Fish Behavior With Respect to Engineered Log Jams: Log Jam Hydraulics

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ABSTRACT

Recent research has shown that large wood has a significant role in determining river processes (Montgomery et al., 2003). For this reason, it has become popularly used as structural components in river restoration projects. Wood jams are commonly used for bank stabilization, as well as a means for improving habitat complexity. Little research has been conducted about how fish utilize the habitats created by these log jams. The purpose of this manuscript is to present the findings of a study on the behavior of several species of fish with respect to Engineered Log Jams (ELJs). The focus of this subset of the study was to look specifically at the hydraulics around an ELJ. Detailed velocity data was collected around the study log jam and used to map velocity and shear stress throughout the water column, in addition to calculating the drag coefficient for the log jam.

INTRODUCTION

Log jams can have a large effect on the hydraulics and geomorphology of streams, creating habitat complexity for aquatic organisms (Collins et al., 2002). In the past, wood jams have naturally formed through the accumulation of wood, but since the intervention and alteration of natural flow regimes by humans, the amount of wood in streams has declined greatly (Collins et al., 2002). Human alteration has been indirect, through the logging of riparian areas, which decreases wood recruitment, and also direct effects, like the removal of wood from streams to increase navigability (Shields & Gippel, 1995). The river restoration movement has attempted to resolve this by creating buffer zones around streams that either limit logging or directly install wood in streams as wood jams. Log jams are introduced in streams to improve habitat richness or bank stability.

Engineered Log Jams (ELJs) increase habitat complexity by altering the fluvial processes and geomorphology of the streams they occupy. They affect the velocity and shear stress distributions in a stream and in turn, drag. Log jams "repartition" the flow, leading to flow separation and altering shear stress distributions (Manners et al. 2006). This creates pockets of higher shear, which lead to scour. This results in geomorphic complexity in the form of diverse bed forms like pools. Debris accumulations can also cause sediment deposition, which can lead to bed forms like riffles (Shields & Gippel, 1995), further adding to the geomorphic diversity of a channel. With regards to velocity, flow separation around the jam can lead to backwatering upstream and slower velocities downstream (Manners et al. 2006), enhancing complexity of fluvial processes. Both hydraulic and geomorphic complexity benefit fish species by creating areas of refuge for spawning, rest, and foraging. Detailed information known about the hydraulics adjacent to log jams could help improve understanding of why fish employ specific habitat regimes. Knowledge like this could have a strong impact on engineered log jam design, by revealing how to best optimize design to yield enriched stream habitat.

Though restoration practitioners realize the importance of wood in streams, little quantitative information is known about the effect of large wood on habitat or channel hydraulics (Shields & Gippel, 1995). The purpose of this overall study is to look both quantitatively and qualitatively at how fish exploit these complex habitat regimes. One component of the research was to study fish behavior around a log jam and made observations about their position and activities. Another component of the research included fine-tuned measurements of the hydraulics of a single log jam. Specifically, create maps of the velocity and shear stress, and perform a calculation of the drag coefficient. The goal of the study is to pair both segments of research to provide a detailed explanation of which areas of the flow fish are utilizing, why they are occupying these regions, and what they are doing.

SITE DESCRIPTION

The site employed for the study included two constructed artificial streams located at the Oregon Hatchery Research Center (OHRC). The OHRC is located West of Alsea, Oregon. The climate can best be described as mild temperate. The area experiences high levels of rainfall and snow through winter months. The study was conducted between the months of December and March. During this period, the water temperature remained within a few degrees of 10 degrees Celsius. The streambeds consisted of river cobble and were formed to mimic the bathymetry of natural streams. The flow was taken from Fall Creek, a stream adjacent to the OHRC. The flow was regulated by a pump, which ensured that it was uniform throughout the entire study period.

METHODS

Data Collection

Velocity Data:

The velocity measurements were taken with four SonTek MicroADV devices held on a truss across the cross-sectional length of the artificial stream (see Fig. 1 for diagram of instruments). The MicroADV measures flow in three coordinate directions (x, y, z) using "acoustic Doppler technology" (SonTek, 2008). The devices consist of three probes that measure the Doppler effect produced in the "acoustic signal reflected off of scattering particles in the flow" (Wahl, 2000) and are attached to a conditioning module (SonTek, 2008). Both of which are connected to a processing module. The processing module can be connected directly to a PC computer. The velocity data was collected at a sampling frequency of 16 MHz and a sampling rate of 0.1 to 50 Hz, using the program Horizon ADV. The resolution of the devices was 0.01 cm/s, while the programmed velocity range was programmed as 3, 10, 30, 100, or 250 cm/s (100 cm/s was commonly used). The measurements were taken 10 cm apart in the x-, y-, and z-directions in a grid pattern (see Fig. 2 in Appendices), where x is the cross-sectional direction, y is parallel to the flow, and z is vertical through the water column. These measurements were intended to capture the zone of influence of the log jam and because of this, have defined the size of the control volume for calculations. Each measurement was collected for a span of five minutes by the devices through the program HorizonADV. Post-processing of the data was done using the program WinADV, where it was filtered based on signal-to-noise ratio and "de-spiked"

(Wahl, 2000). After the data was processed, the summary data was imported into ArcGIS, as well as saved in Excel for analysis.
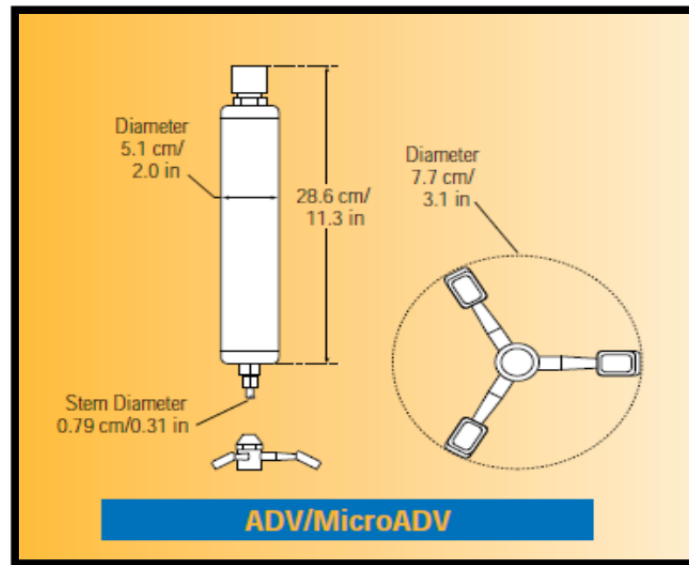
Topography Data:

Figure 1: Diagram of Sontek MicroADV devices.

