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An Analysis of Juvenile Chinook Salmon Outmigration Speed and Survival in Response to Habitat Features: Sacramento River from Knights Landing to Sacramento, California

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This Master's Thesis

An Analysis of Juvenile Chinook Salmon (*Oncorhynchus tshawytscha*) Outmigration Speed and Survival in Response to Habitat Features: Sacramento River from Knights Landing to Sacramento, California

by

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Abstract

Outmigration is an important life stage for Chinook salmon (*Oncorhynchus tshawytscha*) survival in the Sacramento River, and yet our understanding of their behavior and needs during this time is limited. To gain a better understanding of their survival and movement rates during outmigration, late fall run Chinook salmon smolts were tracked using acoustic telemetry techniques. Habitat features were measured and quantified throughout the study area to evaluate how Chinook salmon respond to key levee features including shade, instream woody material, and aquatic vegetation. The overall average movement speed through the entire study area was 0.77 m/s with an overall survival of 86%. Based on multiple linear regressions, vegetation was found to have the largest effect on speed with fish slowing down with increased vegetation cover. Shade, river mile, and velocity also had significant effects on movement speeds, but instream woody material was not significant. The result for woody material was surprising since it was anticipated to have a large impact on movement speeds. A positive correlation was found between faster fish movement speeds and higher survival. No evidence of diel movement patterns was found after releasing the fish. These finding can help managers create sites better designed to help Chinook salmon in the Sacramento River system. Results from this paper indicate that the type of woody material being installed might not be appropriate for this life stage of salmon.

Introduction

Many North American species of salmon have suffered population declines over the last century (Hubley et al. 2008, Welch et al. 2008, Perry et al. 2009, Dempson et al. 2011, Martins et al. 2011, Drenner et al. 2012) Chinook salmon (*Oncorhynchus tshawytscha*) populations in the

Sacramento River have been particularly impacted. Currently, all four of the Evolutionarily Significant Units (ESU) of Chinook salmon in the Sacramento River are listed under the State and/or Federal Endangered Species Act. The winter-run ESU is State and Federally listed as endangered, the spring-run ESU is State and Federally listed as threatened, and the fall and late-fall run ESU's are Federally listed as a Species of Concern (California Department of Fish and Wildlife 2013).

Return rates of Chinook salmon in the Sacramento River used to number in the millions, but by 1970, the number of returning individuals dropped to around 4,000 (Newman & Rice 2002). Outmigration is an important life stage for salmon and survival rates during this stage greatly impacts the adult return rates (Healey 1991, Newman & Rice 2002, Perry et al. 2009, Michel et al. 2012). As juvenile salmon migrate through the Sacramento River and its tributaries, their survival drops dramatically from factors such as predator encounters and water diversions in a highly modified river system that tends to lack complex habitat structure (Perry et al. 2009). Chinook in the Sacramento River have many routes that they can take during migration. Our understanding of these routes is limited and has been the focus of several recent studies. Evidence seems to indicate that some routes have better survival rates than others (Newman & Rice 2002, Limm & Marchetti 2009, Perry et al. 2009, Michel et al. 2012). Perry et al (2009) found survival to be highest for fish that remained in the Sacramento River and lower for fish that migrated through slough and bypasses in the interior of the Delta. The health and survival rates of outmigrating salmon cohorts can greatly affect adult return rates a few years later.

Juvenile salmon have been found to have better growth and survival rates in off-channel routes and floodplains (Sommer et al. 2001, Limm & Marchetti 2009), likely because these areas tend to have optimal temperatures and slower moving water which may provide less predator interactions, more access to food, and better growth rates that improve salmon health prior to reaching the ocean (Sommer et al. 2001, Limm & Marchetti 2009). Larger smolts typically have greater survival rates upon reaching the ocean as well as during migration, compounding effects from the outmigration period (Zabel & Williams 2002).

Unfortunately, the Sacramento River salmon have been largely cut off from floodplain and off-channel habitat due to levees, dams, and diversions. The channelized levee system of the Sacramento River began in the late 1800's. By 1968, the State Flood Control levees were finalized (James & Singer 2008). The narrow system with hardened banks promotes erosion which eventually requires more riprap to repair weakened sections of levees. While riprap is generally thought of as having a negative impact on fish habitat, it has also been found to have some benefits for certain juvenile salmonid species, but not all salmonid life stages (Schmetterling et al. 2001; Fischenich 2003). For example, hardening banks can improve water quality by reducing erosion and sediment loads or provide habitat for aquatic invertebrates that fish rely on as food sources (Fischenich 2003) The scale of impact from riprap or the successfulness of restoration attempts is highly affected by the size of the project (Fischenich 2003, Bernhardt & Palmer 2011). If a small area in a large river is riprapped, it is not likely to have much impact on the system as a whole. However, when the majority of a system is riprapped, similar to the Sacramento River, the impacts can be profound, and small restoration project might be less impactful.

