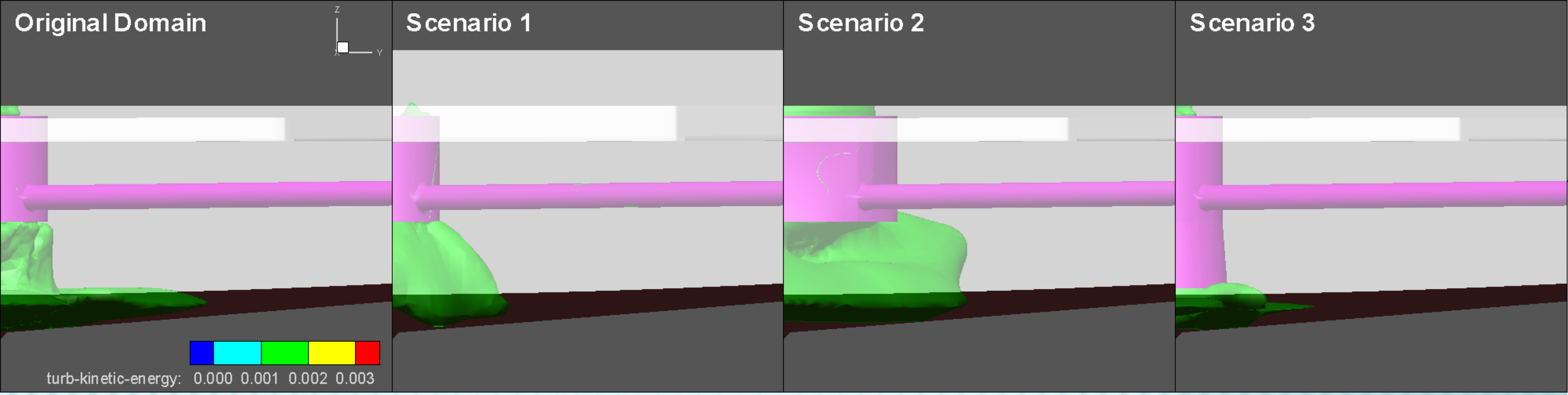


SOLUTION SCENARIO 2 & 3

t = 50min

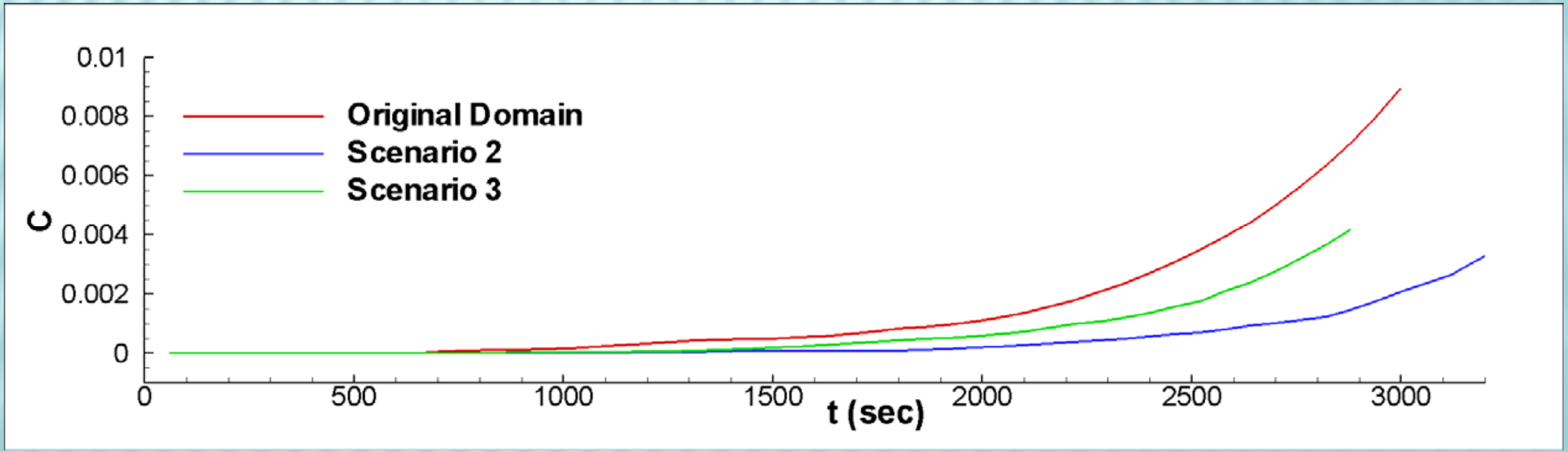


Note much improvement is observed between scenarios.