Topography data was taken using a Canon Total Station surveying device. Points were surveyed along the bed of the artificial streams, in addition to on the banks (left and right edge of water) and top of the log jam (water surface elevation).

Pebble Counts:

Pebble counts were performed on-site using a gravel-o-meter.

Drag Coefficient Calculations

The method utilized to calculate the drag coefficients was momentum extraction, where the difference in momentum [between upstream and downstream of the log, as well as in the lateral direction] was set equal to the forces exerted on the control volume (i.e. drag, shear, pressure) (see Fig. 3). This force balance was conducted in the y-direction between two control surfaces (inflow and outflow) (see Eq. 1), in addition to a balance on the third surface (lateral flow) (see Eq. 2). Both drag forces (in the x- and y-directions) were used to find the resultant drag coefficient (see Eq. 3). The control volume, in addition to the reach length, was limited by the extent of velocity measurements taken. It does not extend across the channel, but is defined as the zone of influence of the Engineered Log Jam (ELJ), which is a commonly used definition (Manners et al., 2006). Velocity measurements were taken in a "grid" that was assumed to capture the total influence of the log (i.e. eddies and backwatering caused by the log) (see Appendices, Fig. 2).

There were several assumptions made in calculating momentum extraction for the given log jam. First, it was assumed that the flow was uniform, which is fairly reasonable given that the flow was held constant through the experiment. Next, it was assumed that the extent of velocity measurements accurately captured the zone of influence of the log jam (this defines the control

volume). Regarding types of resistance, it was assumed that resistance due to bends was negligible (because of the artificial stream's low sinuosity) and that bed form resistance could be neglected.

Assumptions specific to the x-direction calculations were that flow across the surface was entirely due to the force exerted by the jam and that no pressure existed between the bank and surfaces (Manners et al. 2006).
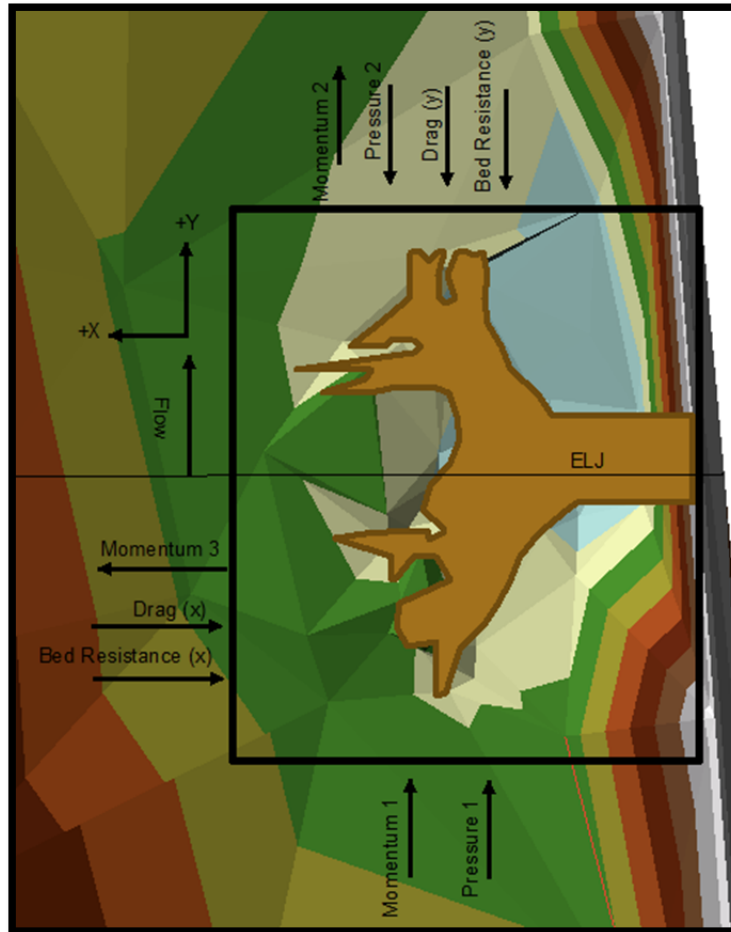
Figure 3: Diagram of log jam control volume with momentum flows and forces balance.

$$F_{p1} - F_{p2} - F_{D(y)} = F_{boundary(y)} - P_1 + P_2 \tag{1}$$

F_{p1}= Force of pressure on the upstream control surface.
F_{p2}= Force of pressure on the downstream control surface.
$F_{boundary(y)}$= Shear stress from the bed in the y-direction.
$F_{D(y)}$= Force of drag in the y-direction.
P_1= Upstream momentum.
P_2= Downstream momentum.

(Manners et al 2006).

$$-F_{boundary\,(x)} + F_{D(x)} = P_3 \tag{2}$$

$F_{boundary(x)}$= Shear stress from the bed in the x-direction.

4

$F_{D(x)}$= Force of drag in the x-direction.
P_3= Lateral momentum.

