M e m o r a n d u m

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Subject: Debris Rack: Debris Capture and Fish Passage

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

This technical memorandum is a summary of the UC-Davis study reports on debris removal and fish passage for the Delta Fish Facility, submitted to the Department of Water Resources (DWR) in 2004. A final report was never submitted to DWR therefore, this memo is an effort by DWR to summarize the work associated on debris capture and fish interaction experiments related to debris racks. The experiments were conducted in support of operation and maintenance at the existing facilities with hopes that the results would help improve debris removal and fish passage efficiency of future fish salvage facilities.

2 PROJECT SUMMARY

The largest diversions in California's Sacramento-San Joaquin Delta are at the federal Central Valley Project's (CVP) Bill James Pumping Plant (formally know as the Tracy Pumping Plant) and the State Water Project's (SWP) Banks Pumping Plant. These facilities can divert as much as 65% of the total Delta outflow, drawing large numbers of fish into the south Delta. Many of these entrained fish are listed species or species of special concern. To aid in the survival of these species, CALFED identified several Preferred Program Alternatives through-Delta conveyance facility actions. They included (1) the construction of a new screened intake at Clifton Court Forebay (CCF) with protective screening criteria, (2) construction of a new screened diversion at Tracy, and (3) construction of a diversion facility off the Sacramento River.

One of the most important components of any of these new facilities would be the debris rack. In 2001, California Department of Water Resources and UC Davis J. Amorocho Hydraulics Laboratory jointly developed the debris rack study, to increase the understanding of debris rack design. The goal of the study was to research, evaluate, and recommend a debris rack configuration for effective debris removal and fish passage by testing several debris rack configurations (bar spacing, incline angle, and water velocities). Debris capture and fish passage percentages were quantified for the different debris rack configurations. Debris capture and fish passage tests were also conducted using a traveling screen in place of a stationary debris rack. Several traveling screen configurations were obtained by combining three different angles and two traveling mesh speeds.

2.1 Project Responsibilities and Coordination

- Project review and comment was provided by the Central Valley Fish Facility Review Team (CVFFRT).
- DWR Fishery Improvements section was responsible for coordinating with the technical teams, in project development, project proposals, interim reports, technical coordination and technical guidance.
- UCD, under contract to DWR, was responsible for conducting the experiments, collecting, evaluating, and analyzing the data, providing technical guidance, and writing the final report.

2.2 Objectives

The information learned from the debris removal and fish interaction with debris rack studies will aid in developing new debris rack designs for potential use at existing and proposed State and Federal facilities. The objectives of the study were:

1. Increase the understanding of debris rack design for effective debris removal and fish passage,
2. investigate how predatory and prey fish interact with debris racks,
3. determine the best possible debris racks configuration for both debris removal and fish passage.

2.3 Background

Debris racks are one of the most important components of any fish facility. They keep aquatic debris such as Egeria and Water Hyacinth from occluding or damaging the positive barrier fish screens, louvers, and other components of a fish protection system.

Materials such as grasses, twigs, logs, trees, peat and tumbleweeds add to the debris problem. Debris at times can occlude the entire debris rack causing excessive head loss across the debris rack and creating a barrier to fish passage. At times this head loss can be excessive, causing pump cavitations and other mechanical problems further along in the system. At the Tracy Fish Collection facility, operators have observed head differentials of as much as seven feet across the debris racks, causing shut down of the pumping plant.

Debris racks may also adversely affect fish passage. Anecdotal evidence indicates that the current configurations of debris racks at the CVP and SWP facilities create mortality problems for many fish species. Debris rack studies have shown that juvenile Chinook salmon show delayed passage through debris racks with a bar spacing of less than six inches (Hanson and Li, 1981). The current debris racks at Skinner have bar spacing of 2-1/4 inches. The delay of fish passing through the debris racks and the large numbers of striped bass near the debris rack increases exposure of fish to predation.

Developing debris racks that are effective at passing fish and capturing debris will reduce mortality to fish and minimize debris problems downstream of the debris racks. Bar spacing should be selected to pass fish safely and capture debris simultaneously. The angle (from vertical) at which the debris rack is installed may also play an important role in the design of a debris rack. It is thought that by increasing the angle or laying the debris rack down, the debris may slide up the debris rack and aid in debris removal and fish passage. As the debris slides up, clear areas would be exposed on the debris rack and allow fish to pass.

3 EXPERIMENT SETUP

3.1 Setup for the Debris Removal Study

UCD engineers designed and constructed a steel flume and pump system at the UCD Hydraulics Laboratory for conducting this study (Figure 1). Construction of the flume was completed in 2001 with a flow capacity of 30 cfs. The first year of experiments were conducted at this 30 cfs flow rate. In 2002, the flow capacity of the flume discharge was increased to 70cfs to conduct more experiments. The flow rates of 30 cfs and 70 cfs produced water velocities of 1 ft/s and 2 ft/s respectively. A flow velocity of 3 ft/s or greater was suggested for the second year of testing by the Central Valley Fish Facility Review Team (CVFFRT) and project management, but budget and time constraints did not permit the work. Testing with larger flow rates were preferred to better mimic existing conditions at the State and Federal pumping facilities,

Following the construction of the flume, debris racks of varying bar spacing (1.5, 3.0, 4.5, and 6 inch) were installed inside the flume for testing debris capture and fish passage efficiency (Figure 2). The debris racks were installed inside the flume at four different angles (15, 30, 45, and 60 degrees) from vertical. A specified volume of debris was then inserted into the flume to test the capture efficiency of the debris racks.

The debris removal efficiency of a traveling screen was also tested inside the flume. The traveling screen mesh opening was 2 inches by 4.5 inches. The two traveling mesh speeds tested were 3.5 ft/min and 7.5 ft/min at flume flow velocities of 1 ft/s and 2 ft/s, respectively.

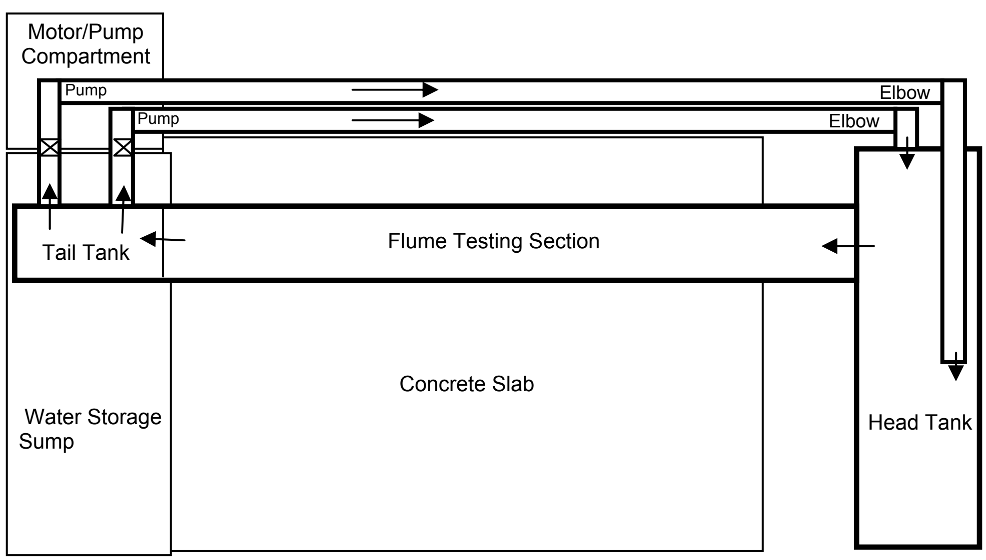


Figure 1 – Flume facility layout and flow circulation.

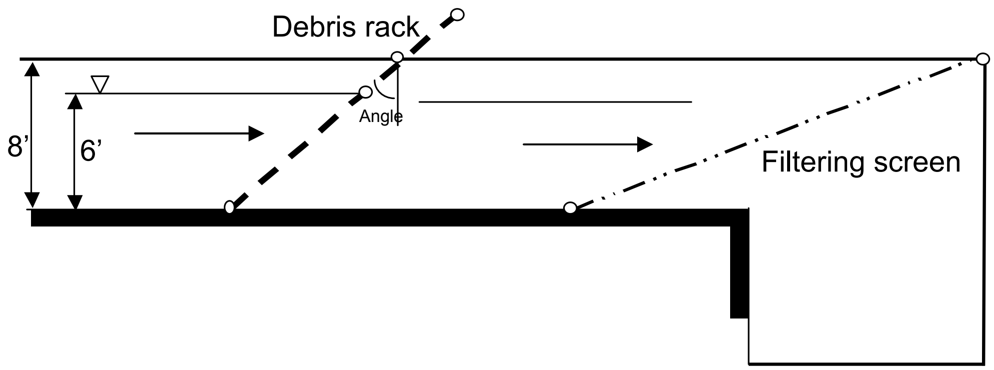


Figure 2 - Schematic of testing section of flume and test debris rack. The installation angle of debris racks varied with testing.

3.2 Testing Setup for the Fish Interaction Study

Experiments investigating fish species-specific passage levels utilized the same outdoor flume as that constructed for the debris removal experiments. Schematics and details on the design and construction of the flume are given in Figure 1. Three debris removal configurations were tested during the fish interaction experiments;

1) "small" bar-spacing, 1.5 inch

2) "large" bar-spacing, 6 inch

3) traveling screen rotating at 4 rpm.

Each design was tested at flume flow velocities of 0 ft/s, 1 ft/s, and 2 ft/s.

Additional fish interaction experiments were conducted in a 50 m long glass flume located inside the UCD Hydraulics Laboratory. This enabled continuation of experiments during a period when water temperatures were too high, 22 – 29 ^{o}C, for the fish being tested in the steel flume located outdoors. Access to chilled well water and an indoor location allowed the temperature in this glass flume to be maintained at the desirable temperature. A small, 1.5" steel debris rack was constructed for the glass flume.

3.3 Flow Control

The water circulation system of the Large Flume Facility is shown in Figure 1. Water was supplied to the Large Flume apparatus by two propeller pumps. The discharge through the flume was regulated by the rotational speeds of the pumps and the water head difference between the head tank and the tail tank. The rotational speed of the two propeller pumps was controlled by two Variable Frequency Drive (VFD) motors. The rotational speed of the two motors was adjusted so that 1 and 2 ft/s approach velocities could be achieved within the testing section of the flume.

Flow rates into the large flume were measured using two Mark 3 Ultrasonic flow meters. The flow meters measured the frequency shift of reflected ultrasonic signal from discontinuities in the flowing fluid. These discontinuities can be virtually any amount of suspended bubbles, solids, or interfaces caused by turbulent flow. The flow meter transducers were mounted externally to the pipe to obtain flow readings without flow interruptions. The accuracy of the two flow meters was within 2% of the flow, which ranged from 0 to 75 cfs. The accuracy of the two flow meters was checked with a removable sharp crest weir installed at the end of the testing section of the flume. The water surface elevation and water depth in the flume were measured by point gages equipped with vernier caliper located at 9 feet upstream of the weir.

4 EXPERIMENTAL PROCEDURES, DATA COLLECTION, AND ANALYSIS

4.1 Debris Racks and Traveling Screen

Four debris racks of different bar spacing (1.5, 3, 4.5, and 6 inches), were tested in this study. A total of sixteen different debris rack configurations were considered by combining the four debris bar spacing with debris rack installation angles of 15, 30, 45, and 60 degrees (from vertical). The sixteen debris rack configurations as shown in Table 1 were tested in flow velocities of 1ft/sec and 2 ft/sec.

A traveling screen with mesh openings of 2 inches by 4.5 inches was also tested inside the flume. The mesh material was made of ¼ inch stainless steel airline cable and was driven by a 1 hp drive motor and gear box (Figure 3). Two traveling screen speeds

(3.5 ft/min and 7.5 ft/min) and three incline angles (15, 30, 45 degrees) created a total of six different traveling screen configurations as listed in Table 2. Similar to the debris racks, the traveling configurations were also tested in flow velocities of 1ft/s and 2 ft/s.

Similar configuration terminology was used for both the debris racks and traveling screen. For example, test configuration S15A45V20 represents a bar spacing (S) of 1.5 inches, a debris rack angle (A) of 45 degrees, and a velocity (V) of 2 ft/s. Configuration T35A15V10 represents traveling screen speed of 3.5ft/min, screen angle of 15 degrees, and a velocity of 1ft/sec.

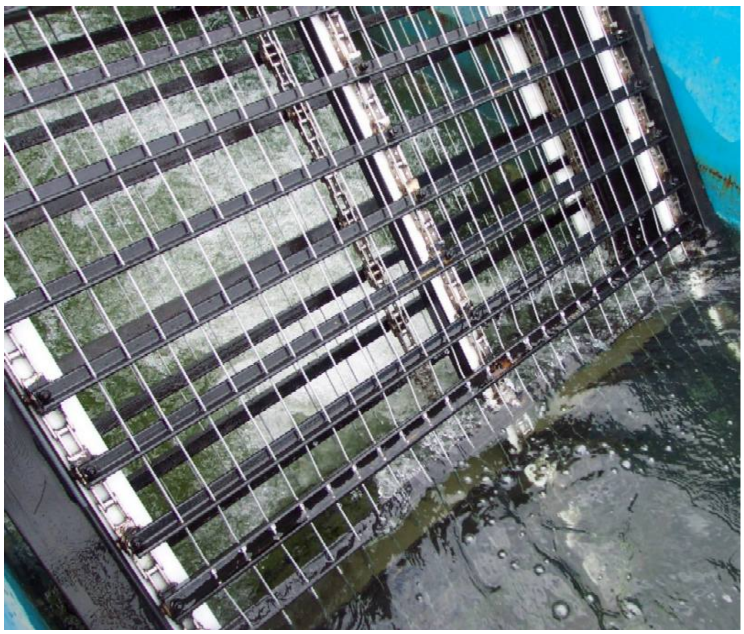


Figure 3 – Traveling screen cable mesh and supporting frame work.