INSTANTANEOUS TURBULENT KINETIC ENERGY (TKE)

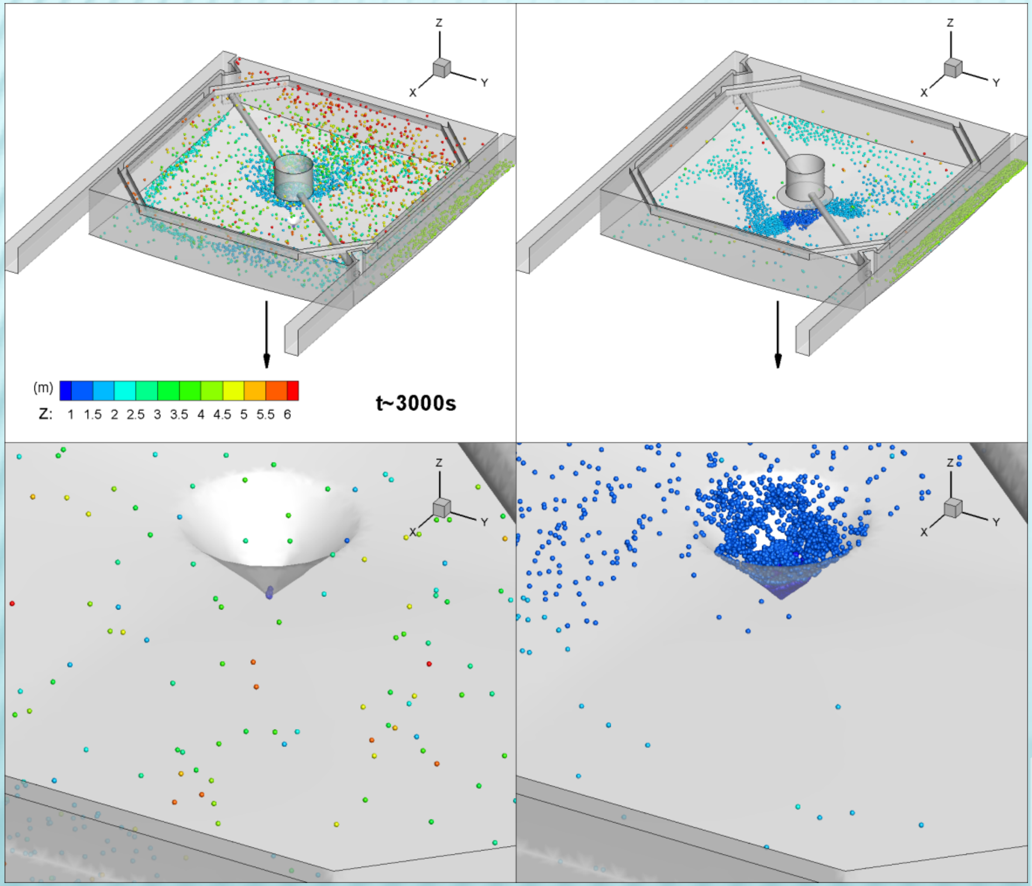
The figure shows that TKE values are higher near the bottom of the tank and these high values penetrates closer to the sidewall of the tanks in the original domain. Deepening the tank in Scenario 1 reduces the high TKE area near the tank bottom and confines penetration distance of high TKE. Similarly changing the diameter and the clearance of central ring from the bottom of the tank affects the size of the area of high TKE.

