

# CFD Analysis of Grand River and Bubble-Line Design

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## ABSTRACT

The 2014 USRowing Masters National Championships was held from August 14-17, 2014 in Grand Rapids, Michigan. The West Michigan Sports Commission and Grand Rapids Rowing Association hosted the event for the first time. The event was held in a section of Grand River, near the Comstock Riverside Park, in Grand Rapids, Michigan.

Since the event was being held in the section of the Grand River which was curved and varying in its width throughout, Grand Rapids Rowing Association wanted to determine if this impacted the flow of the river throughout its width and whether this would give an added advantage to any of the teams. This paper discusses the Computational Fluid Dynamics (CFD) study performed on the section of Grand River where the US Rowing Masters National Championship took place along with the design of bubble-line at the finish line.

The CFD analysis of the section of the Grand River where the US Rowing Masters National Championship took place confirmed that the curved nature of the river does not affect the flow considerably to give an added advantage to any of the participating teams. Also, design suggestions for the bubble-line at the finish of the race are being discussed in this report.

**Keywords:** Computational Fluid Dynamics, River Flow Analysis, Bubble-Line

## INTRODUCTION

Traditional modelling in engineering is heavily based on empirical or semi-empirical models. These models often work very well for well-known unit operations, but are not reliable for new process conditions. The development of new equipment and processes is dependent on the experience of experts, and scaling up from laboratory to full scale is very time-consuming and difficult. New design equations and new parameters in existing models must be determined when changing the equipment or the process conditions outside the validated experimental database. A new trend is that engineers are increasingly using computational fluid dynamics (CFD) to analyze flow and performance in the design of new equipment and processes. CFD allows a detailed

analysis of the flow combined with mass and heat transfer. Modern CFD tools can also simulate transport of chemical species, chemical reactions, combustion, evaporation, condensation and crystallization [1].

The scope of this project is to perform CFD simulation on the section of the Grand River where the 2014 US Nationals Rowing Competition was going to take place and to predict the flow of the river across its varying width and to investigate if the flow would give an added advantage to any of the teams participating in the competition. Image below shows where the competition was to be held in Grand River near Comstock Riverside Park in Grand Rapids, MI.



Figure 1. Section of Grand River where the competition was held.

### Numerical Model of Grand River

The first step towards performing a CFD simulation on the Grand River was to obtain an accurate Numerical CAD data. This was performed by taking a screen shot from Bing Maps of the section of Grand River near the Comstock Riverside Park in Grand Rapids where the event was going to place.

The next step was to import the above image into Unigraphics NX 7.5 (UG NX 7.5) software (see Figure 2) and obtain an accurate top profile of the Grand River. After the image was imported into Unigraphics NX 7.5 CAD software, a yellow straight line was built just above the 100m distance legend present on the map. This yellow line now represented 100m. This line was copied and a yellow vertical line representing 1000m (or 1 KM) was constructed over the river. After locating where the finish line was, the 1000m yellow line was relocated to end at the finish line on the river and that led us to the start of the competition on the Grand River. Green colored horizontal lines representing the start, middle and finish and two sections – one between start and middle and other between the middle and finish of the 1000m event length of the river were

constructed. These green horizontal lines were stretched across the varying width of the river at their respective locations. The location of the Green horizontal lines was also based on the Grand River Map (Figure 3) provided by Grand Rapids Rowing Association, since it contained information about the number of lanes and their location on the Grand River. All the Green lines were measured in inches and were converted into meters by the formula:

$$1 \text{ meter} = 39.37 \text{ inches}$$



Figure 2. Grand River image imported into UG NX 7.5  
(All dimensions are in inches)



Figure 3. Grand River Map provided by Grand Rapids Rowing Association  
(Dimensions are in feet)

Based on the green lines as shown in Figure 2 and the process described above, the top profile of the Grand River was constructed as shown in Figure 4.

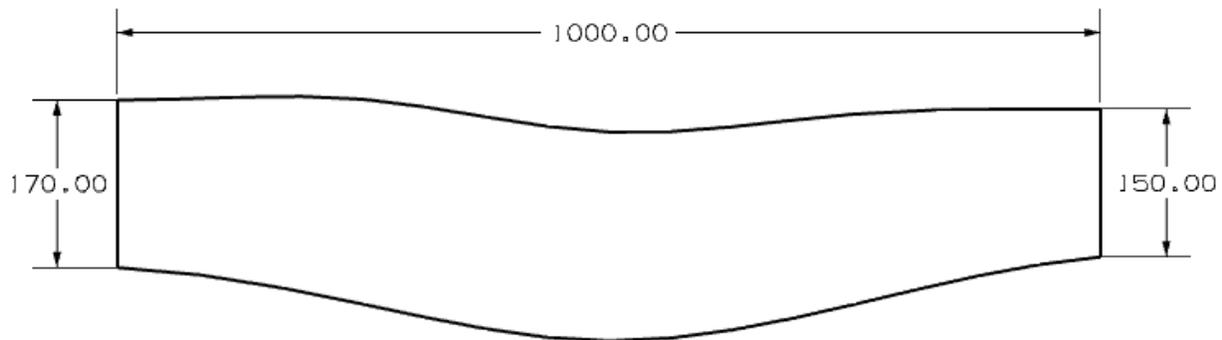


Figure 4. Top profile of the Grand River (Dimensions are in meters)

Once the top profile of the Grand River was completed, next step was to obtain the depth of the river at various locations - across the starting line of the competition, 250m from the starting line, 500m from the starting line (also the widest section of the river), 750m from the starting line and at finish line (or 1000m from the starting line). It was decided that the depth would be measured along 5 points at each of the locations mentioned above.



Figure 5. Measuring Grand River Depth at various locations

Once the Grand River depths were measured at various locations, a 3-Dimensional parametric CAD model was created in UG NX 7.5 CAD software, with the help of sketches, splines and bridge curves. Figure 6 shows the 3D wireframe CAD model of the Grand River.

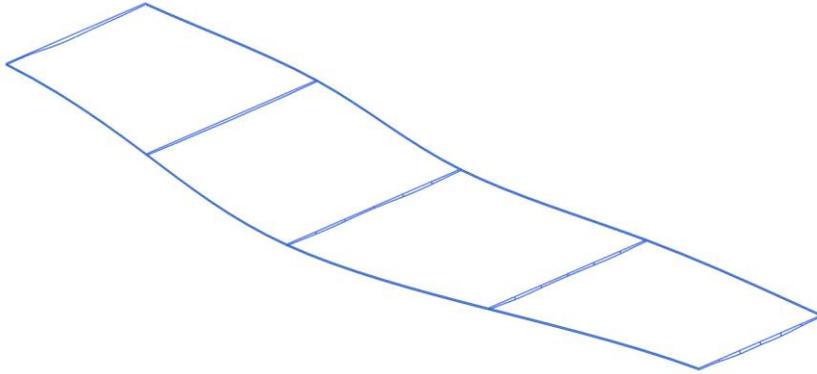


Figure 6. 3D wireframe CAD model of the Grand River

After completing the 3D wireframe CAD model, a solid geometry was created with the help of commands such as Extrude and Through Curves. Through Curves command was used to create the bottom complex surface of the river. The surface generated by Through Curves was used to Trim the bottom of the Grand River CAD data. Once the bottom surface of the section of the Grand River was generated (Figure 7) and the Grand River CAD data was exported as a parasolid (.x\_t) file out of UG NX 7.5 and was imported into Star CCM+ software for CFD analysis. Figure 9 shows the varying depths of Grand River in CAD at various locations.

