Wake characteristics associated with logjams to inform river restoration

by
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Abstract

In the past, logjams have been removed due to concerns about flooding, erosion, and destruction of property. However, logjams have been found to have many ecosystem benefits, including generating pools for salmonid spawning, propagule retention sites, and increasing biodiversity. Due to these benefits, engineered logjams are being placed back into rivers, especially in the Pacific Northwest of the U.S., to promote salmonid populations. Riverine habitats are created by variations in substrate size, depth, velocity, turbulence, temperature, and cover. All species have preferences for certain conditions. Even within a species, the size and age can also impact preference. Specifically for salmon, juvenile salmon prefer shallow and low velocity regions while adult salmon prefer deep and coarse substrate. The presence of the logjams alters the bed morphology of the river and availability of habitats. To better understand how design choices for a logjam can impact habitats, important parameters include solid volume fraction (SVF) and channel width. Thus, these two variables were varied in 8 constructed logjams. The wake generated by each logjam was analyzed in a recirculating flume for velocity, turbulence, and fine sediment deposition. All logjams displayed increased velocity in the unobstructed side and decreased velocity downstream of the logjam side. Varying the solid volume fraction had little variation in stream-wise velocity and root mean square of the stream-wise velocity (proxy for turbulence) to the first order. Differences in the quarter and half width spanning logjams were seen as the half-width logjam had increased velocity in the unobstructed side, a recirculation region, and lower turbulence in the center of the logjam and unobstructed side. Deposition of fine sediment for the quarter-spanning logjams were not greater than that of the open bed case with the same conditions. Thus, the fine sediment deposition observed downstream of logjams are not correlated with the solid volume fraction. Indicating the deposition could be correlated with bed depth or depositing further downstream, which could not be studied. The logjam width had a greater impact on velocity and turbulence than variations in solid volume fraction. All the logjams provided variation in available habitats for riverine fish. Considering both fish preferences and wake effects from logjam characteristics will result in more effective river restoration projects.

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1. Introduction

Rivers are a natural flow of freshwater that provide a unique habitat for more than 10,000 species of freshwater fish or 10% of all known species. These freshwater fish have faced threats including overfishing, riverine pollution, competition from invasive species, and habitat loss. This has led to an 86% decline in freshwater vertebrate since 1970 and over a third of freshwater fish are endangered (National Geographic, 2021). The large decline in riverine organisms have prompted major research into the cause of the decline and avenues for restoration. One of these avenues is an engineered logjam (ELJ). A logjam is an accumulation of logs that blocks all or a part of the river channel. The logjam typically creates a region of low velocity and scour downstream of the jam, followed by a region of deposition. The scour provides a location of salmon scour, whereas deposition decreases the water depth which is consistent with juvenile salmon preference.

Historically, logs and logjams have been removed from rivers due to concerns of flooding, erosion, and destruction of property (Pess, 2012). This was the case because logjams can become dislodged during flooding and damage infrastructure. Another issue is that logjams can create backwater rise (the water level upstream of the jam increases is due to the obstruction) which can flood neighboring areas. Many rivers have lost habitat complexity, which is the availability of different flow velocities, water depths, etc. which provide niches (areas that a species live in). Rivers have become more homogenous, due to riparian deforestation, channel and snag clearing or removal, and construction of levees (McHenry et al. 2007). These are examples of actions that would reduce the number of natural logjams in a river system. New research has demonstrated that logjams have beneficial properties including generating pools that promote salmonid spawning, propagule retention sites, providing cover, and increasing biodiversity (McHenry et al. 2007). For these specific reasons, logjams have been reintroduced into rivers to restore ecosystems and promote salmonid populations. An image of logjams and the habitat it creates can be viewed in Figure 1. This thesis aims to give a better understanding on how to arrange the large woody debris to generate beneficial habitat to fish.

This thesis will shed light on how wake characteristics, such as velocity and turbulence, vary as the dimensions of a logjam changes. These habitats created by logjams provide lower velocity regions for juvenile fish and regions with low turbulence that allow fish to exhort less energy to stay in one location (Hockley et al. 2014). These variables can greatly affect habitats available for different fish species so understanding the repercussions of design choices is essential to optimize the beneficial aspects of logjams and restore salmonid populations.

Figure 1: Large wood in streams creates habitat necessary for spawning and rearing of salmon. Illustration by Owen Caddy.

Logjams are one tool to promote salmon populations. In the Pacific Northwest, there is an emphasis on maintaining and increasing the number of salmonid fish. This can easily been seen with the Governor's salmon strategy update, where Governor Inslee states that Washington commits to honoring Native American tribes as it works to recover salmon populations (Goodsell, n.d.). Examples of this in practice include the Lower Elwha Klallam Tribe constructing 21 engineering logjams into the Elwha River, Washington and the Yurok Tribe implementing engineered logjams in the Trinity River, California as seen in Figure 2 (Pess et al. 2012). The logjams in the Elwha River were funded by the Salmon Recovery Funding Board (SRFB), and they commissioned a 5-year effectiveness study. By the fourth year, the logjams had showed positive results on the increase in salmon, such that the SRFB began funding more logjam grants (McHenry et al. 2007). Logjams are only a small sample of the widespread stream restoration projects. As of 2005 there have been over 37,000 stream restoration structure projects implemented in the United States (Bernhardt et al. 2005). Now, 17 years later, with salmon populations still in critical condition, understanding the flow characteristics in the vicinity of engineered logjams to optimize their design for habitat creation is ever more important.

Figure 2: Engineered logjam placed in the Trinity River (Northern California). It was designed by the Yurok Tribe for restoration purposes (photo credit: D.J. Bandrowski). The vertical logs are the key logs to hold the logjam in place.

Logjams have some key factors that allow them to be effective in increasing salmon populations. One benefit of logjams is that the deep pools provide salmon spawning habitats. These pools protect salmonids and their eggs from predators and provide a safe region for the eggs, as they can be destroyed by the velocity of the water. This pool is also good protection for juvenile fish that live in the rivers until they become adults and migrate out to sea. The logjams themselves also trap propagules that float down the river, which leads to a macrophyte growth near the jam. The logjams also increase the particulate organic matter (POM) deposition downstream of the jam. Particulate organic matter is continually input into the river by upland erosion or from the riparian zone. Deposition of POM was observed in the 1 mile reach of Elwha River that contained 21 engineered logjams, with the measured area of alluvium (a deposit of clay, slit, sand and gravel typically from soil) doubled in the span of around 5 years (McHenry et al. 2007). The increase in POM is considered a precursor to vegetation growth (Jones et al. 2012). This intuitively makes sense as POM can provide nutrients and a growth substrate for plants. POM deposition was observed in Elwha river engineered logjams with total organic matter increasing sixfold on the wood of the ELJ compared with on cobble in the same area or other reference cobble (McHenry et al. 2007). The logjams itself can also be a source of POM (Wohl and Scott 2017a).

In rivers where riparian forests shade a good part of the channel and prevent photosynthesis, the POM can be an alternative nutrient source for the microbial and macroinvertebrate communities (Tank et al. 2010). The presence of nutrients on the logjam attracts many organisms and increases biodiversity. Theories in ecology suggest that habitat heterogeneity/complexity is positively correlated with fish species diversity and flow patterns influence species richness (number of species) (Guégan, Lek, and Oberdorff 1998). With different habitats, there are more locations for fish to adapt to thus less competition if they can use habitats different from fish.

Current understanding of how logjams effect deposition is limited. Most of the sediment studies done with logjams have pertained to the scour and deposition of larger sediment. Even though deposition of POM downstream of logjams has been documented (McHenry et al. 2007), there are relatively few studies on the mechanisms that cause this deposition. According to Beckman and Wohl (2014), sediment volume stored downstream of jams did not correlate with jam characteristics, including volume of wood in jam and mass of carbon in wood. However, Beckman and Wohl (2014) do not explicitly try to determine the cause of the POM accumulation downstream of logjams. Instead, they use their existing data to statistically rule out causational properties. Leaving the questions of what causes this deposition to occur, since there is increased deposition near logjams, and why does deposition not change with jam characteristics, since a study also finds that without logjams there is a substantially reduced storage in POM in steep channels (Wohl and Scott 2017b). Wohl and Scott (2017b) even call out the lack of studies that quantify how logjams impact POM as they only found two studies with data on wood volumes and POM storage. Thus, furthering the understanding the effect that logjams have on POM deposition can lead to better informed river restoration.

One way to assess how beneficial the logjam will be for restoring a river is to understand the habitat types created by variation in velocity, turbulence, POM deposition, and bed morphology that fish prefer. One factor that affects the preference of habitats is the age and size of a fish. Juvenile salmonids live in the river while adult salmonids migrate from the ocean once a year into rivers for spawning. This means that younger salmonids face a larger range of environments in the river with seasonal changes including flood events, dry periods, and temperature fluctuations. Larger fish may prefer high velocity regions where the spatial and temporal variables are more stable and predictable (Hockley et al. 2014). Turbulence can be beneficial by reducing energy loss when swimming, however high turbulence levels caused by rotating turbines in hydroelectric dams can cause spills (Webb and Cotel 2011). A spill is when a fish loses control of posture or swimming trajectory, possibly overturning. The size of vortices or length scale of turbulence can greatly affect the swimming performance of fish. If a vortex is relatively small compared to the size of the fish, then the force is evenly distributed, however if the vortex is about the same size as the fish there is a torque that could cause the fish to overturn (Lupandin 2005). In contrast, in cases of high velocity, species like chub *Nocomis micropogon* use the vortices to maintain their position (Hinch and Rand 2000). Generally higher turbulence and larger turbulence size have a negative effect on fish, however if the fish is bigger, it can endure both larger vortices and higher turbulence intensity.

Other than turbulence, preferences on velocity, water depth and substrate grain size were studied in young Atlantic salmon and brown trout in the Gjengedalselva River, Norway. Velocities around 20 cm/s were preferred giving a mid-range velocity preference. The study found that velocity was the most important hydro-physical variable that determined 34-35% of the variance in habitat use, followed by water depth, and range of substrate sizes (Heggenes, Saltveit, and Lingaas 1996). This means that the velocity can have a significant impact on suitable environments for fish. The combination of these variables is important to keep in mind when implementing river restoration to generate ideal habitats. Especially when a wide range of fish species live in an area and thrive under different conditions, ensuring that there is not only one type of environment or increasing habitat heterogeneity is important. Even within one species, there is variation as juvenile salmon that live in the river year-round whereas the adult salmon only travel up the river once a year.

1.1. Research Goals

The goal is to define characteristics of the wake around a logjam and link each characteristic to fish preference. This will improve the river restoration efforts to increase riverine fish population and increase biodiversity within the ecosystem. To better identify the key parameters (velocity, turbulence, and deposition) that enable logjams to create a more suitable habitat for riverine fish, physical experiments were conducted to model logjams. This study investigated how the change in solid volume fraction (SVF) of the logjams affects the wake time-mean and turbulent velocity and the deposition of POM. The turbulence and velocity will directly impact how easily a fish can swim in the river. While the POM, which is modeled by using suspended fine sediment, will impact the plant propagules and ecosystem diversity, as it allows microorganisms to metabolize carbon and other nutrients from POM for energy and growth (Beckman and Wohl 2014). After characterizing the SVF and channel spanning effects of the logjams, they will be linked to wake structures of different logjams to fish preference. The focus is on bar apex jams which come off the riverbank into the river/ adjacent to the side of the river channel (Figure 2), as opposed to deflector jams that are largely in the middle of the river. As these bar apex jams are more likely to generate pools and influence habitat characteristics (McHenry et al. 2007).

The results will inform how to design future engineered logjams to create habitats for salmonid fish. Based on this study, the understanding of what type of logjam would best fit their needs were improved and will further allow for more restoration projects to occur. As juvenile salmon prefer shallower water whereas adult salmon prefer deeper waters for the cooler temperatures (McHenry et al. 2007). Thus, a logjam geared more towards increased scour with would be used for promoting adult salmon populations, and a logjam geared towards increasing deposition would be used for juvenile fish. There are more complexities with fish preferences than just one parameter, but in general matching the characteristics fish prefer with the habitat that a logjam creates.

2. Literature Review

2.1. Logjams in the Environment

A study done by Schalko et al. (2020) displays what the scour (decrease in bed height due to erosion) and deposition (increase in bed height due to the accumulation of sediment) might look like in a river. These locations are seen in Figure 3. The figure on the left shows minor scouring near the edge of the log as well as downstream of the logjam, with flow going from left to right. After the scour there is a region of deposition. This deposition case is beneficial for juvenile salmonids that occupy relatively shallow and low velocity regions (<1m water depth and <40 cm/s velocity) (Bjornn and Reiser, 1991). Since larger rivers are often deeper and have higher velocities, these fish can find lower velocities and depths behind logjams and near channel margins (Beechie et al. 2005). As for the figure on the right, the increased velocity caused a much deeper scour like pools that are created downstream of logjams. The pool created by logjams are beneficial for salmonid spawning and providing lower temperatures (McHenry et al. 2007). There is almost no deposition in this case, as the sediment that was eroded to make the pool would have to deposit downstream by conservation of the sediment mass.

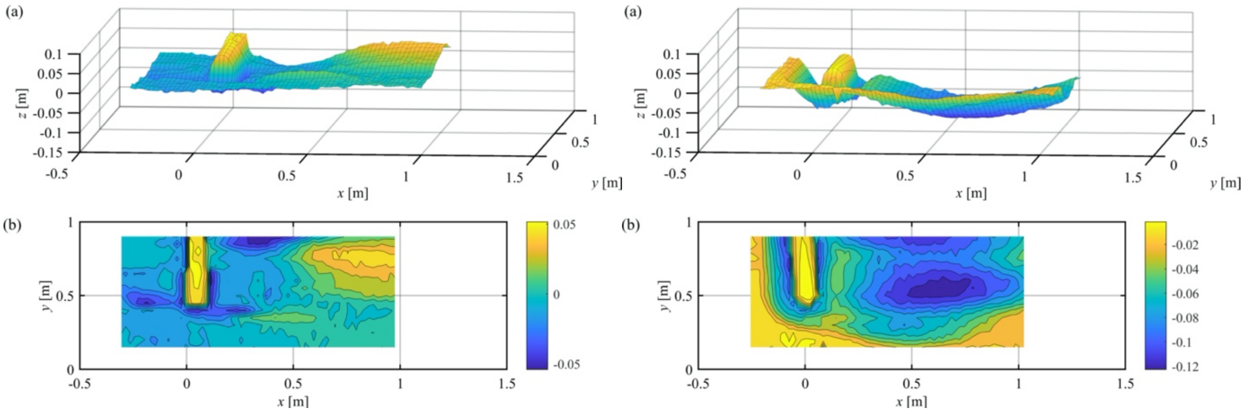


Figure 3: Scour and deposition created by a single log. Both test cases show a log obstruction adjacent to the channel wall. The different in the cases is the initial velocity, the left case had u = 0.29 m/s the case on the right had u = 0.50 m/s (a) shows a 3D view of the channel and (b) shows the 2D contour with a color bar in meters. The increased velocity resulted in larger scour downstream of the log. Schalko and Nepf (2020)

A report by the Salmon Recovering Funding Board (SRFB) Interagency Committee for Outdoor Recreation (IAC) has information on 21 engineered logjams (ELJs) that were placed into the Elwha River from 1999-2006 (McHenry et al. 2007). The report summarizes the many effects of the logjam as well as characterizes each one. The types of logs used to create the ELJs were key, loose, and racked. Key pieces are dead trees that are still upright that are used to hold the loose wood that would otherwise float down the river. Racked pieces are smaller logs that get stuck on larger pieces of the logjam. This information was used for the design of the experimental setup, specifically, the dimensions and number of logs in each ELJ and the range of porosity. By designing the logjams based on ELJ in the environment it will be easier to link the results back to field applications. The effects on salmonoids in the area is also beneficial to understand some of the key mechanisms that are beneficial to fish. ELJs also affect spawning and juvenile salmonoids that utilized the ELJs as cover.

The Elwha River report denotes that certain species such as bull trout do not tolerate high temperatures well and the creation of deep scour downstream of logjams contribute to lower water temperatures, as water temperature decreases with depth. In the Elwha river, 20 of 21 ELJ created a pool downstream of the jam (McHenry et al. 2007). The McHenry et al. study found that there was significant temperature differences in the water column with a difference as much as 2-3°C during peak summer temperatures (McHenry et al. 2007). There is also increasing groundwater exchange rates from scour processes which can also contribute to lower water temperatures that adult anadromous fish (fish that migrate from the sea to rivers to spawn) prefer. Species such as bull trout have low tolerance for elevated temperature.

Bar apex jams had the most impact on sediment storage compared to deflector logjams. With the bar apex logjams resulting in a reduction of dominant substrate from cobble (64-256 mm) to gravel (2-64 mm). There was also a 60% increase in the amount of sediment stored in gravel bars over the 5-year study. In five out of seven ELJs, there was a significant increase in fines (<8 mm) downstream of the logjam. The change in sediment composition had a direct impact on spawning of adult salmon that were consistently observed utilizing the habitats created by the ELJs (McHenry et al. 2007). Significant differences in the biomass of salmonid fish in ELJ and non-ELJ banks was denoted in the summer of 2001 and 2003 Figure 4. While the other survey times saw a consistently higher amount of biomass in the ELJ bank units than in ones without (McHenry et al. 2007). This goes to show the salmonid fish do prefer to use the areas around logjams.