(Manners et al 2006).

$$C_D = ((C_{D(x)})^2 + (C_{D(y)})^2)^{1/2} \qquad\qquad (3)$$

The method used in this study to calculate the drag coefficient for the single study log jam was influenced heavily by calculations presented in Rebecca Manners' "Structure and Hydraulics of Natural Woody Debris Jams," which is a study that looked at the relationship between jam composition and stream hydraulics. Similar methods of calculating momentum extraction have been employed broadly in log jam hydraulics research. To see the detailed calculations, please see the Appendices.

Velocity Distribution

The reasoning for analyzing the velocity data through the means of vector and contour plots was initially influenced by Manners et al. 2006, a study that looked at the hydraulics and composition of log jams.

Matlab contour and quiver functions require data sets that increase in equal intervals. Due to the fact that the ADV data was spread out, it did not meet this requirement. A grid was created in which the data points would then be formatted in a way that was compatible with Matlab.

This two dimensional grid process used Excel and acted as a means to transfer floating integer values (the velocity coordinates) to the given grid integer values used in Matlab. The ADV's locational data, given by a three dimensional vector, was separated into three planes (XY, YZ, and XZ) and then filtered to create slices within each plane. These slices were determined based on measurement (measured in centimeters) and height layer (top, second, third, fourth, and fifth). Upon separating the data, the velocity coordinates were again filtered to determine maximum and minimum values based on the coordinates within that plane (i.e. XY plane used X and Y coordinates). The maximum and minimum values gave shape to the axes on the grids. The same grid was used on the slices within each plane, but the grids varied from plane to plane.

The contour plot requires only one grid per slice in which the values plotted within the grids are the magnitudes of the velocity components in that plane (converted to meters per second) (See Eq.11). For example the magnitudes used for the grid in the XY plane used the X and Y components of velocity. The quiver plot requires two grids per slice. Each grid has the plotted values of the velocity components. For example slices in the XY plane will have a grid with the X components of velocity plotted and a grid with the Y components of velocity plotted.

The calculations used to determine the magnitude are given by:

The XY plane	*The YZ plane*	*The XZ plane*	(11)
$\sqrt{((V_x)^2+(V_y)^2)}$	$\sqrt{((V_y)^2+(V_z)^2)}$	$\sqrt{((V_x)^2+(V_z)^2)}$	

The contour and quiver plots in Matlab require the use of matrices. The contour function uses three matrices, X, Y, and Z. The main data of focus (the grids with the velocity data) are used for the Z matrix. The X and Y matrices describe the dimensions of the Z matrix (X being the horizontal dimensions and Y being the vertical dimension). Quiver plots are very similar but use four matrices, X,Y,U,V. The two grids required for the quiver plots will go in the U and V matrices (i.e. the XY plane: X component of velocity grid will be the U matrix and the Y component of velocity grid will be the V matrix). The X and Y matrices describe the dimensions of the U and V matrices, which should be equivalent in size. The dimensional matrices for both the contour and quiver plots, X and Y, require the meshgrid function in order to produce a full two-dimensional coordinate array that is the same size as the entire Z, U, or V matrix.

The contour and quiver plots are then created using Matlab. See Appendices for functions used.

Shear Stress Distribution

The velocity matrices that were used above to map the velocity distribution around the log jam will also be used to map the shear stress distribution. Matlab will be used to create a "Meshgrid" with the matrices (similar to above). Shear stress will then be calculated on a point-by-point basis, in the x- and y-directions, at each point on the grid that a velocity measurement was taken. The resultant vector will then be computed to find the magnitude of shear stress at each point. The equation that will be employed is the basic definition of shear stress (see Eq. 4).

$$\tau_{(x \text{ or } y)} = \mu * \frac{\partial U}{\partial (x \text{ or } y)} \qquad (4)$$

For the functions that will be used in Matlab, see the Appendices.

RESULTS

Drag coefficient

The overall drag coefficient that was calculated for the wood jam was 23.2, with 23.1 in the y-direction of the flow, and 1.96 in the x-direction. The full calculations may be found in the Appendices section of the manuscript.

Velocity Distribution

Two planes were analyzed, the XY and YZ plane. Contour and quiver plots were created for the five slices within each of the planes. The plots can be found in the Appendices section.

Shear Stress Distribution

Due to time constraints, the matrices were not completed and the shear stress calculations could not be performed.

DISCUSSION

Drag coefficient

The resulting drag coefficient for the study log jam seems very large. The values obtained by Manners in "Structure and Hydraulics of Natural Woody Debris Jams" fell within the range of 0.7 to 9.0. Upon inspection of the data, it appears that the study control volume may not fully capture the extent of the log jam's influence. The effects of an eddy can be seen across the downstream surface, which drastically influences the momentum balance. The momentum flowing into the control volume differs greatly from that flowing out. If the control volume were extended downstream further and the entire eddy was captured, then it is possible that the downstream momentum would end up being higher.

Improvements to the drag coefficient calculations include extending the downstream control surface to include the full eddy and interpolating velocities over this region. If this is not feasible, this discrepancy should be compensated for somehow in the momentum calculations. An addition improvement, though a minor one, would be to re-calculate shear stress using the integral form, which would produce a more precise result.

Velocity Distribution

Analysis of the XY plane slices showed that within this specific log jam, the lower section (down river) showed areas of high velocity as the slices moved closer to the bottom or the stream. This is explained by looking at YZ plane slices. These slices show a central concentrated flow of high velocity, showing that as you move across from bank to bank there is a higher velocity flow underneath the log jam. Overall the contour plots showed higher velocity values in isolated spots and locations further from the jam, and lower velocity values along to the jam and lower sections of the jam on layers closer to the surface.

The quiver plots were less enlightening and useful for analysis than the contour plots. However they show that as the stream nears the log jam, closer to the bank, the water starts to form an eddy.