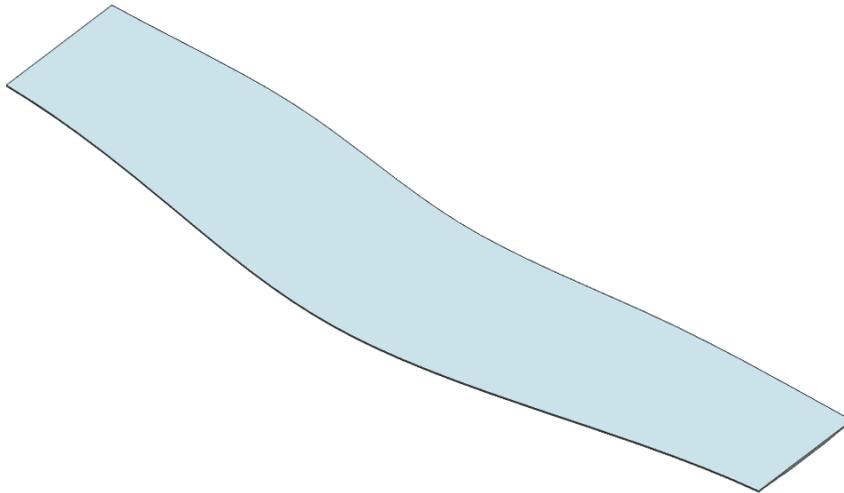


Figure 7. 3D solid CAD model of the Grand River

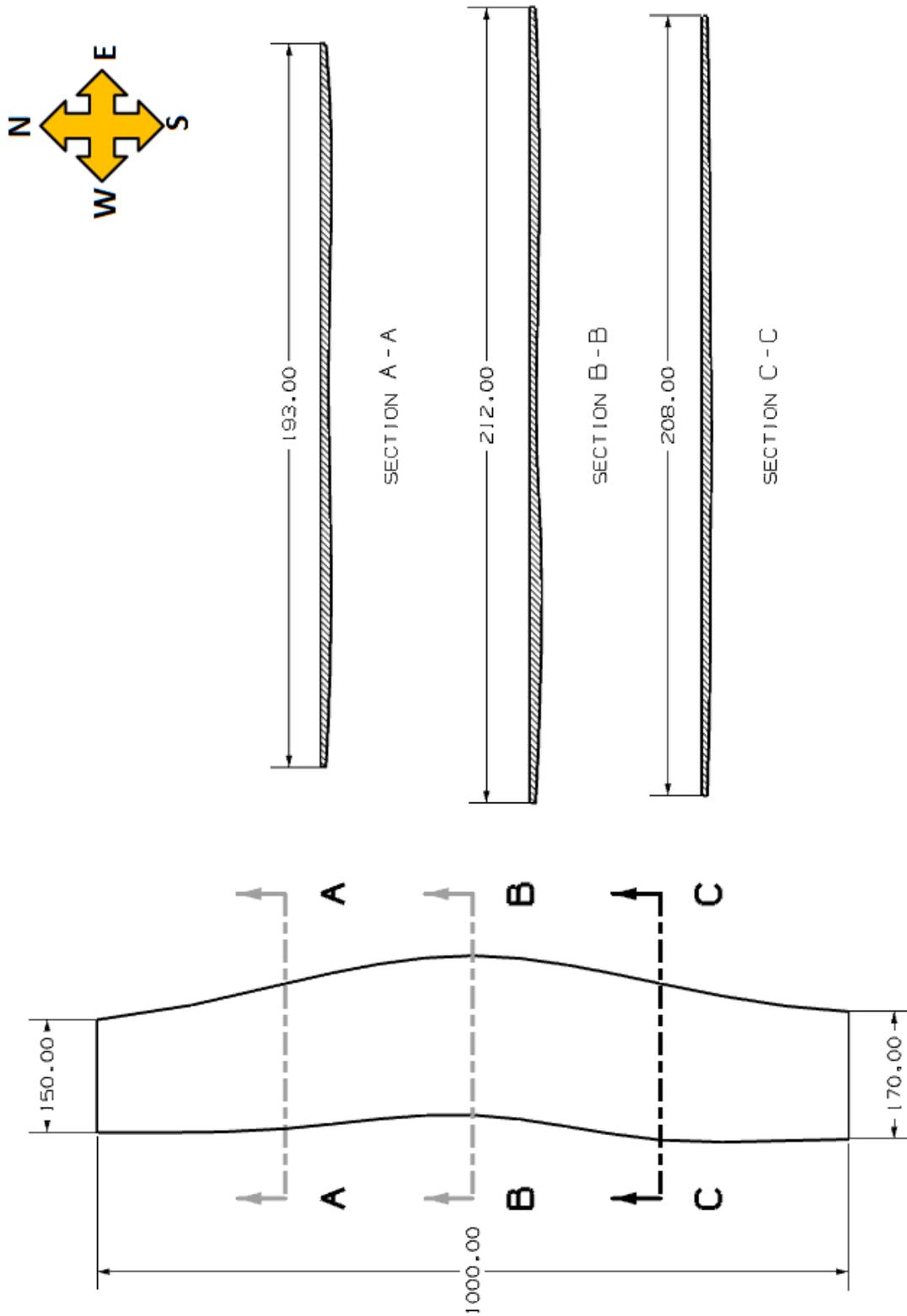


Figure 8. Depths of Grand River at various locations as modeled in CAD software.(Dimensions are in meters)

## DATA GATHERING

First part of the CFD analysis involved gathering data related to flow and depth of the Grand River. This was done via United States Geological Survey (USGS) website [www.waterdata.usgs.gov](http://www.waterdata.usgs.gov)

USGS has a monitoring station in Grand River, Grand Rapids (site # 04119000) as shown in Figure 9. Data ranging from discharge to gage height can be obtained via USGS website. Data for discharge (in cubic feet per seconds) and gage height (in feet) was obtained via USGS website for the months of July and August 2014 [2]. The data is summarized in the Graphs 1 & 2.