Riprapped streams tend to lack woody debris (Lassettre & Harris 2001, Schmetterling et al. 2001). Hardened banks halt channel migration and reduce the input of new IWM such as fallen trees which provide food and cover for salmonids, and their hardened banks don't easily recruit snags (Lassettre & Harris 2001, Schmetterling et al. 2001). Since 2001, repairs in the area that is the focus of this paper have incorporated placement of anchored IWM on riprapped sites to mitigate for the loss of naturally occurring woody debris recruitment (NMFS 2008, USFWS 2008). The effectiveness of these mitigation measures is not clear due to their patchwork nature of their locations and the large scale of the Sacramento River. Over time as more sites with installed IWM are built, their overall effectiveness might increase as a larger area of banks become covered with IWM. This will increase the complexity of riprapped banks.

Since conditions in most years only allow juvenile salmon access to the mainstem of the river above the delta, this study takes a fine-scale look at a section of the lower Sacramento River where the U.S. Army Corps of Engineers (USACE) has constructed numerous levee repairs, which incorporated habitat structures for juvenile salmon on the levee banks to provide more natural features with the intent of improving juvenile salmon survival (USACE 2012). Many of these repairs were implemented under the Sacramento River Bank Protection Project (SRBPP), which has been an ongoing project since its authorization in the 1960's and has a project area encompassing more than 1,300 miles (2092 km) of levee (USACE 2012). Repair designs along the Sacramento River typically include some combination of rock, riparian vegetation consisting of live cuttings, grasses, and woody plants, anchored instream woody material (IWM), and either a sloping bank or riparian bench. This study used acoustically tagged juvenile hatchery late fall run Chinook salmon to analyze change in outmigration speeds and survival through a stretch of the Sacramento River. The movement and survival rates were then compared to existing habitat features to determine how much of the change in speed and survival can be explained by shoreline environmental features, river flow, or average river velocity.

Study Site

The Sacramento River is the largest of California's rivers. It flows from its headwaters at the McCloud River to the San Francisco Bay with an average annual runoff of 27 billion cubic meters (Domagalski et al. 2000). The analysis in this study focused on an approximately 30 mile (48 km) stretch of the Sacramento River from Knights Landing at approximately river mile (RM) 93 (river km (rkm) 245) to Sacramento, California at approximately RM 62 (rkm 193) (Figure 1). This section of the river is constrained from levees and unable to meander. It contains variable habitats and several USACE repair sites of various ages and types. Some sections are more naturalized with eroding banks sloughing off into the river. The majority of this reach in covered with riprap or other rock armoring such as cobble or concrete rubble.

The upper reach of the study area is fairly narrow and somewhat sinuous. About mid-way through the study area (near RM 80; rkm223), the Feather River joins the Sacramento River, and the river becomes slightly wider with less naturalized banks and more docks and marinas as it approaches the city of Sacramento. The river is widest at the end of the study area. The average flows through the study area during the study period (December 2012 – March 2013) ranged from approximately 22,000 cfs (623 cms) to 12,000 cfs (340 cms) (DWR 2013). There was one peak flow event during the study period. It occurred after the first release and flows had significantly decreased by the second release, therefore the peak flow event was not captured in any of the analysis for this study (Figure 2).

Methods

In order to monitor salmon migration speed and survival, acoustically tagged, hatchery raised, late-full run Chinook salmon smolts from the Coleman National Fish Hatchery in

Anderson, CA were released in the Sacramento River from December 2012 to March 2013 and used as surrogates for wild Chinook salmon smolts (Table 1).