Due to the interval spacing on the axes, some points were found to be "duplicates" because they did not fit exactly within the given points along the axes. This raises the problem of excluding points that may be important for interpreting patterns within the velocity data set. Improvements to the data analysis could include creating grids with axes that increase at smaller intervals than 0.1.

Shear Stress Distribution

The authors hope to finish the shear stress calculations once the matrices are completed and the gaps in the velocity data are interpolated over to create a finer scale to access the shear stress. This is important in areas directly adjacent to the log jam, particularly the boundary layer, which is very thin. The boundary layer is the location of the highest velocity gradient. For this reason, too coarse of a scale could lead to an underestimate of the shear stress.

CONCLUSION

Large wood has a large effect on stream velocities, shear stress distributions, and drag forces. This is why engineered log jams create hydraulic complexity in streams. Shear stress in particular can create scouring, which increases geomorphic complexity (Manners et al. 2006). This, in addition to hydraulic complexity, leads to enriched habitat, which is utilized by fish for forging, refuge, and spawning. Engineered log jams are increasingly utilized in restoration projects. Research [like that presented in this manuscript] on how log jams specifically affect the hydraulics of stream is crucial for this reason. Observations on the velocity and shear distributions, as well as drag, can be paired with quantitative and qualitative observations made on fish behavior to better understand how fish utilize these habitats. Future research recommendations include a more refined calculation of the drag coefficient, in addition to completed contour maps of shear stress and velocity. Once these are completed, along with fish observations, both can be paired for a direct comparison.

LITERATURE CITED

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APPENDICES
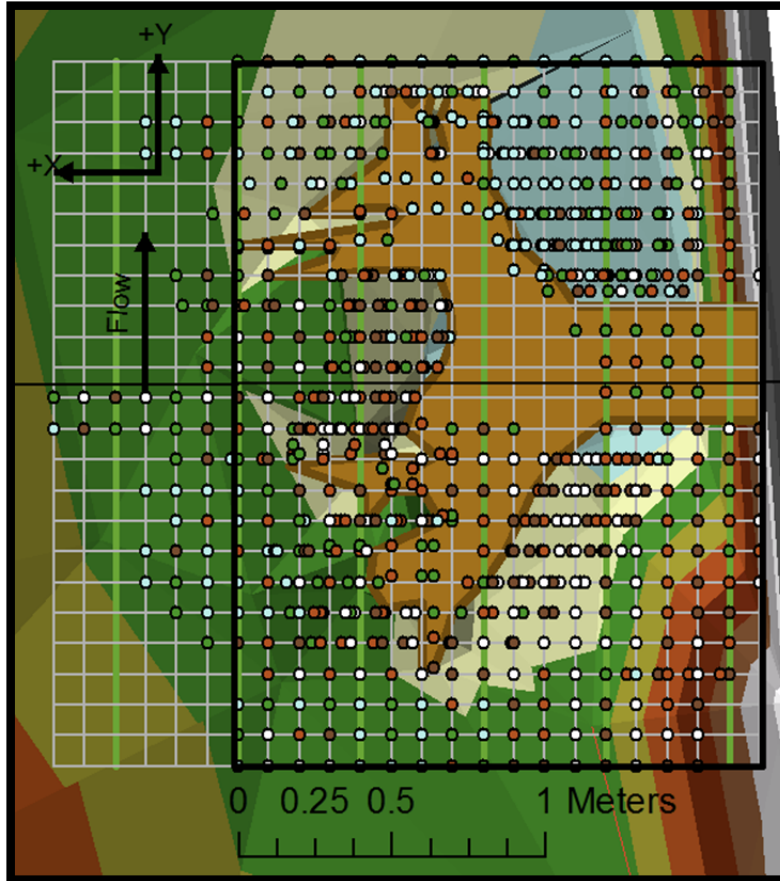
Figure 2: Grid of summary velocity measurements.

Drag

Cont.

Coefficient Calculations

The pressure forces (F$_{p1\&2}$) for the upstream and downstream control surfaces were calculated using Eq. 5.

$$F_{1\&2} = \gamma * \bar{y}_{avg} * A_{1 \ or \ 2} \tag{5}$$

γ= Specific weight of water (9800 N/m^3)
$\bar{y}_{avg}$= Average y-bar of all of rectangles in cross-section.
A$_{1 \ or \ 2}$= Cross-sectional area of inflow or outflow surface.

The cross-sectional area of each control surface was found using a trapezoidal sum. Elevation data in both cross-sections was extrapolated from a TIN (Triangulated Irregular Network) that was created with topography data in ArcGIS. Lines were interpolated through the TIN layer of the data, using the 3-D Analyst tools, at the upstream and downstream ends of the control volume and the profile data was extracted and exported into Excel. A trapezoidal sum, where each cross-section was discretized into trapezoids, was computed using the profile data (depth vs. cross-section points) (see Eq. 6).

$$A_{1\ or\ 2} = \frac{x_n - x_1}{n} * (y_1 + y_2 \dots + y_n) \qquad (6)$$

x= Distance across cross-section.
y= Depth along cross-section.
n=Number of trapezoids.

*Note: Coordinate system was corrected by subtracting the bed elevations from the stage at each cross-section (taken from the "LEW" (left edge of water) layer in ArcGIS) to give water depth.

      The average y-bar was found by first discretizing each cross-sectional area (using data exported from ArcGIS) into rectangles, then dividing the water depth (height of rectangle) in half to obtain each y-bar. The overall average was then found (see Eq. 7).

$$\bar{y}_{avg} = AVG(\bar{y}_1 + \bar{y}_2 \dots + \bar{y}_n) \qquad (7)$$

The boundary forces ($F_{boundary\ (x\ \&\ y)}$) were calculated for in both the y- and x-directions using Eq. 8.

$$F_{boundary\ (x\ or\ y)} = \tau_{bed(x\ or\ y)} * A_{bed} \qquad (8)$$

$\tau_{bed(x\ or\ y)}$=Shear force from streambed.
A_{bed} = Area of bed within the control volume.