Table 1 - Debris rack test configurations.

Debris Rack Configuration			Velocity	Flow Map Runs
Configuration No.	Bar Spacing (inches)	Incline Angle (degrees)	ft/s	
S15A15	1.5	15	1	S15A15V10R0
			2	S15A15V20R0
S15A30		30	1	S15A30V10R0
			2	S15A30V20R0
S15A45		45	1	S15A45V10R0
			2	S15A45V20R0
S15A60		60	1	S15A60V10R0
			2	S15A60V20R0
S30A15	3	15	1	S30A15V10R0
			2	S30A15V20R0
S30A30		30	1	S30A30V10R0
			2	S30A30V20R0
S30A45		45	1	S30A45V10R0
			2	S30A45V20R0
S30A60		60	1	S30A60V10R0
			2	S30A60V20R0
S45A15	4.5	15	1	S45A15V10R0
			2	S45A15V20R0
S45A30		30	1	S45A30V10R0
			2	S45A30V20R0
S45A45		45	1	S45A45V10R0
			2	S45A45V20R0
S45A60		60	1	S45A60V10R0
			2	S45A60V20R0
S60A15	6	15	1	S60A15V10R0
			2	S60A15V20R0
S60A30		30	1	S60A30V10R0
			2	S60A30V20R0
S60A45		45	1	S60A45V10R0
			2	S60A45V20R0
S60A60		60	1	S60A60V10R0
			2	S60A60V20R0

Table 2 – Traveling screen test configurations.

Traveling Screen Configuration			Approach Velocity (ft/s)	Flow Map Runs
Configuration No.	Screen Speed (ft/min)	Incline Angle (degrees)		
T75A15	7.5	15	1	T75A15V10R0
			2	T75A15V20R0
T75A30		30	1	T75A30V10R0
			2	T75A30V20R0
T75A45		45	1	T75A45V10R0
			2	T75A45V20R0
T35A15	3.5	15	1	T35A15V10R0
			2	T35A15V20R0
T35A30		30	1	T35A30V10R0
			2	T35A30V20R0
T35A45		45	1	T35A45V10R0
			2	T35A45V20R0

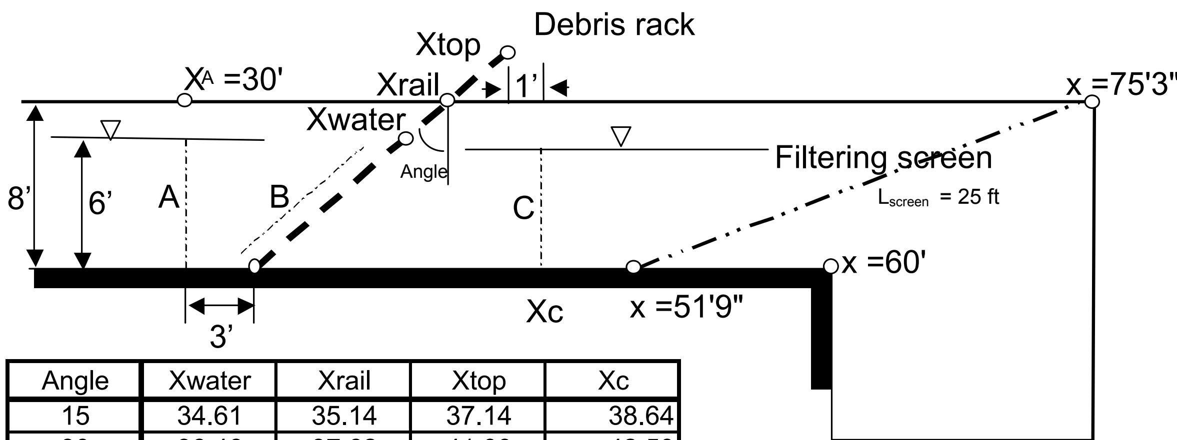
4.2 Hydraulics

4.2.1 Velocity Measurements near Debris Racks

For each flow regime, velocities in the testing section of the large flume were measured in three transects using a Swoffer propeller velocity probe. The three transects for the velocity measurements in the flume are shown in Figure 4 as Transect A, Transect B, and Transect C. The upstream vertical transect "A" is located at 3 feet upstream of the toe of the debris rack in the flume at all times. The position of Transect B and Transect C changes with the incline angle of the debris rack. This is due to changes of the Xwater, Xrail, and Xtop, as shown in Figure 4, where Xwater is the longitudinal coordinate of the intersect point between the upstream surface of the debris rack and the water surface, Xrail is the longitudinal coordinate of the intersect point between the upstream surface of the debris rack and the rail installed on the top of the flume walls, and Xtop is the longitudinal coordinate of the top of the debris rack. The inclined transect "B" is located at 1 feet upstream of the debris rack, and the downstream vertical transect "C" is located at 1 ft downstream of the top of the trash rack.

The probe measured velocity only in the horizontal direction. Velocity readings were recorded in each transects using the grid pattern shown in Figure 5. At each grid measurement point, the count reading, N, of the velocity propeller meter over thirty seconds was recorded. The velocity at the grid measurement point was computed using the calibration relationship in Equation 1,

$$V \text{ (ft/s)} = 0.0014\, N + 0.1 \qquad (1)$$



Angle	Xwater	Xrail	Xtop	Xc
15	34.61	35.14	37.14	38.64
30	36.46	37.62	41.00	42.50
45	39.00	41.00	44.31	45.81
60	43.39	46.86	46.86	48.36

Figure 4 - Debris rack location and velocity transect locations.

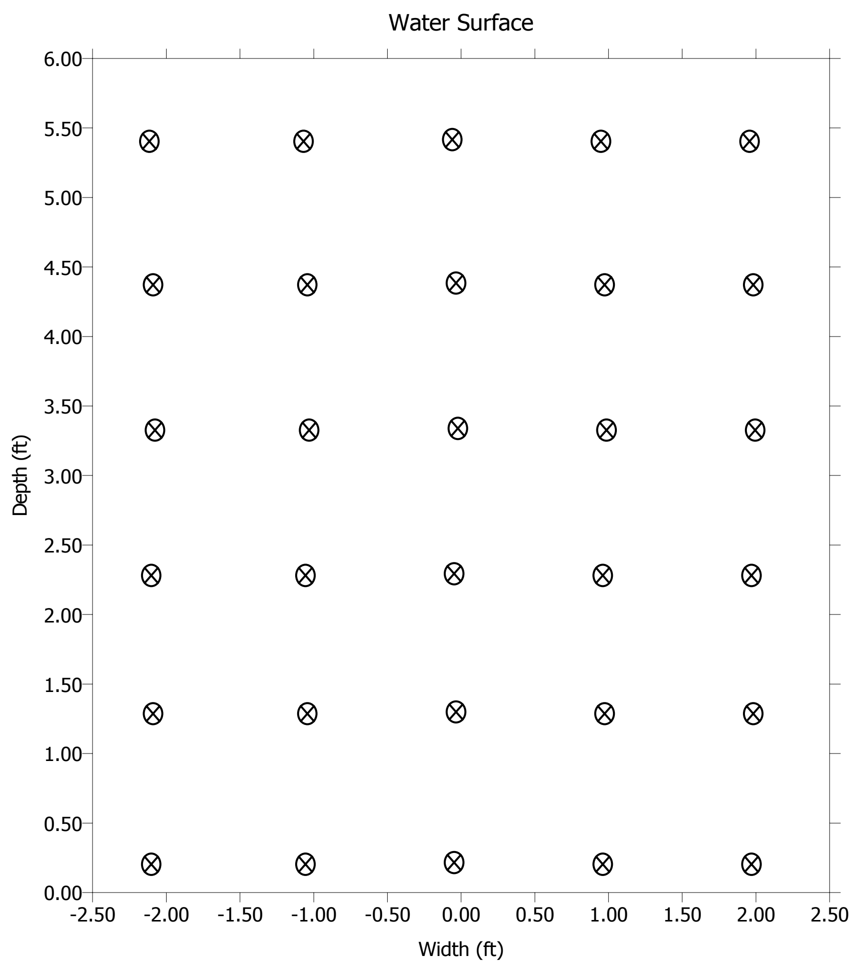


Figure 5 - Pattern of velocity grid measurement locations at transects A, B, and C.

4.2.2 Averaged Velocity Profiles near Debris Racks

To examine the effect of the debris racks on flume flows, averaged velocity profiles were generated from the velocity data collected at transects A, B and C. Velocity values were plotted as a function of water depth between 0.5 and 5.5 feet. The profile maps describe the velocity at the three transects, and show how the flow velocity changes as the debris rack installation angle is changed. An example of a velocity profile map is shown in Figure 6. Velocity profiles for other debris rack bar spacing were not included in the UCD report.

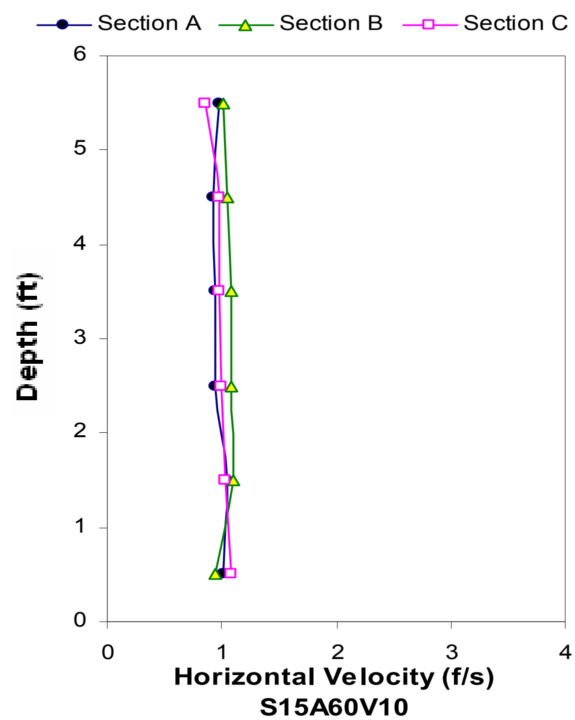


Figure 6 - Average horizontal velocity profile plots for the debris rack configuration S15A60 at flow velocities of 1 ft/s.

4.3 Debris Handling and Testing

4.3.1 Collection and Composition

Debris was collected weekly from the CVP Tracy Fish Facility debris rack and transported to the UC Davis Hydraulics Lab. The debris collected from the Tracy Fish Facility was typically composed of aquatic weed (primarily Egeria) and other various types of trash. The debris was loaded into 7 to 13 plastic containers each with a volume of approximately 30 gallons and capable of holding between 15 to 25 kg of wet Egeria and other trash. A debris handling platform was built adjacent to the head tank. The platform consisted of a water volume measuring plastic tank, an electrical weight measuring scale, and the wastewater collector.

Debris from one container was used for characterization of the approximate composition of debris loading. Debris composition was determined by dividing the debris into 5 groups: trash, Egeria 18” and longer, Egeria between 12” and 18”, Egeria between 6” and 12”, and Egeria with a length of less than 6” (Figure 7). Figures 8 and 9 show that 50% of the debris is composed of Egeria that is of length 6 inches or less, and that the composition of debris changes on a seasonal and even daily basis. This seasonal and daily change potentially can greatly affect the capture efficiency of a debris rack. Although debris from the Skinner fish facility was not used, it is reasonable to assume that the debris composition of both facilities is the very similar.

Figure 7 - Classification of five debris groups.

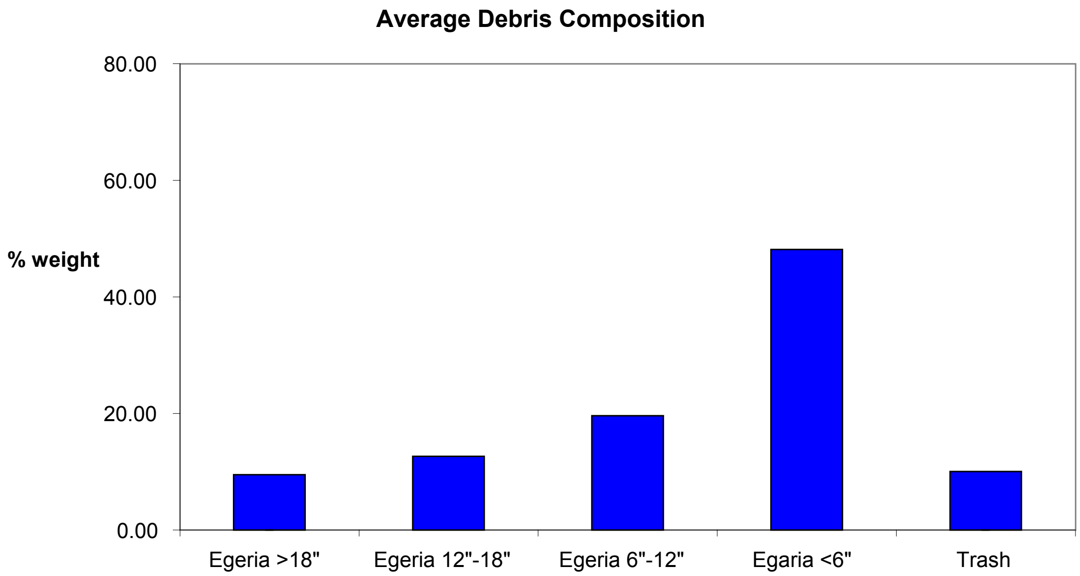


Figure 8- Average debris composition results (October 2002 - June 2004).