Array

Our study used Vemco 180 kHz VR2W receivers to monitor fish survival and movement; in order to stabilize receivers within the flow of the river, receivers were attached to large mounts consisting of rebar and heavy weights. The receivers were attached to the custom mounts using hose clamps and zip ties to reduce any vibration or noise interference. Cable was attached to the bottom of the mounts for retrieval then secured to the shore. The receivers were deployed at 11 migration timing stations (MS) in the mainstem of the Sacramento River (Figure 1, Table 2) that consisted of two to five receivers to create an acoustic gate with a high likelihood of detecting tagged fish. The station at Knights Landing Bridge (KLB) was the only one with two receivers due to the narrow channel. Most stations consisted of four receivers positioned near the banks in a box pattern. Areas below the Feather River used an additional fifth receiver in the center of the river to improve detection probability.

We focused our monitoring on the area between the release site at approximately RM 93 (rkm 245) and MS 11 at RM 62 (rkm 193) to match with available hydraulic modeling and environmental data. Additionally, there are several SRBPP sites in this area with installed habitat features that are the focus of this study. The linear distance between the release and MS 11 is approximately 179,000 feet (54,559 m). KLB served as the first migration timing station for the array. A station called MS 0 was installed after the second release of fish to provide additional information about how the fish behave just after release. MS 0 was located between the release site and KLB, near RM 92 (rkm 239). Since this station was not available for all releases, it was only used to gain insight on the initial movement of the salmon just after release and was not used in statistical analysis.

Tagging and Release

Juvenile hatchery raised Chinook salmon from the Coleman National Fish Hatchery were tagged with Vemco 180 kHz V5 tags which weigh 0.65 g. The tags are cylindrical with a length of 12 mm and a diameter of 5 mm; they last approximately 55 days after activation. A total of 617 fish weighing between 9 and 88 g (26 g average) and with a total length between 93 and 193 mm (133 mm average) were tagged. Fish size was limited by the size and weight of the tag to not overburden the fish or cause behavioral changes from excessive weight. Fish were anesthetized using Finquel MS-222 prior to tagging. After tagging, fish were held in recovery tanks overnight and transported from the hatchery in Anderson, California, to the release site just above Knights Landing, California.

Fish were released in six separate groups of approximately 100 fish (Table 2). The six releases occurred on five separate days between December 2012 and March 2013. Release groups were limited to 100 fish to reduce the possibility of tag collisions, which occur when too many tags are transmitting at the same time. When this happens, the receivers can miss signals and tags might not be recorded when they are within range of the receiver.

Twenty four hours after tagging, the fish were loaded into five or six coolers, each containing 15 to 20 fish. Once at the release site, the coolers were slowly tempered with river water to acclimate the fish to the river conditions. The fish were released when the water temperature within a cooler was within 0.5°C of the river temperature, one cooler at a time in 20 minute intervals over 2 hours to further reduce tag collisions when the fish migrated through the array.

In order to evaluate potential differences in diurnal vs. nocturnal movement, the final release was split into two groups, with paired day and night releases which both occurred on the same day. Release 5b was released during the day at a similar time to other release groups, and 5c was released around midnight.

Environmental Data

Average river flows for the entire study area during the study period come from three Department of Water Resources (DWR) California Data Exchange Center (CDEC) stations in or around the study area (DWR 2013) (Figure 2). CDEC station Sacramento River at Wilkins Slough is located approximately 26 river miles (42 rkm) upstream of the study area, Sacramento River at Verona is located in the array between MS 7 and 8, and Sacramento River at Freeport is located approximately 12 miles (19 km) downstream from the study area in a tidally influenced part of the river.

Average water velocity for each reach between stations was derived from the Adaptive Hydraulics (AdH) model (Saltus 2014). The model contains several river variables including average velocity values at 5 m^2 intervals. The model covered the entire study area from Knights Landing to the Interstate 5 bridge just above Sacramento. River gauges and ADCP data from Knights Landing, Fremont Weir and Verona were used to calibrate the model (Threadgill 2014).

Shoreline habitat data for shade, vegetation and IWM in the study area were quantified using the USACE Revetment Database, which contains continuous GIS data for the Sacramento River from river mile 0 (rkm 0) at Collinsville to river mile 194 (rkm 312) at Chico Landing (USACE 2007). Data were collected by visual surveys from the water or shoreline by a team of three surveyors. Data were recorded between 2003 and 2007 for features at the mean summer water level and were grouped by bank type (e.g., natural, revetment, etc.). Surveyed bank lengths were not equal since bank type was used to break up surveyed segments. GPS equipment was used in the field to accurately document surveyed bank lengths (USACE 2007). For SRBPP sites built after 2007, additional surveys were conducted, and that information was added to the Revetment Database. For this study, only data on vegetation, IWM, and shade were used since they are the primary features installed along repair sites for salmonid habitat. Each segment surveyed was assigned a categorical value of percent cover for each habitat feature. For example, IWM for a segment was recorded as either 0%, 1-10%, 11-50% or >50% (USACE 2007). For the purpose of this analysis, data from the Revetment Database were converted to an index by taking the median of each of the habitat feature categories, and multiplying it by the total amount of that category in the study area. Each reach (area between stations) was then assigned an index value for each habitat type.