(Manners et al 2006).

      The bed area was the same for both and x and y calculations. This was found using the area interpolation tool in the 3-D Analyst toolbar in ArcGIS (extent of control volume measured). To calculate the shear force, shear velocity (U^*) first had to be calculated (see Eq. 9). Shear from the bed was then calculated using Eq. 9.

$$U^*_{x\ or\ y} = \frac{U_{avg(x\ or\ y)}}{\frac{1}{k} * \ln\left(\frac{h}{e * z_0}\right)} \qquad (9)$$

$U_{avg\ (x\ or\ y)}$=Average velocity over control volume in x- or y- direction.
k= von Karman's constant (0.4).
h= Average water depth over control volume.
z_0=Roughness height (0.1*D90)
D90= 90% particle size.

(Manners et al 2006).

      The average velocity in the x- and y-directions respectively were found by averaging V_x $_{or\ y\_avg}$ in the raw filtered velocity data. These measurements were the time average of the velocity in the x- and y-directions at each discrete measurement point within the control volume.

The average water depth was found using exported cross-section data for the upstream and downstream cross-sections (see "Cross-sectional Area" calculations for detailed description of how depth was found using bed elevation and stage). Depths found for the upstream and downstream cross-sections were averaged to yield overall average water depth.

The D90 particle size was taken from pebble count data that was collected on-site with a gravel-o-meter.

$$\tau_{bed\ (x\ or\ y)} = \rho * (U^*_{x\ or\ y})^2 \hspace{4cm} (9)$$

ρ = Density of Water (1000 kg/m^3)
$U^*_{x\ or\ y}$ = Shear Velocity in x- or y-directions (calculated above).

(Manners et al. 2006).

The drag forces ($F_{D(x\ or\ y)}$), similar to in the case of shear stress, were solved for in both the x- and y-directions.

$$F_{D\ (x\ or\ y)} = 0.5 * \rho * C_{d\ (x\ or\ y)} * A_{f\ (x\ or\ y)} * (U_{app\ (x\ or\ y)})^2$$

ρ = Density of water (1000 kg/m^3)
$C_{d\ (x\ or\ y)}$ = Desired value.
$A_{f\ (x\ or\ y)}$ = Submerged frontal area of log jam perpendicular to directional flow.
$U_{app\ (x\ or\ y)}$ = Average approach velocity (U_3 or U_1).

The program VidSync, created by a Ph.D. student at the University of Alaska, was utilized, in junction with photos of the log jam, to find the respective submerged frontal areas in the x- and y-directions. Coordinates were extrapolated from the photos and the distance formula was used to find the lengths given below.

-Total Length: found using side view of ELJ (cut end to root wad bottom*)
-Height of Root wad: found using full on view of the root wad*
-Width: found using full on view of root wad*
-Length of log: found using side view (cut end to top of root wad)
-Diameter: found using side view
*Does not include full extend of roots

The full frontal area of the log (perpendicular to y-component of flow) was estimated by multiplying the diameter of the log by the length (Manners et al., 2006). The areas of the root wad facing the x- and y-components of the flow were estimated using the area of a cube. The area of facing the y-component was added to the area of the log.

A similar procedure was followed for the portion of the jam protruding from the water. Coordinates were extrapolated using photos on VidSync, then the frontal area was calculated using the areas of rectangles and cubes. These values were subtracted from the values found for the total jam to find the portion submerged. The frontal area that was used for the x-direction calculation was the portion of the submerged rootwad "end", while the area of the log and side of log jam were used for the y-direction calculation.

The average approach velocity was found using data extrapolated from points along each cross-section in ArcGIS. V_{y_avg} (time averaged velocity in the y-direction) values were extrapolated from the upstream cross-sectional and averaged to give $U_{app\,(y)}$, while V_{x_avg} (time averaged velocity in the x-direction) values taken from the third (lateral) cross-section and averaged to yield $U_{app(x)}$.

Momentum ($P_{1,\,2,3}$) was solved for along each control surface: upstream, downstream, and lateral using Eq. 10.

$$P_{1,2,3} = \rho * \Sigma(V_{x\,or\,y\_avg\_n})^2 * A_n \qquad\qquad (10)$$

ρ = Density of water (1000 kg/m^3)
$V_{x\,or\,y\_avg\_n}$ = Time averaged velocity in the x or y direction corresponding to the "nth" rectangle.
A_n = Area of "nth" rectangle

The time averaged velocities in both the x- and y- directions were found by extrapolating velocity data from ArcGIS along the upstream, downstream, and lateral cross-sections.

The area of the "nth" rectangle was found by multiplying water depths by a constant width of 10 cm (each measurement is spaced 10 cm apart along the cross-section). The water depths were found by extrapolating elevations adjacent to each velocity measurement from the TIN layer, then subtracting each elevation from the cross-section water surface elevations.

Shear Stress Distribution Matlab Functions

Meshgrid Function

Used to create two full two-dimensional coordinate arrays that are the same dimensions.

[X,Y]=meshgrid(x,y)

Where "X" and "Y" are two matrices that contain coordinates on the x- and y- axes corresponding to each velocity measurement.

Gradient Function

Used to find the numerical gradient of velocity in both the x- and y- directions.

[FU, FY]=gradient(F, h)

Where "FU" (velocity) and "FY" (y-coordinate) refer to the two spatial dimensions that the gradient is taken in, "F" is the output matrix, and "h" is a scalar that represents spacing between points (10 cm).

Contour Function

Creates a contour plot of Z using X and Y to determine the x- and y-axis limits.

Contour(X,Y,Z);

Where "X" and "Y" are two matrices that contain coordinates on the x- and y- axes corresponding to each velocity measurement and "Z" is the matrix containing the velocity data.