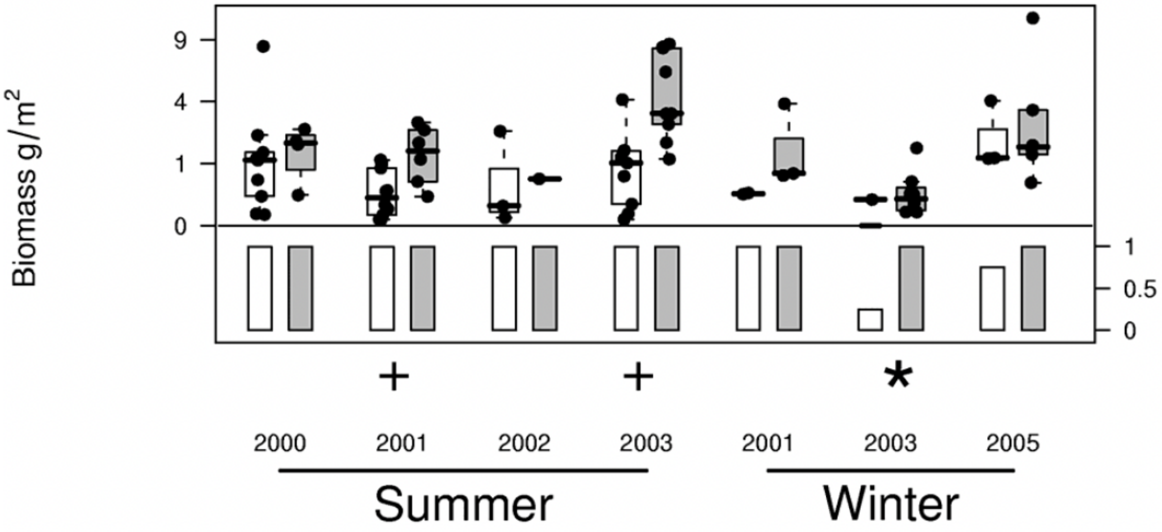


*Figure 4: Salmonid biomass proportion and density in ELJ and non-ELJ bank units in the Elwha River 2000 to 2005. The shaded bars represent bank units with ELJs while the white bars represent bank units without ELJs. The bars in the bottom panel represent the proportion of lanes occupied by that species/size class. The box plots in the upper panel describe the distribution of fish densities for bank units that are occupied. The lowest and upper marks represent the 5 and 95 percentile, while the middle mark is the median. Statistically significant differences in proportion are denoted with an *, while significant differences in fish density +. (McHenry et al. 2007).*

Sediment storage increased by 40% in the treatment reach and changed the surface bed substrate particle size to go from cobble to various gravel sizes (McHenry et al. 2007). This happens by the ELJ tapping bed load transported in floods. The new gravel beds are used by anadromous fish during spawning (McHenry et al. 2007).

In the South River, Virginia cores were taken of fine-grained channel margin (FCGM), accumulations of fine sediment from sand, silt, clay (all less than 3 mm) and organic matter, as a study of Mercury and contaminants that can rapidly absorb onto fine-grain material (Skalak and Pizzuto 2010). The study found that there is a slope threshold for these deposits and any channel bed slope greater than 0.0025 would not have any of these deposits. Typically, sediments are either transported by suspended load (grains transported without touching the bed) or bedload (grains that move along or near bed by sliding, rolling, or hopping), with the smaller sizes being suspended and larger sizes only moving along the bed. However, there is a range of sizes that can be transported by either suspended load or bedload, based on the channel flow rate, and it is generally between 125 microns and 8 mm (Wilcock, Pitlick, and Cui 2009). This means that the fine sediment could be moving in suspension or bedload so to distinguish the mechanism that causes this deposition the sediment size is not enough. This paper concludes that the fines that they observe is mostly in suspension because for the sediment to deposit downstream of the obstruction it would need to have been suspended.

These papers present a wide range of characteristics of logjams, however, testing how SVF alone affects the wake near logjams has not been widely published. As well as limited research into the deposition of fine sediment downstream of logjams, presents a unique opportunity to contribute to improving the understanding of key characteristics of logjams and its impacts.

2.2. Studies on Porous Structures

This thesis studies various SVFs that could be found in a logjam in the environment. Flow around a porous structure often have similar features so it is beneficial to have some background on how the wake behind other structures behave. As well as data from other logjam studies can confirm the validity of a research result. In Ismail, Xu, and Liu (2021), ELJs were studied in a recirculating flume with sediment, and velocity measurements were made with an acoustic doppler velocimetry (ADV) (Ismail, Xu, and Liu 2021). The test channel was 15.29 m long and 1.52 m wide run at a velocity around 26 cm/s with a bed slope of 0.00075. An engineered logjam with a 0.29 porosity was compared to a solid structure. They measured the velocity fields at different depths and showed that behind the porous and solid obstruction both of which resulted in decreased flow and the creation of shear stress. However, the solid structure resulted in a wider range of velocities downstream of the ELJ meaning a higher maximum velocity and lower minimum velocity. A test on the side-channel porous ELJ had deposition downstream of the structure, along the shear layer. The shear layer is where the two different velocities (the low velocity downstream of the obstruction and the high velocity region that went around the obstruction) interact and this velocity gradient causes eddies to form, which could move the sediment. This is different from many logjams in the environment which typically have scour directly downstream of the jam, but this did not happen for the porous side-channel case (McHenry et al. 2007).

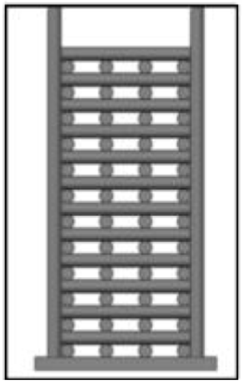


Figure 5: Engineered logjam in Ismail, Xu, and Liu 2021 study. The pictured logjam has a SVF of 0.29.

Deposition of fine organic material in rivers have been found to accumulate downstream of large wood or logjams. Although this has been observed in gravel bed South River in Virginia (Skalak and Pizzuto 2010), Elwha River in Washington (McHenry et al. 2007), and headwater streams in the Front Range in Colorado (Beckman and Wohl 2014). Beckman and Wohl (2014) found that the percentage of carbon per unit volume could be explained by the SVF since large jams can raise water levels that wash over floodplains bringing POM into the river in high flows. Beaver dams are also known to trap POM as the beaver ponds (created downstream of a beaver dam) had a benthic stock of 4075 g/m^2 compared to 125 g/m^2 in riffles Naiman et al. (1986). For boreal forests, beaver dams are known to have greater stocks of POM than the levels from the original forest soil (Naiman et al. 1994). Beaver dams generate a similar effect as logjams in the way that they obstruct rivers and create similar downstream patterns such as the scour/pools downstream of them.

The effect of different porosities in vegetation patches can inform expected wake behavior in response to porosity changes in logjams. Chen et al. (2012) analyzed the wake downstream of a patch of emergent vegetation using physical model tests. The bleed flow, which passes through the patch and enters the wake downstream of the patch (circular array of cylinders) creates a delay in the creation of the von Karman vortex street. The von Karman vortex street occurs where there are two shear layers interacting. In addition, bed friction may suppress formation of vortex street. This thesis investigates logjam generated turbulence and velocities which may have similarities to that of vegetation patches which also varies the solid volume fraction/porosity.

2.3. Studies on Fish Preference

Several studies have analyzed the effect of different wake parameters on fish preference. A study by Hockley et al. (2014) was one of the few studies analyzing how both the velocity and turbulence influences fish preference. To understand their preferences, researchers placed guppies into a flume with submerged boulders then analyzed how long the fish stayed in four different regions, denoted in Figure 6 (Hockley et al. 2014). The regions being high-velocity, moderate-velocity, recirculation zone (region downstream of an obstruction where the water recirculates to fill a region of low velocity), and velocity-deficit zone. The velocity regions created by the boulders have a lot of similarity with those created with logjams. The only difference is that a logjam may not have a recirculation zone.

The study by Hockley et al. (2014) showed that the guppies spent the most time in the moderate zone, which ranged from 40-63% of the total time. The high-velocity zone is where the guppies spent the second longest time (17-32%) but not much longer than the low (3-27%) or recirculation zones (0-12%). In the high-velocity region, larger guppies spent a longer time than smaller ones. The velocity-deficit zone had significantly more male guppies. The region that fish spent the least amount of time was the recirculation zone, smaller fish spent a longer time in this region than larger fish. Even though the recirculation region is relatively small compared with the other regions (with a length of about 8 cm), there is still considerable amount of space compared with the lengths of the guppies. The female guppies had a mean length of 21 ± 3.5 mm, and the male guppies had a length of 16.2 ± 1.3 mm. The preferences for moderate zone yet range of locations that the guppies spent time at shows the complexity of fish preference behind a structure.

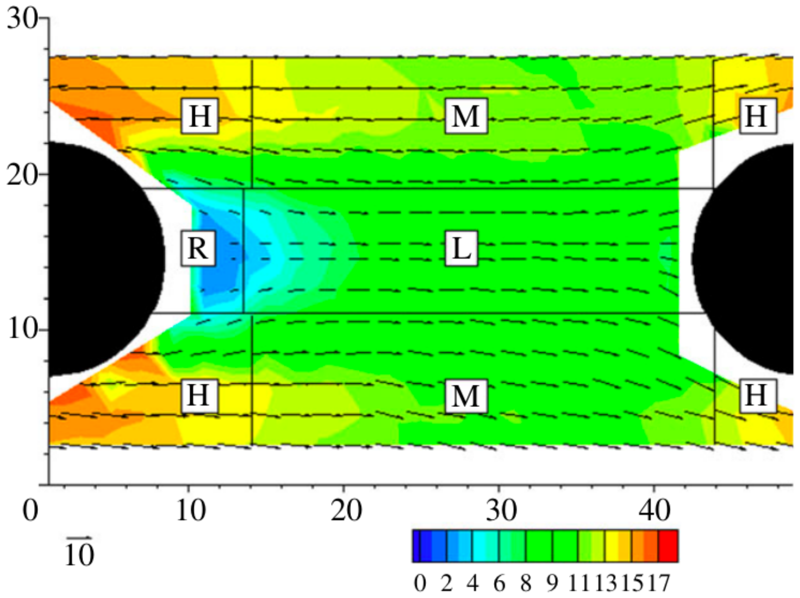


Figure 6: Flow regions around boulders defined by depth- and time-averaged longitudinal velocity u ¯. (H) High-velocity region where there is an acceleration of flow between the side walls and the boulder, (M) moderate-velocity region where the flow from region H decelerates, (R) the recirculation zone, and (L) the velocity-deficit zone in the wake of the boulder (solid black areas). The white areas around the boulders are the limits of the ADV probe so measurements were not taken in these areas. Velocity units are in cm/s and length units are in cm. Taken from (Hockley et al. 2014).

A study on young Atlantic salmon and brown trout, collected 1454 salmon mainly between 7 and 12cm total length and 314 trout between 5 and 12 cm and found that within these ranges the lengths had no effect on habitat preference (Heggenes, Saltveit, and Lingaas 1996). From principal component analysis, seven different habitat variables explained the variance in habitat. The seven were surface, mean and snout velocity, depth, height above bottom, substrate, and cover. The surface velocity is taken at the surface of the water and the mean velocity was an average of velocity measurements by a flow meter. The snout velocity is a relatively high velocity stream or jet of water due to porous structures or irregularities in the water.

The results from a study on Atlantic salmon and brown trout habitat preferences is outlined in Figure 7 (Heggenes, Saltveit, and Lingaas, 1996). The scaling is based on the usage compared with the availability which is different from the Habitat Suitability Index (HIS) (based on hypothesized species-habitat relationships). The calculation for habitat preference (D) followed $D = r - p)/((r + p) - 2\,r\,p)$, where r = proportion of resources used by fish, and p = the proportion of resource available in the environment. The axis from -1 to 1 means that -1 is habitats that the fish do not use at all and 1 is that fish want to be in this habitat, but it is not available. And the middle of 0 being there is an equal amount of demand for the resources as there is the resource. Therefore, anything positive in the fish habitat preference is where there is a preference for these variables that is not reflected in the proportion of the resource.

Figure 8 shows that young Atlantic salmon prefer velocities between 10 and 60 cm/s and between 40 and 110 cm of depth. Whereas for brown trout, they prefer velocities between 10 and 40 cm/s and depths between 30-100 cm. In Norway for the salmon and brown trout study documented would have low flows of from 3 cm/s to 58 cm/s (Heggenes, Saltveit, and Lingaas, 1996). As for substrate preference both preferred larger grained substrate from cobble to large boulder. Heggenes et al. (1996) find that suitable habitat decreased dramatically below a critical minimum flow and even slight increase in velocity from the low flows can make a huge difference. There was no similar case with high flows. The pool areas were more temporally stable and provide a refuge during extreme habitat events. This study highlights the importance of water velocity and pools, however, does not mention turbulence.

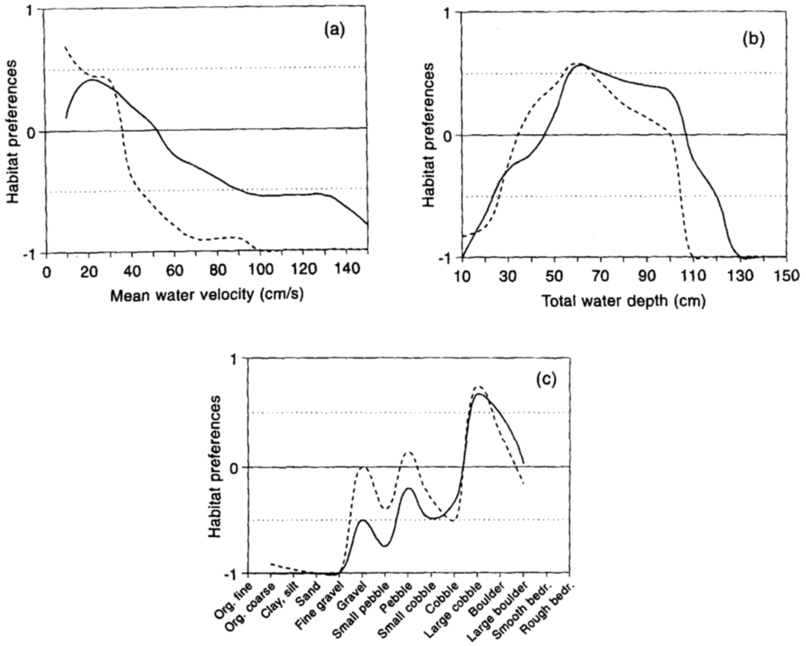


Figure 7: Atlantic salmon and brown trout habitat preference curves based on usage and availability, for young Atlantic salmon (solid line) and brown trout (broken line) in the Gjengedalselva River. (a) Mean water velocity; (b) depth; and (c) substrate. Figure taken from (Heggenes, Saltveit, and Lingaas 1996).

The wide variation in fish preference based on species and age was captured in Beechie et al. (2011). Studying the use of edge habitats of juvenile salmonid throughout winter, spring, and late summer. In the summer, the coho salmon densities were significantly different in use of edge habitats, favoring bank and backwaters over bars. Thus, favoring regions which tend to have wood accumulations and fine sediment. In the winter coho salmon under 1 year old and steelhead selected bank units, where the most complex wood cover was located. Chinook and chum salmon fry were found in all edge units but had a little higher density in regions of velocity <15 cm/s (Beechie et al. 2005). Overall, the fry preferred these edge habitats compared with the midchannel areas. This study highlights the preference by juvenile salmon for wood accumulations and the shallower and lower velocities they provide.

3. Methodology

3.1. Logjam Construction

To model the effects of a logjam in a river, a physical model of the logjam was constructed and placed into a 16 m long, 1.2 m wide recirculating flume. A schematic of the flume is depicted in **Figure** 8. A total of eight logjam configurations were constructed. The logjams spanned either ¼ or ½ of the total channel width, with a length of 10 cm and height of 20 cm. To change the characteristics of the logjams, the logjam width and/or Solid Volume Fraction (SVF) were modified. The SVFs were calculated with this equation: $SVF = (V_w)/(B_j\ h_j\ l_j)$ where V_w = wood volume (sum of individual log volumes within the logjam) and it is divided by the volume of the rectangular prism in which all the logs lie. This is B_j = width of logjam, h_j = height of logjam, l_j = length of logjam. Then the desired wood volume for each specific SVF was calculated by multiplying the SVF with the total volume (0.006 m^3 for the 1/4th channel spanning logs).