Analysis

Survival within each segment, as well as through the entire array, was determined using the Cormack-Jolly-Seiber model for mark and recapture type analyses (Cormack 1964, Jolly 1965, Seiber 1965). A one-way analysis of variance (ANOVA) with the Holm's sequential Bonferroni correction was used to determine differences in survival between reaches (Holm 1979).

Migration speeds within individual sections were determined by using the last detection time for an individual from the prior station and the first detection time from the preceding station. Speeds for all fish in each release were averaged together to provide the migration speed for each reach as well as the overall array. Any fish that showed upstream movement were considered mortalities and removed from the analysis. A one-way ANOVA with the Holm's sequential Bonferroni correction was used to determine differences in average migration speed between reaches (Holm 1979). A paired t-test was used to determine differences in movement rates between the day and night release groups (release 5 and 5N).

Simple and multiple linear regressions were used to determine relationships between migration speed and survival between stations and the environmental variables, including percent cover of vegetation, shade, IWM, river mile, and river velocity. Simple regressions were conducted first to determine significance of each individual habitat category with all release groups analyzed together (Average Speed= α*Environmental Index + β). All variables that were significant in the individual simple regressions were included in the final model.

All analysis was done using R (R Core Team 2014). Release groups were included in the analysis as replicates.

Results

Average velocity magnitudes for the reaches ranged from 0.06 m/s to 0.3 m/s based on results from the AdH. Vegetation index values decreased somewhat downstream (Figure 3). Shade and IWM index values were strongly correlated with each other (r=0.85) and also decreased slightly downstream (Figure 3). In general, the study area had more habitat features in the upper reaches and these decreased downstream.

The SRA and vegetation indices, river mile, reach velocity, and release group were all significant correlated with migration speed (Figure 6). Those variables were included in the final model relating migration speed to habitat features (Average Speed$_i$=$\beta ø$+$\beta 1$(SRA Index)+$\beta 2$(Veg Index)+ $\beta 3$(River Mile)+ $\beta 4$(Average Reach Velocity)+ $\beta 5$(Release Group)+ ε_i). The IWM index was not found to be a significant predictor of speed and therefore was not included in the final model.

Survival through the study area was generally high; by the end of the array at Sacramento approximately 86% of all tagged fish survived through the 48 km stretch of river. The first release had the lowest overall survival rate of 69%, while release two had the highest with 97% survival. In addition, survival between reaches was fairly consistent, with no significant differences in survival between reaches based on ANOVA. Survivorship between individual reaches was very high, usually greater than 98% with decreasing survival in the lower reaches (Figure 7).

Average speed for all release groups by station varied from 0.39 m/s to 1.07 m/s with an overall average of 0.77 m/s (Figure 4 and Figure 5). There was a consistent peak in speed at MS 4, RM 85 (rkm 232) on all sampling dates. The AdH model shows a strong hydraulic feature in that location that is associated with high water velocities. A smaller peak in speed occurred at MS 7, just before the Feather River confluence. This second peak developed as the season progressed indicating a seasonal change in flows in that area, while the peak at MS 4 remained fairly consistent. A possible explanation could be a backwater effect from the Feather River that decreases later in the season. The ANOVA results show significant differences in movement speed between several reaches. As mentioned previously, speed inMS 4 was the most different, followed closely by MS 3. MS 7, though visibly different was not found to be significantly different from any other station. Speed in the upper stations were significantly different from speeds at the end of the array at MS 11. Additionally, there was a positive relationship between faster moving fish and higher survival rates (r=0.34) (Figure 8).

Initial rates of movement between the release site and the first station at KLB for all releases were found to be much slower than throughout the rest of the array. The initial movement speeds averaged 0.19 m/s and were significantly lower than the average movement speed through the rest of the array, which averaged 0.39 m/s through the slowest reach and 0.77 m/s overall. Migration rates were not found to differ significantly between the day and night release groups when tested during the last release on March 27, 2013 (P=0.53).