Quiver Function

Displays velocity vectors as arrows.

Quiver(X,Y,U,V);

Where the coordinates of the vectors are specified in "X" and "Y" and the given components of velocity at these coordinates are represented with "U" and "V"

Contour Plots
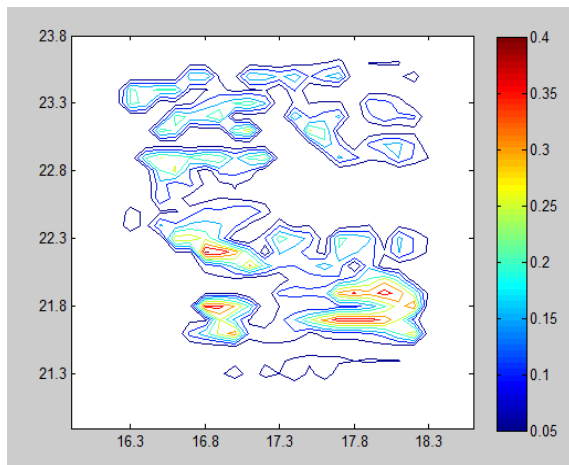
Figure 2: Figure 3: XY-plane Top Slice   **Figure 3: XY-plane Second Slice**
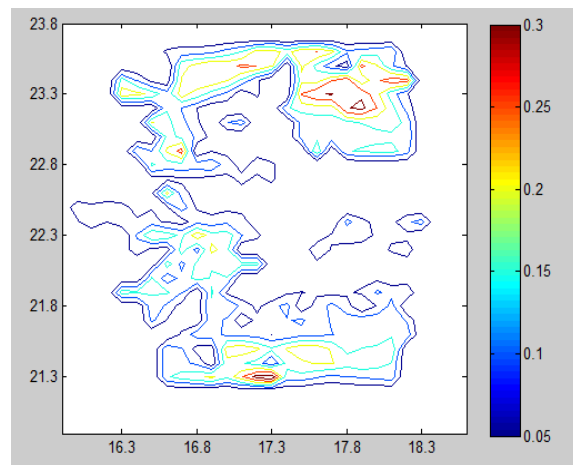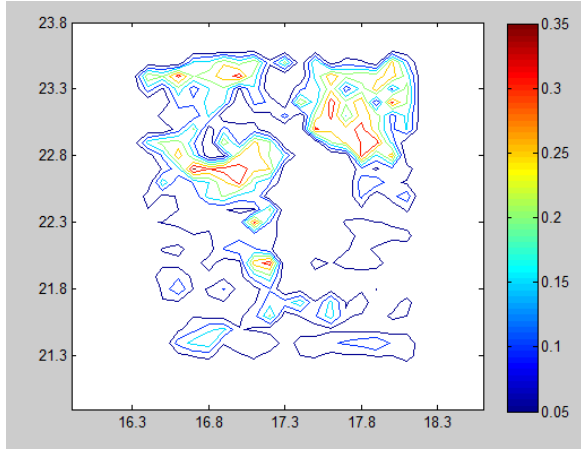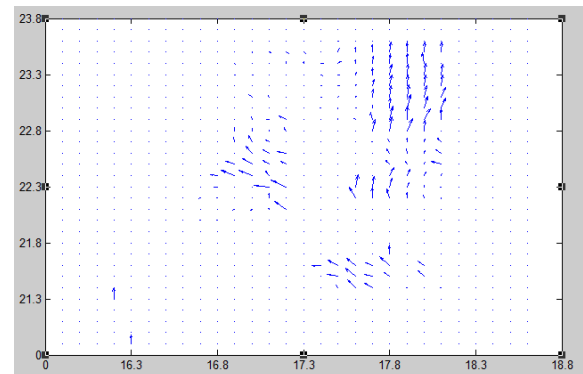
Figure 4: XY-plane Third Slice
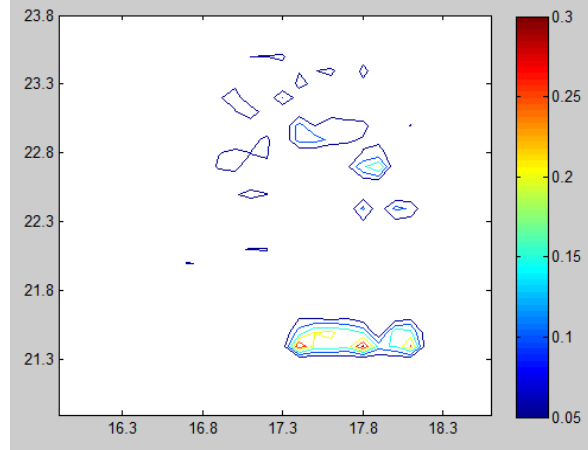
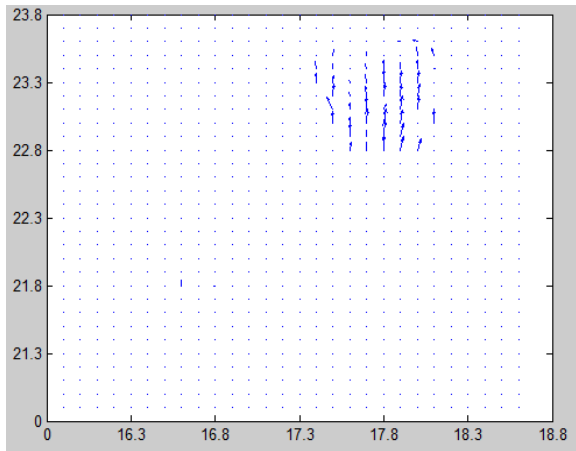**Figure 5: XY-plane Fourth Slice**
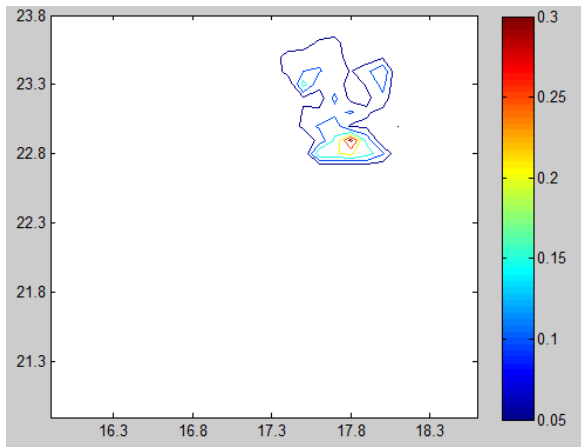
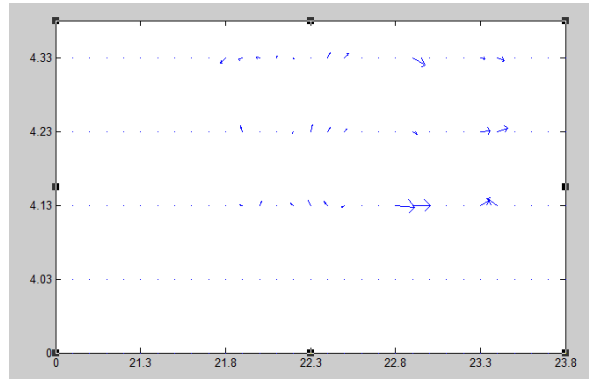**Figure 6: XY-plane Fifth Slice**
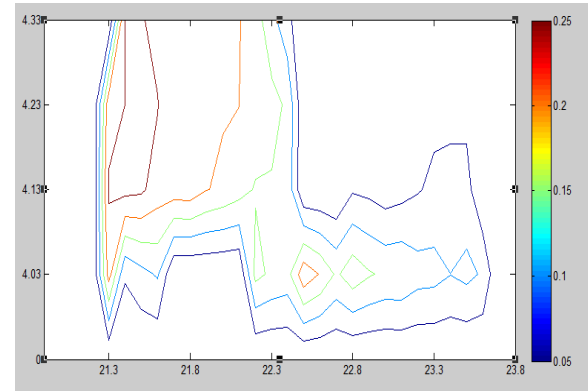
Figure 7: YZ-plane First Slice (16.0cm-16.49cm)
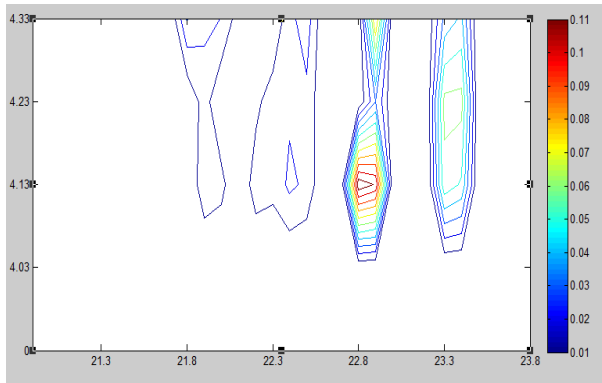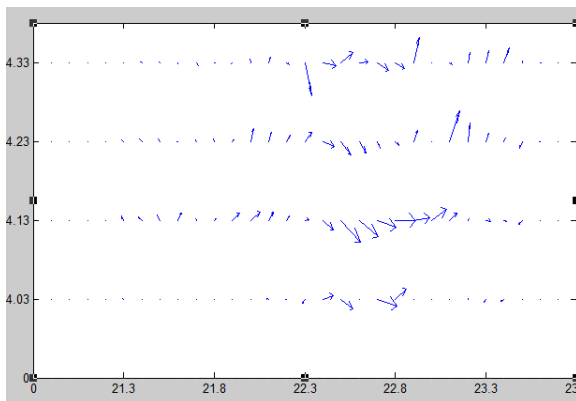