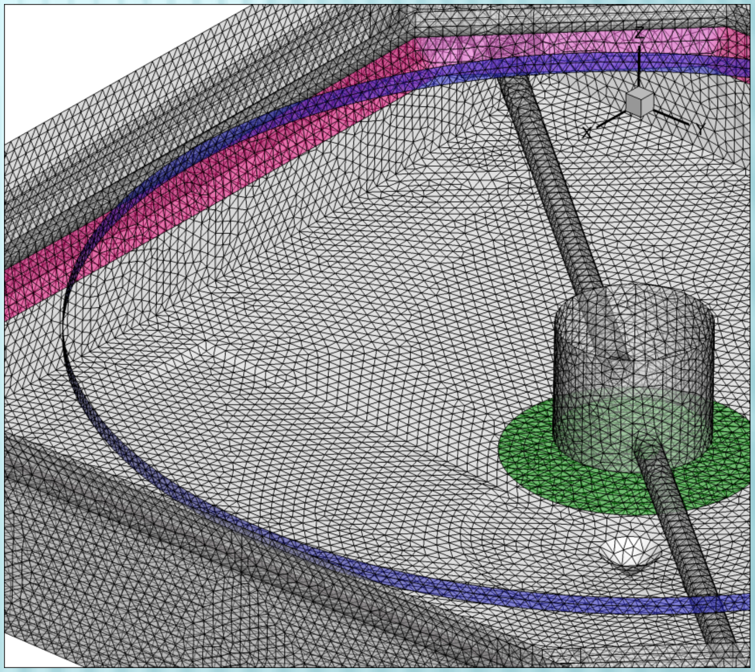


AVERAGE CONCENTRATION OF THE EFFLUENT LEAVING THE SYSTEM

POSSIBLE SOLUTION SCENARIOS

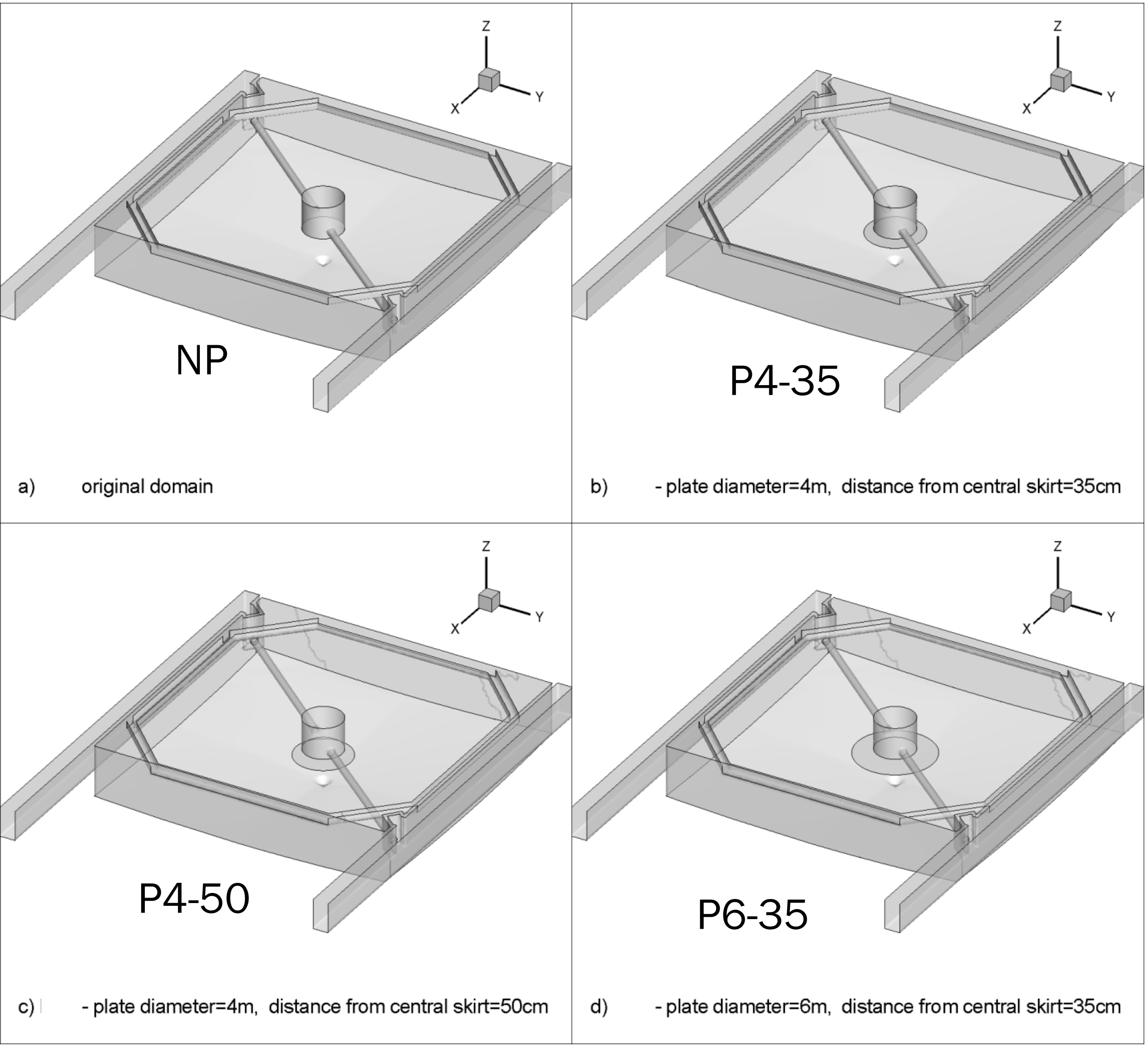
- Locate a round plate to spread the flow laterally and away for the sludge hopper (Solution Scenario 4)