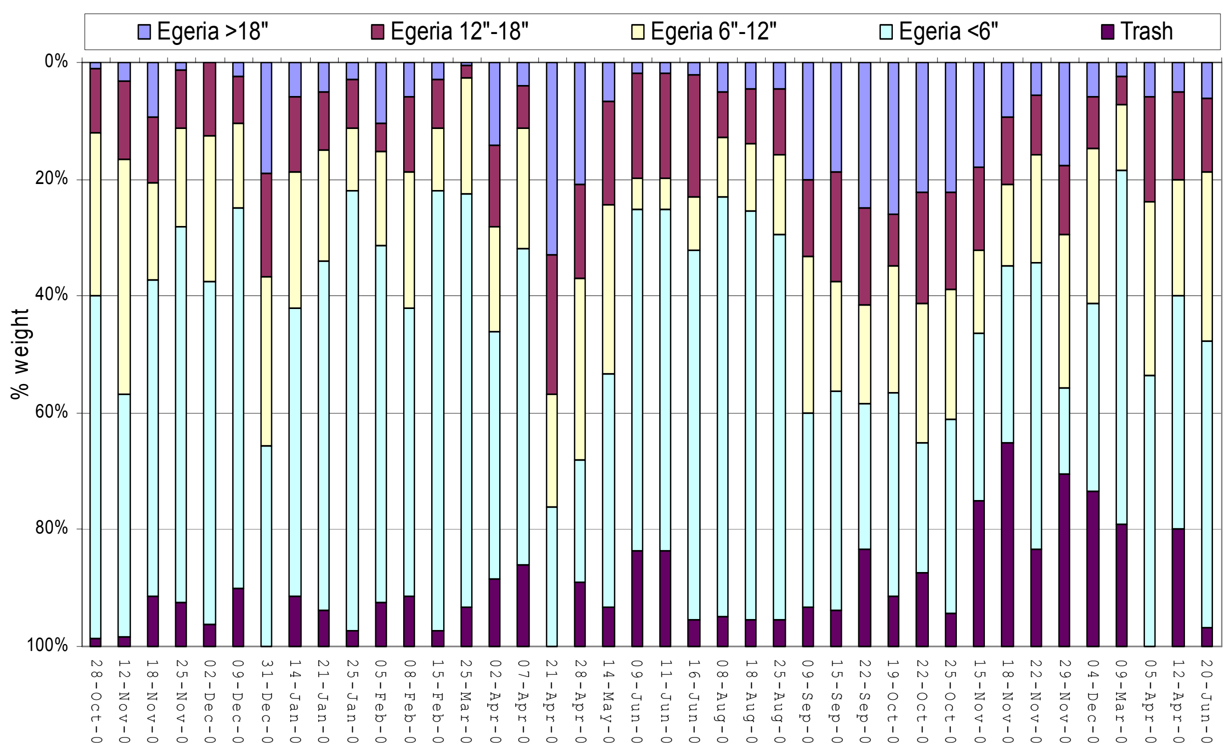


Figure 9 - Comparison of debris composition. The plot shows the weight by percentage in terms of the Egeria length classes at various dates.

4.3.2 Debris Capture Testing with Debris Racks

A sample size of six replicates for each flow regime was selected in order to reflect the variability of the Egeria that reaches the fish facilities. A debris capture test included the following steps:

1) Establishment of pre-release flow condition
2) Pre-release debris measurement
3) Debris release and collection
4) Post-release measurement
5) Data processing.

The pre-release flow condition was established in the flume by adjusting the water velocity (1ft/s or 2ft/s) and the water depth (6ft) in the flume to the target values. The pre-release measurement included weight measurement and volume measurement of the debris. A five-gallon bucket was used to transfer the debris from the debris container to the flume. A bucket full of debris was soaked with water before releasing it into the head tank of the large flume. The release bucket was weighed twice at 1 minute and 2 minutes after it was soaked with water to ensure that all the water was drained out.

The debris was then deposited into the head tank. The first bucket of debris was allowed to mix in the head tank and was given five minutes to make its way to the debris rack. The next bucket of debris was then released into the head tank and allowed to make its way to the debris rack. Debris was either caught on the debris rack or it passed through and was caught on the wire mesh filter downstream of the debris rack. After dewatering the flume, the debris that was captured on the trash racks, and wire mesh filter were collected and weighted (Figure 10).

Figure 10 - Debris accumulation on the debris racks with 2 ft/s approach velocity and 15 degrees incline angle. The debris rack bar spacing are: 1.5, 3, 4.5, and 6 inch from left to right. Photos were taken after dewatering of the flume.

4.3.3 Debris Capture Testing with Traveling Screen

The traveling screen was tested at incline angles of 15, 30 and 45 degrees. The testing procedure for the traveling screen was similar to the testing procedure for the debris racks. The only difference was in the way the debris was removed for weighing after a test was performed. Debris from the debris racks was removed after the flume was dewatered. In the traveling screen test, the debris was removed during the experiment by the traveling screen (Figure 11). The debris travels up the traveling screen and is knocked loose by water jets on the back side of the screen. It then drops into a collection box located just behind the screen. Similar to the debris rack testing, a sample size of six replicates for each flow regime was selected.

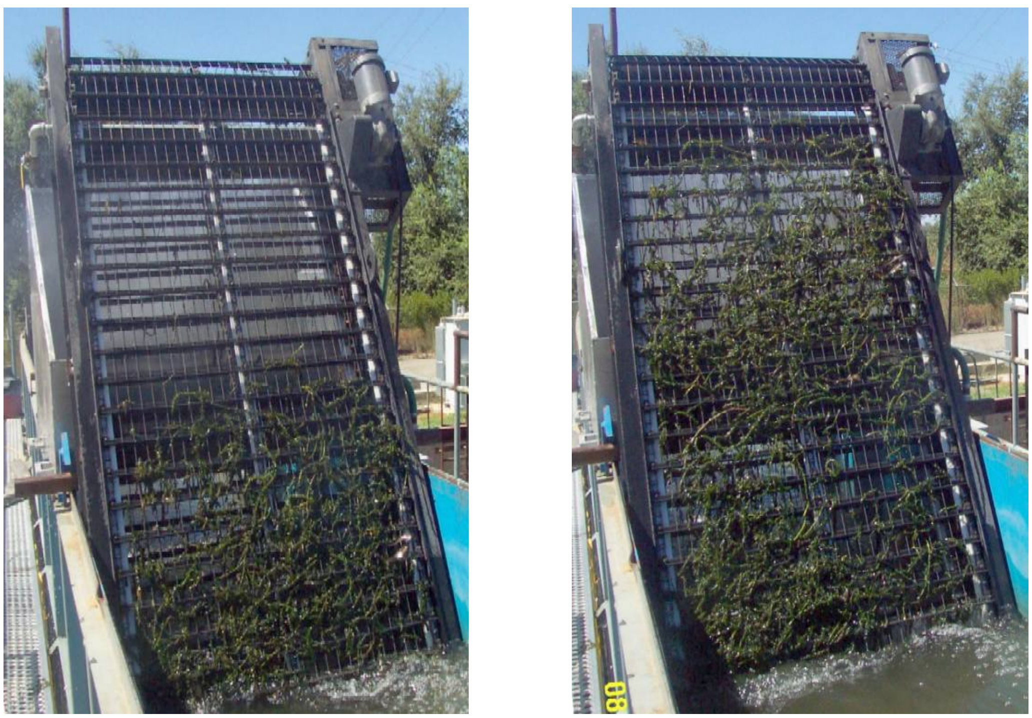


Figure 11 - Debris accumulation on traveling screen. Photos were taken 1 minute apart under the flow regime T35A30V20.

4.4 Fish Species and Passage Testing

4.4.1 Fish Species Utilized for Testing

The fish used in the experiments (Table 3) were obtained from a wide range of locations and facilities. Delta smelt were obtained from the UC Davis Delta Smelt Culture Facility in Tracy, CA. Sacramento splittail were obtained from the Cosumnes River. All winter-run ESU Chinook were obtained from the culture facilities of the Bodega Marine Laboratory of UC Davis, Bodega Bay, CA. Fall-run ESU Chinook were obtained from the Mokelumne River Hatchery. Threadfin shad and striped bass were obtained through collection processes at the Tracy Fish Facility, Byron, CA. Steelheads were obtained from the Nimbus River Hatchery and Green sturgeon were progeny of Klamath River fish raised at the Center for Aquatic Biology and Aquaculture at UC Davis. Because of seasonal fluctuations in species availability and numbers, not all fish species were used in all experimental treatments. The fish species used in these experiments are morphologically diverse and provided an array of body plans and associated swimming modes and physiologies.

Fish were held in tanks supplied with a continuous flow of air-equilibrated, unchlorinated well water at temperatures matching that of the flume (15-19 ^{o}C; except the striped bass and prey fish for the predator-prey experiments) and a natural photoperiod. Holding tanks were located at both the UCD Hydraulics Laboratory and the Center for Aquatic Biology and Aquaculture. During all transport and handling, fish were placed in aerated coolers to maintain a constant water temperature, with salts and a synthetic handling solution (NovAqua™).

Table 3 – Total number of species (n), and their mean standard lengths (SL), used in the fish interaction studies.

Species Tested	SL (S.E.) cm	n
threadfin shad	8.4 (0.58)	919
“large” striped bass	38.8 (3.9)	9
“small” striped bass	22.4 (4.6)	30
“large” winter-run (WR) Chinook	19.8 (2.3)	15
“small” winter-run (WR) Chinook	7.5 (0.74)	330
fall-run (FR) Chinook	9.65 (0.18)	450
Sacramento splittail	4.5 (0.43)	101
delta smelt	6.4 (0.4)	438
green sturgeon	10.3 (1.2)	60
steelhead	13.1 (1.8)	75

4.4.2 Fish Passage and Behavior Experiments

Fish were released into the outdoor, steel flume at the upstream end of the experimental channel, approximately 11 meters from the debris rack. A net was used to keep the fish within a 0.5 m section as the pumps were activated. The initially static water was gradually brought up to a velocity of either 1 or 2 ft/s. The restraining net was removed just as the water began to flow.

Three observation locations were used; one situated just downstream from the debris rack and another just upstream of the debris rack, both in front of acrylic windows placed in the side of the flume channel. The third observation location was stationed on a catwalk that spanned the length of the experimental channel and afforded an overhead view of the water. Most experiments utilized two human observers as a video system recorded many of the details of passage; one observer was stationed on the catwalk and one at the upstream window. Observation periods lasted one hour. The observers stationed around the debris rack recorded the time of each passage, the orientation of the fish as it passed through the debris rack, whether or not any contact was made with the debris rack, and the residence time of fish that spent some portion of the experimental time around the debris rack. The observer stationed on the catwalk recorded the position of fish in the channel relative to the debris rack. This observer utilized a glass viewing box to ameliorate viewing problems due to surface turbulence.

Aside from passage data, which were recorded whenever a fish passed through the debris rack, all records were made at least once per 5 minute interval. Each observer monitored a stopwatch, which was synchronized and started when the observer on the catwalk indicated that the water flow had started. Water temperature and fish length (standard and total) were taken for every experiment.

The video system consisted of two to four miniature black and white cameras in a waterproof housing that was constructed of optically clear acrylic. The housings containing the cameras were magnetically attached to the debris rack or the walls of the flume. All wires were run through pvc pipes out of the flume to a video monitor and programmable recorder. The signals of multiple cameras were fed into a digital quad splitter that allowed for simultaneous viewing and recording of the images from each camera. In any given experiment at least two cameras were used. One camera was mounted on the debris rack and was aligned parallel to the debris rack to capture the submerged portion of the debris rack and 1 m of the flume bottom. A second camera was located approximately 3 m from the debris rack and was aligned perpendicular with the debris rack, affording a view of the entire debris rack. Other cameras were placed upstream and were used to record the presence of fish in two large upstream sections of the flume. These upstream cameras were used infrequently as the recorded images were often obscured by venturi-type bubbling when the pumps were on. A human observer was deemed more reliable for upstream observations.

During the study period of July-August 2003 several passage experiments were conducted in the glass flume located inside the hydraulics laboratory building. This enabled continuation of experiments during a period when water temperatures were too high in the outdoor flume. Green sturgeon and steelhead were the only species tested during this time period, and all data pertaining to these two species came from experiments utilizing the glass flume. All experimental and observational procedures were identical to those used with the large, outdoor flume detailed above.

Passage level was scored as the number of fish that passed completely through (i.e., > 1 body length away from the downstream side of the debris rack) during the one-hour experimental duration, and was expressed as the proportion of the total fish passing (for a given type or species) when all replicates were combined. For the limited cases where individual fish passed through the debris rack and then swam back upstream through the debris rack, those fish were scored as one passed fish. Passage levels were scored for all fish listed in Table 3. Three methods were utilized to count and confirm the number of fish passing; 1) observation during the actual experiment; 2) recovery of fish at the downstream screen of the flume; and 3) analysis of the video records.

Threadfin shad were used in groups of 10, 20, or 50 fish for the experiments at 1 ft/s (for both the 1.5 and 6 inch clear debris racks); the rationale for varying group size being that there may be differences in individual behaviors in different size groups for this schooling species. Group size, however, did not significantly affect passage levels or rates as was shown in a Preliminary Report submitted to DWR. Therefore, all replicates for a given treatment were combined irrespective of group size. For all experiments at 2ft/s groups of 30 threadfin shad were used, this number reflecting a compromise between having a large number of fish for observation and the total number of available fish. "Large" striped bass were observed as individuals (i.e., one fish per experiment), while "small" striped bass were used in groups of five fish. All Chinook salmon (fall- and winter-run) were used in groups of 30 fish for each treatment. Splittail were observed in groups of 20 fish, except for one replicate of the 2 ft/s, 6 inch bar treatment when 11 fish were used (the last replicate utilizing the remainder of unused fish). Delta smelt were used in groups of 20 fish for each replicate of all treatments, and green sturgeon and steelhead were observed in groups of five fish (reflecting a balance between the maximum number of individuals for observation, and the size of the fish and the glass flume).