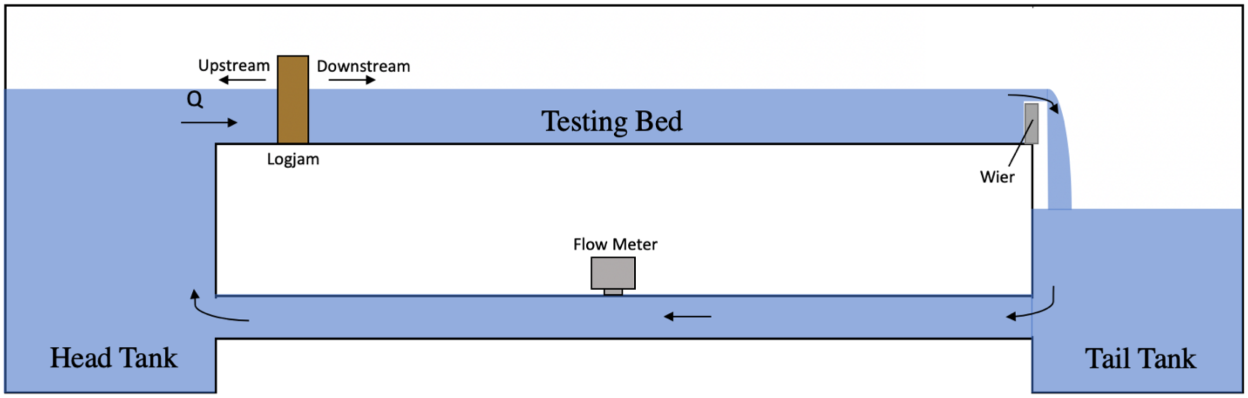


Figure 8: Recirculating flume configuration. Schematic of the recirculating flume used for the characterization of the wake from logjams.

The logjams were constructed by first inserting 8 to 10 (for 1/4-spanning jams) or 20 (for ½-spanning jams) vertical metal rods into an acrylic sheet with holes, outlining base area of the jam to attain the desired length and width and hold the logjam in place. These key pieces resemble conifers with the roots attached that naturally create logjams in rivers (McHenry et al. 2007). Then the natural logs/dowels were arranged in between the two rows of vertical rods to attain the desired height and solid volume fraction. This took some iteration to ensure that the total volume remained the same with the different number of logs needed for each solid volume fraction (SVF).

Solid volume fractions were selected based on what has been measured in the field. The logjams in the Elwha River were described in terms of the wood volume and total volume, from which SVF values of 0.07 to 0.3 were estimated (McHenry et al. 2007). Eighty logjams measured in Rocky Mountain National Park, Colorado had a mean porosity of 0.38 and standard deviation of 0.16, with a range of SVFs from 0.1 to 0.7, also supporting the tested range in this thesis (Livers and Wohl 2021).

The desired volume of wood/logs was achieved by measuring the volume of each natural log by water displacement. In the case of the dowels, the diameter and length were constant, so a simple cylindrical volume equation was used. Since the logs do float a graduated cylinder was used in most cases and a thin rod was used to push the log down just enough that the entire log was submerged. The potential error from the thin rod was less than 5%, calculated by the volume of the rod that could have been in the water over the total volume of the log. The graduated cylinder was filled to a height greater than that of the logs, ensuring that it could be fully submerged. A water volume with and without the log was noted, and the difference was the log volume. Natural wooden logs with kinks or multiple branch connections that couldn't fit into a graduated cylinder, so they placed into an 8L beaker and known amounts of water were poured in until the water level reached the 8L mark at which the logs were also held down to, using an acrylic sheet. Once the measured natural logs/dowels met the wood volume needed the logs were carefully placed between the vertical rods to reach a height of 20 cm.

Table 1 summarizes the eight test cases that were run with different logjam widths, log types, and SVF. Three of the logjams spanned half of the channel width (logjam width $B_j = 0.6$ m) and the rest spanned a quarter of the channel width ($B_j = 0.3$ m). The first two cases were designed to analyze the impact of jam construction on wake structure by comparing how jams with the same SVF can vary the wake structure. The conditions that were be held constant throughout the experiments are the water velocity, water depth (controlled by a weir downstream), and logjam outer dimensions. The discharge, Q, was measured with the flow meter and used to calculate the channel average velocity, which is discussed further in the next section.

Test #	Discharge	Channel Average velocity	Water Depth	Type of Logs	Jam Width	Number of Logs	Solid Volume Fraction
#	Q [l/s]	U [m/s]	h [m]		B_j [m]	n [-]	SVF [-]
1	10.93	0.0876	10.3	Regular	0.60	32	0.30
2	10.88	0.0872	10.3	Regular	0.60	32	0.30
3	10.91	0.0855	10.3	Irregular	0.60	38	0.30
4	10.70	0.0858	10.2	Irregular	0.30	17	0.30
5	10.72	0.0859	10.3	Irregular	0.30	28	0.51
6	10.83	0.0860	10.3	Irregular	0.30	22	0.20
7	11.41	0.0906	10.3	Irregular	0.30	50	0.20
8	11.25	0.0902	10.3	Single Log	0.25	1	1.00

Table 1: Summary of logjam experiments. Regular logs indicate that they are cylindrical dowels/PVCs, whereas irregular logs indicate that they are natural wood with kinks and uneven diameters and lengths.

The SVF of the submerged section was assumed to be consistent with that of the entire jam. However, for SVF 0.2 Big in Figure 9, there were fewer logs in the upper half of the logjam which is above the water. Thus, the SVF that was submerged in the water would be higher than the overall logjam SVF and the reported SVF is a lower bound for what the flow experiences. To ensure that the logjam remains intact, vertical metal rods acted as key logjam pieces.

An issue for reproducibility includes the fact that the logs in each logjam could be easily moved and change formation which meant when putting the logjams back in for the deposition study they could have shifted a bit from when the velocity profiles were taken. The photos in Figure 9 were taken after the velocity and deposition studies and since the velocities were taken first the position of the logs more accurately represent that of the deposition study.

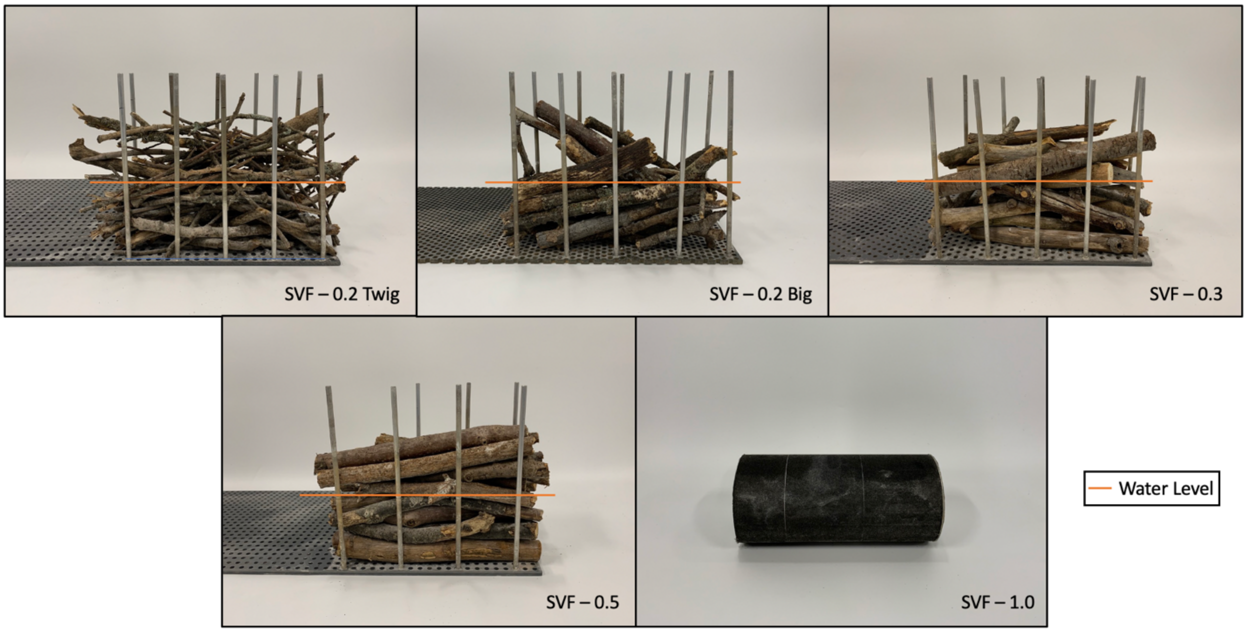


Figure 9: Images of quarter width logjams. Photos above display the four different solid volume fractions that were tested throughout the experiment as well as the difference between the twig and big logs that both have a SVF of 0.2. The orange line indicates where the water level reaches on each of the jams. All the logjams shown above are 1/4th channel spanning logjams.

To better visualize the logjams submerged in the water, Figure 10 shows a side view of three of the logjams and the water level for that experiment. The jams were constructed at almost double the water level to ensure that the entire water column was influenced by the logjam and with a higher velocity potential backwater rise might have made the height necessary.

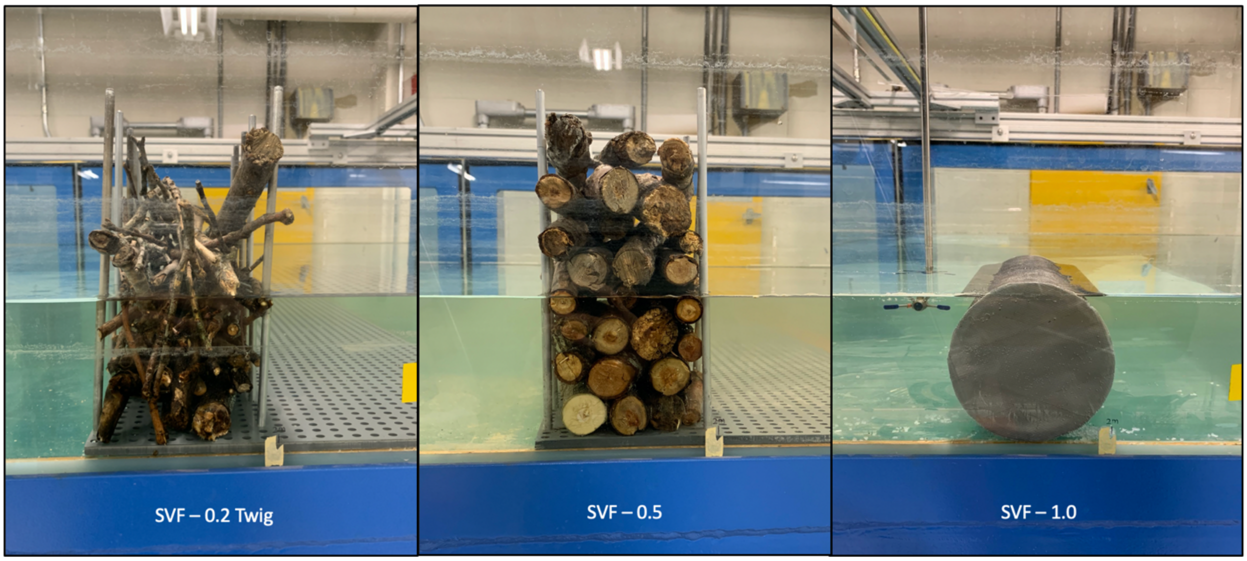


Figure 10: Side profile of logjams during testing with flow direction from right to left. From left to right is the 0.2, 0.5 and 1.0 SVF that span about 1/4th of the channel width. This demonstrates that the logjams are indeed emergent structures as well as a height comparison of the logjams and solid log.

The half spanning logjams are illustrated in Figure 11 and the dowel configuration corresponds to test #2 in Table 1.

Figure 11: Images of the half width logjams with a SVF of 0.3. On the left using uniform dowels and, on the right, using natural wood logs. The natural logs had a similar but slightly smaller averaged diameter thus 38 logs were used in comparison to 32 dowels. Both images are taken in the flume looking downstream.

3.2. Velocity Measurements

To study the wake structure the streamwise (x), cross-stream (y), and vertical (z) velocity was measured using a side-looking acoustic doppler velocimeter (ADV; Nortek Vectrino). Each velocity record was 120 seconds long with a sampling rate of 200 Hz. To ensure a correlation of at least 80% between the two measured pulse echoes, seeding material was added as needed. All the jams had the velocity and u_{rms} (root mean square velocity in the x-direction) measurements, the u_{rms} is used in this study as a proxy for turbulence. The results of which would be compared with studies on fish preference to suggest the characteristics desired to promote the ideal fish habitat.

After collecting the data, a MATLAB script was used calculate the time-mean ($\bar{u}$, $\bar{v}$, $\bar{w}$) and fluctuating components (u', v', w') to de-spike the data. Based on these measurements, the following terms were determined: the average velocity ($\bar{u}$, $\bar{v}$, $\bar{w}$) and the streamwise root mean squared values (u_{rms}). The u_{rms} was calculated by taking the square root of the sum of the squared fluctuating component of the streamwise velocity (u') : $u_{rms} = \sqrt(\sum_{i=1}^{n} u_i'^2)$.

A 7.4 cm tall weir at the end of the channel controlled the flow depth. With the variable speed pump at 18 Hz frequency, the resulting water depth was 10.3 cm making the logjams an emergent structure, and the resulting velocity was $U = 9$ cm/s. The velocity U was evaluated using the flow rate Q from the flow meter and applying the continuity equation $U = Q/(B\,h)$ where B = channel width and h = water depth. The water depths were determined by a ruler which was positioned at 1.5 m downstream of the logjam. The logjams were all positioned along the side of the channel like a bar apex jam in natural rivers.

To characterize the wake from each logjam, longitudinal (x-direction), lateral (y-direction), and vertical (z-direction) profiles were taken. Figure 12 shows the schematic of the testing plan for each of the logjams. Two longitudinal profiles were taken, one in the middle of the logjam and one in the middle of the unobstructed channel adjacent to the jam. Vertical profiles were also taken around the logjam and specifically downstream of the jam to show the progression of the wake as well as to account for the heterogeneity in the logjam.

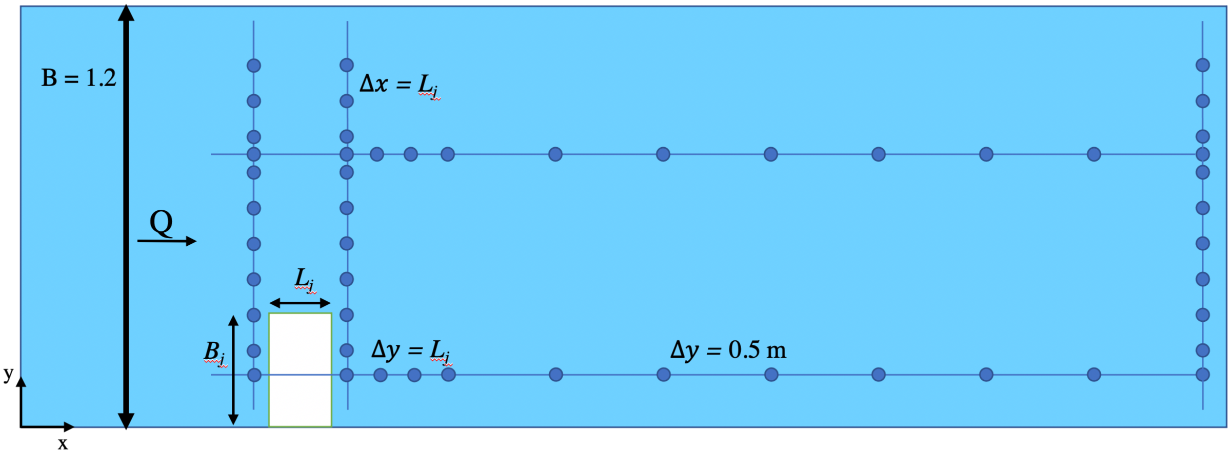


Figure 12: Locations for velocity testing using the Nortek ADV. Two longitudinal profiles and three lateral profiles were taken for each configuration. The two lateral profiles near the logjam are 5 cm in front and 5 cm behind the logjam. The third lateral profile is 4 m downstream of the logjam. The lateral profile increments with L_j (10 cm) except for where the longitudinal profile cuts through it and then its ½ L_j (5 cm). The longitudinal profiles are taken in the middle of the logjam and the middle of the unobstructed channel. This figure documents the quarter width spanning logjam, however the testing is the same for the half spanning, as longitudinal profiles are still taken in the middle of each channel. The points initially scale with L_j then are taken at 0.5 m intervals until 8 m downstream (only 4 m downstream is in the figure above).

A vertical profile of streamwise velocity was measured upstream of the jam to confirm that a well-developed flow is present upstream of the logjam, illustrated in Figure 13(a). The measurements were taken one meter downstream of the start of the test section, and the start of the logjam was located two meters downstream of the start of the test section. A display of additional vertical profiles at three locations upstream and downstream of the logjam (SVF = 0.2

Big) demonstrates the accuracy of the simplification to measure the longitudinal and lateral profiles at $z = 0.5\ h$ (Figure 13b-d). While it is a good approximation for the open bed case (test without any logjams in the flume) (Figure 13a), the profile measured 5 cm upstream of the logjam (Figure 13b) shows that $z = 0.5\ h$ is a good approximation for the upper half of the channel depth, while it does not average in the lower part of the water column.

Figure 13(c) is located 5 cm downstream of the logjam for SVF = 0.2 Big. At this location, $z = 0.5\ h$ is not a good approximation as it corresponds to the extreme values for u, v, and u_{rms}. However, further downstream at $x = 0.15$ m, the approximation improves, and $z = 0.5\ h$ represents a good column average, except for the v vertical profile. In summary, $z = 0.5\ h$ is a good approximate for u and u_{rms} if the measurement is taken 15 cm downstream of the logjam and is a good approximate for v in the open bed or unobstructed channel side. Therefore, all the lateral and longitudinal profiles were taken at half of the water depth with $z = 0.052$ or 0.053 m. Since the ADV needs to be submerged to get measurements, the vertical profiles went up to 8 cm out of the 10.3 cm water depth. For the measurement at 8 cm, the top two receivers were 1 to 2 mm above the water surface, however, the correlation was still above 80%, and the focus of the measurements was put on u and v and not on w.