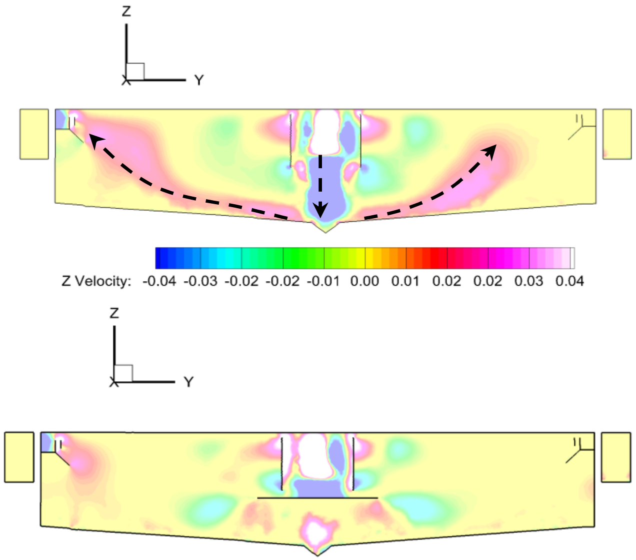


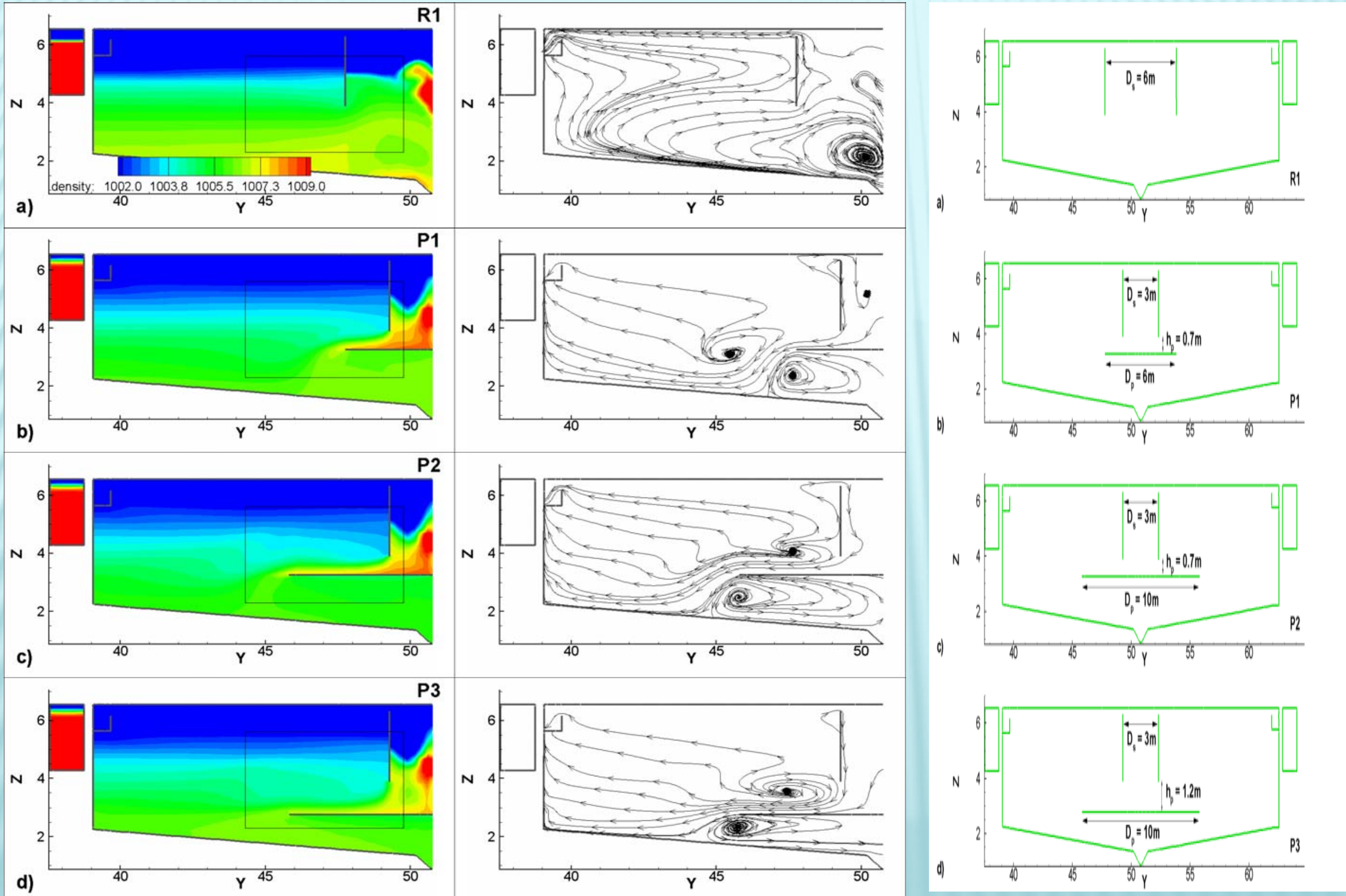


Particles clump at the center of the tank bottom when a plate is placed under influent well.