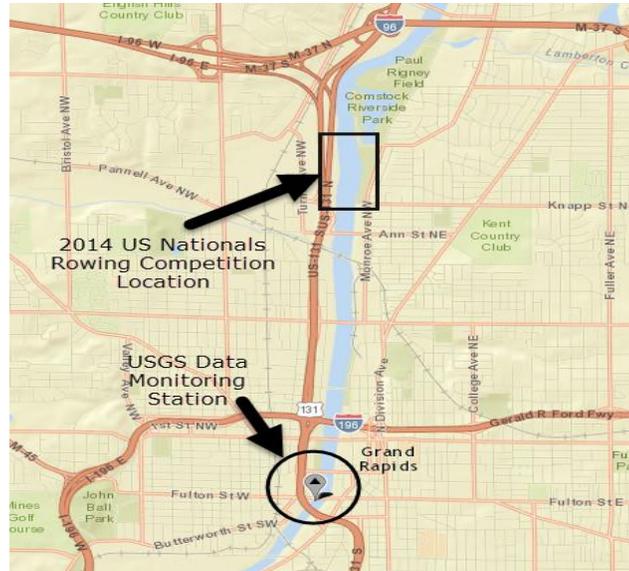
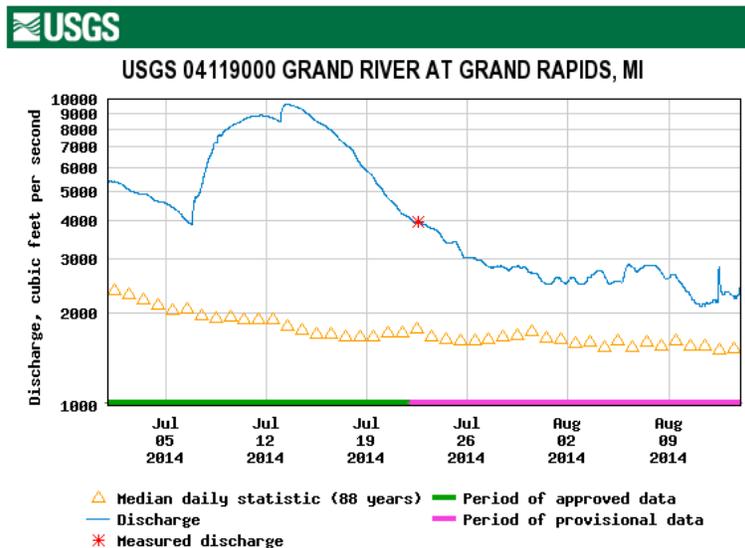
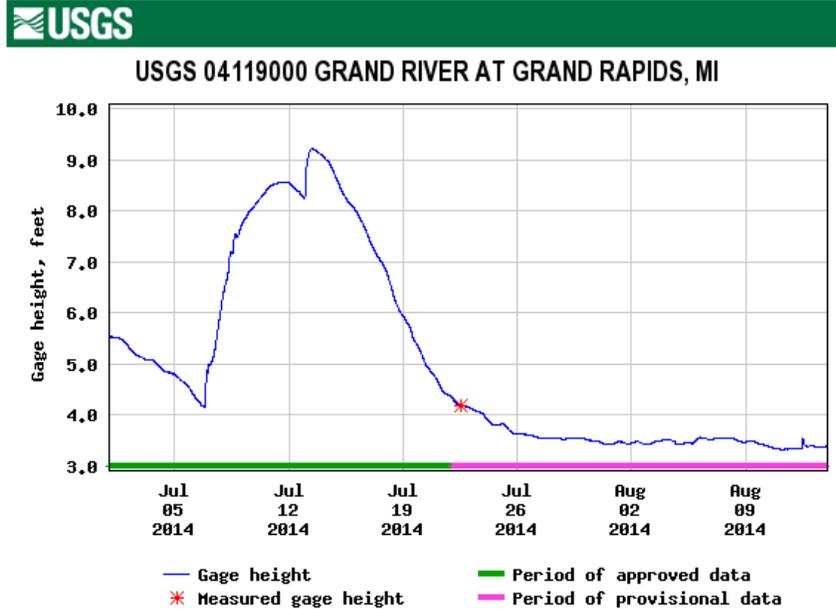


Figure 9. USGS Data Monitoring Station in Grand Rapids [m.waterdata.usgs.gov] [3]



Graph 1. Grand River Discharge Data for July-August 2014

[[http://waterdata.usgs.gov/mi/nwis/uv?site\\_no=04119000](http://waterdata.usgs.gov/mi/nwis/uv?site_no=04119000)] [4]



Graph 2. Grand River Gage Height Data for July-August 2014  
[\[http://waterdata.usgs.gov/mi/nwis/uv?site\\_no=04119000\]](http://waterdata.usgs.gov/mi/nwis/uv?site_no=04119000) [4]

Based on the Discharge data obtained from USGS website, an average discharge of 5000 cubic feet per second (cfs) was selected to perform the CFD analysis.

Now, 1 cfs = 28.32 liters of water per second or kg per second.

Therefore, 5000 cfs = 5000\*28.32 kg/s of water

5000 cfs = **141600** kg/s of water

In order to obtain a decent and a good representation of the river flow simulation, the discharge was selected as 5000 cfm (2360 kg/s) instead of 5000 cfs (141600 kg/s).

### CFD ANALYSIS

Next part involved importing the parasolid file of the Grand River into Star CCM+ software and assigning names to all the surfaces of the Grand River, as shown below

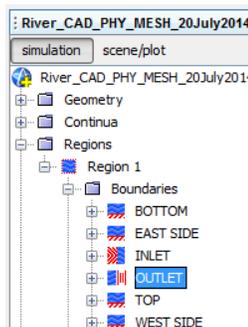


Figure 10. Names assigned to different surfaces of Grand River

Mass Flow inlet was selected as an inlet parameter, with an Mass Flow Rate of 2360 kg/minute. Outlet was selected as Pressure Outlet. Bottom and two side surfaces were selected as Walls and the Top surface was selected as Wall but with “Slip” condition, so that the fluid does not include effects of friction on the Top Surface of the Grand River.

Once the Regions were defined, **Physics Continua** was selected as below:

Physics Model:

1. Water (IAPWS-IF97) was selected as the fluid
2. K-Epsilon Turbulence model was selected
3. H2O was selected as the liquid
4. Reynolds –Averaged Navier-Stokes equation was used
5. Segregated Flow was selected
6. Steady State
7. Three Dimensional
8. Turbulent Flow

Once Physics Continua was defined, **Mesh Continua** was defined as below:

Mesh Model:

1. Prism Layer Mesher
2. Surface Remesher
3. Trimmer

The mesh model and reference values used for the simulations in this study are shown in Table 1.

Table 1. Mesh Model Settings

<b>Mesh Settings</b>	<b>Absolute Value</b>
Base Size	10.0m
# of Prism Layers	10.0m
Prism Layer Stretching	1.1
Prism Layer Thickness	3.0 inches
Surface Curvature	100
Surface Growth Rate	1.3

Surface Size	
Rel Min Size	0.5m
Rel Target Size	10.0m
Template Growth Rate	
Default Growth Rate	Fast
Boundary Growth Rate	Medium

The Surface Mesh of the Grand River is shown in Figure 11, while the Volume Mesh is shown in Figure 12. The number of cells in the Volume Mesh for Grand River was 4,155,216.