Statistical testing of proportions passing in both interspecies and intraspecies comparisons among the various treatments was performed using unpaired rank-based non-parametric methods (Kruskal-Wallis and Wilcoxon-Mann-Whintney rank-sums); these also had the advantage of being insensitive to the low sample sizes and non-normal distributions of the measured parameters encountered during data analysis. These tests were performed and all graphical output generated utilizing Kaleidagraph, JMP, and Excel. Statistical significance was ascribed at $\alpha \leq 0.05$.

Passage times were quantified as the number of fish passing the debris rack by a particular point in experimental time. Inter- and intra-species comparisons of the distributions of passage times among the various treatments were analyzed via rank-based statistics due to non-normal (heavily left-skewed) forms and unequal sample sizes. The actual distributions are not given in this report; graphical representation of passage times are presented as probability curves illustrating the cumulative number of fish passing by a particular time of the one-hour experimental duration. All statistical and graphical procedures were performed with Kaleidagraph, JMP, and Excel. Statistical significance was ascribed at $\alpha \leq 0.05$.

For the fish that did not pass the debris rack during the one-hour experimental duration, their behavior upstream (relative to the debris rack) was quantified and compared among groups and treatments. For these observations the experimental channel was divided into 0.5 m sections, 0 m representing the debris rack and 11 m representing the upstream limit of the flume. Every five minutes the numbers of fish at a given location in the flume were noted, and qualitative observations of their swimming behavior and activity levels were noted. Tests of differences in these distributions were made by applying Wilcoxon-Mann-Whitney rank-sums; this test was deemed appropriate as it is distribution-free and thus insensitive to the changing distributions of the positional counts, and is impervious to disparate sample sizes, which arose due to heterogeneous passing levels among the three flow conditions. Statistical significance was ascribed at $\alpha \leq 0.05$.

5 RESULTS AND DISCUSSION

5.1 Hydraulics

The following discussions are based on the average velocity profiles for the 1.5 inch bar spacing. The hydraulic results for the other bar racks were not included in the report submitted by UC-Davis.

Results show that the 1.5 inch debris rack, for all inclines angles, had little effect on velocities in front of and in back of the debris rack (Figures 12 through 15). The average velocity profile for the 1 ft/s scenario show uniform velocities at the three transects for all debris rack angles. Under the higher velocity scenario (2ft/s), changes in the average velocity profile due to the debris rack becomes discernable. At debris rack installation angles of 30, 45, and 60 degrees, the flow velocity decreased at the top and increased at the bottom of the flume as the flow passed from transect A to transect C (Figures 12-13). At a debris rack angle of 15 degrees, velocity at the top of the flume remained consistent and velocity at the bottom of the flume slightly increased (Figure 15).

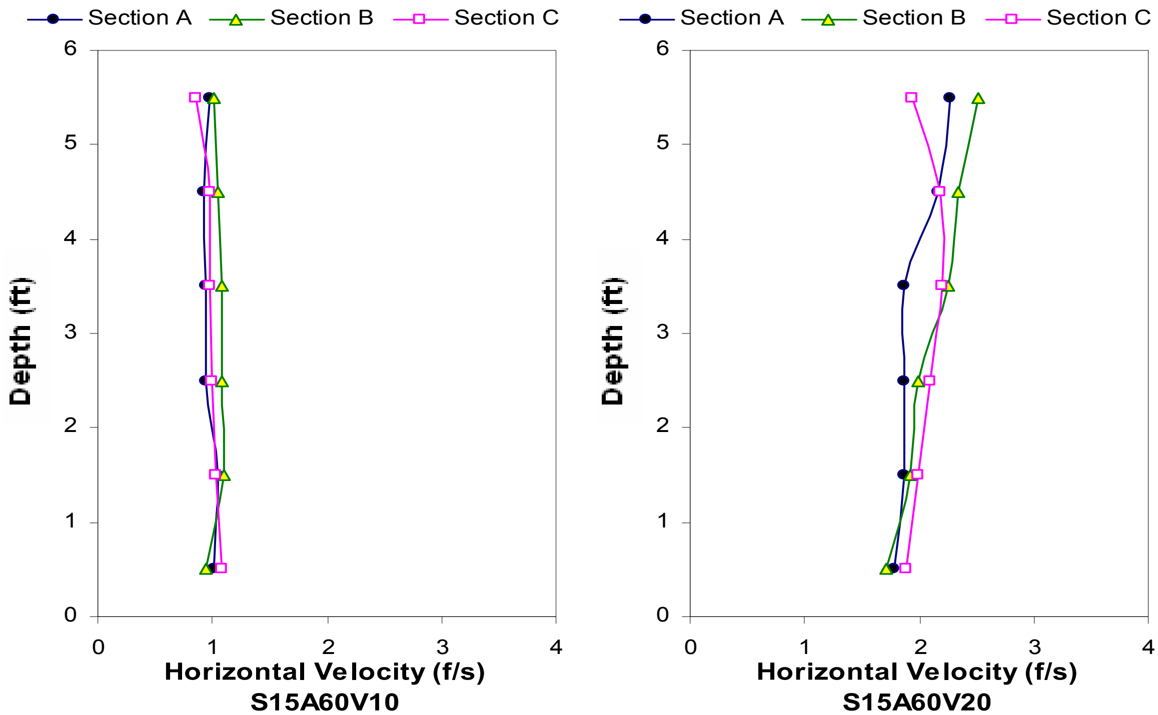


Figure 12 - Average horizontal velocity profile plots for the debris rack configuration S15A60 at flow velocities of 1 ft/s and 2 ft/s.

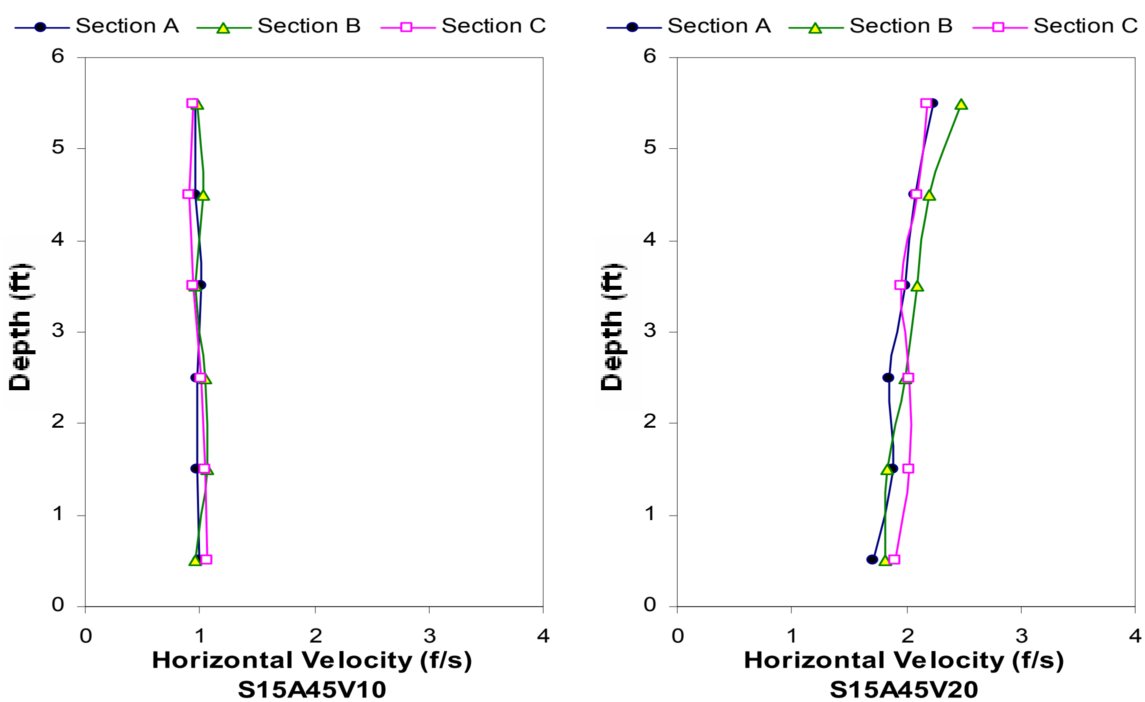


Figure 13 - Average horizontal velocity profile plots for the debris rack configuration S15A45 at flow velocities of 1 ft/s and 2 ft/s.

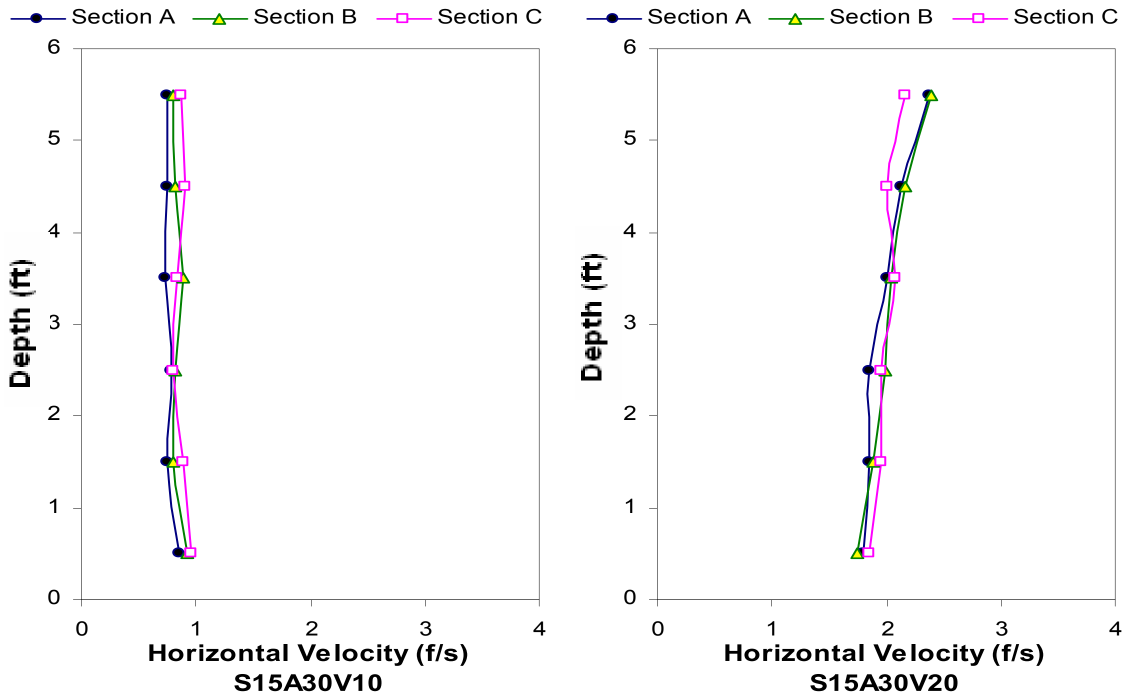


Figure 14 - Average horizontal velocity profile plots for the debris rack configuration S15S30 at flow velocities of 1 ft/s and 2 ft/s.

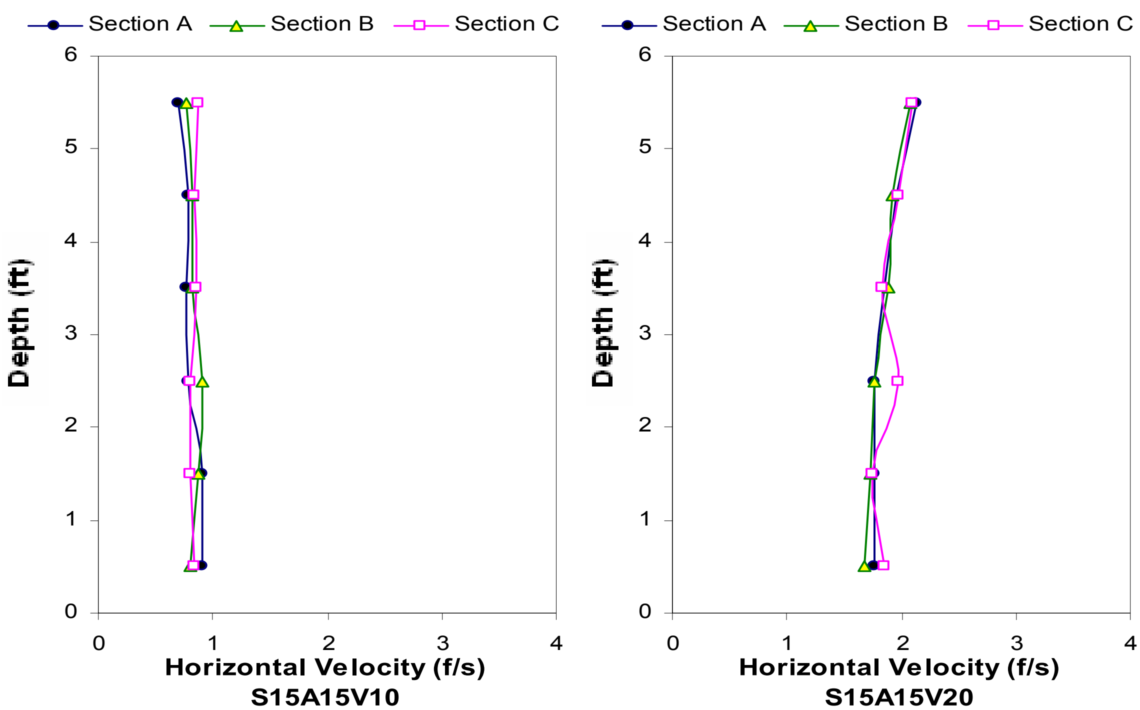


Figure 15 - Average horizontal velocity profile plots for the debris rack configuration S15S15 at flow velocities of 1 ft/s and 2 ft/s.