Figure 8: YZ-plane Second Slice (16.5cm 16.9cm)
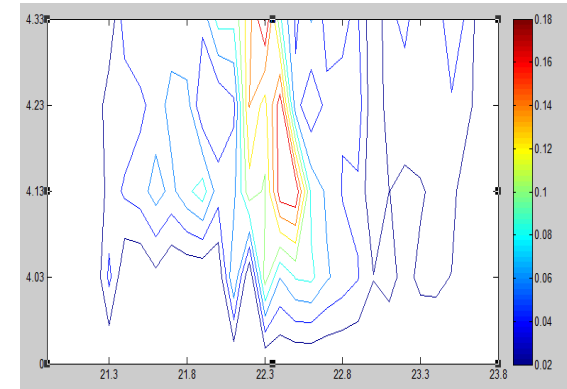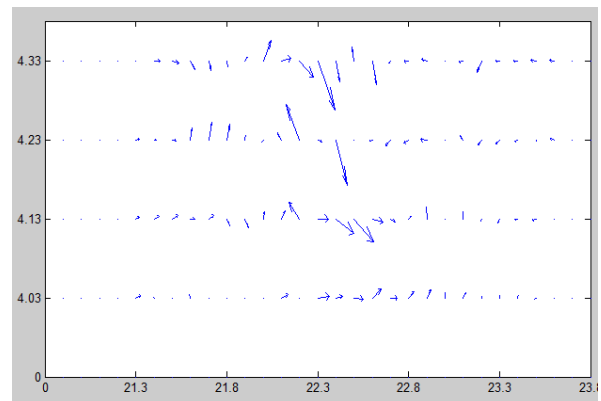