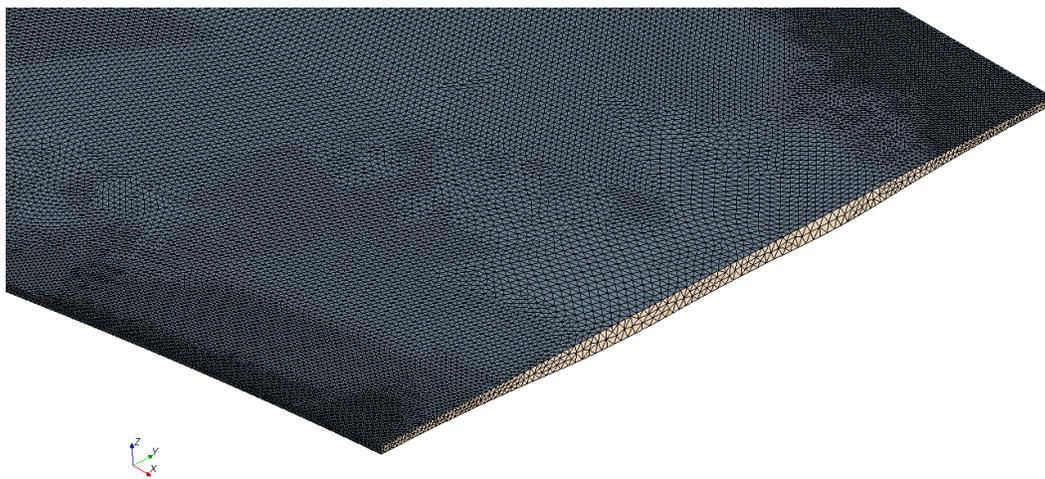


Figure 11. Surface Mesh of Grand River at Inlet

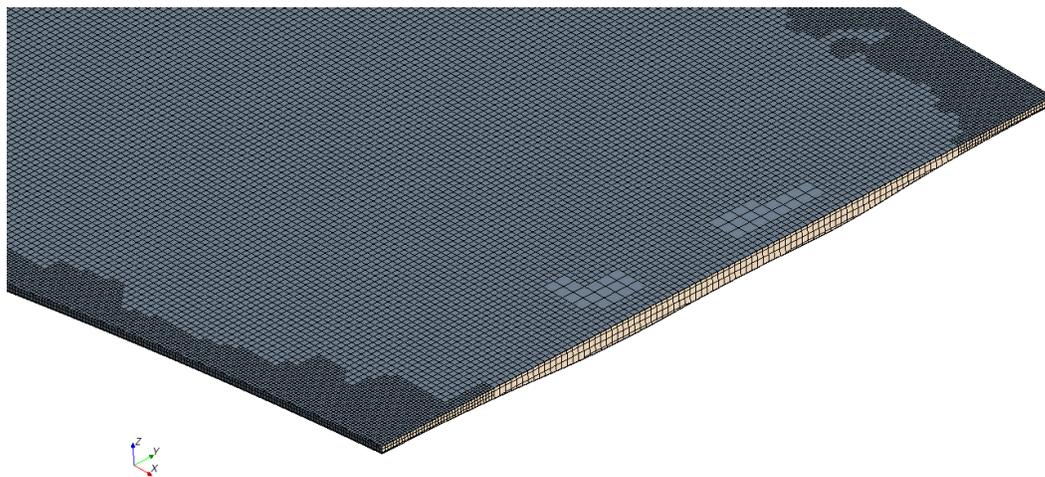


Figure 12. Volume Mesh of Grand River at Inlet

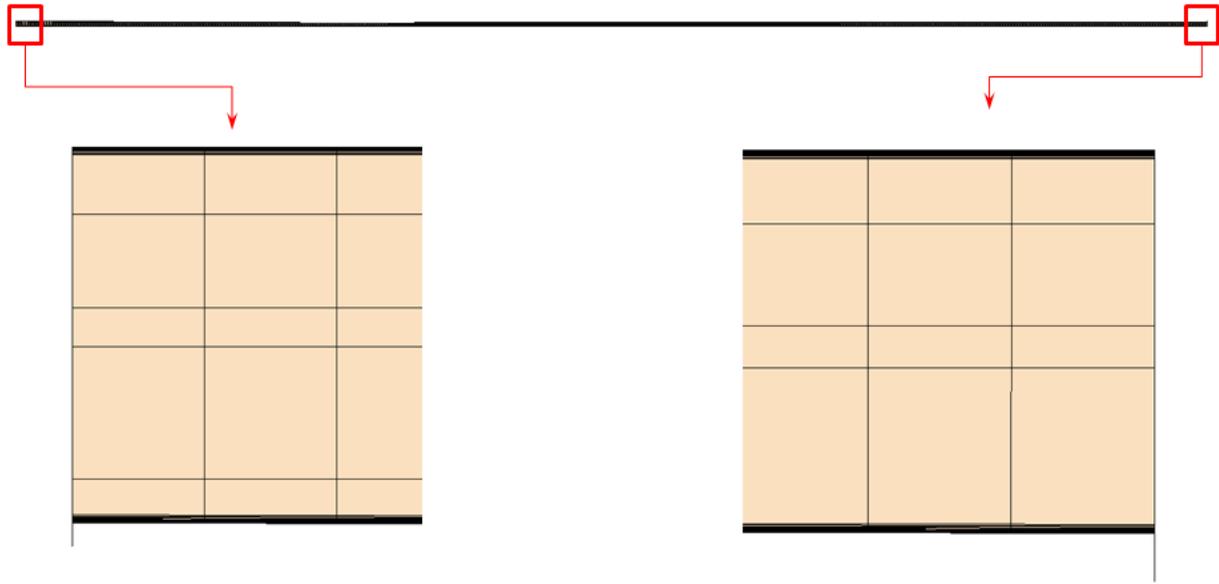
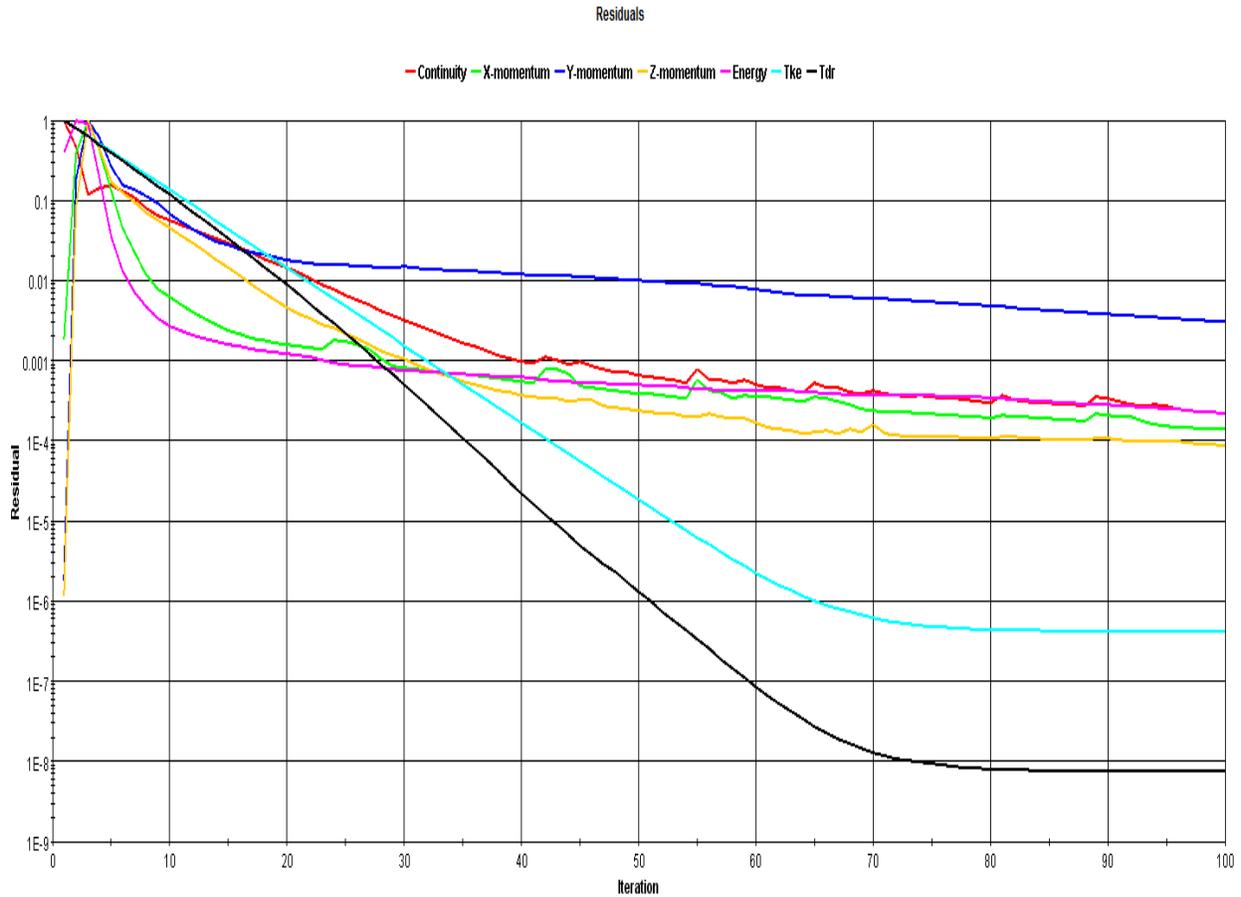


Figure 13. Cross-Sectional View of Volume Mesh of Grand River



Figure 14. Direction of flow across Grand River

The CFD simulation of flow through Grand River was the performed with inlet mass flow rate of 141600 kg/s. The resulting residual plot is shown in Figure 16.