5.2 Debris Rack Efficiency Results

More than 200 Egeria runs were performed for the debris rack study. The average, minimum, and maximum capture efficiencies for all debris rack combinations tested during the study are shown in Table 4. The table shows variability in the debris capture efficiency of debris racks within a given flow regime. This variability can be attributed to the change in debris composition shown in Figures 8 and 9, and indicates that capture efficiency is dependent on the composition of the debris. This is clearly shown by the capture percentage range of 34% to 62% for the 1.5 inch debris rack installed at 30 degrees and 2 ft/s flow velocity. Even with the large variability in debris capture efficiency, a sample size of six replicates was adequate enough to reveal debris rack efficiency as a function of bar spacing, installation angle and flow velocities.

Table 4 – Debris rack efficiencies with different bar spacing, installation angles and velocities.

Debris Rack Configuration			Initial Velocity (ft/s)	Average Capture Efficiency (%)	Minimum Capture Efficiency (%)	Maximum Capture Efficiency (%)	Number of Debris Runs
Configuration No.	Bar Spacing (inches)	Incline Angle (degrees)					
S15A15	1.5	15	1	70.59	57.43	81.67	6
			2	60.16	45.37	72.17	6
S15A30		30	1	60.95	55.23	65.33	6
			2	54.13	33.78	62.15	6
S15A45		45	1	68.52	53.10	80.00	6
			2	68.87	48.72	87.64	6
S15A60		60	1	56.08	45.92	75.13	6
			2	53.39	24.28	74.49	6
S30A15	3	15	1	47.17	35.14	61.56	6
			2	44.22	30.68	65.82	6
S30A30		30	1	49.95	34.60	63.64	6
			2	40.11	28.57	46.33	6
S30A45		45	1	32.26	7.89	46.09	6
			2	32.55	21.36	38.73	6
S30A60		60	1	25.47	8.87	34.60	6
			2	25.50	22.16	30.56	6
S45A15	4.5	15	1	34.21	20.76	42.40	6
			2	25.89	8.19	37.08	6
S45A30		30	1	32.29	24.73	39.66	6
			2	28.49	22.38	32.29	6
S45A45		45	1	26.23	9.01	44.38	6
			2	23.12	15.94	30.06	6
S45A60		60	1	20.17	3.83	40.37	6
			2	21.71	16.96	26.39	6
S60A15	6	15	1	34.19	15.38	52.59	7
			2	21.46	10.94	32.73	6
S60A30		30	1	30.44	10.00	58.78	6
			2	23.46	18.49	27.01	6
S60A45		45	1	16.25	3.58	27.62	6
			2	17.18	14.59	24.54	6
S60A60		60	1	16.72	3.85	34.93	6
			2	21.04	7.42	36.36	6

5.2.1 Debris rack efficiency as a function of bar spacing and velocity

The results indicate that as bar spacing is reduced the efficiency of the debris rack increases. This was true for all debris rack angles. The 1.5 inch bar spacing performed best overall at both flow velocities, with an average capture percentage of 71% at 1ft/s and 60% at 2ft/s (Figure 16). The 3 inch bar spacing produced the second highest capture percentage for all debris rack installation angles. The 4 inch and 6 inch bars spacing yielded similar results across all debris rack angles and both velocities. The average capture percentage of the debris rack decreases as the velocity is increased from 1ft/s to 2ft/s by 10% or less.

5.2.2 Debris rack efficiency as a function of angle & velocity

At 1 ft/s flow velocity, the results show debris rack efficiency generally increasing as the installation angle (from vertical) decreases (Figure 17). Decreasing the angle from 60 degrees to 15 degrees for the 1 ft/s velocity increased the capture percentage by an average of 16%.

Under the 2 ft/s scenario, bar spacing of 3, and 4.5 inches show the same trend of debris rack efficiency increasing as the angle (from vertical) decreases. The results for the 1.5 and 6 inch bar spacing varied and did not show this trend. The average debris capture percentage of the 1.5 inch bar spacing was 59 % and for the 6 inch bar spacing was 21% for all installation angles.

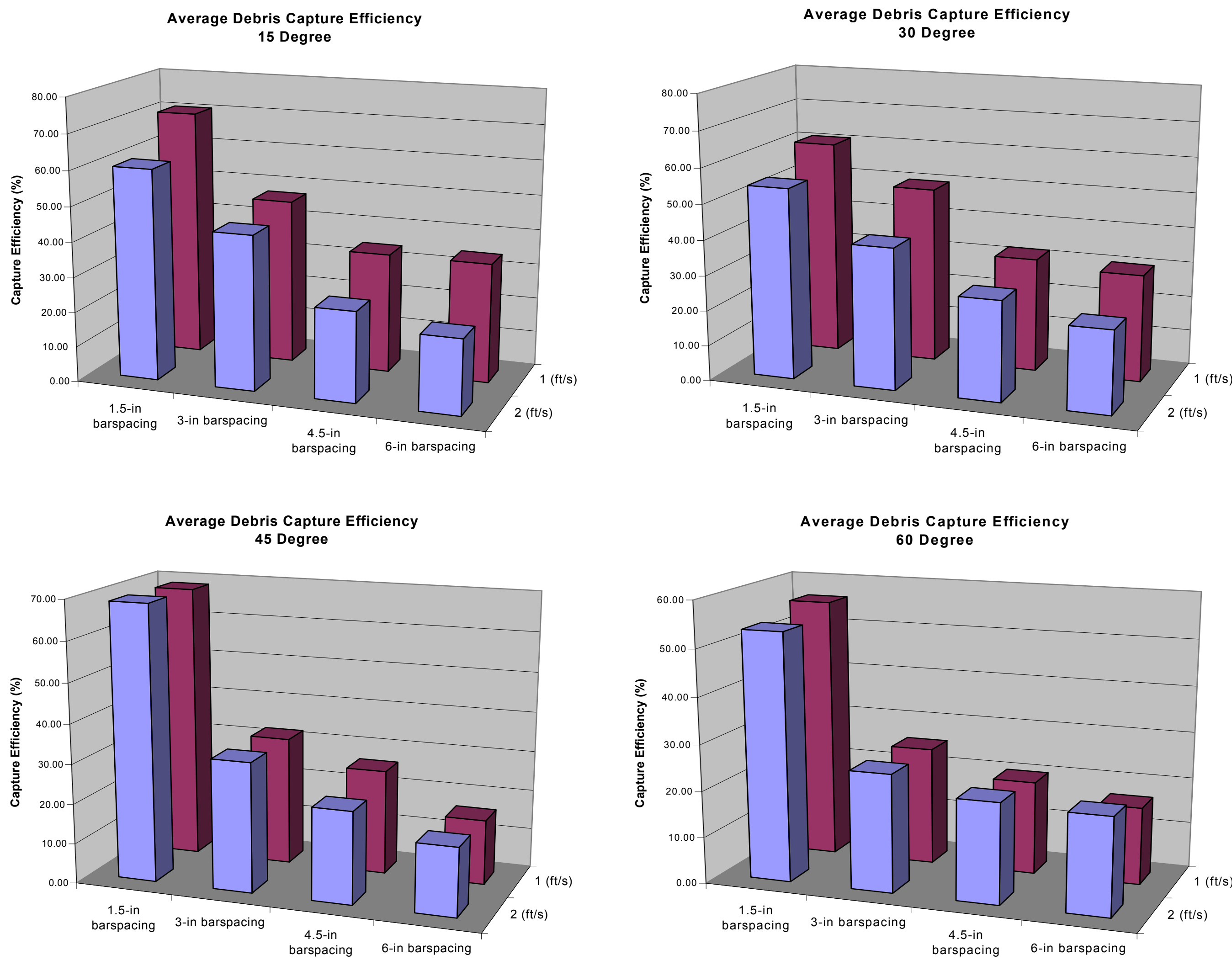


Figure 16 - Average debris capture efficiencies of debris racks as function of bar-spacing.

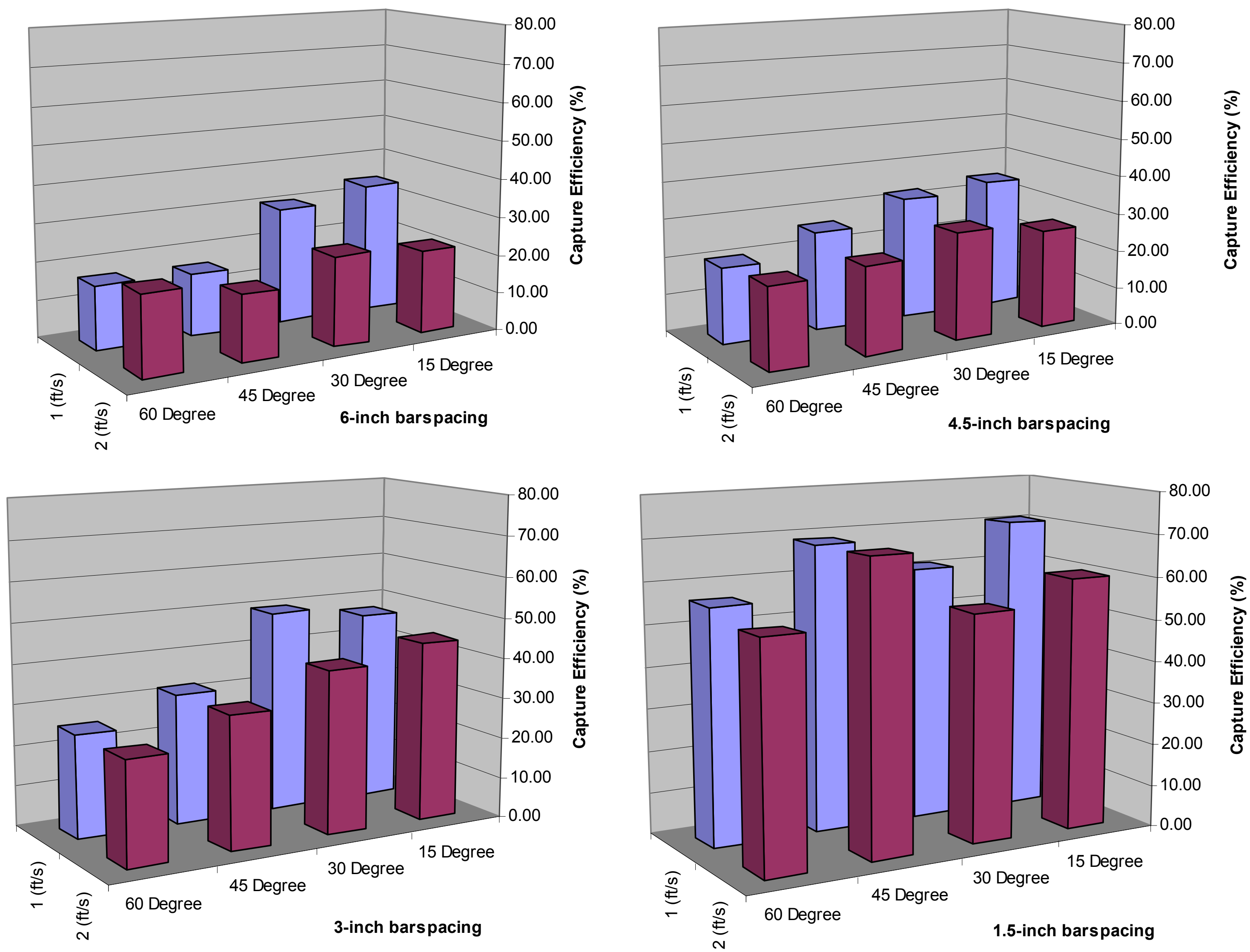


Figure 17 - Average debris capture efficiencies of debris racks as function of incline angle.

5.2.3 Debris rack efficiency as a function of angle and bars spacing

To better illustrate the relationship between bar spacing, debris rack angle and velocity, Figures 18 and 19 were generated for each individual flow velocity. The figures clearly show capture efficiency increases as the debris rack angle decreases and the bar spacing decreases.

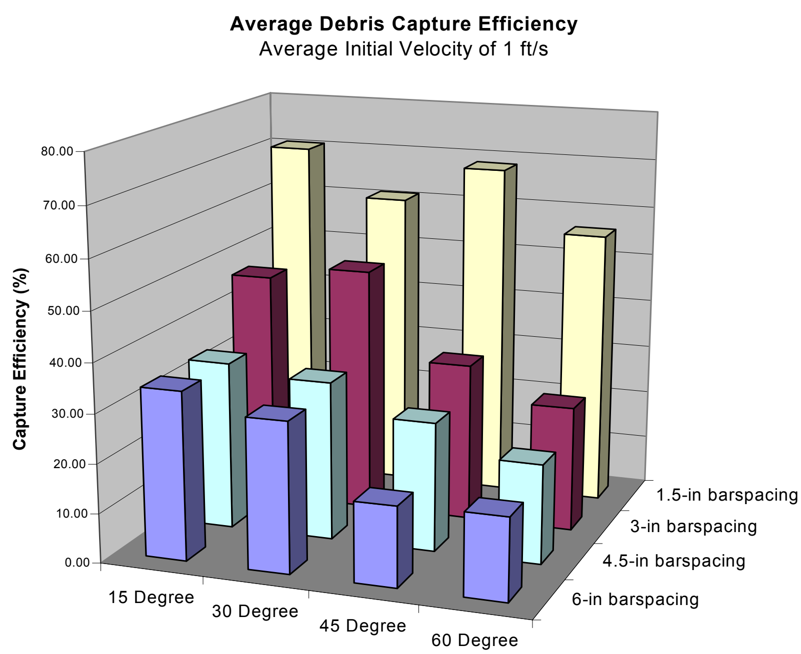


Figure 18 - Average debris capture percentage of debris racks at a flow velocity of 1 ft/s.