Figure 9: YZ-plane Third Slice (17.0cm-17.49cm)
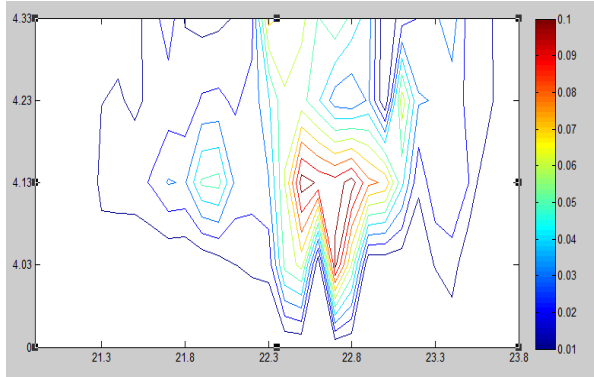
Figure 10: YZ-plane Fourth Slice (17.5cm-17.9cm)
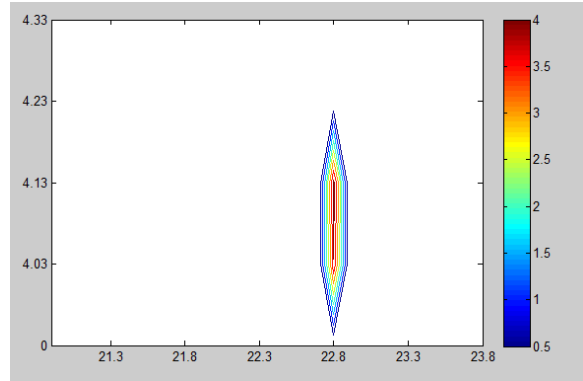
Figure 11: YZ-plane Fifth Slice (18.0cm-18.5cm)

Quiver Plots
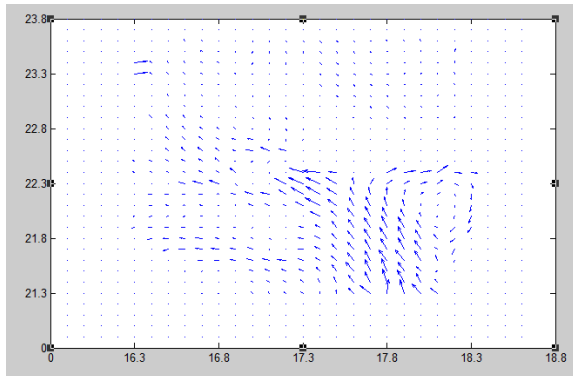
Figure 12: XY-plane Top Slice
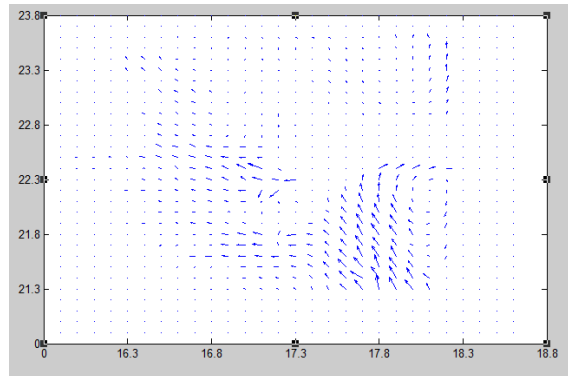
Figure 13: XY-plane Second Slice
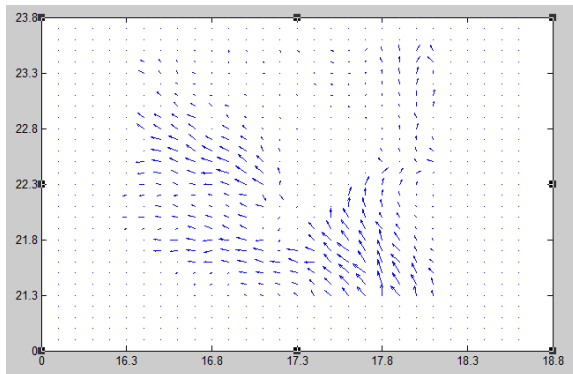
Figure 14: XY-plane Third Slice

Figure 15: XY-plane Fourth Slice

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Figure 16: XY-plane Fifth Slice

Figure 17: YZ-plane First Slice (16.0cm-16.49cm)

Figure 18: YZ-plane Second Slice (16.5cm-16.9cm)

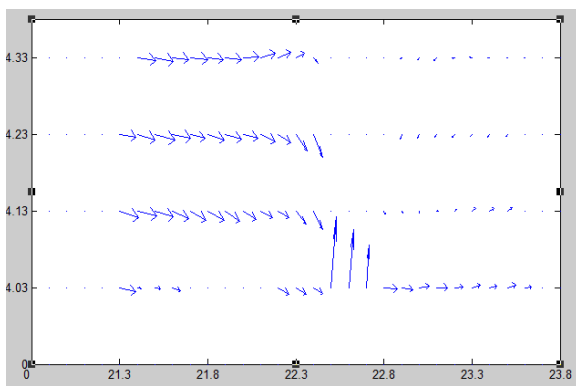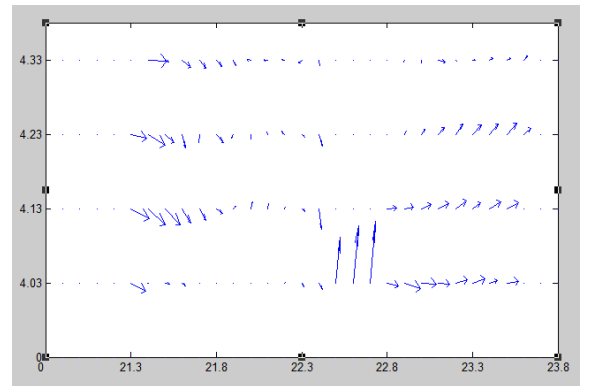**Figure 19: YZ-plane Third Slice (17.0cm-17.49cm)**

Figure 20: YZ-plane Fourth Slice (17.5cm-17.9cm)

Figure 21: YZ-plane Fifth Slice (18.0cm-18.5cm)