Graph 3. Residual Plot of Flow across Grand River

Above graph shows that the residuals (errors) continued to reduce throughout the analysis and converged to a very less value by the time iterations reached 75 and were steady by the time 100<sup>th</sup> iteration was reached. Since the residuals were almost steady from 75<sup>th</sup> iteration till 100<sup>th</sup> iteration, it was concluded that the analysis has converged by the time 100<sup>th</sup> iteration was completed. Hence, analysis was stopped at 100<sup>th</sup> iteration.

## Post Processing

### 1. Pressure Contour – Grand River

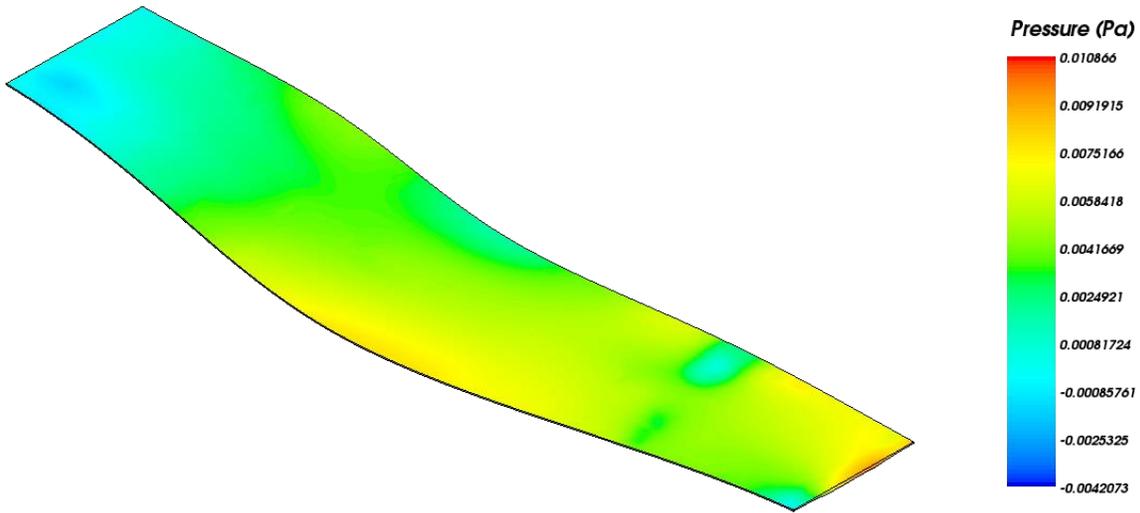


Figure 15. Pressure Contour on top surface of the Grand River

Figure 15 shows that the pressure distribution across the Grand River is almost uniform. It can be seen that the pressure distribution throughout the section of Grand River does not vary much.

### 2. Velocity Contour – Grand River

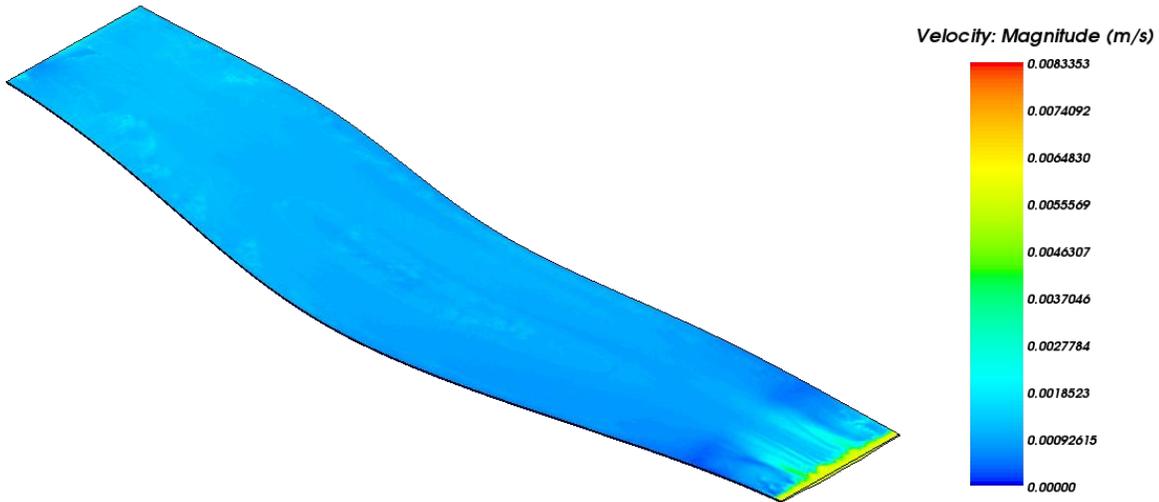


Figure 16. Velocity Contour on top surface of Grand River

Figure 16 shows that the Velocity profile on the top surface of the Grand River is almost uniform, and flow across the Grand River does not seem to differ too much, regardless of the depth or profile of the Grand River.

### 3. Velocity Vector Contour – Grand River

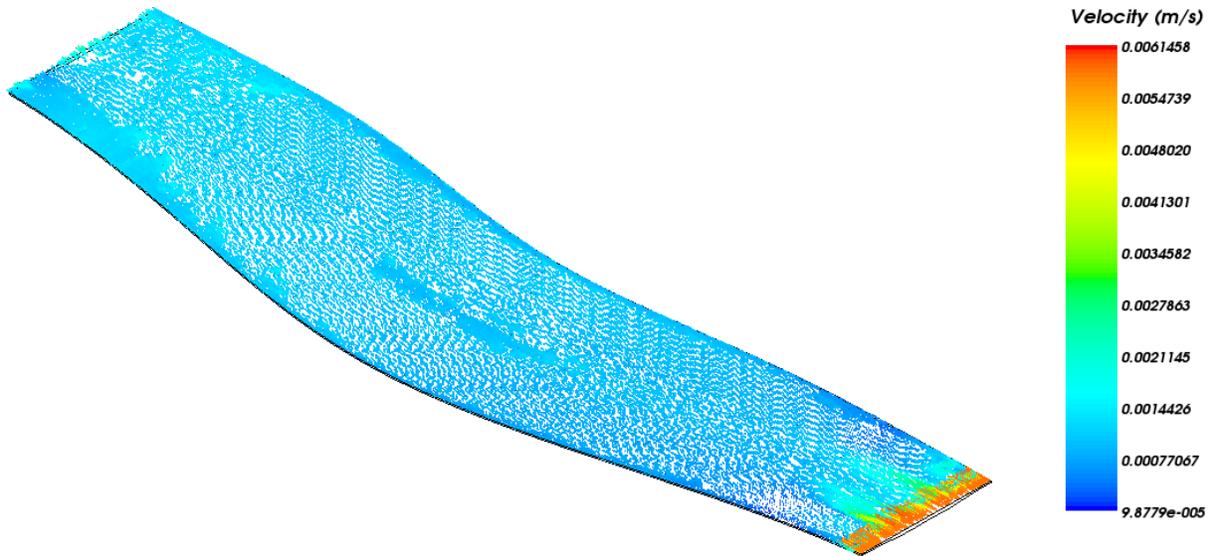


Figure 17. VelocityVector Contour on top surface of Grand River

Figure 17 shows that the Velocity Vector profile on the top surface of the Grand River is almost uniform, and flow across the Grand River does not seem to differ too much, regardless of the depth or profile of the Grand River and there does not seem to be any reverse flow.