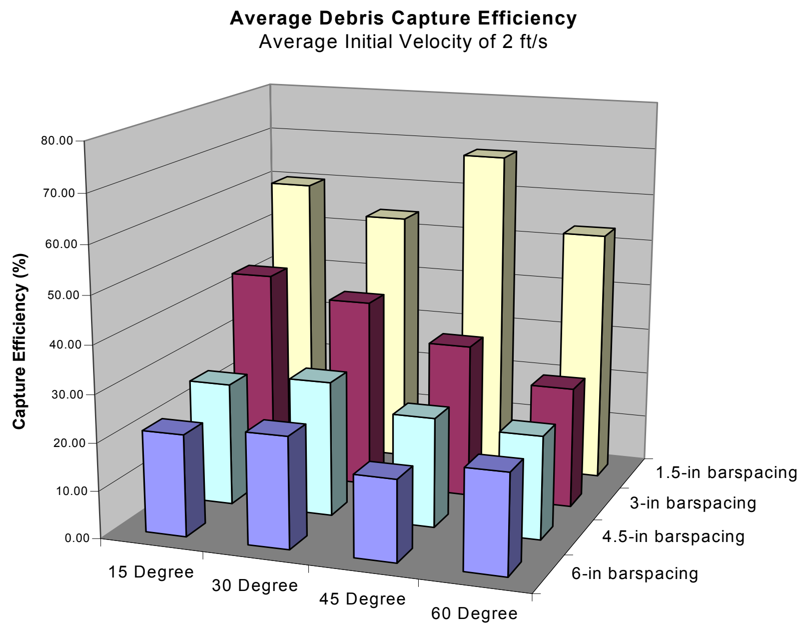


Figure 19 - Average debris capture percentage of debris racks at a flow velocity of 2 ft/s.

5.3 Traveling screen debris efficiency

The average, minimum, and maximum debris capture percentage of the traveling screen are shown in Table 5. The average capture percentages with respect to debris rack angle and screen speed are plotted in Figure 20. Results indicate that the peak capture percentage occurred at a screen speed of 3.5 ft/min, at an angle of 15 degrees, and a flow velocity of 1 ft/s. Considering all three installation angles, the efficiency of debris capture for a screen speed of 7.5 ft/s decreased as the flume flow velocity increased from 1 ft/s to 2 ft/s. The 3.5 ft/s screen velocity did not show this trend, showing little change in capture efficiencies as the flow velocity increased. Results also show that capture efficiency decreases for the 7.5 ft/s screen speed (at both velocities) as you increase the angle from 15-45 degrees. The 3.5 ft/ s screen velocity again did not show this trend.

Table 5 – Traveling Screen debris efficiency.

Traveling Screen			Approach Velocity (ft/s)	Median Capture Efficiency (%)	Minimum Capture Efficiency (%)	Maximum Capture Efficiency (%)	Number of Debris Runs
Configuration No.	Screen Speed (ft/min)	Incline Angle (degrees)					
T35A15	3.5	15	1	47.85	31.89	57.76	6
			2	37.55	29.34	42.80	6
T35A30		30	1	46.57	36.33	58.04	6
			2	46.37	34.11	54.47	5
T35A45		45	1	44.23	36.69	58.82	6
			2	44.74	42.28	54.01	6
T75A15	7.5	15	1	39.04	26.58	52.36	6
			2	37.62	29.69	44.14	6
T75A30		30	1	42.63	33.33	61.98	6
			2	36.00	26.94	46.03	6
T75A45		45	1	36.53	29.93	44.44	6
			2	34.84	29.26	52.55	6

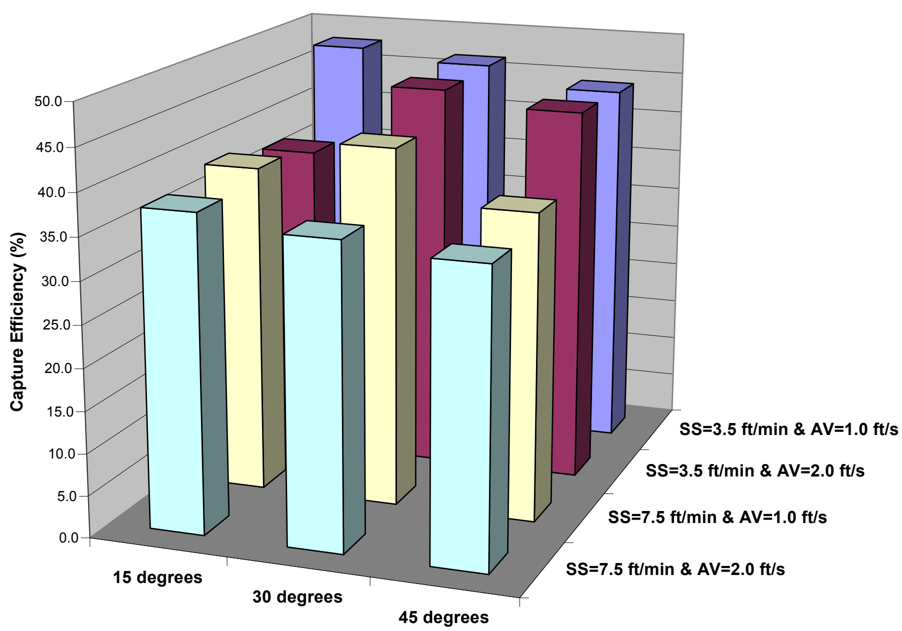


Figure 20 - Average debris capture efficiencies of traveling screen, where SS=screen speed and AV=approach velocity.

Capture percentage of the traveling screen and debris racks (1.5, 3, and 4.5 inch) at flows of 1 ft/s and 2 ft/s, are plotted together in Figures 21 and 22. The UCD report did not include graphs for the 6 inch bar spacing.

At a flow of 1ft/s, a traveling screen speed of 3.5 ft/min produced a higher capture percentage than two out of the three debris racks (Figure 21). The debris rack with 1.5 inch bar spacing produced a higher capture percentage than the traveling screen for all installation angles. Results also show that changing the incline angle produced little difference in efficiency of the 3.5 ft/min traveling screen. Increasing the traveling screen speed to 7.5 ft/ min slightly reduced the efficiency for all incline angles. At a traveling screen speed of 7.5 ft/min, the highest efficiency is obtained at an angle of 30 degrees.

Under a 2 ft/s flume flow scenario, results varied and showed no clear trend (Figure 22). Of the two traveling screen speeds, the 3.5 ft/min speed produced higher capture percentages. The 3.5 ft/min speed also produced higher capture percentages than the two debris racks (3.5 and 4.5 inch). Overall, the greatest capture percentage was produced by the debris rack with 1.5 inch bar spacing. The efficiency of the traveling screen at both speeds was much more consistent across the different incline angles when compared to the debris racks. The traveling screen (both speeds) and 1.5 inch bar spacing, produced the greatest capture percentage under a 30 degree installation angle.

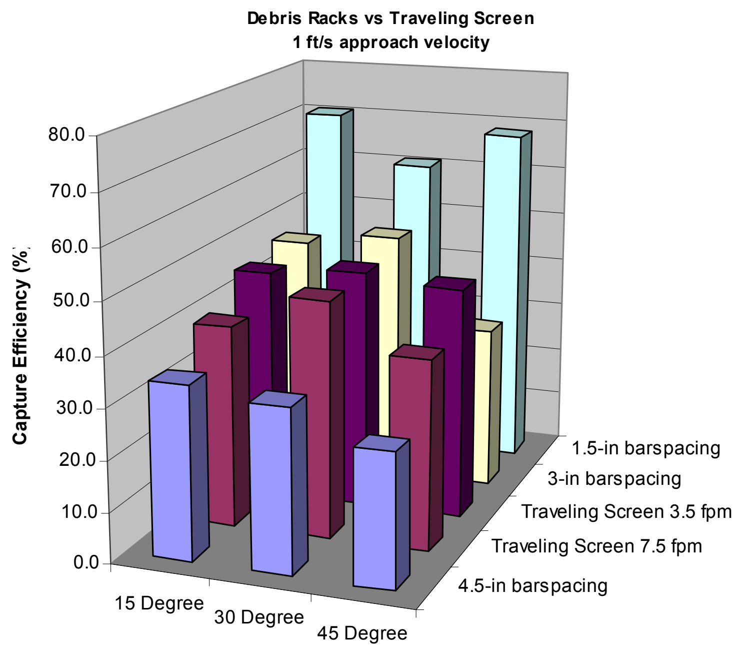


Figure 21 – Comparison of debris capture efficiencies of debris racks and traveling screen for 1 ft/s.

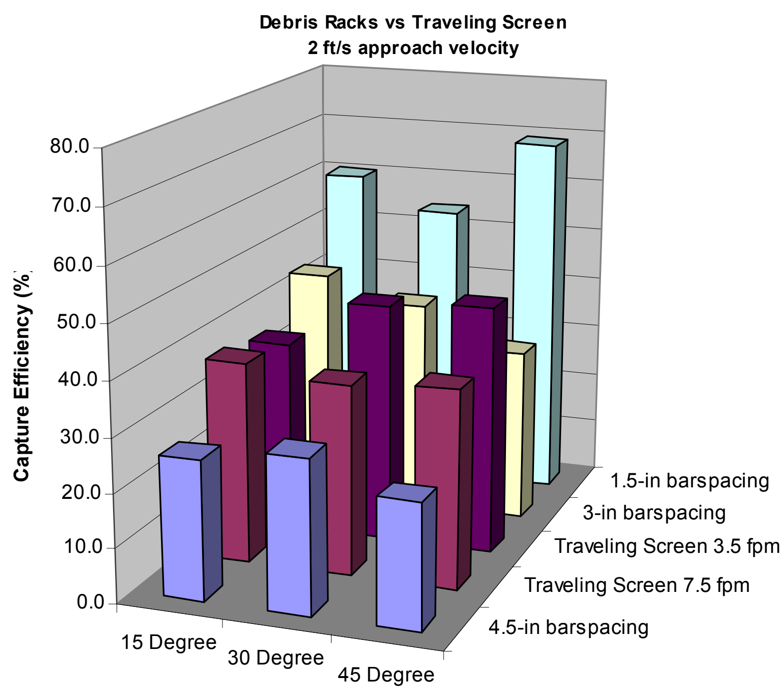


Figure 22 - Comparison of debris capture efficiencies of debris racks and traveling screen for 2 ft/s.

5.4 Fish passage levels

At 2 ft/s (the most complete data set in terms of species comparisons) Threadfin shad, delta smelt, and splittail demonstrated the highest levels of passage, while the Chinook salmon, striped bass, steelhead, and green sturgeon showed much lower passage levels, with the rigid debris rack configurations (Table 6). Similarly, in the presence of the traveling screen, delta smelt realized much greater passage than the fall-run Chinook salmon (Table 7) at 1 ft/s and 2 ft/s.

Passage levels of threadfin shad increased as water velocity was increased (Table 6), with the greatest passage levels found at 2 ft/s (98% of the fish passing at the 6 inch bar spacing, and 84% passing at the 1.5 inch bar spacing). These levels at 2ft/s were significantly different from those at each bar spacing for 0 and 1 ft/s. Within-flow comparisons, which tested for the effect of bar spacing on passage levels, showed no significant differences between the two bar spacing at either the 0, 1 or 2ft/s treatments. Thus, there was no effect of bar spacing on passage levels by threadfin shad.

The significance of the result that most threadfin shad passed at 2 ft/s while half of the fish passed at 1 ft/s led to a more detailed examination of the groups of shad used in the 1 ft/s experiments. There was a clear difference in the distributions of standard lengths (SL) for the shad that passed the debris rack versus the shad that resisted passage, at both debris rack spacing. The distributions of the lengths of the fish that did not pass clearly skewed towards larger sizes. The size difference between the shad that passed and the shad that did not pass the debris racks was about 0.9 to 1.2 cm; this difference was significant (Table 8). Larger shad were thus able to avoid passage through 1.5 and 6 inch debris racks at 1 ft/s. An increase in water velocity to 2 ft/s prevented all shad, regardless of size, from resisting passage through the debris racks.

At 2 ft/s most (83-99%) delta smelt and splittail passed both the 1.5 and 6 inch debris racks (Table 6). There were no significant differences between the levels of passage for the 1.5 and 6 inch debris racks. Thus, bar spacing had no effect on passage at 2ft/s for delta smelt and splittail. Similarly, there was no effect of bar spacing on passage by the two size classes of striped bass or the winter-run Chinook salmon (Table 6). Large striped bass completely avoided passage at 2 ft/s, while the small bass realized low levels of passage, as did the winter-run Chinook (Table 6).

Steelhead exhibited very low levels of passage past the 1.5 inch debris rack in the glass flume at each of the three water velocities and only one large winter-run Chinook salmon passed the 1.5 debris rack at 1 ft/s while 33-47% of the green sturgeon passed the debris rack (Table 6). About half of the green sturgeon, however, passed the debris rack volitionally and either passed back upstream through the debris rack or remained in very close proximity or in contact with the debris rack. This is in contrast to the other fish species which passed the debris rack, at similar or higher levels, which, after passing through debris rack, were often collected at the downstream screen that prevents the fish from entering the pumps. These fish were unable to maintain position once they passed the debris rack.

Fall-run Chinook salmon exhibited a decreasing level of passage through the traveling screen as water velocity increased (Table 7). The proportion passing the traveling screen at 2 ft/s (4%) was significantly less than the proportion passing (21%) at 0 ft/s. The inverse was true for delta smelt, where the proportions passing at 1 and 2 ft/s (100% and 90% at 2 and 1 ft/s, respectively; Table 7) were significantly greater than the proportion passing at the 0 ft/s.

Table 6 - Passage levels of the fish tested in the various experimental treatments of two debris rack spacing (1.5 inch and 6 inch) with average water flows of 0, 1, or 2 ft/s.