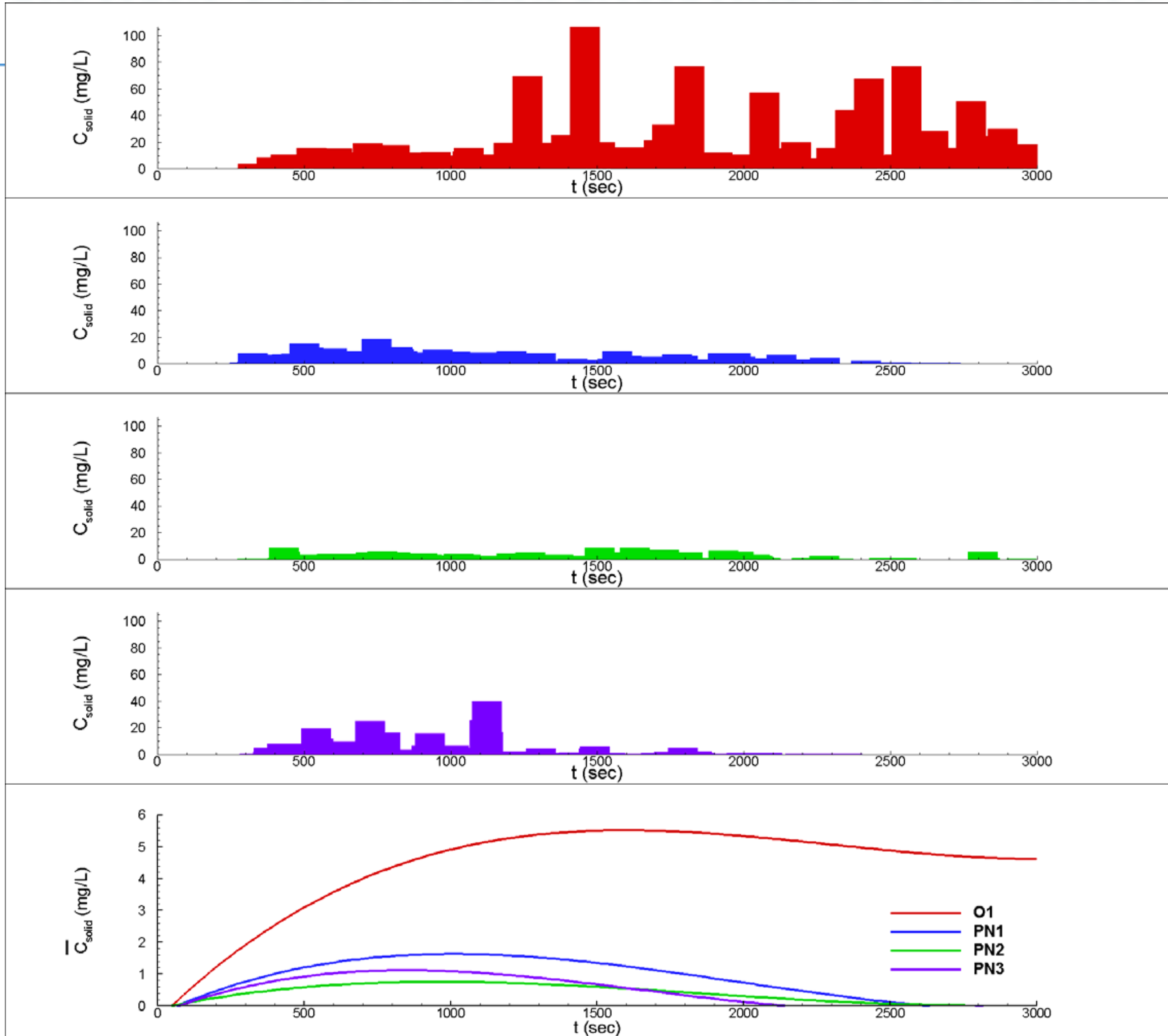
SIMULATION DOMAINS WITH AND WITHOUT PLATES





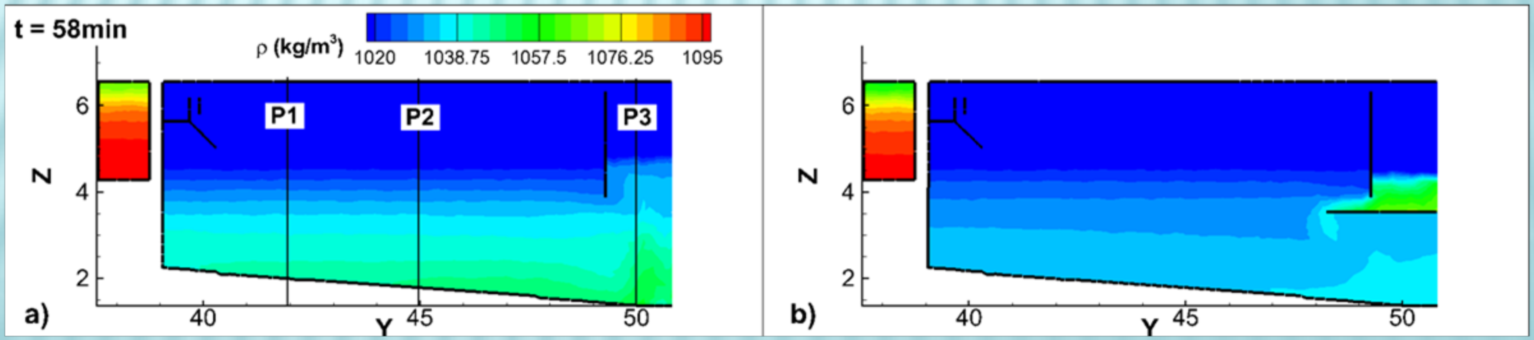

R1
P1
P2
P3
a)
b)
c)
d)
Z
Y
N
density: 1002.0 1003.8 1005.5 1007.3 1009.0
D_s = 6m
D_s = 3m
h_p = 0.7m
D_p = 6m
D_p = 10m
h_p = 1.2m

AVERAGE SOLID CONCENTRATION AT THE OUTLET



CONCLUSIONS AND RECOMMENDATIONS

- Installation of a plate under the influent well is an economical alteration of the final settling tanks.
  - This alteration will direct flow to lateral walls of the tank
  - This will greatly reduce disturbance of already settled particles near the sludge hopper at the tank bottom, allowing for more efficient solids collection in the hopper
  - The solids concentrations in the effluent will be considerably reduced
- Based on simulation results, a plate with diameter of 5m placed about 35cm below the influent well is recommended.