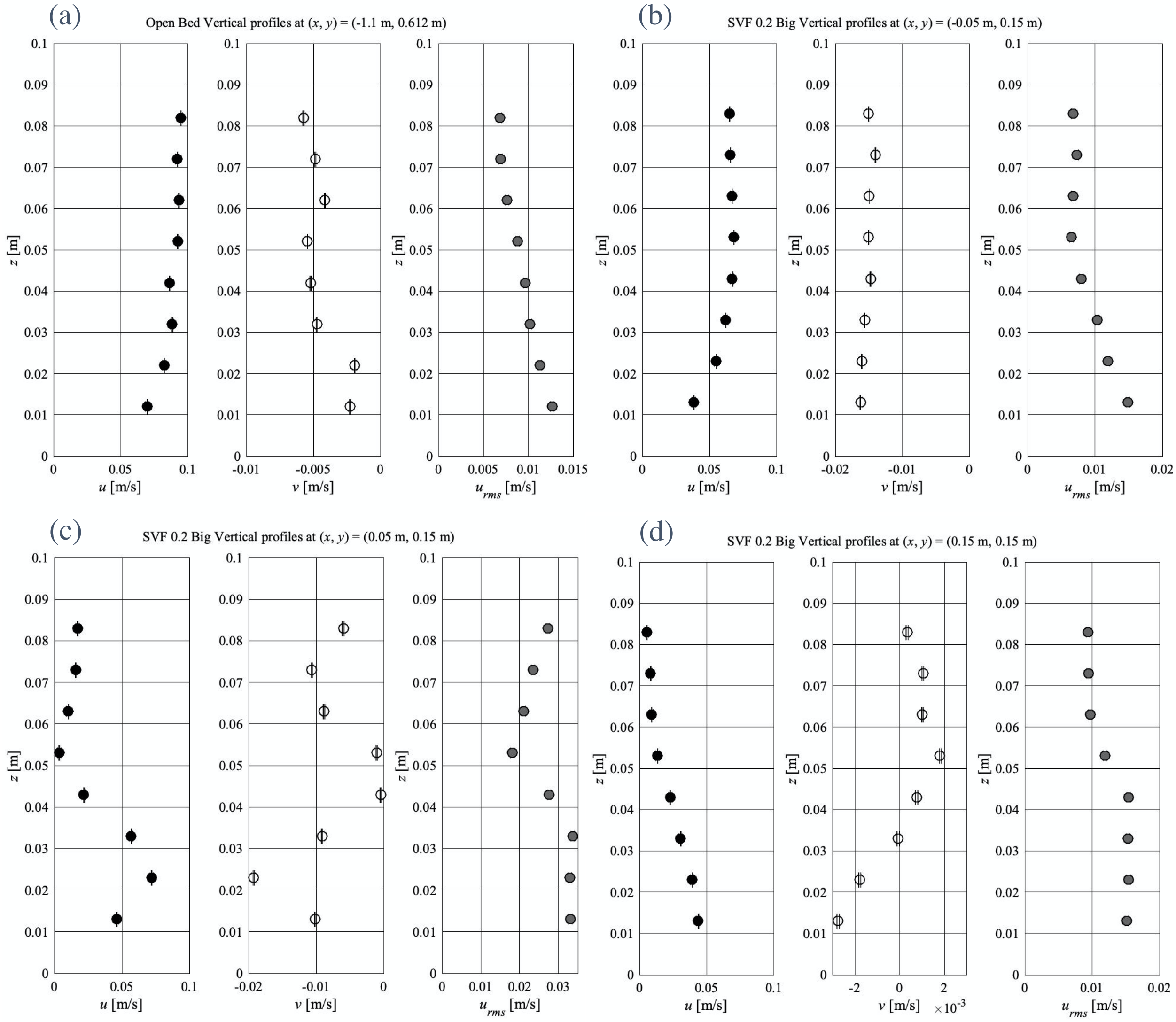


Figure 13: Vertical velocity profiles of u, v, and u_{rms} to show heterogeneity in water column and the estimation when using z = 0.052/0.053 as a proxy for the entire column. (a) are the vertical profiles of u, v, and u_{rms} for at the center of the flume width and 1 m into the test section. (b), (c) and (d) are all vertical profiles of u, v, and u_{rms} for the SVF=0.2 big log test, with (b) 5 cm upstream of the logjam, (c) 5 cm downstream of the logjam, and (d) 15 cm downstream of the logjam.

3.3. Deposition of Fine Sediment

After completing the velocity measurements for each of the constructed logjams, deposition studies were done for 5 of the logjams with $B_j = 0.30$ m (tests 4-8 in Table 1). The footprint of organic matter deposition in the vicinity of logjams was simulated by studying the deposition of A4000 Potters spherical solid glass spheres on glass microscope slides (2.5 cm by 7.5 cm by 0.12 cm). The glass spheres had a mean diameter of 25 microns and settling velocity of w_p = 0.0005 m/s. The process of inserting the spherical beads, duration of run, slowly decreasing the water speed as to not affect the deposition and drying the slides closely followed that of Shi, Jiang, and Nepf (2016).

The decision on slide placement largely depended on locations of velocity measurement and areas of interest. Similar to the velocity measurements, longitudinal profiles in the channel and logjam center were taken, but with less spatial resolution. In addition, slides were added perpendicular to the edge of the logjam to document the effects of the velocity shear, as well as, near the wall of the flume to analyze the deposition downstream of the logjam. The decided placement of the glass slides is shown in Figure 14. The location of the center of each slide in the $y = 0.15$ (center of the logjam) and $y = 0.75$ (center of the unobstructed region) longitudinal profiles corresponded to locations with velocity and u_{rms} measurements.

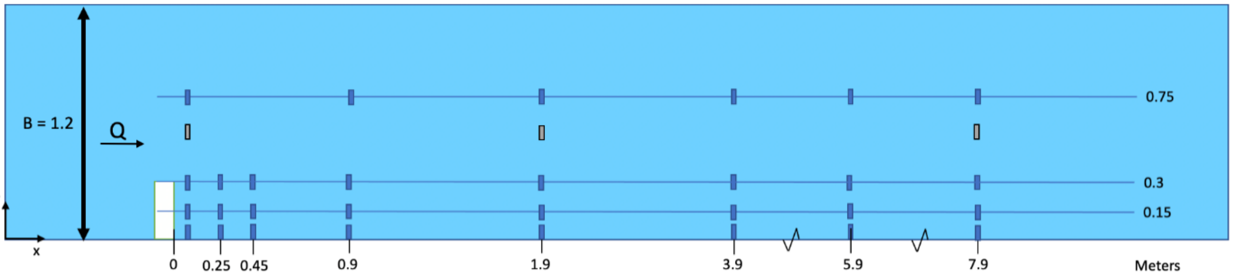


Figure 14: Glass slide locations for measuring sediment deposition. The center of each glass slide in the y = 0.15 and y = 0.75 aligns with velocity and u_{rms} *values for easy comparison. Three additional glass slides in grey were placed in the center of the flume following the run to measure deposition.*

The process started by filling the flume and placing the logjam into the test bed. At an initial water level of $h = 4$ cm, the incoming flow of water was turned off and then the variable pump was set to 18 Hz. This is the same set up as with the velocity measurements. The glass slides were numbered and weighed prior to being placed on the bed of the flume. With the pump running, 550 g of the glass beads were added to the flow. This was done by mixing the 550 g of particles with 5 gallons of water until it was well mixed. Then the solution was poured into the tail tank and the water in the tail tank was mixed with a paddle as some glass beads floated on the surface. To ensure all the particles were emptied from the container, the container was rinsed with water from the flume. After the particles entered the flume and were seen entering the test section, a 500 mL water sample was taken upstream of the logjam near the head tank. Following this, a timer was set to run the experiment for 4 hours.

After 4 hours, another 500 mL water sample was taken, and extra slides were inserted into the test bed, the pump was turned off, and the tank was drained. Three slides were placed into the middle of the width of the jam and at three *x* locations from near the logjam to near the tail tank, grey colored slides in Figure 14. These slides served as a reference that sediment was not kicked up due to the draining process. To not disturb the deposited sediment the pump frequency was slowly decreased at a rate of about 1 Hz every 45 seconds from the set 18 Hz to 0 Hz. Following this, the weir was slowly lifted to equalize the water depth in the testing section and the tank. To drain the water, a draining valve was opened halfway letting the water drain for 20 mins, allowing the flume to drain just below the test bed. Then the slides were left to dry for over 8 hours, such that there would be no surface tension making it hard to carefully pick up the slides without disturbing the sediment dried on it. When the test bed was dry the glass slides were picked up by the sides and placed into aluminum trays. These trays were placed in a drying oven heated to 60°C and left for 4 hours to get rid of any left-over water weight. Then the glass slides were cooled for 10 minutes and reweighed to obtain the net deposition, which was the difference in slide weight before and after the experiment, divided by the area of the glass slide (Shi, Jiang, and Nepf 2016).

To measure the suspended concentration, the water sample was filtered through a glass microfiber filters using a three-cup water filtering system. The 0.7-micron glass microfiber filters with a diameter of 4.7cm were placed onto aluminum weighing dishes. The filter and dish pair were weighed to get the initial weight without any sediment. Then for each water sample the filter was placed into the filtering system and then the water was poured over the filter and the machine sucked the water through, leaving the glass spheres on the cloth. To ensure there were not any sediment still in the bottle holding the water, it was flushed with tap water. This was then also put in the 60°C drying oven for 4 hours to dry out the filter and was let cool for 10 mins prior to weighing again. The weight difference in the initial and final filters gave the grams of glass beads and divided by the water amount gave the concentrations.

To ensure that the placement of the glass slides was consistent for each deposition study, markers were placed on the underside of the glass flume bed at each slide position. The markers were two strips of tape forming a right angle corresponding to the upper right-hand corner of each slide. A schematic was also drawn to match the numbered slides with a position on the testing section. This allowed for easily matching the position with the slide when weighing each slide.

3.3.1. Mass Balance of Sediment

The water sample concentrations and glass slide deposition were compared to achieve a mass balance of the amount of sediment that is available for deposition. All experiments started with the same amount of sediment. However, after completing a few deposition studies the results of the logjam tests showed reduced deposition when compared with the open bed case. Thus, mass balance completed in Table 2 showing the observed sediment deposition and water samples. To calculate the estimated fine sediment deposition across the entire testing section, an average was taken of all the sediment deposited onto the glass slides which was then translated to a fraction of the total testing section and multiplied to the entire area. This value is summarized in the second column of Table 2. Then the water sample taken at the end of the experiment was used to calculate the remaining fine sediment left in suspension. This was done by dividing the dried sediment over the volume of water and multiplying it by the total volume of water in the flume. Assuming that all the initial 550 g of sediment was available for deposition, the sum of the deposition over the test bed (total estimated deposition; column 4 of Table 2) and the sediment in suspension at test end (column 8 of Table 2) was subtracted from the initial 550 g of glass beads. Thus, the loss of fine sediment is the amount that is not accounted for by bed deposition or suspension. For the open bed case there was a loss of 30.1% which could have been deposited in or on the slide of the head/tail tanks. Another reason could be the lack of glass slides upstream of the logjam where there would be higher deposition (since the open case showed decreasing deposition with length into testing section) which would lead to having a lower estimate of the total deposition of the testing section.

The fine sediment available for deposition that was measured at the start of the experiment, as estimated by the 500 mL water sample, is represented in column 7 “Available Sediment at test start (water samples)” of Table 2. In some cases, this value is less than the total estimated deposition, meaning that there was more available sediment to be deposited than what was determined by the water sample. This is likely due to the inconsistent time between pouring in the fine sediment mixture and taking the sample. Because of this inconsistency, the initial 550 g was used as the initial available sediment.

The results of the water samples taken for each of the fine sediment deposition studies are seen in column 7 of Table 2. The initial concentration/sediment amount is largely the same except for the 0.2 SVF logjam which could be due to the timing of the water sample. This could have been the issue because after pouring in the glass bead (fine sediment) mixture the tail tank was mixed and after observing particles enter the testing section the sample was taken, and there was no consistent time for the sample. The range of available sediment difference between all the cases is 77.5 g (14% of the 550g initially put into the flume).

Test Case	Ave Deposition /Slide	Std Error	Total estimated deposition	Loss of fine sediment	Loss of fine sediment	Available sediment at test start (water samples)	Available sediment at test end (water samples)
	[g]	[g]	[g]	[g]	[%]	[g]	[g]
1	48.6	1.1	348.8	165.67	30.1%	337.0	35.5
2	27.2	1.7	195.4	341.15	62.0%	313.2	13.4
3	38.4	1.0	275.2	225.18	40.9%	261.5	49.6
4	36.6	1.0	262.2	228.84	41.6%	332.8	58.9
5	36.5	1.2	261.6	271.58	49.4%	347.3	34.1
6	34.1	0.8	244.3	258.97	47.1%	328.7	49.6

Table 2: Mass balance on deposition of fine sediment. The test cases increase with SVF with 1- open bed, 2- 0.2 SVF twig, 3- 0.2 SVF big, 4- 0.3 SVF, 5- 0.5 SVF, and 6- solid log. The available sediment at the start and end of the test was calculated by multiplying the fraction of sediment in the sample with the volume of water in the entire flume.

3.3.2. Replicated Deposition Case

A replicate experiment was done for SVF = 0.3 to observe the uncertainty between runs and get an estimation of error. Since the tests were not taken one after the other, the logjam was taken out and put back into the flume which could have altered the configuration of the logjam. The repeated experiment also included additional measurements upstream of the logjam for comparison with an open bed deposition. There were 12 additional slides placed upstream of the logjam in the same four *y* locations as seen in Figure 14. The three rows were placed at x = -0.15, -0.4, and -1.1, which corresponded to 0.05 m, 0.30 m, and 1.00 m upstream of the logjam as the jam is placed from x = -0.1 to 0. Since the logjam is constructed on an acrylic sheet with a depth of 5mm, additional acrylic sheets were placed upstream of the logjam to have consistent heights for all the upstream measurements. The rest of the experiment was the same, from starting the flume to drying and weighing the glass slides.

4. Results

4.1. Velocity and Turbulence Comparisons

4.1.1. Variation in logjams with the same SVF

To assess the variability of wakes within the same uncertainty, three different half-width spanning logjams with a SVF = 0.3 were tested. The first two logjams were created with regular dowels that were 2.54 cm in diameter and 25.4 cm in length. The third logjam was made with natural wood that had a similar length but on average smaller diameter (38 logs instead of 32 dowels were used, as seen in Table 1). Comparing the velocities, the maximum difference in the unobstructed side was 0.19x the approach flow velocity (at $x = 4.5$ m) which is only 5% of the averaged velocity between the dowel logjam 2 and natural logjam. As for the logjam side of the channel, there is a significant difference with dowel logjam 1 having high velocities downstream of the logjam, likely due to gapping in the logjam allowing a jet of water to pass through the logjam. The maximum difference for the logjam side is 0.22x approach flow (at $x = 2$ m). The natural logjam has a wider range of velocities, but this is likely because of the heterogeneity of the logs, there is a higher frontal area. As for the u_{rms} values, the logjams follow the same pattern where there is an initial spike right downstream of the logjam, followed by a second, smaller peak at $x = 4$ m ($x = 6.7\ B_j$). In addition, farther downstream from the jam ($x > 1$ m) the turbulence in the unobstructed side is higher than the logjam side (circles vs. triangles, respectively, in Figure 15). Overall, logjams with similar SVFs but consisting of different log shape act very similarly with exceptions for changes in frontal area or locations of local water jets.

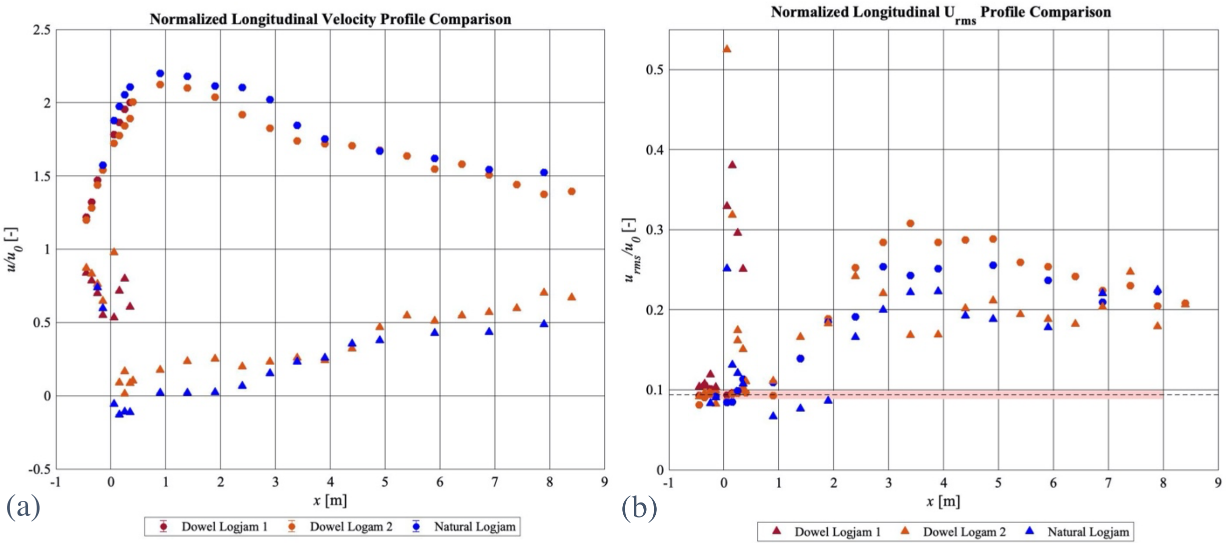


Figure 15: Variation in logjams with the same SVF. The profiles are for half spanning logjams with SVF = 0.3. The triangles are located at logjam center (y = 0.3 m) and the circles are at the unobstructed channel center (y = 0.9 m). (a) plots the velocities while (b) plots the u_{rms}. The dowel logjam 1 in red only has points between x = -0.35 m to x = 0.45 m.