Vegetation had a significant slowing effect on migration speed (P<0.0001) and the largest effect size. While less significant than the vegetation, shaded area (P=0.007) and reach velocity (P=0.005) were found to increase migration speed slightly. Reach velocity has the second greatest effect size after vegetation. IWM was dropped from the final model due to colinearity with the shade variable. IWM also was not found to have a significant effect on speed when analyzed individually (P=0.07) (Figure 6).

In the final model, the river mile variable, or location in the river, had a significant effect on speed (P<0.0001). The relationship was negative, indicating the fish slow down as the move downstream. As fish moved lower in the system where the river gets wider and shallower, their average speed decreased. They also move into a more tidally influenced zone which can be seen on the hydrograph (Figure 2) Flows downstream fluctuate with the tides which may be contributing to the reduction in speed.

Discussion and Conclusion

Habitat features were not as influential as expected

Habitat features were not found to have a large effect on fish movement or survival. Some amount of variation in movement rates was attributable to habitat features but not to a great extent. These results were unexpected, especially for IWM which has been documented to be a key habitat attribute by providing cover and food resources for fish in healthy riverine systems. (Lassettre & Harris 2001, Schmetterling et al. 2001, Zanjac et al. 2013). A key reason smolts might not be responding to the installed habitat features is scale. The SRBPP sites with installed habitat features are located in patches along the river. The lack of influence of IWM in this study could be due to the small size of wood at repair sites given the size of the Sacramento River. The anchored wood can break down and lose some of the intricate structure that typically provides cover for small fish. Additionally, the IWM is usually installed at the mean winter water line. Therefore it is not inundated unless flows are relatively high. This study was conducted during the second year of a drought in the area, and the system experienced relatively low winter flows. Lastly, the smolts in this study might be too large or too focused on migrating to use the structures for cover. An updated shoreline survey documenting existing habitat features in finer detail might help answer some of these questions in future studies.

Additionally, it is believed that smolts respond to hydraulic cues during migration. For example, salmon smolts tend to wait for high pulse flow events prior to beginning downstream migration (del Rosario 2013). They tend to use hydraulic cues to find suitable habitat, such as velocity and strain (Nestler et al. 2012). It is possible that the size of the repair sites is too small to offer slower velocities for foraging, and cover habitat is too small in a system as large as the Sacramento River. Therefore the hydraulic cues may be missed as fish migrate in the higher velocity channel. Background noise and hydraulics of the river could cause these sites to be bypassed. The smolts could be moving with river currents that do not interact with the shoreline features. This is something that should be considered when planning restoration projects along the Sacramento River. Larger features may be needed to provide suitable refuge for migrating juvenile salmon.

Similar to other studies, we observed a pattern of decreasing movement speed as fish moved closer to the delta. (Michel et al. 2012). This could be due to lower flows in these areas and increasing tidal effects closer to the delta. Several studies have also found flow to be a key factor affecting outmigrating salmon in multiple river systems (Giorgi et al. 1997, Newman & Rice 2002, Petrosky & Schaller 2010, Smith et al. 2002). Lower flows in this area also may make it easier for smolts to access habitat features on the banks.

Faster Fish Survived Better

Overall, movement speed was fairly high through the study area. Other studies in the area observed similar rates of movement around 0.50 m/s (Michel et al. 2012), which was within our observed range of 0.39 to 0.77 m/s. This could be due to higher flows and water velocities through our particular study boundaries, as fish migration was strongly correlated with water velocity (Figure 6). For example, the bend between MS 3 and MS 4, at River Mile 85.6 (rkm 232), had some of the highest velocities in the array, and fish speeds were consistently fastest there, close to or greater than 1 m/s. This particular hydraulic feature tends to push fish away from the installed habitat features at RM 85.6 (rkm 232) (Sandstrom et al., 2012)

Previous studies have shown that fish exposed to floodplains and other habitats with adequate nutrients and feeding opportunities tend to have higher survival rates. Contrary to those findings, our study indicated that fish that migrated faster survived better (Figure 8). A study focused on steelhead in the Puget Sound also found higher survival rates among faster moving fish (Goetz et al. 2015). The pattern of faster fish surviving better indicates that for this section of the Sacramento River, exposure time might be the most important factor for predation rather than distance traveled (Anderson et al. 2005).