Species	0 ft/s		1 ft/s		2 ft/s	
	1.5”	6”	1.5”	6”	1.5”	6”
threadfin shad		0.3	0.5	0.55	0.84	0.98
delta smelt					0.99	0.98
Sacramento splittail					0.95	0.83
“small” WR Chinook					0.23	0.4
“large” WR Chinook			0.07			
“small” striped bass					0.06	0.4
“large” striped bass	0.0		0.0		0.0	0.0
steelhead	0.07		0.0		0.07	
green sturgeon	0.33		0.47		0.47	

Table 7 - Mean proportion passing and passage times of fall-run Chinook salmon and delta smelt through the traveling screen at each of three average water velocities; 0, 1, and 2 ft/s.

Species	0 ft/s			1 ft/s			2 ft/s		
	Mean Prop. Passing	Mean Passage time (s)	n	Mean Prop. passing	Mean Passage time (s)	n	Mean Prop. passing	Mean Passage time (s)	n
FR Chinook	0.21 (0.14)	2765 (61.39)	180	0.09 (0.07)	3018.6 (162.44)	90	0.04 (0.02)	1592 (319.51)	180
delta smelt	0.0	---	60	0.9 (0.1)	211.11 (76.01)	60	1.0 (0.0)	74.74 (7.59)	99

Table 8 - Standard lengths (SL) and total length (TL) of shad that passed and did not pass the two debris rack bar spacing (1.5 inch and 6 inch). P = probability level of the test of significance (Wilcoxon-Mann-Whitney rank-sums) that there is no difference in lengths. * indicates a significant difference

Bar spacing (in)	Passed fish SL, TL (cm)	No-pass fish SL, TL (cm)	p
1.5	6.1, 7.3	7.1, 8.3	< 0.001*
6	6.3, 7.2	7.5, 8.6	< 0.0001*

5.5 Fish passage times

At 2 ft/s it took significantly less time (185.16 s) for threadfin shad to pass the 6 inch debris rack than at 1 ft/s (218.77 s). The opposite was true for the 1.5 inch debris rack, where the mean time of the shad to pass the debris rack at 2 ft/s (342.73 s) was significantly greater than the mean time at 1 ft/s (195.89 s). Thus, an increase in water velocity decreased the time to pass the 6 inch debris rack, while that same increase in water velocity increased the time to pass at the 1.5 inch debris rack.

At 2 ft/s the mean time for the threadfin shad to pass the 6 inch debris rack (185.16 s) was significantly less than the mean time to pass the 1.5 inch debris rack (342.73s). Thus, decreasing the bar spacing significantly increased passage time as the smaller debris rack spacing (1.5 inch) delayed passage of the shad relative to the larger debris rack spacing (6 inch) at 2 ft/s. However, changes in water velocity can reverse the effect. At 1 ft/s the larger debris rack spacing (6 inch) delayed passage of the shad relative to the smaller debris rack spacing (1.5 inch).

Figure 23 illustrates the combined effects of water velocity and debris rack bar spacing on threadfin shad passage time. For a given point in experimental time the cumulative number of shad passing, expressed as the percentage of total passed fish, can be seen to diverge almost immediately for all treatments. This divergence becomes more pronounced as experimental time passes, especially with regard to bar spacing. This divergence is much more pronounced at 2 ft/s than at 1 ft/s; at 1 ft/s the two curves cross at around 700 s when approximately 90% of the fish that will ultimately pass have passed.

Bar spacing also significantly influenced the mean time for passage for delta smelt, splittail, and winter-run Chinook salmon. For the smelt and splittail, the mean time to pass at 2 ft/s was significantly greater for the 6 inch clear debris rack than the 1.5 inch debris rack (111.88 s versus 61.81 s and 568.04 s versus 313.04 s for the delta smelt and splittail, respectively). The opposite was true for the salmon. At 2 ft/s winter-run Chinook salmon realized a significantly greater mean time for passage (2821.9 s) at the 1.5 inch debris rack than at the 6 inch debris rack (2138.9 s).

Inter-species comparisons at 2 ft/s revealed that winter-run Chinook had the greatest mean time to pass at both bar spacing; this was significant in pair-wise comparisons with all other species. For the 6 inch debris rack the mean times to pass for delta smelt and splittail were not significantly different, but the mean time to pass for delta smelt was significantly less and the mean time for splittail to pass significantly greater, than threadfin shad. For the 1.5 inch debris rack the mean time to pass for the delta smelt and splittail were significantly different, the splittail realizing a greater mean time to pass than the smelt. The mean times of both were significantly less than that of the threadfin shad.

Inter- and intra-species comparisons of the effect of bar spacing on passage time at 2 ft/s are visualized via plots of the cumulative number fish (percentage of total passed fish) passing the debris rack as a function of experimental time (Figure 24). For the threadfin shad and winter-run Chinook salmon the curves are pushed to the right when bar spacing is increased from 1.5 inch to 6 inch. An increase in bar spacing pushes the curves of the delta smelt and splittail to the left (Figure 24). As a result, more Chinook salmon and threadfin shad have passed the 6 inch debris rack at a given point in experimental time than the 1.5 inch debris rack, while more delta smelt and splittail have passed the 1.5 inch debris rack than the 6 inch debris rack at any given point in time. These relations are non-linear, however, and tend to become more pronounced as experimental time moves forward, i.e., we see more of an effect of bar spacing on the fish that appear to resist passage rather than those that pass more readily.

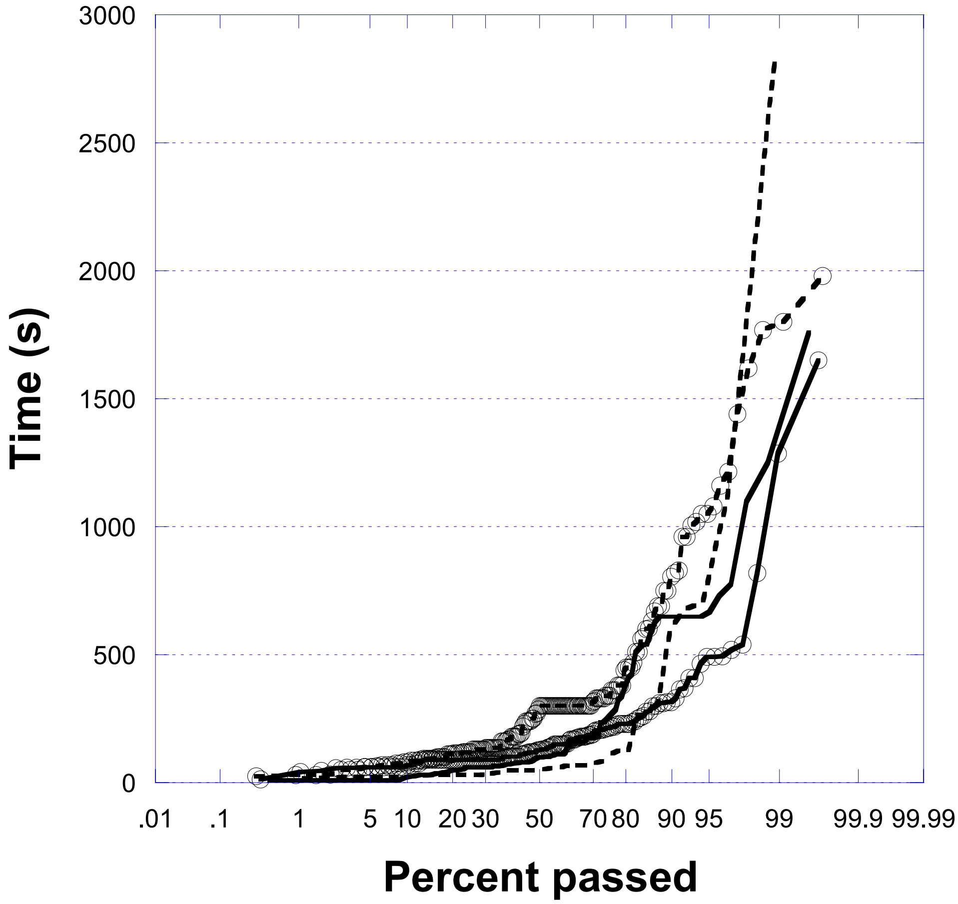


Figure 23 - The percentage (of the total threadfin shad that will ultimately pass) of threadfin shad passing the 1.5 inch and 6 inch debris racks at average velocities of 1 and 2 ft/s as a function of experimental time (s).

Solid line = 6 inch debris rack at 1 ft/s; dashed line = 1.5 inch debris rack at 1 ft/s; solid line with circular marker = 6 inch debris rack at 2 ft/s; dashed line with circular marker = 1.5 inch debris rack at 2 ft/s.

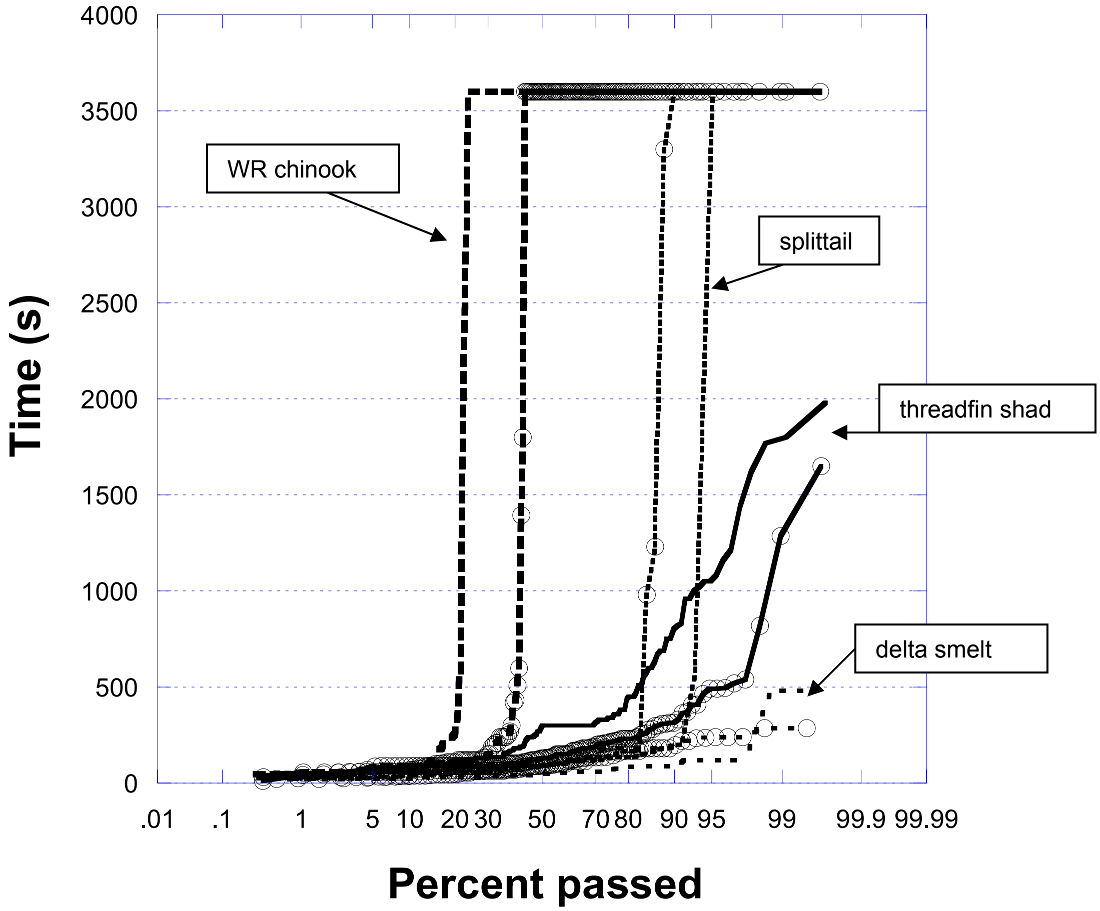


Figure 24 - The percentage (of the total fish that will ultimately pass) of all species passing the 1.5 inch and 6 inch debris racks at an average velocity of 2 ft/s, as a function of experimental time (s). Species curves are indicated on the figure; lines without circular markers indicate curves for the 1.5 inch debris rack spacing and lines with circular markers indicate curves for the 6 inch debris rack spacing.

Mean passage time through the traveling screen varied with water velocity for both the fall-run Chinook salmon and delta smelt (Table 7). For the salmon, the passage time at 2 ft/s was significantly less than the passage time at 0 ft/s, while the times at 0 and 1 ft/s and 1 and 2 ft/s were not significantly different. Although there was a qualitative decrease in delta smelt passage time (Table 7) through the traveling screen as water velocity increased, the difference in passage time between 1 ft/s and 2 ft/s was not significant. The mean passage times (Table 7) for delta smelt were significantly smaller than those of the fall-run Chinook salmon that passed the traveling screen at both 1 and 2 ft/s.

The effects of water velocity on delta smelt and Chinook salmon passage through the traveling screen can be visualized through probability plots of the cumulative number of the fish, expressed as a percentage of the total fish that passed the screen within the one-hour experimental time, as a function of experimental time (Figure 25). For the Chinook salmon, the curve at 2 ft/s diverges immediately and extensively from those of 0 and 1ft/s, indicating a much faster accumulation of passed fish at 2 ft/s than at 0 or 1 ft/s. The curves for the Chinook at 0 and 1 ft/s do not diverge greatly, as is the case of the 1 and 2 ft/s curves for the delta smelt (Figure 25), indicating similar dynamics of accumulation of passed fish. This follows from the insignificance of the differences in mean passage time between the Chinook at 0 and 1 ft/s, and the delta smelt at 1 and 2 ft/s. The curves for Chinook salmon are, qualitatively, more linear than those of the delta smelt (Figure 25), indicating a much more gradual accumulation of passed fish. The salmon passed as individuals, separated in time, throughout the course of the experimental duration; the smelt passed in groups early in the experiment.