4.1.2. Varying Channel-Spanning Width

A comparison between the velocity and u_{rms} values for the 0.3 SVF quarter width and half width spanning jams is seen in Figure 16. In the unobstructed side of the channel (circles) the velocities for $B_j = 0.60$ m were much greater for the entire length of the testing section with a maximum of 2.2x the initial velocity. In comparison, the maximum velocity in the quarter width logjam is only 1.67x the channel average velocity. However, both the quarter and half spanning logjams do peak at the same location, $x = 0.9$ m or 3x the width of the quarter width logjam or 1.5x the width of the half width logjam, which means the dominating length scale for velocity is not B_j. Interestingly after 2 meters the velocity behind the logjam (triangles) for both cases were roughly the same. As for the velocity in the unobstructed channel, the decline in velocity in both cases has a similar linear decrease after 4 meters. The u_{rms} is higher for the half spanning logjam near the logjam because more water is being redirected around the obstruction. However, behind the logjam center and in the unobstructed side center, the u_{rms} is much lower because the locations are farther from the shear layer than the logjam center in the quarter spanning case. As for the unobstructed side for the quarter spanning case, the turbulence is also lower potentially because the flow is steadily high.

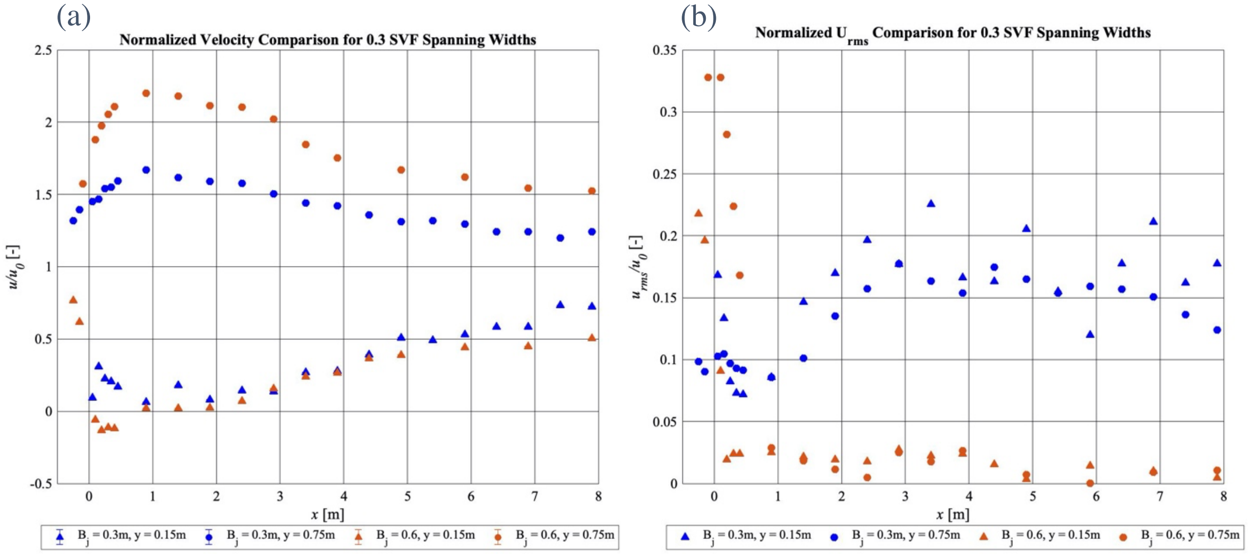


Figure 16: Comparison of a half width and quarter width logjams in the velocity and u_{rms} *profiles. The velocity in the unobstructed channel gets larger for the half spanning logjam and lower downstream of the logjam. The* u_{rms} *values were higher everywhere for the half spanning as compared with the quarter width jam.*

The differences in velocity and u_{rms} indicate that the half-width logjam is more beneficial for juvenile salmon as it is creating a region with lower velocity and low turbulence. However, the half-width logjam does have some recirculation immediately downstream of the logjam ($x < 0.5$ m) which would not be utilized as much by fish species. The quarter spanning logjam offers a very similar velocity profile in the logjam section of the channel, while not increasing the water velocity in the unobstructed region nearly as much. Lower velocity in the unobstructed region can benefit migratory fish as they are able to travel farther without expending as much energy (Brodersen et al. 2008). These are a few of the tradeoffs that arise when deciding what type of logjam to construct.

4.1.3. Varying SVF

The longitudinal velocity profiles in Figure 17 show that increasing SVF resulted in increasing velocity in the unobstructed side of the channel and decreasing velocity downstream of the logjam side of the channel. This occurs because the flow obstruction increases with increasing SVF, and more flow is diverted to the unobstructed side due to conservation of mass. The velocity downstream of the logjam ($y = 0.15$ [m]) shows recirculation for SVF = 0.5 and solid log (SVF = 1). With the log diameters of around 2.6 cm, which corresponds with SVF 0.2, 0.3 and 0.5 (not SVF 0.2 twig), the streamwise velocity grows in the unobstructed side as the porosity increases. This confirms our expectation: since more water needs to be redirected, there are higher velocities with higher SVF.

The longitudinal u_{rms} values for varying SVFs are shown in Figure 18. The u_{rms} values are an indication of turbulence. With this assumption, the turbulence levels downstream of the logjam increase with increasing SVF. After the initial increase and decrease that occurs 1 m downstream of the jam the u_{rms} typically ranges between 1.5 and 2.5x the open bed u_{rms} values. The location of the maximum u_{rms} for the logjam side is different for every case from 5 cm downstream for the 0.2 SVF big and 0.3 SVF to around 3.9 m for the other cases. The location of the maximum u_{rms} for the unobstructed case ranges from 2.9-4.4 m.

In all instances, the 0.2 SVF logjam made with twigs acts more like the 0.3 SVF rather than the other 0.2 SVF. Comparing the two 0.2 SVF cases (one with the average log diameter of 2.7 cm (big) to one about 1.0 cm (twig)), we see that the twig case showed higher velocities in the unobstructed side. This could have resulted from an increase in turbulence from log flow around more logs, as 0.2 SVF twig has 50 small logs compared with 22 larger logs (test 6-7, Table 1). The increase in logs could have also resulted in a higher frontal area that could have also played a role in the turbulence increase as the flow diversion increases.

Within the span of 8 meters downstream of the logjam, none of the cases regained uniform flow across the channel width. By extrapolating, the data suggests that by 10 meters (about 33 length scales behind the logjam) the flow conditions would return to the initial flow conditions. For both the unobstructed side and behind logjam the velocities across the SVFs recover at the same rate after 4 meters downstream of the logjam (about 13 logjam lengths).

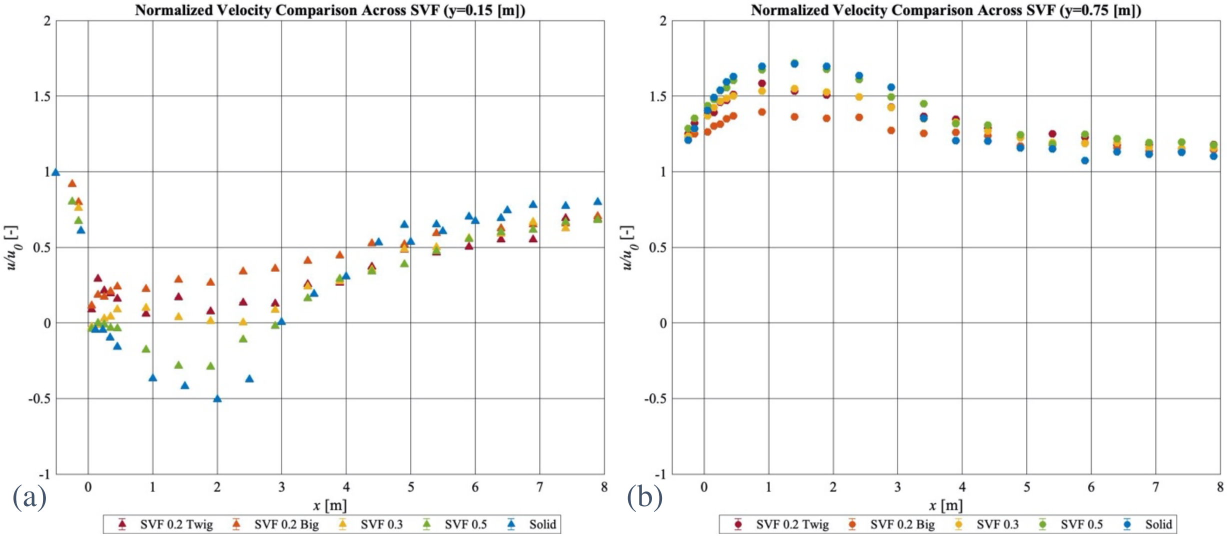


Figure 17: Normalized longitudinal profile of U for varying SVF for (a) taken in middle of logjam and (b) in the middle of the unobstructed side. The location of the jam is -0.1 to 0 on the x axis which shows that for the velocity behind the logjam is clearly diminished and there is even recirculation for the SVF = 0.5 and solid log.

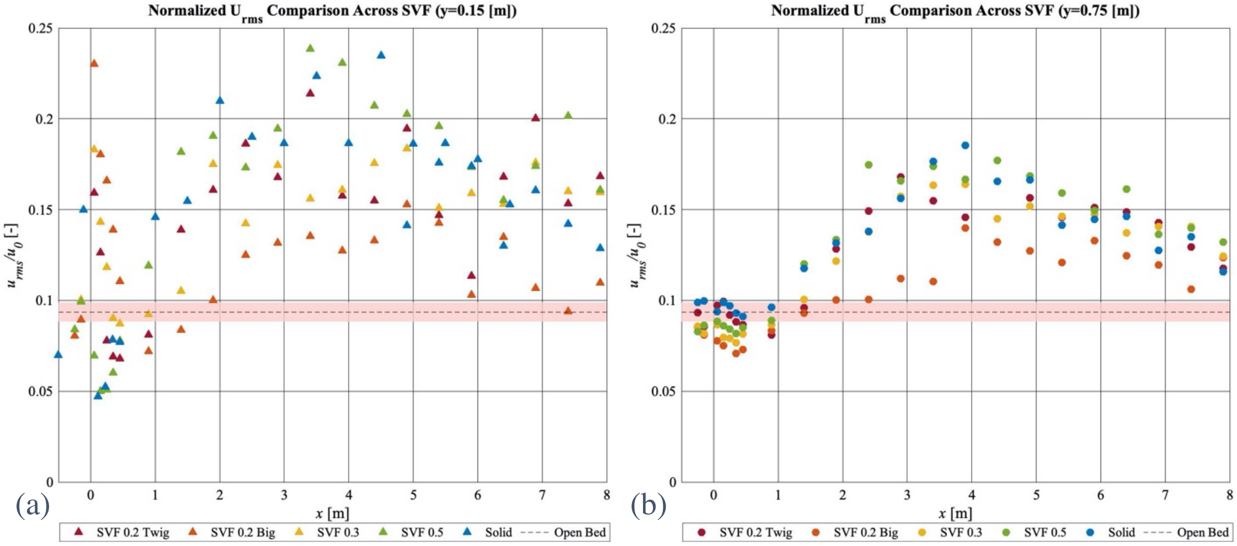


Figure 18: Normalized longitudinal profile of u_{rms} for varying SVF with (a) measured in the middle of the logjam (y = 0.15 m) and (b) measured in the middle of the unobstructed side (y = 0.75 m). The u_{rms} values were generally larger behind the logjam and more variable. Both (a) and (b) show a general patter of increasing with increasing SVF, although it is much less clear on the logjam side.

The evolution of the shear layer is displayed in the lateral profiles upstream and downstream of the logjam in Figure 19. Upstream of the logjam, the velocities are already influenced by the logjam, as velocities near the logjam side of the channel are less than the approach flow, and velocities on the unobstructed side are above the approach flow. However, there is still a gradual gradient between the two sides. Then 5 cm downstream of the jam, there is a clear distinction between the logjam and unobstructed side with a difference of around 1.5x the approach flow velocity. A distinction between the SVFs is only seen close to the logjam with velocities on the unobstructed side increasing with SVF. The logjam side still had very similar velocities except for the 0.2 SVF Big test which showed higher velocities which could be due to the configuration of the logjam, allowing jets of water through the jam. Noticeably, the u_{rms} values immediately downstream of the logjam ($x = 0.05$ m) are higher near the logjam than in the unobstructed side. This is due to the interacting of different velocities and the shear layer.

At 3.9 m downstream of the logjam, there is little difference in velocity and u_{rms} values across the different SVFs. This is also the point where the wakes of each logjam become almost the same as seen in the longitudinal profiles as well (Figure 17).

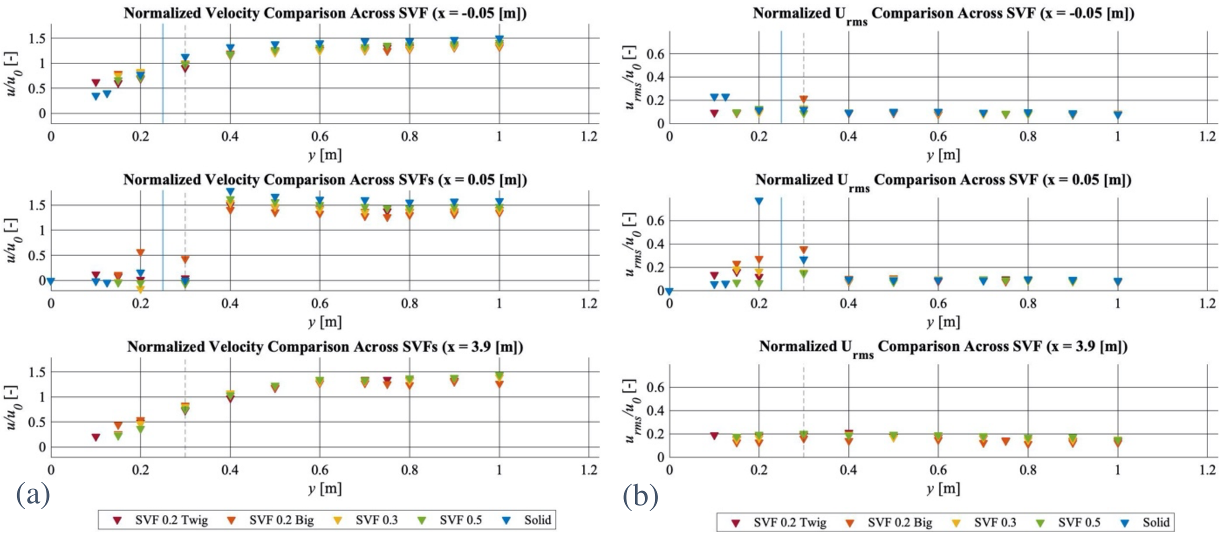


Figure 19: Normalized lateral profile of U and u_{rms} for varying SVF. (a) are the velocity profiles and (b) the u_{rms} values. The figures show the evolution of the lateral profile from 5 cm upstream of the logjam, 5 cm downstream of the logjam and then 3.9m downstream of the logjam. From 0 to the solid blue line corresponds to the location of the solid log. From 0 to the dashed line corresponds to the location of the logjam. A lateral profile was not done for the solid log at 3.9m downstream.

4.1.4. Correlation between velocity and u_{rms}

To identify the relationship between the velocity and u_{rms} in the wake of logjams, a linear regression, correlational coefficient, and p-value was calculated. The regression was done with MATLAB's corrcoef function. The results of this analysis are shown in Table 3. A significant p-value ($p < 0.05$) for the velocity versus u_{rms} in the unobstructed region shows that the relationship between the velocity and u_{rms} are not due to chance. Although there is a negative relationship (increases in one lead to decreases in the other) as shown with the negative correlational coefficient, the confidence in the linear fit is weak (low r^2 value). Concluding that there is a significant relationship between the velocity and u_{rms} in the unobstructed side of the channel but the impact of one on the other is not well defined by the data points available. The correlation between velocity and u_{rms} is not significant in the logjam side of the channel ($y = 0.15$ m).

	p-value	Correlation Coefficient (r)	Coefficient of Determinant (r^2)
$y = 0.15$ m	0.6032	0.0329	0.1%
$y = 0.75$ m	**0.0329**	-0.4075	16.6%

Table 3: Statistical significance and correlation between U and u_{rms}. The bolded value is statistically significant.