### 4. Streamlines across Grand River

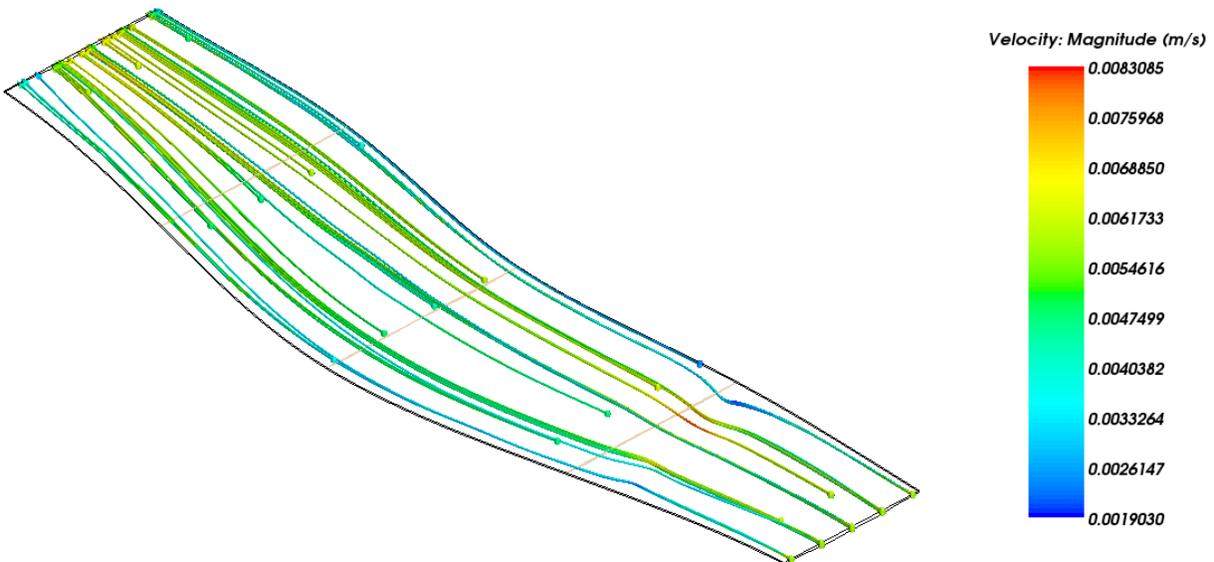
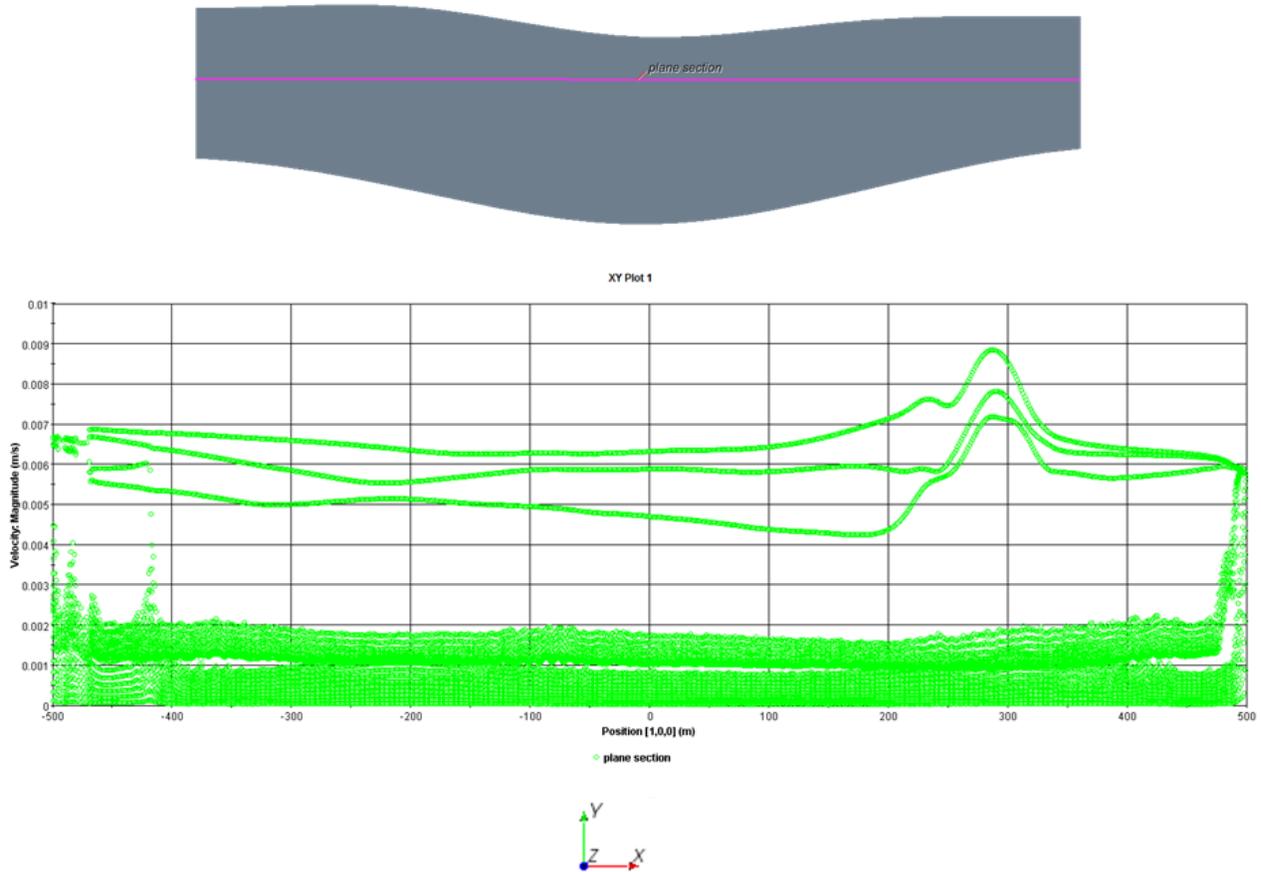


Figure 18. Streamlines across Grand River

Figure 18 shows Streamlines across the Grand River. CFD analysis simulation predicts that the flow across the Grand River is more or less uniform, with little variations in flow rate across the river.