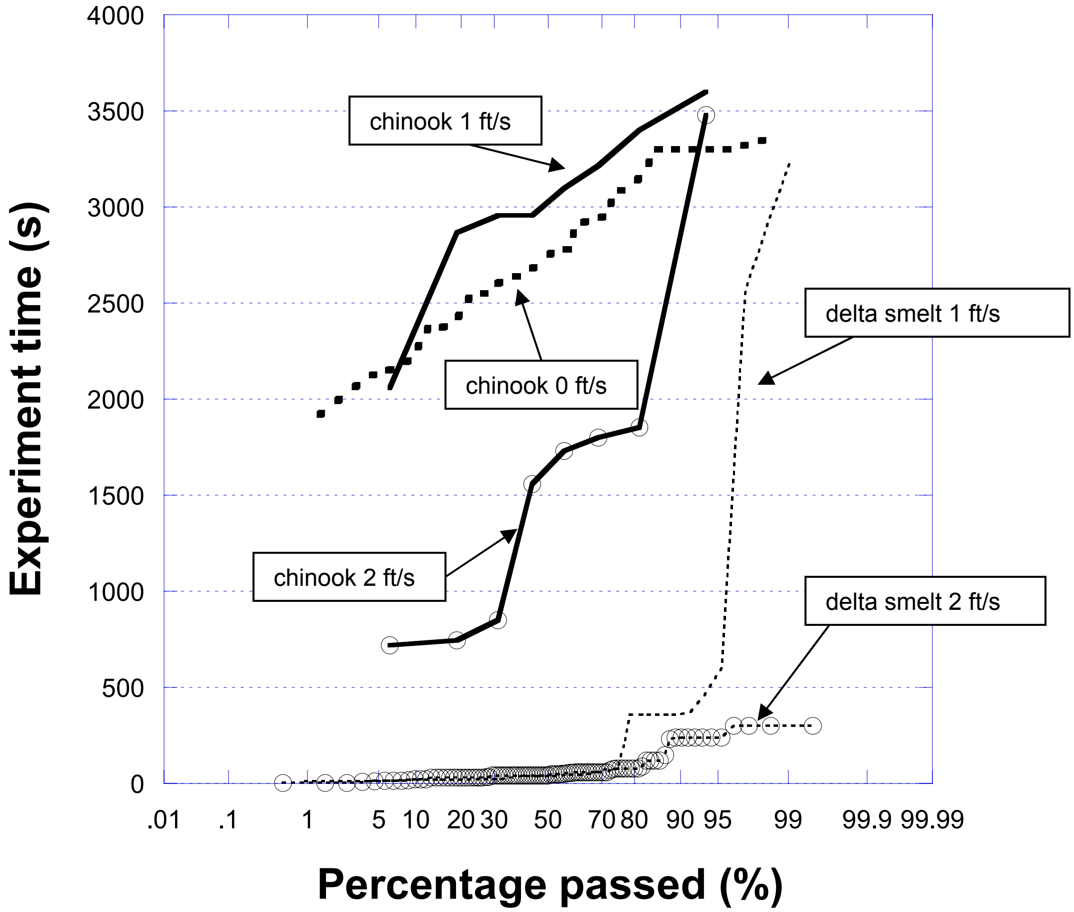


Figure 25 - The percentage (of the total fish that will ultimately pass) of fall-run Chinook salmon and delta smelt passing the traveling screen at average water velocities of 0, 1, and 2 ft/s (indicated on the figure) as a function of experimental time (s).

No curve exists for delta smelt at 0 ft/s as no delta smelt passed the traveling at that average water velocity.

5.6 Fish behavior related to debris rack configuration

Observation of the fish that resisted passage through the different debris rack configurations revealed some species-specific positional preferences directly next to the debris rack and upstream of the debris rack. Results showed that at 2 ft/s steelhead and green sturgeon dominated the observations 10-12 m upstream of the 6 inch debris rack, at the upstream extent of the flume channel, while the small winter-run Chinook, small striped bass, and those splittail that resisted passage are the predominate species occupying position at (0m) or just upstream (≤ 1 m) from the debris rack. A small cluster of observations at –1 to –3 m (1 to 3 m behind or downstream of the debris rack) represented the green sturgeon that passed the debris rack and held position behind it or passed back through it. Large striped bass were found throughout the upstream flume channel, represented by small levels of observation 1m, 7 to 8 m, and 11 to 12 m upstream of the 6 inch debris rack. Large striped bass, unlike the other species observed in this study, actively switched positions in the upstream channel, constantly swimming throughout the upstream expanse rather than maintaining position at some consistent point (M. Karagosian, personal observation). A similar observation was made with the 1.5 inch debris rack at 2 ft/s. The large striped bass were observed throughout the channel upstream of the debris rack, actively swimming. The small striped bass were also found throughout the expanse of the upstream channel, unlike their behavior in front of the 6 inch debris rack, while the small winter-run Chinook salmon were observed most frequently at or just upstream (0 – 2 m) of the 1.5 inch debris rack, as with the 6 inch debris rack observations. There is distinct mid-channel cluster of observations 6 to 8 m upstream for the small salmon.

Positional observations were made for fall-run Chinook salmon and delta smelt at three flows (0,1, and 2 ft/s) in the presence of a traveling screen. When there was no flow (0 ft/s) the fall-run Chinook salmon exhibited three distinct peaks in frequency of occurrence; at the traveling screen (0-1 m upstream), mid-channel (around 6 m) and at the upstream extent (11 m). In flowing conditions of 1 and 2 ft/s these peaks are removed and the salmon are found throughout the channel upstream of the traveling screen. Statistical tests of these distributions revealed that the distribution of observations in the channel of fall-run Chinook salmon at the no-flow condition (0 ft/s) were significantly different from the positional distributions of the salmon at 1 ft/s and 2 ft/s. The distributions at 1 ft/s and 2 ft/s were not significantly different.

Delta smelt were found distributed rather evenly throughout the flume channel when there was no flow (0 ft/s). When the water velocity was increased to 1 ft/s there was a distinct movement of observations towards the traveling screen, with a large peak at 0 – 1 m and some clustering between 3 and 7 m. The observational distributions at 0 and 1 ft/s were significantly different. No positional observations were made, and thus distributions constructed, of delta smelt in the presence of the traveling screen at 2 ft/s due to the complete passage of these fish at this velocity.

6 CONCLUSIONS AND RECOMENDATIONS

6.1 Debris capture

The goal of the debris study was to gain an understanding of debris rack design and how it affects debris capture. A total of 16 debris rack configurations and six traveling screen configurations were tested at the UCD Hydraulics Laboratory. The 16 debris rack configurations consisted of four debris rack installation angles (15, 30, 45, and 60 degrees) and four debris bar spacing (1, 3.0, 4.5, and 6.0 inches). The six traveling screen configurations were obtained by combining three installation angles (15, 30, and 45 degrees) and two traveling speeds (3.5 ft/min and 7.5 ft/min). The traveling screen mesh was constructed of ¼ inch diameter stainless steel cable with mesh openings of 2 inches by 4.5 inches. The mesh was the same for all traveling screen tests. Both the debris racks and traveling screen were tested for flow velocities of 1 ft/s and 2 ft/s.

The results demonstrate that debris capture is directly related to the bar spacing of the debris rack and the incline angle at which the rack is installed. As the bar spacing is reduced from 6 inches to 1.5 inches, the efficiency of the debris rack increases. A debris rack with a bar spacing of 1.5 inches might seem like the obvious choice since it captures the most debris, but debris is not always the only concern. At the State and Federal fish facilities, others elements such as fish passage and head loss are just as important and must be considered when selecting a debris rack for a fish facility. Studies by Hanson and Li showed delayed passage of juvenile Chinook salmon through debris racks with a bar spacing of less than 6 inches. However, test results for the 6 inch bar spacing show debris capture percentages of only 20% to 25%. A balance between successful fish passage and sufficient debris removal must be obtained to effectively operate any fish facility.

The angle at which the debris rack is installed also plays and important role in debris capture efficiency. As the incline angle (from the vertical plane) of the debris rack is increased from 15 degrees to 60 degrees, the efficiency decreases. This was true for both test flow velocities.

Water velocity also plays an important role in debris rack efficiency. As velocity increases the efficiency decreases. The highest water velocity attained inside the test flume was 2ft/s. It is unknown whether this trend would continue with higher water velocities.

The traveling screen produced results similar to the debris rack with 3 inch bar spacing. One could argue that although the debris removal is similar, the traveling screen would provide better fish passage due to the fact that debris is constantly being removed by the traveling mesh. It is unknown though how the traveling mesh would affect fish passage. The fish may be deterred by the moving mesh or may hesitate to pass through increasing the chance of predation.

6.2 Fish interaction with debris rack configurations

The evidence thus far suggests that fish resist passage through a debris rack, regardless of design, in flowing water. There was no influence of bar spacing or debris rack movement (i.e., the traveling screen) on fish (intra-species) passage levels. Water velocity was the major determinant of passage levels for threadfin shad but not for steelhead or green sturgeon. At 2ft/s passage levels were species-specific for both the rigid debris racks and the traveling screen. These appear to be related to the constraints placed upon swimming performance and endurance by swimming mode, muscle physiology and arrangement, body form, and/or body size of the fish species. Chinook salmon, steelhead, green sturgeon and striped bass have more (absolute and relative) red muscle mass, and thus a greater capacity for aerobic (and therefore sustained) swimming, than delta smelt, threadfin shad, and splittail. Further, the larger caudal fins and more rigid fin rays of the sturgeon, bass and salmonids, and the sturgeon's ability to use its pectoral fins as hydrofoils and lunate tail as a source of drag-minimizing thrust, most likely confer some additional advantage in contending with sustained, higher flows. Sturgeons were the only species to pass back and forth at will through the rigid debris racks. Also, several sturgeons were observed to wedge themselves in between the bars of the debris rack and use their pectoral fins as anchors (M. Karagosian, personal observation).

Threadfin shad provided the opportunity to examine intra-species size-related differences in swimming capacity and passage resistance. Larger threadfin shad were able to resist passage through the debris racks at 1 ft/s while smaller individuals could not. This is presumably a consequence of the greater mass, or a larger percentage of, red muscle and/or greater muscle energy stores of the larger shad. At 2 ft/s this advantage was apparently removed.

Swimming motivation may also play a role in the generation of species-specific passage levels, as is suggested when examining the fall-run Chinook salmon data from the traveling screen studies. The salmon were able to resist passage through the traveling screen, unlike the delta smelt, as passage levels fell with increasing water velocity; the delta smelt passed completely regardless of water velocity. At 0 ft/s, however, 21% of the salmon observed passed through the traveling screen, while no delta smelt passed through. In static water the salmon moved around the extent of the flume channel, in loose aggregations (M. Karagosian, personal observation), and some would cross the screen. When flow was created, the salmon became positively rheotactic and maintained position rather than actively swimming throughout the flume channel and constantly changing positions. In static water the delta smelt formed an aggregation and did not move from a small part of the upstream extent of the flume channel (M. Karagosian, personal observation).

Unlike passage levels, there was a significant influence of debris rack design on flow-dependent, species-specific passage times. At 2 ft/s threadfin shad and those winter-run Chinook salmon that did pass the debris rack took significantly longer to pass the 1.5 inch debris rack than the 6 inch debris rack. The smaller (1.5 inch) spacing appears to be a perceived barrier, and it may force the fish to delay the decision to pass or resist passage more, than the wider (6 inch) spaced debris rack. Two possible reasons for delay or resistance are positional adjustment (i.e., to pass through the debris rack) or avoidance of potential contact. Video records of fish behavior immediately upstream (≤ 1 m) of the debris racks have provided inconclusive evidence regarding an increased temporal contribution of positional adjustment or swimming effort to residence time at the debris rack in the presence of the 1.5 inch debris rack relative to the 6 inch debris rack. At 1 ft/s, we see a reversal of this pattern in threadfin shad; the "delay" in passage occurs at the larger debris rack spacing, 6 inch. This is most likely a result of the heterogeneous passage rates attributable to the larger shad resisting passage. It is unclear why the delta smelt exhibited a significant increase in the time to pass the 6 inch debris rack compared to the time to pass the 1.5 inch debris rack. Splittail showed no effect of bar spacing on time to pass the debris rack at 2 ft/s.

Species-specific variation in the ability or motivation to resist passage, and its concomitant effect on design-dependent passage time, results in species-specific behaviors at and upstream of the debris rack. Small winter-run Chinook and splittail that avoided passage through the rigid debris racks aggregated at (< 1 m away) the debris racks, while the large striped bass were found actively swimming throughout channel 0 – 12 m upstream of the debris rack. Delta smelt concentrated at 0 to 1 m upstream of the traveling screen at 1 ft/s. Chinook salmon, unlike their behavior in the presence of the rigid debris racks did not concentrate just upstream of the traveling screen, but were found throughout the upstream channel at both 1 and 2 ft/s. These species-specific differences in positional and swimming behavior upstream of the debris racks have the potential to significantly affect inter-species interactions, most notably predator-prey relationships. The roaming behavior of the striped bass coupled with the delay and concentration of small fish could contribute to a favorable foraging environment for the striped bass and thus be partly responsible for the (largely) hypothesized role of debris racks facilitating predation by striped bass and other opportunistic predatory species.

6.3 Future study recommendations

- Experimental results show that the efficiency of debris racks decreases with increased velocity (1ft/s to 2ft/s). Further experiments with velocities of 3 ft/s or higher could provide valuable information on debris rack efficiency. Velocities of 3 ft/s and higher are normally encountered at the State and Federal facilities.
- Additional experimental runs are recommended to establish more obvious correlation between capture efficiency and the rack angle and bar spacing.
- Fish passage tests conducted concurrently with debris would provide valuable information on how debris affects fish passage rates through the debris racks.
- Predator-prey studies were originally planned as part of the fish interaction component of this study, but those experiments were not carried out. Experiments exploring fish behavior near debris racks should be revisited to determine if debris racks facilitate predation.

7 REFERENCES

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