4.2. Deposition

4.2.1. Repeated Experiment and Uncertainty

Reproducibility of the deposition was evaluated by repeating a test with the quarter width spanning natural logjam with SVF = 0.3. The differences can be seen in Figure 20. Generally for the deposition downstream of the logjam the values agree within the error bars. However, there were a few instances with a noticeable difference, with the maximum difference being in the unobstructed channel at 1.9 meters downstream. This could be due the slides in the unobstructed channel not accurately representing to or the logs in the logjam shifting between from taking it out and putting it back in for the deposition cases.

Figure 20 also displays six additional deposition measurements upstream of the logjam. The deposition upstream of the logjam was on average 136% higher than downstream of the logjam, indicating that the combination of lower velocity and lower turbulence levels promote sediment deposition. However, the deposition in the logjam center is comparable to the unobstructed channel section (1.2-4% relative difference), concluding that the “lost” sediment as mentioned in Table 2 had not deposited on upstream of the logjam. There is lower turbulence and lower velocity upstream of the logjam which correlates with the higher sediment deposition. However, this could have also been related to the concentration of sediment was higher, as the system is deposition dominated. Therefore, further testing and analysis are needed to vaildate this hypothesis.

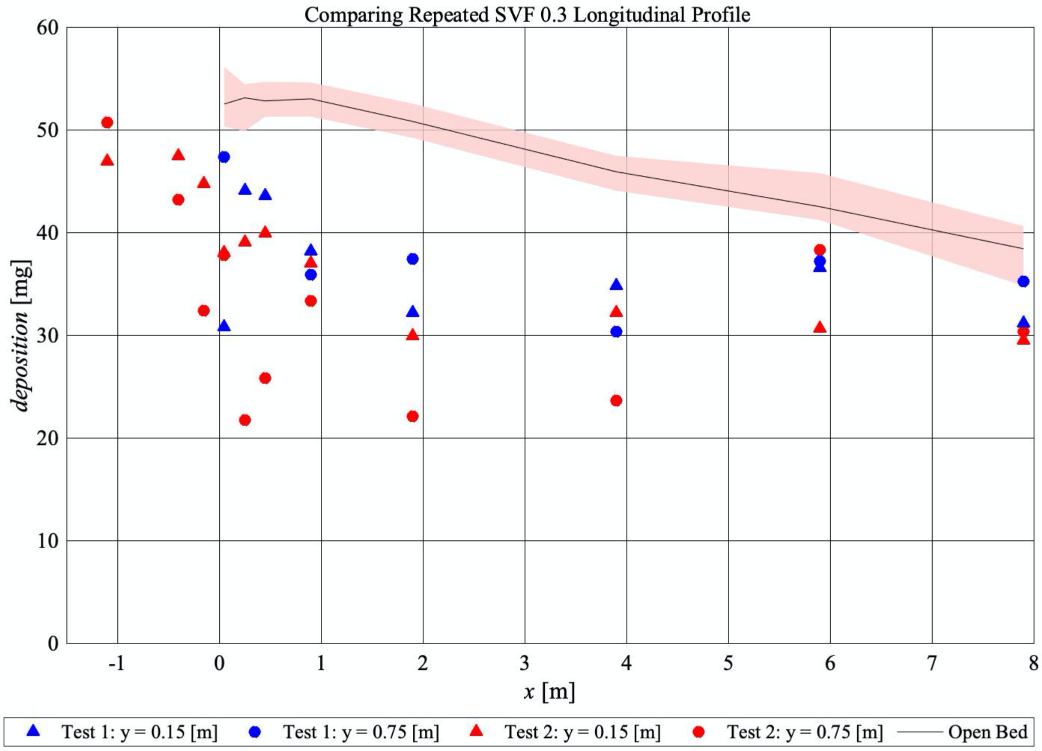


Figure 20: Repeated deposition case for SVF 0.3 to understand reproducibility in the deposition patterns. The error bars around the logjam side stem from the standard error of the three glass slides placed behind the logjam at y = 0.05m, y = 0.15m and y = 0.3m. For the second case, additional upstream values (x<0) were added.

A summary of the average difference between the two 0.3 SVF deposition experiments, highlights the difference between the logjam side of the channel at $y \leq 0.30$ and the unobstructed side of the channel at $y = 0.75$ (Table 4). The uncertainty in the logjam side was 13.2% while the uncertainty in the unobstructed side was 20.7%. The overall uncertainty from the system heterogeneity found by the repetition of the logjams is 14.5%.

y Location of Longitudinal Profile	Difference/Average	Standard Error
$y = 0.05$	11.7%	4.5%
$y = 0.15$	13.2%	2.6%
$y = 0.30$	12.6%	2.0%
$y = 0.75$	20.7%	7.4%
Total	14.5%	2.7%

Table 4: Error estimation from repeated deposition case. Averaged across the y-position for each slide location present in both experiments.

One factor that could also have influenced the glass slides immediately following the logjam (5 cm downstream), was the fact that the plate holding the logjam is 0.5 cm above the glass bed of the flume which created a space of no deposition directly downstream of the platform. The slides also were 0.5 mm above the glass bed which sometimes caused a build up in front of the glass slide as opposed to on it as visible in Figure 21. While the sediment was suspended, after depositing the sediment could have also been transported through bedload, which would explain the build up in front of the glass slides. If the glass slides are also moving through bedload (sliding or rolling along the bed) a higher velocity would cause more transport in the glass beads which is how more is accumulated in front of the slide since there is a slight height increase that would stop the glass bead. This could explain why the unobstructed side of the channel had a higher uncertainty in sediment on the glass slide (row 5 of Table 4). Since bedload transport could have rolled the sediment off the slide created decreases in deposition. On the other hand, the build up of fine sediment upstream of the glass slide could have rolled onto the glass slide. These two events could have created that larger range in sediment on the slide.

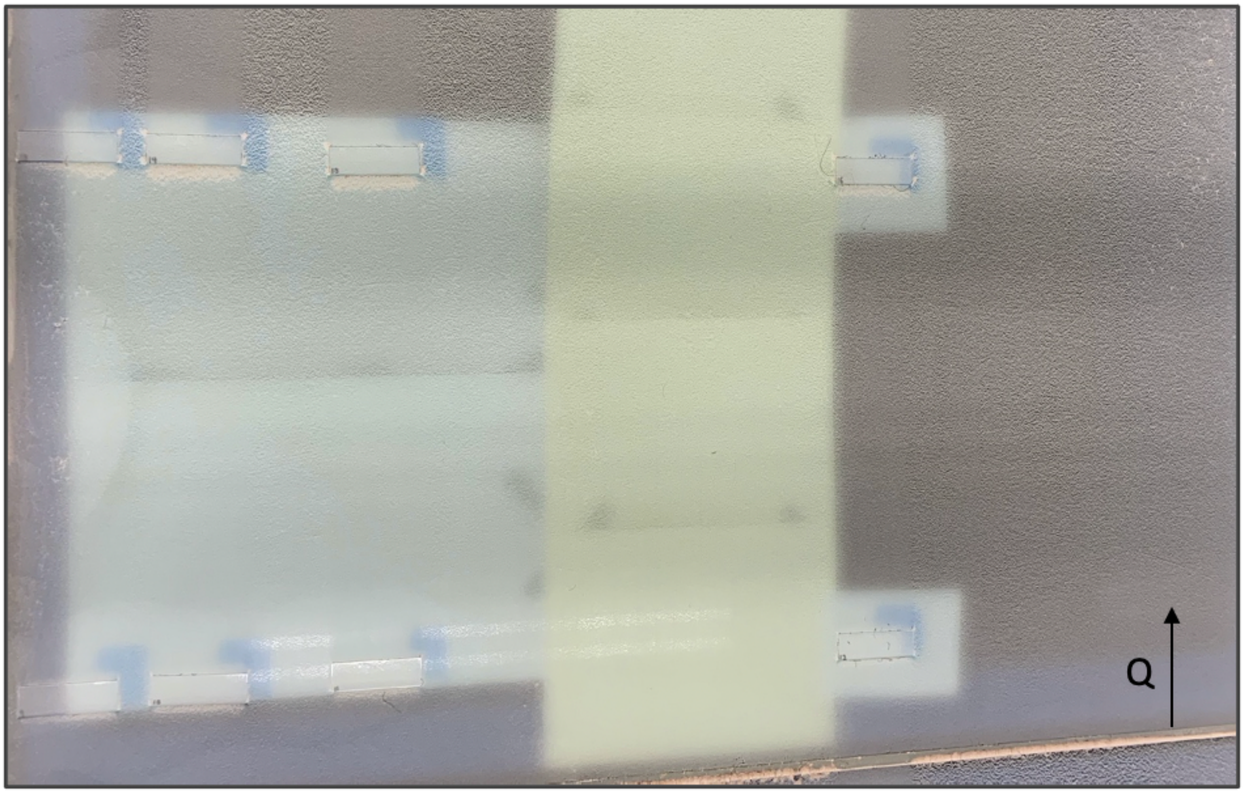


Figure 21: Deposition of fines upstream of slides. Glass slides at locations y = 0.5 m and y = 1 m in the open bed scenario, displaying the buildup of fine sediment upstream of the glass slides.

In Figure 22, the sediment deposition doenstream of the 0.5 SVF logjam looks similar to that of the open bed case and appears like a blanket of glass beads, whereas the open side has areas of little deposition between clumps of sediment. This aligns with the fact that the velocity is higher in the open side and could push the fine material on the bed into clumps. However, after comparing the deposition on the glass slides in both the logjam center and unobstructed channel center, the amount of deposition is about the same except for at about 2 meters downstream (seen in Figure 25(e)). The reason for the exception could be due to random variability. In the other quarter spanning logjam deposition cases, a visual difference between the logjam and unobstructed side was also observed similar to that of Figure 22. The deposition in the other SVF cases showed no pattern or significant difference in deposition across the channel width.

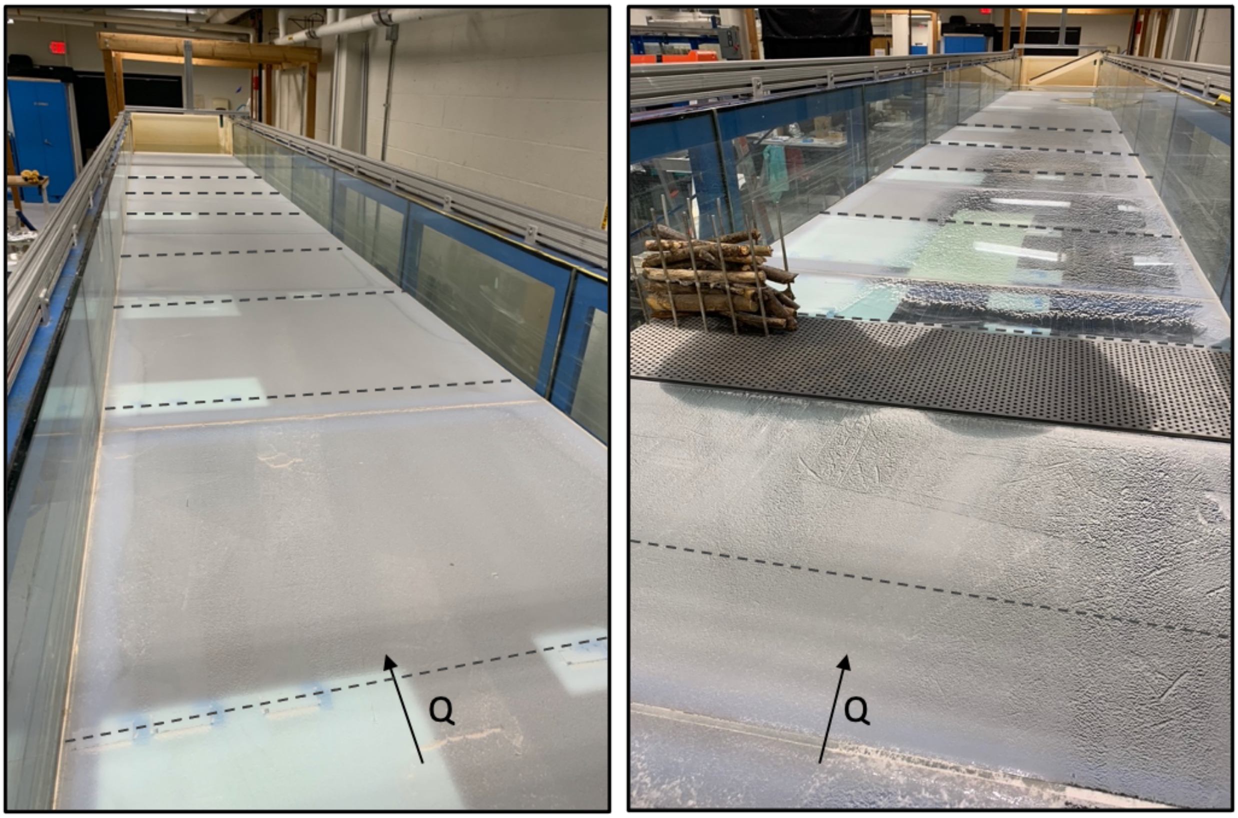


Figure 22: Images of fine sediment deposition on glass bed. On the left is an image of the deposition in the empty flume looking in the streamwise direction. The image on the right is the 0.5 SVF logjam with the resulting deposition, visually quite different from the open bed case. The dashed lines are a meter apart for spatial reference and the arrow represents the flow direction

4.2.2. Deposition Pattern

The deposition in the logjam side of the channel with a logjam of any SVF (SVF = 0.2-1) is different from the open bed case. This shows that the fine particles are not depositing behind the logjam due to the SVF. Since in the field, POM does deposit downstream of the logjam, a few other mechanisms could have led to this including flooding events were water pushes floodplain fine sediment into river, the bed morphology plays a role in the deposition, or the logjam itself produces a lot of POM that deposits over time. As for the unobstructed side there is a much wider range in sediment deposition, which was also captured in the repeated deposition study as seen in the uncertainty (row 4 of Table 5).

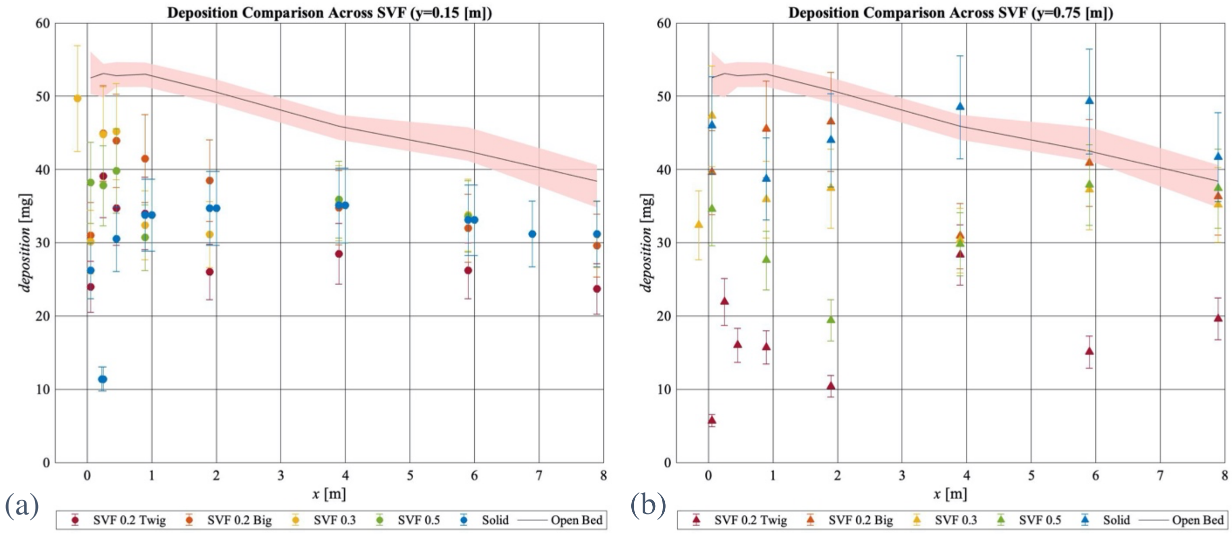


Figure 23: Deposition for varying SVF. The error in each point is the percent error found from the sediment repetition case. The deposition in (a) the logjam side of the channel, converges with distance downstream, yet remains lower than the open bed case. The deposition in (b) the unobstructed side does not seem to have a pattern of deposition. The solid log in the unobstructed channel is the only deposition case that almost perfectly agrees with the open bed case.

4.2.3. Correlation between Velocity, Turbulence, and Deposition

To test if there was any correlation between the velocity and deposition or turbulence and deposition, they were potted against each other in Figure 24. The points were split up by the longitudinal profile aligned logjam center and the longitudinal profile aligned with the unobstructed channel center. A linear regression was fitted to each figure to show any trends and found that the r^2 is less than 0.2 for all of the cases, indicating that there is no linear relationship. When the correlational coefficient and p-value was computed for each of the figures and is listed in Table 5. The only significant p-value (less than 0.05) occurred for the u_{rms} versus deposition at the logjam center. The p-value was 0.0181 wheareas the other p-values were greater than 0.08 for the velocity versus deposition in the unobstructed section of the channel. This shows that there was a correlation between deposition and u_{rms} on the logjam side, while there was no correlation found between velocity and fine sediment deposition.