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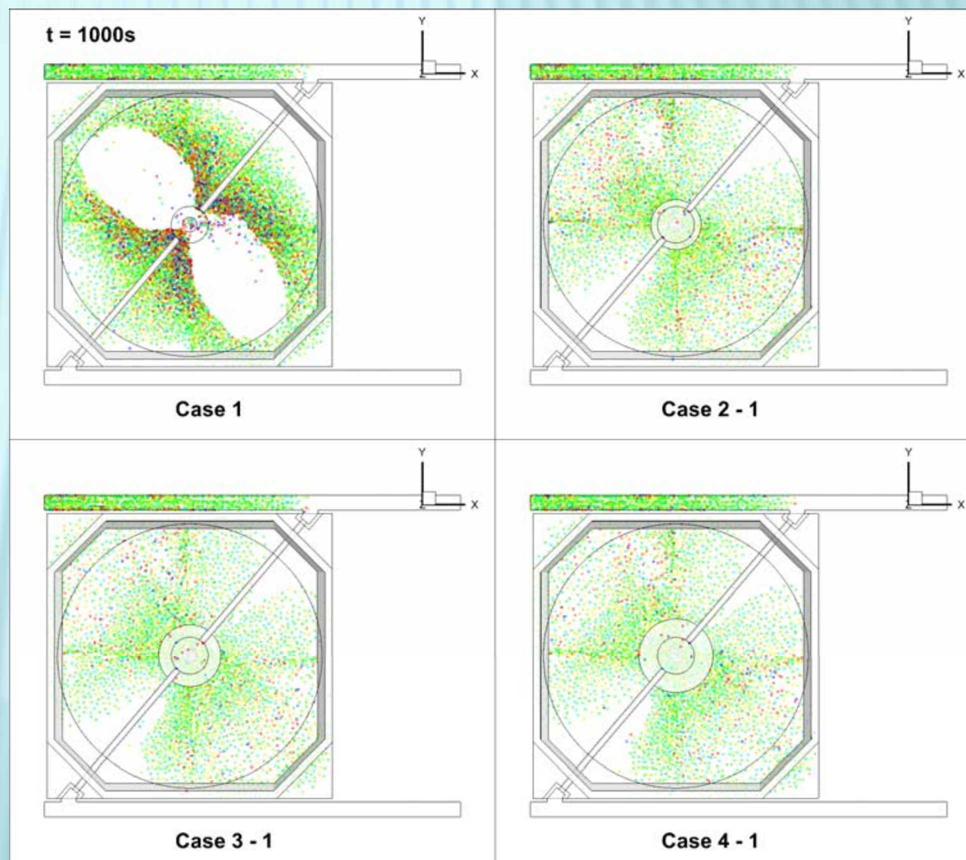
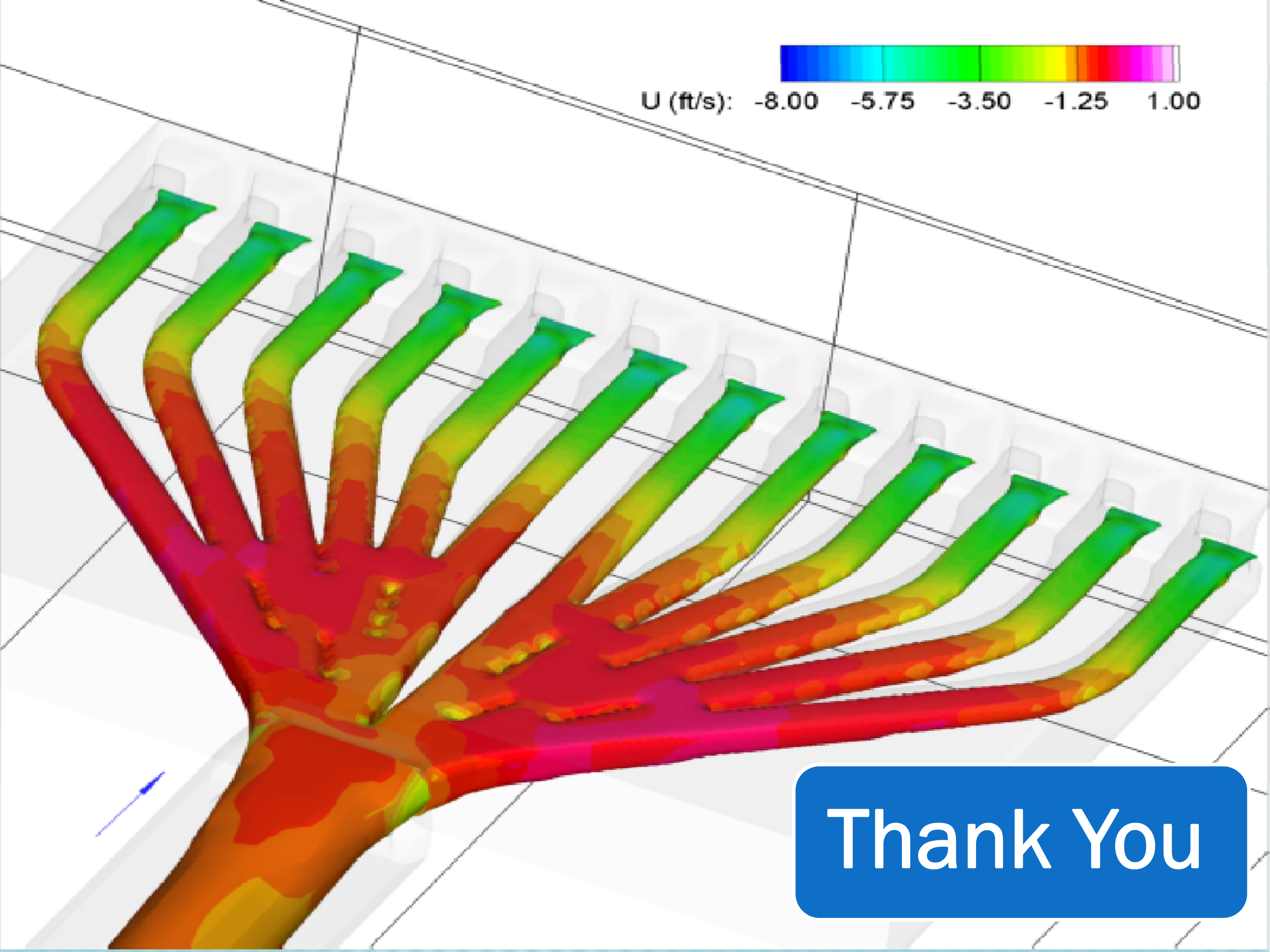
Protecting Our Water Environment
Metropolitan Water Reclamation District of Greater Chicago





Thank You