## Velocity Plots

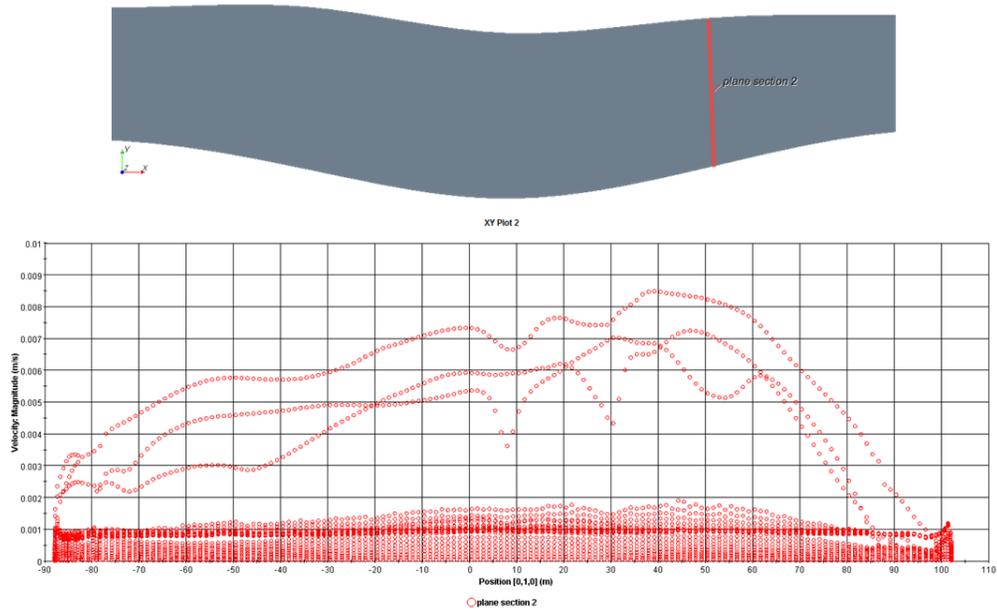
### 1. Across the Grand River



Graph 4. Velocity Plot across the Grand River in 'x' direction

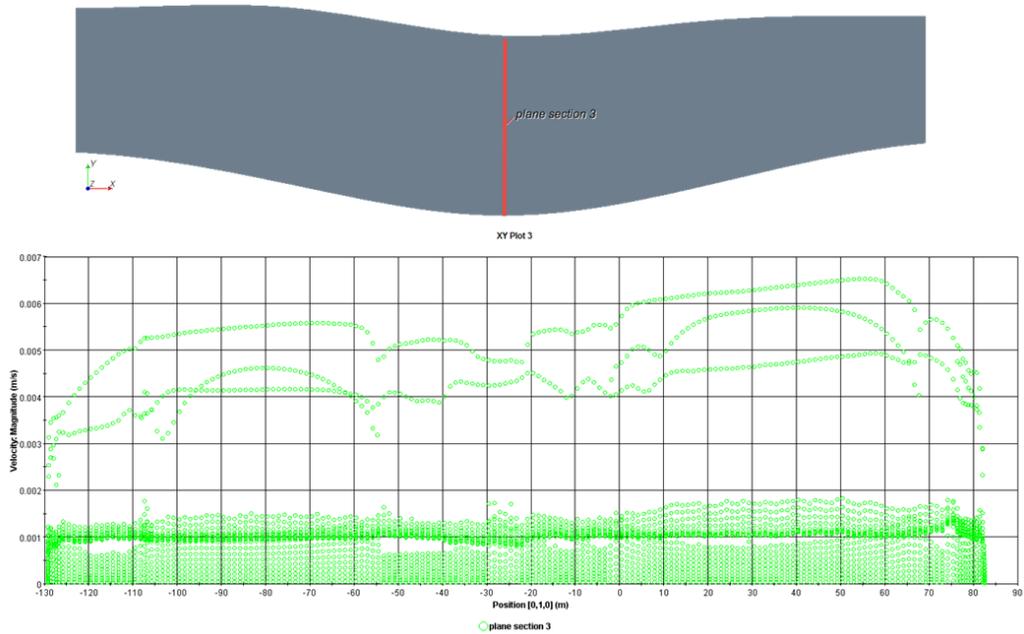
Graph 4 shows that the velocity profile across the length is fairly uniform and constant, except around 250 m from the start line. However, the velocity spike at 250m from the start line isn't so drastic as to make any significant impact.

## 2. At Section A-A



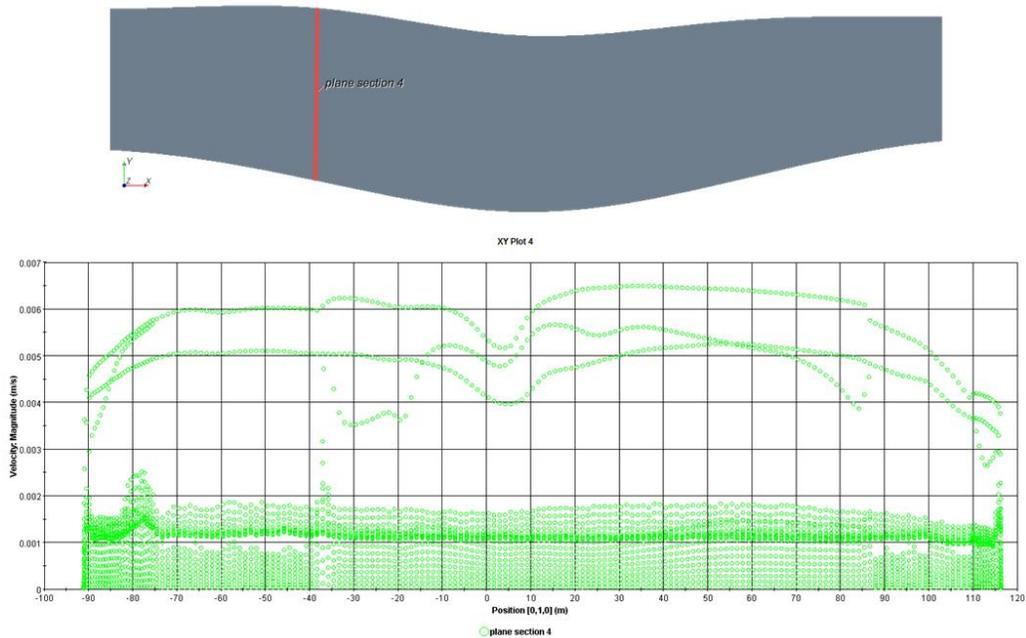
Graph 5. Velocity Plot across section A-A in Grand River in 'y' direction

## 3. At Section B-B



Graph 6. Velocity Plot across section B-B in Grand River in 'y' direction

#### 4. At Section C-C



Graph 7. Velocity Plot across section C-C in Grand River in 'y' direction

Graphs 5, 6 and 7, show velocity profiles at various locations across the width of Grand River, It can be seen that the velocities across the width of the river do not fluctuate considerably as to make an y considerable impact.

#### Bubble-Line Design

The bubble line marks the finish line on the water by creating a well-defined and regular straight line of air bubbles across the width of the course. This is a very effective visual aid for the crews finishing their race, for the spectators and for television broadcast.

The bubble line was first introduced into rowing competitions at Eton Dorney for the London Olympic Games and Paralympic Games in the year 2012.

#### Bubble Line Functional Requirements [5]

The bubble line must:

1. Meet International Federation requirements for Rowing and Canoe Sprint.
2. Provide a continuous line of regular air bubbles on the surface of the water and across the width of the course.
3. Be set at 800mm past the finish line.
4. Be operational for all the races during the events.