	Lateral Location	p-value	Correlation Coefficient (r)	Coefficient of Determinant (r^2)
Velocity vs. Deposition	$y = 0.15$ m	0.1135	-0.1135	1.3%
	$y = 0.75$ m	0.0858	-0.3369	11.4%
u_{rms} vs. Deposition	$y = 0.15$ m	**0.0181**	-0.4091	16.7%
	$y = 0.75$ m	0.7847	-0.0551	0.3%

Table 5: Statistical significance and correlation between deposition with U and u_{rms}. The bolded value is statistically significant.

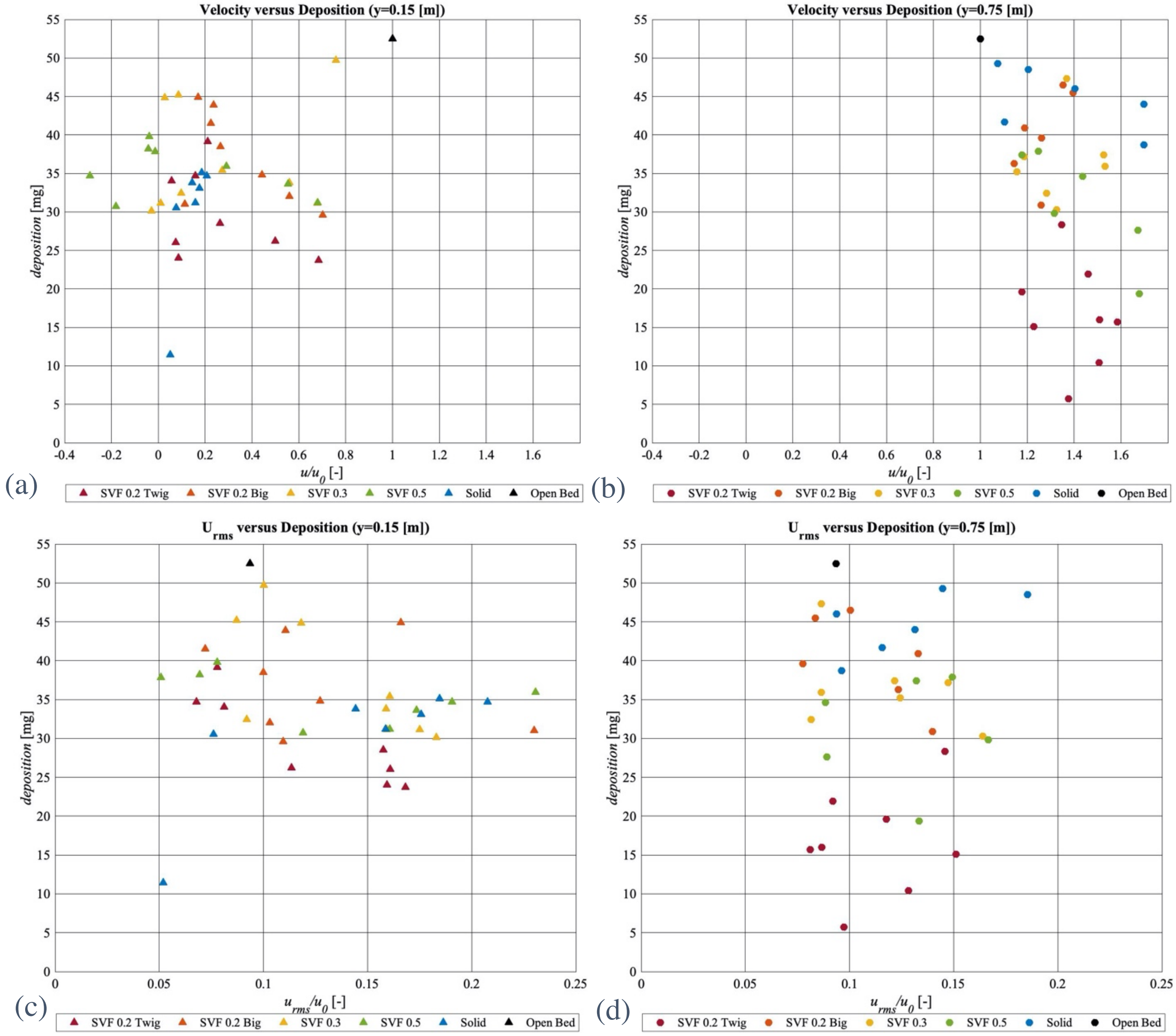


Figure 24: Velocity and turbulence vs deposition. The triangles were taken at y=0.15 which corresponds to the logjam center and the circles were taken at y=0.75m corresponding to the middle of the unobstructed side of the channel. (a) compares the velocity and deposition for the logjam case, (b) compares the velocity and deposition for the unobstructed side, (c) compares the u_{rms} and deposition for the logjam case, and (d) compares the u_{rms} and deposition for the unobstructed side. The open bed case used the average velocity and u_{rms} at 1 meter and deposition average at 2.1 meters so this might be slightly lower deposition than would be seen at 1 m. There are no solid log points at logjam center because the measurements were slightly different so there was no comparison able to be made.

4.3. General Trends Across Velocity, U_{rms}, and Deposition

The longitudinal velocity, u_{rms} and deposition values for each of the quarter channel width logjams (tests 4-8 in Table 1) is reported in Figure 25. In each subplot, a solid curve shows the laterally averaged values measured in the open bed control experiment, with shading around the line indicating the standard deviation. The logjam or solid log was located between -0.1 to 0 m in the *x* direction. The extra slides placed at the end of the experiment to measure additional deposition during draining collected a sediment weight less than 10% of the lowest sediment weight on the slides exposed to the full experiment. This indicated that the deposition pattern was not significantly altered during the draining process.

The velocity for the solid log case in Figure 25(a) quickly decreases before the logjam and downstream of the jam there is a recirculation zone that lasts until 3 m or 10x the logjam length. The u_{rms} values, that are a measure of turbulence, are near the unobstructed channel values until 1 m downstream of the logjam. Deposition is higher in the unobstructed channel, however not significantly more than in the open bed case.

For the 0.2 SVF twig results in Figure 25(b), the velocity pattern was as expected as the unobstructed side of the channel had a higher velocity. The deposition in this case was interesting since it was the only case in which we see a difference between longitudinal profiles of deposition in the unobstructed side of the channel and behind the logjam. Compared to the other cases, the difference lies in the open side of the channel which is markably lower deposition values. The differences are greater than the error from the repeated test case. However, the velocity profile in that region as well as the u_{rms} plots were quite similar to that of the solid log that does not display the same low deposition on the open side.

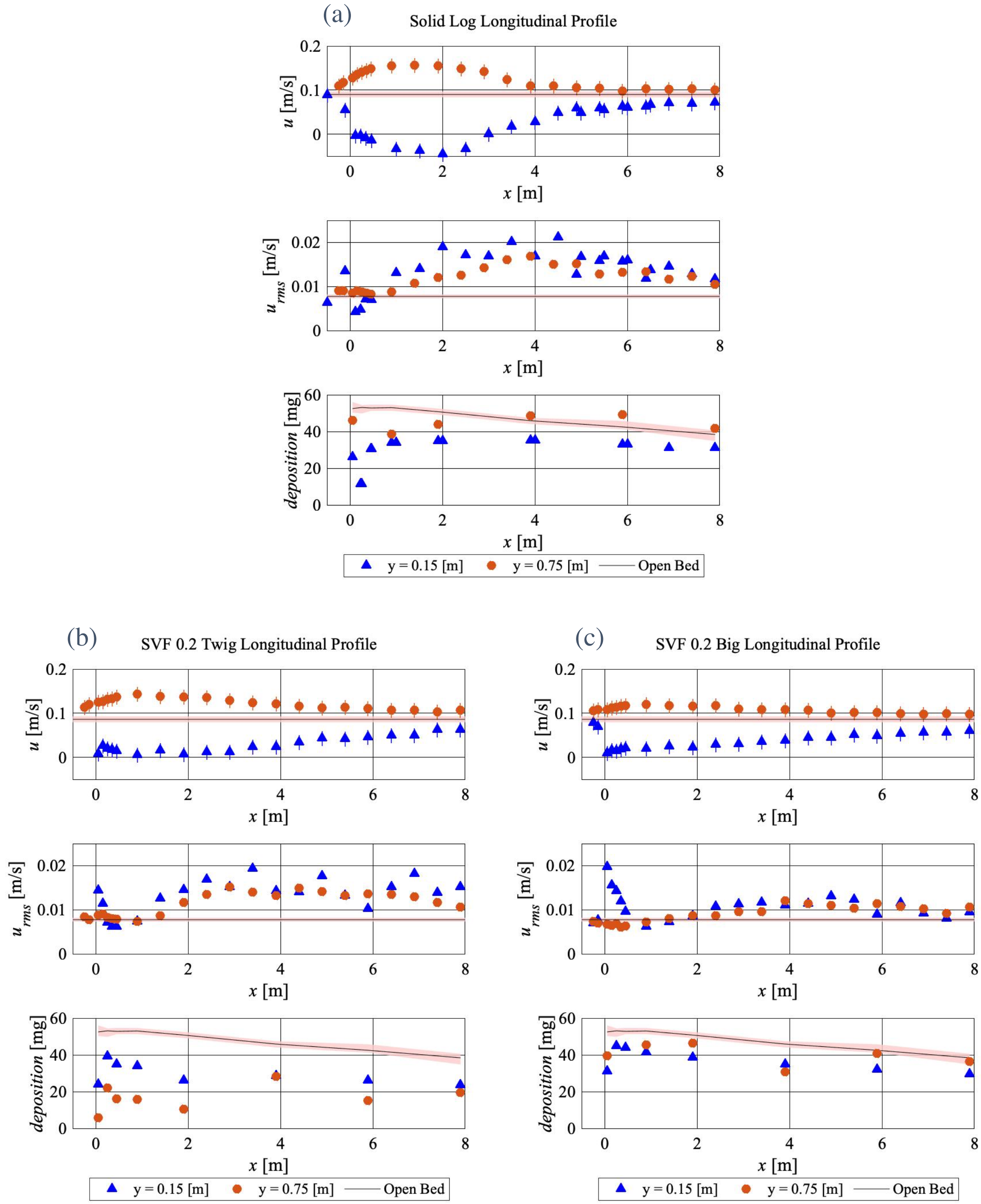
For the 0.2 SVF big results in Figure 25(c), the turbulence for within 40 cm downstream of the logjam has quite high values compared with the near zero averaged velocity. This can be explained by the fact that turbulence arises from shear and since there is low velocity there is greater shear with the adjacent higher velocities. The deposition in the unobstructed channel is almost the same as that of the logjam side, which is strange since visually the logjam side appeared as a blanket of glass beads whereas the unobstructed side of the channel showed more clumps of sediment deposition, as seen in Figure 22. Thus, there was an expectation that some of that range might show up in the weight of the slides.

In the 0.3 SVF case in Figure 25(d), a zero averaged velocity can be observed directly downstream of the logjam for about 2.5 m, followed by a linear increase in velocity of about 5 cm/s for every 3 m. The unobstructed channel side has a velocity peak of about 1.4x higher than the approach flow, then decreases back down to the approach flow. The u_{rms} is enhanced downstream of the logjam but otherwise the turbulence is the same for both longitudinal profiles. The deposition values were largely the same for both y values, potentially mimicking the consistent u_{rms} values.

The 0.5 SVF case presented in Figure 25(e) shows a similar progression of velocity measurements with the other cases. However, the u_{rms} peaks around 3.5 m downstream (about 11.7x the length of the logjam) which is closer to the pattern of the solid log. The deposition is the same for both longitudinal profiles except for the logjam side deposition at 2 m downstream, which will be discussed further later.

The deposition for each scenario showed a decrease in the total deposition (sum of all the fine material deposited on the slides) when there was a logjam in the flume compared with an open bed scenario (seen in column 4 of Table 2). This contradicts our initial assumption that there would be more deposition downstream of the logjams, as in the field it has been documented that fine suspended sediment deposits downstream of logjams. This was attributed to the lower velocities downstream of the jams that were causing the deposition. However, since for most cases, the deposition downstream of the logjam was similar to that of the middle of the open side, it calls into question what is causing the high rates of fine sediment deposition. One significant difference between the flume experiments and the field is the bed height. In the field, logjams often create pools downstream of the logjam which can promote deposition (McHenry et al. 2007). Since the flume bed cannot replicate the erosion, there is a decreased deposition downstream of the jam which is consistent with the logjam producing scour.

A hypothesis for the low deposition in the wake is that particles were resuspended due to increased turbulence. These resuspended particles then deposit in the flume head/tail tank due to the high settling velocity. Since the end concentration in the open bed scenario is consistent with the end concentration of the tests with logjams and solid logs (based on water samples in Table 2), this indicates that there was a consistent concentration of suspended particles for all deposition cases. In other words, if the sediment just got resuspended then we would observe this in a higher concentration of fine sediment in the water sample. However, this is not the case and so it is likely that deposition occurred up- and downstream of the testing section.



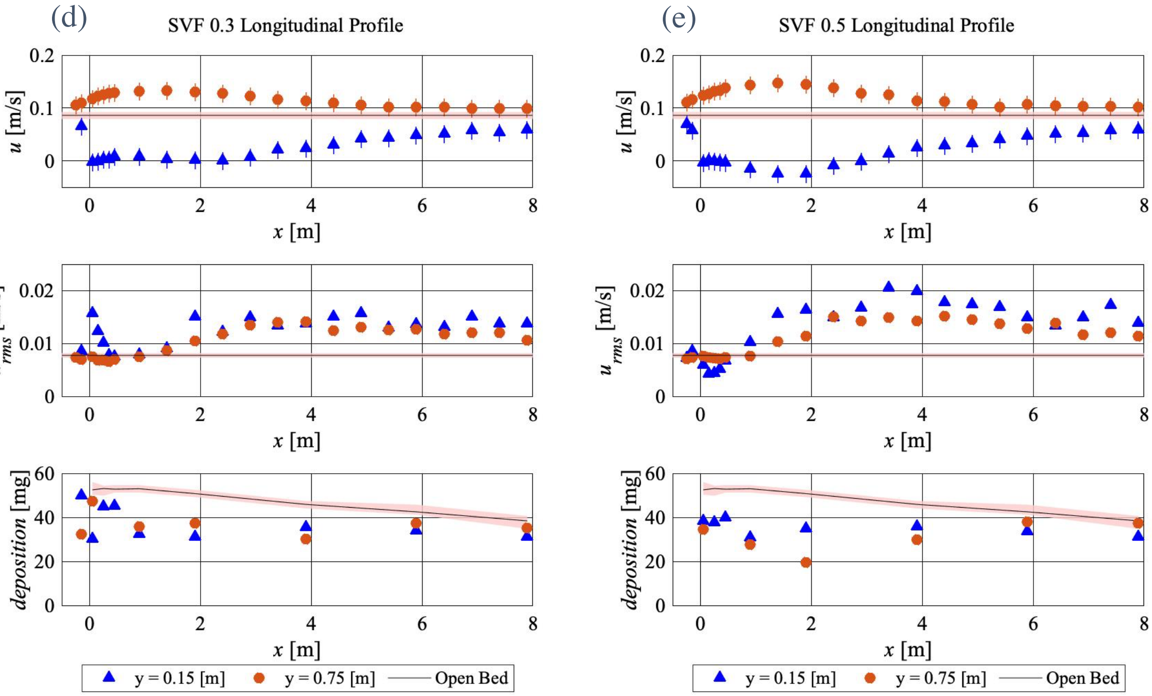


Figure 25: Comparison of U, u_{rms}, and deposition for varying SVF . The two different longitudinal profiles correspond to the middle of the logjam/log (triangles, y =0.15 m) and the middle of the open side (circles, y = 0.75 m). The light red is the standard error for the open bed case.

5. Discussion

5.1. Velocity and Turbulence

While there were noticeable differences in the velocity and turbulence, after 4 m, the wake is quite similar for all SVFs. The wake generated by bar apex logjams (adjacent to the channel side) differ from that of a deflector logjam (placed in the middle of the channel) in a few keyways, the first being the von Karman vortex does not occur and the second being the turbulence is much weaker (Schalko, Wohl, and Nepf 2021). These differences can be accounted for by the fact that with the side-channel logjam there is only one shear layer, so that the von Karman vortex street does not form.

Ismail et al. (2021) preformed tests on a side-channel logjam with a SVF = 0.29. When comparing the relative TKE values from Ismail et al. (2021) with the u_{rms} (proxy for turbulence) in this study for SVF = 0.3, there is turbulence only 2x the open bed case (Figure 25(d)) downstream of the logjam, whereas finding for the 0.29 SVF show higher turbulence for the same location downstream of the logjam (Ismail, Xu, and Liu 2021). This could be since the frontal area of the jam is different. There are regular gaps in the ELJ of Ismail et al. (2021) that the water can pass right though, whereas in the natural logjam of this thesis, logs overlap and there are no or very few straight paths for water to flow directly through the jam, thus there is increased shear/drag. In this way, the porous engineered logjam (ELJ) as seen in Figure 5 by Ismail et al. (2021) acts more like a porous fence.

In contrast to the irregular logjams in this thesis, the porous structure in Ismail et al (2021) was very ordered, and the logs were stacked. Ismail et al. (2021) also found that the bleed flow, flow that passes through the structure, and flow around the structure remained at differing velocities for at least four times the width of the ELJ. Compared to the non-porous structure in their study, the turbulent kinetic energy (TKE) near the side-channel porous structure had relatively lower TKE behind the logjam and lower values of TKE in the unobstructed region adjacent to the logjam. Which is the same for comparisons between the solid log and SVF = 0.3 in this thesis, as the u_{rms} is lower in both the unobstructed and logjam regions of the channel.

Porous fences as studied in Raine and Stevenson (1977) and Perera (1981) both show a similar study of porosity from 0-50% using wind instead of water as the medium. Results from Raine and Stevenson (1977) show that with increasing porosity there is lower turbulence intensity at any location downstream of the fence. The relative u_{rms} (a proxy for turbulence) values were impacted less with changes in porosity than with changes in velocity. The study also finds that there is higher turbulence downstream of the porous fences than in the unobstructed region, which agrees with the findings of this thesis.

Results from Perera (1981) show that as porosity increases, bleed flow increases, and thus less recirculation, which is consistent with Ismail et al. (2021) as well as this study. Specifically, there was only recirculation in area fractions greater than 0.7 (porosity < 0.3) (Perera 1981), which is higher than the results of this study which still shows recirculation at SVF = 0.5 (Figure 17). Area fractions can be compared with SVFs if we assume that the structure is homogeneous. However, this assumption does not hold since the lower SVF still produces a recirculation zone due to the length aspect that is not present in the porous fences. The study on porous fences also identifies that turbulence intensity decreases with increases in permeability (Perera 1981).

Porous groins were studied by Kang et al. (2011). The study reports velocity profiles for porous groins with SVF of 0.6, 0.8, and 1 (as the length was 2 cm). While the results were not directly comparable as the logjam results only go up to SVF = 0.5, in Kang et al. (2011) study, SVF was 0.6 and 0.8 and they observed no recirculation. The lack of recirculation at SVF = 0.8 is even higher than the recirculation cutoff of 0.7 SVF in the porous fence study by Perera (1981). In the case of the logjams, with SVF = 0.5 there was still recirculation. This is likely because the length (streamwise direction) of the logjam allows for a higher frontal area than that of a porous groin of the same SVF. Since the flow resistance of a structure depends on both the SVF but also the length in the streamwise direction. This means that the water cannot just flow straight through the jam as it can through the groin or the porous fence. For the 0.2 and 0.4 SVF (porosity = 0.8 and 0.6), there was no recirculation zone (Kang et al. 2011), which is consistent with the results from the logjams. The 0.6 SVF porous groin had a maximum velocity of 1.3x approach flow, but for the 0.5 SVF quarter spanning logjam the maximum velocity was 1.7x approach flow in the open region. For the solid groins, the maximum velocity was 1.9x approach flow, for the solid log the max velocity was 1.75x approach flow. This also highlights the difference between the porous groins, porous fences, and logjams since the logjam has the length aspect that allows more obstructions to the flow.

Comparing the results of this thesis to that vegetation patches in the center of the channel with SVF varying from 0.49-1 (Chen et al. 2012), the wake recovery is very similar with the higher SVF having more of a recirculation zone. The normalized u_{rms} values in Chen et al. (2012) show two peaks in the longitudinal profile, similar to the two peaks that are present in the logjams, although the logjam peaks are less defined. The first peak directly behind the structure, which is associated with the stem/diameter scale turbulence, then the second is associated with the von Karman vortex street (Chen et al. 2012). Due to the side placement, a von Karman vortex street will not occur for the constructed logjams.

Shi et al. (2016) investigated the critical shear velocity that causes resuspension in a river environment and fine sediment deposition in vegetation patches. The porosity of the vegetation patch was 0.13, which is typical of aquatic vegetation. In this study there was higher deposition downstream of the vegetation channel than in the unobstructed channel. Since the vegetation patch was modeled with wooden rods, it does show that there can be enhanced deposition downstream of a porous obstruction. The SVF = 0.87 is most closely related to the solid log, however the rods are most similar with the SVF = 0.2 twig case since the diameter for each rod in the vegetation patch was 0.1-1cm. Comparing the two cases the twig logjam did have higher sediment deposition for 2 m downstream of the logjam relative to the unobstructed side, which was the most significant difference within all the cases. Given the observed deposition difference for the SVF = 0.2 logjam with many logs obstructing the flow and small diameters, the other logjams are likely not seeing this deposition because they act like a solid obstruction with the large diameters.

Velocity was also very important for deposition, Shi et al (2016) found that if the velocity is too low resuspension is eliminated and the deposition is uniform, and if the velocity is too high then deposition is inhibited. The velocity in this thesis could have affected the logjam’s abilities to deposit fine sediment in its wake.

5.2. Deposition

Key takeaways from the results of the deposition study include that the deposition downstream of the logjam is diminished over the entire channel width, when compared to the open bed case. Which is well explained by the strong relationship negative between u_{rms} and deposition (increases in u_{rms} lead to decreases in deposition) in the logjam side of the channel. This means that the turbulence (gauged by the u_{rms} values) was resuspending the particles and preventing the deposition of fine sediment. Another result was that the varying SVF did not alter the amount of deposition. This could be since the range of velocities and turbulence generated by the varying SVF was not distinct enough to result in significant differences in deposition.

Wohl and Scott (2016b) found that their regression analysis of published studies, with logjam wood volumes and stored sediment values, indicated that wood volume was likely not significant in the model. This agrees with the result of the thesis that the SVF does not affect the sediment deposition. Since Wohl and Scott (2016b) hypothesized that an increasing SVF would lead to an increase in sediment volume, their reason for the poor performance was that some logjams could have very logs in the jams and thus the wood volume would not be a good indicator of the SVF or frontal area to trap the sediment.

One study that documented POM accumulation downstream of a logjam is seen in Figure 26 (Skalak and Pizzuto 2010). This example includes two logjams (LWD) in series that created a fine-grained channel margin (FCGM) deposit (Skalak and Pizzuto 2010). The accumulation occurs less than two width-scales downstream of the LWD, which is where the enhanced deposition was found in the SVF = 0.2 twig case. The authors assume that the FCGM deposition was due to suspended load transportation, similar to this study, as bedload transport may be reduced due to the position of the LWD.

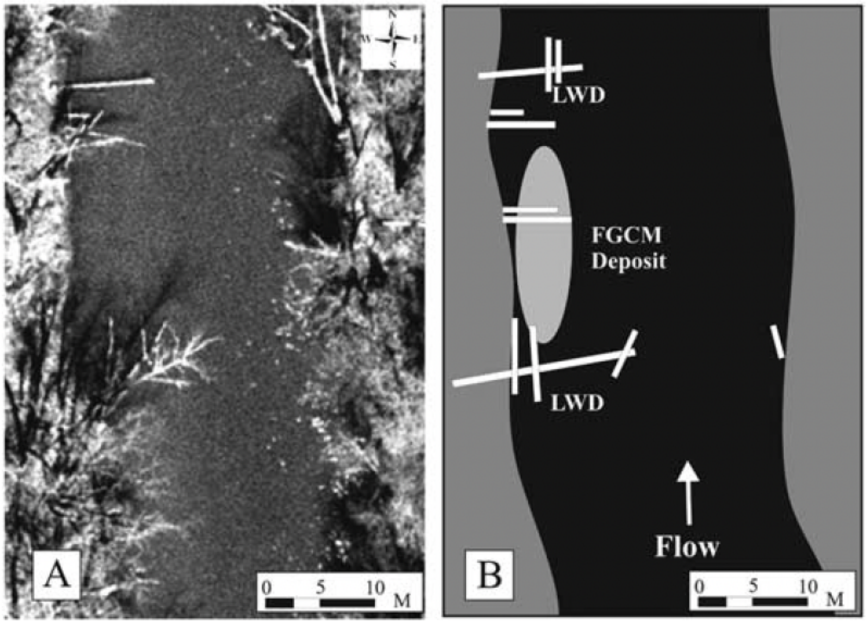


Figure 26: Typical 'fine grained channel margin' FGCM deposit in South River. (A) Aerial photograph taken in April 2005. (B) Line drawing of the same reach. The LWD indicated in the line drawing is debris that is in the river. Many of the trees in the aerial photograph are either living trees leaning over the river, or debris that is not entirely in the channel. Figure taken from (Skalak and Pizzuto 2010).

The higher deposition that is seen in the field however, not documented in the results of the deposition study could be attributed to the influence of bed load transport or changes in water depth. Although there is an indication that enhanced deposition occurs within 2 width-scales, no significant relationships were found. This is consistent with the conclusion by Beckman and Wohl (2014) that the fine sediment accumulation is not explained by logjam characteristics. However, Wohl and Scott (2016b) found that POM and fine sediment deposition can occur near the logjam or 10-100 m in river reach. Since this thesis only looked at 8 m downstream of the logjam, there could be effects farther down that are not captured here.

There was uneven deposition on the unobstructed side of the channel, so the slides may not be accurately representing the bed deposition on this side. Since the unobstructed channel side (y = 0.75) data might be underestimating the deposition on the bed due to the issue of the buildup of sediment upstream of the slides. This was not an issue for the logjam side (y = 0.15) because the deposition was even around and on top of the slide. The initial fine sediment weight, final concentration of the water, and run time was the same for every experiment so the decrease in deposition is likely because of the logjam as opposed to differences in the available sediment. The system was deposition dominated, so there was more deposition upstream where there was more sediment available for deposition. This explains the downward sloping deposition with the distance into the flume which is seen very clearly in the open bed case (Figure 22).

5.3. Fish Preference

The parameters that govern fish preference are velocity, turbulence, water depth, temperature, and cover. The specific species, as well as age and size play a role in the preferred habitat.

If the preference of guppies can relate to that of salmon, the fact that side-channel logjams produce less turbulence than logjams in the center is beneficial to fish of all sizes, as lower turbulence allows the fish to navigate a more predictable and stable river. The quarter width logjam below SVF = 0.5 is also more aligned with fish preference as it does not create the recirculation zone that the fish spent the least time in (McHenry et al. 2007). As for the fact young salmon and brown trout prefer boulders and larger sediment to POM, if there is not increased fine deposition downstream of the logjam then it can be beneficial to these fish (Heggenes, Saltveit, and Lingaas 1996). Which is juxtaposed by the mention of POM increasing salmon populations in the pools downstream of logjams (McHenry et al. 2007). However, the salmon populations in the pools were largely said to be adult spawning salmon. Thus, the POM could positively affect adult salmon but negatively affect young salmon.

The region downstream of logjams with more moderate velocities and decreased turbulence may be of higher preference than the more homogeneous flow without a logjam as noted in (Hockley et al. 2014).

The different velocity and turbulence regions are linked to different types of habitats. Figure 26 illustrates the wake regions with respect to fish habitat preferences. The recirculating zone (green arrows in Figure 26) is often not inhabited with fish as it is harder to navigate and typically more turbulent. For the quarter spanning logjams, SVF less than 0.5 resulted in no region of recirculation. In the unobstructed side of the channel (red arrows in Figure 26) there is high velocity and low/moderate turbulence is often where larger fish will reside as they do not have to expend as much energy to hold their position that would've come from having to respond to every eddy in a turbulent region. The last region (orange arrows in Figure 26) is further downstream (about 15 width scales) where there is moderate velocity and moderate turbulence, this was linked to being beneficial for smaller fish (Hockley et al. 2014).

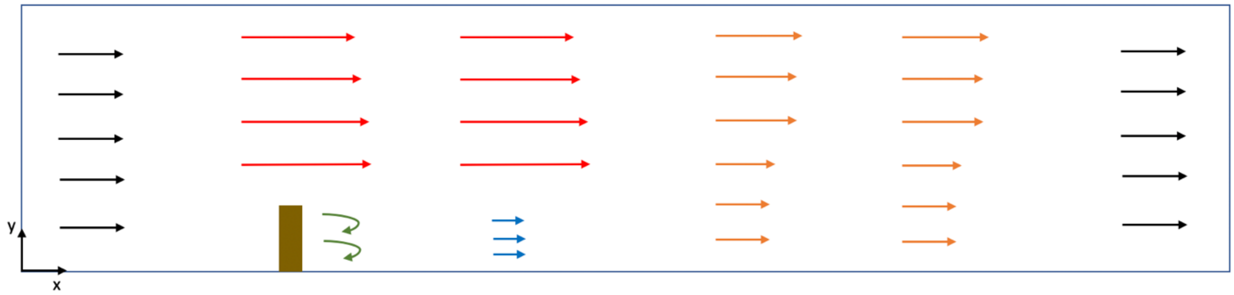


Figure 27: Wake regions created by logjams for fish habitat. The black is the approach flow, the red is the high velocity region, the green is the recirculation zone, the blue is low velocity zone, then orange is moderate velocity transition zone. The uniform approach flow is obstructed by the logjam and thus the water is deflected towards the unobstructed side which gains velocity. Some of the flow makes it through the logjam, however there is a lower velocity. Thus, a shear layer is generated which can lead to a recirculation zone. After this zone there is a region of low velocity then further downstream the velocities recover/decline through turbulence generating a moderate velocity zone followed by uniform velocity again. The recirculation zone is not always present downstream of a logjam as this depends on the level of flow obstruction. This figure depicts a quarter spanning logjam; however, the regions also remain for half spanning logjams.

5.4. Limitations to Research

A few limitations of this study include the issue of not having bed load transport which also affects deposition of fine sediment. An expansion that would have benefited the study would be to include bed load transport of larger particles to see how the bed morphology evolves, as it would not only influence the deposition of POM but also provide more complexity in the velocity and turbulence profiles.

The use of u_{rms} as a proxy for turbulence instead of the turbulent kinetic energy was a limitation of this study. With the TKE values could be directly compared with results from other engineered logjam studies and provide a more accurate understanding of the turbulence that a fish would feel. Since a fish would not only feel the fluctuations in the streamwise velocity but in all directions, which is better captured with TKE.

A clear timing of putting the particles into the flume and time of initial water sampling would have improved the accuracy of initial water sample concentrations. This would have led to a better understanding of the sediment that was available for deposition and understanding of the sediment budget. It would have also been utilized as a normalization factor if there was a wide range in the sediment that made its way from the tail tank to the head tank and into the testing section.

6. Conclusions

The wake downstream of logjams creates four main regions of flow: recirculating, high (1.25x u_0), and low (0.25x u_0) velocity. The recirculating region is not always present, as with quarter width spanning logjams with SVF <0.5. Instead, the region will be a low velocity region. There is a significant p-value between velocity and u_{rms} in the unobstructed side of the channel, and while results indicate there is a negative correlation, it is very low confidence. Thus, the nature of the correlation cannot confidently be concluded, only that the velocity and u_{rms} values are linked in some way.

A characteristic that was analyzed in this study was the solid volume fraction (SVF). There was a clear pattern showing that as SVF increased the velocity behind the logjam decreased and the velocity in the unobstructed channel increased (Figure 17). Similarly, turbulence in the unobstructed channel increased as SVF increased (Figure 18). As for the turbulence downstream of the logjam, the effect within five logjam length scales is that higher SVF corresponds with lower turbulence but after this region ($x > 0.5$ m) increasing SVF corresponds with increasing turbulence. In all SVF cases, after about 13 logjam width-scales, the velocities converge. However, the turbulence remained distinct. The deposition study for fine sediment found that the solid volume fraction of a logjam does not affect deposition rates. This could be linked to the fact that the velocity and turbulence were generally similar and thus no substantial differences were noted. There was also a significant relationship between u_{rms} and turbulence in the downstream of the logjam in which higher turbulence induced lower deposition.

The study of the same SVF with differing log diameters found that with smaller log diameters, the logjam will act more like a higher SVF. Thus, using more logs to create the same SVF increases the velocity and turbulence generated by the logjam, as there is more interaction between logs. The smaller diameter increases the frontal area (the amount of water needing to be diverted around the structure) since more logs are needed to achieve the same SVF. The study on logjam width covering ¼ or ½ of the channel found that velocities were higher in the unobstructed channel and lower downstream of the logjam for the ½ width spanning jam. This is consistent with conservation of mass, since blocking a larger fraction of the channel, the water must be diverted creating a higher velocity in the unobstructed channel. In comparison, the turbulence was lower everywhere downstream of the middle of the logjam for the half width jam compared to the quarter width jam (Figure 16). This is likely due to the measurements being taken farther from the shear layer. Lower turbulence is generally preferred by fish species as they can hold their position easier and spend less energy when navigating through more homogenous flows.

All the logjams produced distinct regions of velocity and turbulence that provide more options/habitat diversity for riverine fish. Results from this study suggest that side-channel logjams of SVF < 0.5 and ¼ width spanning logjams are the most beneficial for promoting fish habitats due to their limitation of recirculation zones, lower turbulence values, and creation of two distinct regions of flow velocity diverse habitats. The consideration of the quarter versus the half spanning logjam is more complicated with a tradeoff between recirculation zones at SVF = 0.3. For the half spanning logjam, the benefits include a larger region behind the logjam with lower turbulence as the shear layer is farther and an increase in velocity which is beneficial in times of low flow that significantly reduce fish habitat. The effect of POM or fine sediment on fish is still unclear as there are findings that they can negatively affect young fish but also benefit spawning fish.

When designing an engineered logjam to promote salmonid populations, it is important to consider the complexity in fish preference and balance multiple factors, including species, temperature, velocity, turbulence, substrate, age, and size. It is also critical to consider the effect of increasing the SVF or the width of the logjam. Understanding the implications of the logjam characteristics on fish habitat will increase the effectiveness of logjams to restore salmonid fish and ecosystems.

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