The bubble line must account for the following:

1. Air should be pumped into a straight and rigid pipe from a compressor.
2. The pipe must be laid across the course at the same depth as the Albano cables (resting on the top of the cables).
3. The total width of the six (6) Rowing lanes is 81 meters.
4. The pipe must have a series of holes to release the bubbles which will appear on the surface of the water.
5. It is recommended the pipe have a diameter of between 40-50mm.
6. The pipe could be metal or poly-irrigation pipe.
7. Holes must be drilled in the hose at 20-30 cm intervals. It is recommended the holes be 1mm-3mm in diameter.
8. The pipe is attached to a rope (diameter 8mm) by means of a cable connection at 20 cm intervals.
9. The whole apparatus should be fastened to each bank of the course and also to anchors on the bottom of the lake, to prevent the line from rising. It is recommended the anchors are 600kg, at intervals of about 27m. It is recommended the tightening and installation of the system should be carried out in steps.
10. The finish line hose is filled with air by a compressor (capacity 7-9m<sup>3</sup>/min). The pressure is a minimum of 4-6 bars (60-90psi).
11. The location and size of the generator for the compressed air has to be considered carefully to ensure it does not impact a busy operational area around the finish line, in full view of broadcast and spectators.
12. The generator for the compressed air should be silent. It is recommended the compressor is driven by an electrical motor to avoid noise and smell problems.
13. The compressor should be capable of being switched on and off between races to ensure the finish line is clear of rough waves.
14. The pressure in the pipe must be adjustable to enable the pressure to be increased or decreased as required.
15. The bubble line installation should not obstruct the set-up of the Albano cabling system during the lane transition from Rowing to Canoe Sprint.
16. Bubble line should be installed and tested prior to the Rowing event.

### **Bubble Line Design Phase**

Research was done on various types of hoses available with different diameters. The most easily available hose, in different diameters was made out of Polyvinylchloride (PVC). Hence, a decision was made to proceed with PVC schedule 40 as the material for creating the setup for bubble line.

PVC pipe with 10 feet length and five different diameters – 1.00, 1.25, 1.50, 1.75 and 2.00 inches each were procured. Next step was to evaluate which ID PVC pipe would be ideal for bubble line. The purpose of the experiment is to determine the pipe diameter and hole spacing that

will produce the highest-quality bubble line. The experiment consisted of running pressurized shop air into a capped, submerged PVC pipe with several 0.094 in (~2.39 mm) holes drilled along its length. The tests will be performed in water at a depth of 1ft (0.3048 m). To cap one end of PVC tube, it was first cleaned with PVC cleaner solution and then a PVC primer was applied to both PVC tube and cap. PVC cement was applied on both the tube and cap, once the primer dried. Then the cap was pressed onto the PVC pipe. Other end of the PVC pipe was connected to shop air via a series step-up fittings, as shown below.



Figure 19. Various Step-up fitting for PVC pipes



Figure 20. Various PVC pipes with Cap at one end and threaded fitting at the other end and with drilled holes.

Once the PVC pipes were capped at one end and a threaded fitting attached to the other, it was time to drill holes with a drill bit of 0.094 inches diameter. Holes were drilled on all the tube sizes with 15 cm, 20 cm and 30 cm apart. Once the holes were drilled, the tubes were connected to the

shop air and submerged 1ft deep inside the drag tank in the fluids lab in Grand Valley State University. Once the 1 inch ID tube was submerged, the ball valve attached to the shop air was slowly released and the performance of bubbles coming out from the tube was recorded. Similar exercise was performed for all the available tube sizes and it was observed that the 1.5inch ID PVC pipe gave the best result, with holes being 20cm apart.



Figure 21. Side view of the bubbles being generated inside the drag tank in GVSU.



Figure 22. Top view of the bubbles being generated inside the drag tank in GVSU.

Now, since a PVC pipe with ID of 1.5 inch was selected, it was time to search for an effective means of connecting various PVC pipes. A 1.5inch diameter PVC schedule 40 Union was selected for this purpose. The key features of the Union were that it was rated for up to 150 PSI at 73 degrees Fahrenheit.



Figure 23. 1.5 inch ID Schedule 40 PVC Union

Once the Union was selected it was time to create the bubble line pipeline that was 100 meters long. The bubble line had to be longer than the width of the rowing competition, which was 81 meters. Hence a length of 100 meters was selected.

$$\begin{aligned} \text{Since, } 1\text{ft} &= 0.3048\text{m,} \\ 100\text{ m} &= 328.08\text{ft} \approx 330\text{ ft} \end{aligned}$$

Hence, 33 numbers of 10ft 1.5inch ID PVC schedule pipe were procured, along with a threaded fitting, one end cap and 32 Unions. PVC cleaner, primer and cement was also purchased. 0.094inch hole was drilled on all the 1.5 inch PVC pipes at 20 cm apart and the ends were primed, cement was applied and the pipes were connected with the Unions. First PVC pipe on one end had the threaded fitting, to which the step-up connectors were to be connected. Last PVC pipe was capped at the open end.

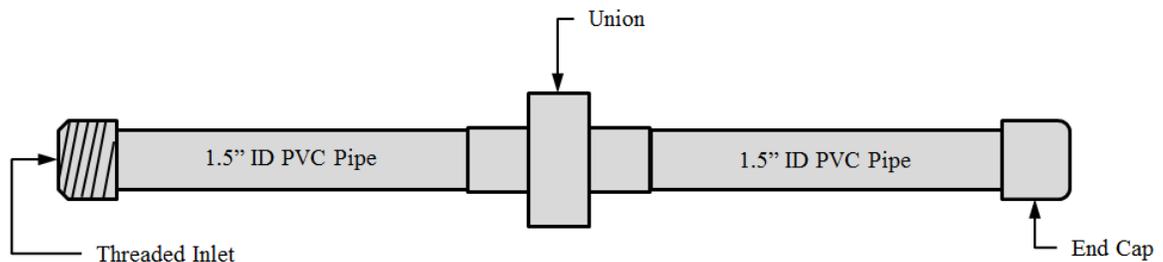


Figure 24. A schematic representation of the pipeline for bubble-line.

Once the pipeline for Bubble Line was complete, it was decided that it will be constrained every 25m while it would be inside the water, connected to the Albano Lines. 1.75inch

ID hose clamps were to be installed over the pipeline, 25m apart throughout its length of 100m. Some means of attaching the pipe line to anchors at every 25m was to be designed.

## **Conclusion**

After reviewing the CFD analysis simulation results of Grand River based on the numerical model, it can be concluded that the flow across the Grand River, in the section selected for the 2104 US National Rowing Competition is almost uniform. The contour or profile of the Grand River does not seem to affect the flow as indicated by various velocity plots at different sections across the Grand River. Rowing teams in any of the lanes will not have any added advantage over other teams.

A design solution for bubble-line across the width of the river was proposed, and a small section of the proposed design was tested for design validation. Based on the results of the design validation, a 100m long pipeline that can be used to generate bubble-line for rowing completion has been created using 1.5 inch schedule 40 PVC pipe, which are rated to withstand pressures up to 330 psi. This setup can be used to generate the bubble-line across the width of the river for the Rowing competition.

## **Acknowledgments**

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3. USGS Mobile Waterdata, [www.m.waterdata.usgs.gov](http://www.m.waterdata.usgs.gov), Site # 04119000, Grand River at Grand Rapids, MI
4. USGS Waterdata , [http://waterdata.usgs.gov/mi/nwis/uv?site\\_no=04119000](http://waterdata.usgs.gov/mi/nwis/uv?site_no=04119000)
5. Provided by Grand Rapids Rowing Association, <http://www.growing.org/>.