Lack of Diel Movement Patterns

Studies have documented diel migration patterns for Chinook through the Sacramento River (Chapman et al. 2012, Michel et al 2012, Zanjac et al. 2013). While our study did not find a significant difference in the migration patterns of the fish released at night versus the fish release during the day on March 27, 2013, we did observe a pattern of holding prior to movement after the fish are introduced to the river. The daytime releases appeared to hold somewhere soon after being released, and then begin their migration after sunset. All release groups took approximately 4 hours to travel from the release site to Knights Landing Bridge. The average movement speed for all releases across the entire study area was 0.77 m/s with a minimum average reach speed of 0.39 m/s. However, movement speed from the release site to the first station at the Knights Landing bridge was approximately 0.19 m/s, indicating a lag prior to migrating. The day and night release group had the same average speed getting to Knights Landing Bridge, 0.21 m/s. This indicates that the smolts in our study seem to be waiting for a cue other than nightfall to begin migration. It is possible that 4 hours is the time the salmon need to acclimate to their new surroundings before deciding to begin migration.

Two potential limitations of this study are the use of hatchery fish as surrogates for wild fish and the database used to quantify shoreline features. While hatchery fish provide a reliable source of fish to meet the needed sample size requirements, they can have significant behavioral differences from wild fish. Studies have found difference in size, survival, migration speed and timing, and other behavioral differences between hatchery raised and wild salmonids (Wessel et al. 2006, Thériault et al. 2009, Jackson & Brown 2011). However, hatchery raised fish are commonly used in similar studies and therefore still a valuable tool for analyzing salmon responses during migration. Additionally, the USACE Revetment database was the best available source of comprehensive environmental data for the study area. Unfortunately, this database was created in 2007 and is several years old. However, we feel that the data were still reliable because they were collected at a very broad scale, and a visual comparison against current satellite images showed the data to be similar to current conditions. Updated environmental data could improve future studies in the area.

This study provided a more detailed look at Chinook movement through a relatively small reach of the Sacramento River. While habitat features do appear to be of some value to migrating salmon, they are not as influential as anticipated. Two additional years of data in this area are currently being collected by the USACE and could provide further insight into habitat use by migrating salmon. Larger habitat features placed lower on the river banks might provide a better migratory corridor for salmon smolts in large rivers.

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Tables and Figures

Table 1. The summary of the release groups, including release dates, sample size and average weights and lengths.

Release Group	Release Date	Sample Size	Mean Weight (g)	Standard Deviation	Mean Length (mm)	Standard Deviation
Release 1	12/20/2012	95	22.55	± 14.68	123.06	± 20.62
Release 2	1/10/2013	100	23.36	± 8.61	129.50	± 15.19
Release 3	1/30/2013	100	26.11	± 9.64	133.42	± 15.46
Release 4	3/6/2013	100	25.32	± 9.04	131.30	± 14.21
Release 5	3/27/2013	108	29.96	± 11.54	141.31	± 16.93
Release 5N	3/27/2013	104	28.44	± 10.13	139.34	± 15.51

Table 2. The migration timing station identification numbers and approximate corresponding Sacramento River location.

Station ID	Approximate River Mile	Approximate River Kilometer
Release	93	245
KLB	90	239
MS 1	88	237
MS 2	87	234
MS 3	86	233
MS 4	85.5	232
MS 5	85	231
MS 6	82	226
MS 7	81	224
MS 8	77	217
MS 9	73.5	213
MS 10	70	208
MS 11	62	193

Table 3. Summary of the multiple regression model used to evaluate the relative influence of habitat features on migrating juvenile Chinook salmon speed in the Sacramento River.

	Coefficient	Std. Error	t-Statistic	Probability		R^2	Adjusted R^2
Shade Index	0.1600	0.0576	2.78	7.40E-03	**		
Veg Index	-0.8181	0.1581	-5.18	3.18E-06	***		
Velocity	0.2245	0.0784	2.87	0.0059	**		
River Mile	0.0151	0.0013	12.02	2.00E-16	***		
Release 1	0.1929	0.1661	1.16	0.2506			
Release 2	0.1844	0.1574	1.17	0.2464			
Release 3	0.2248	0.1570	1.43	0.1579			
Release 4	0.1227	0.1530	0.80	0.4261			
Release 5	0.2203	0.1533	1.44	0.1561			
Release 5N	0.2047	0.1533	1.34	0.1870		0.9932	0.992

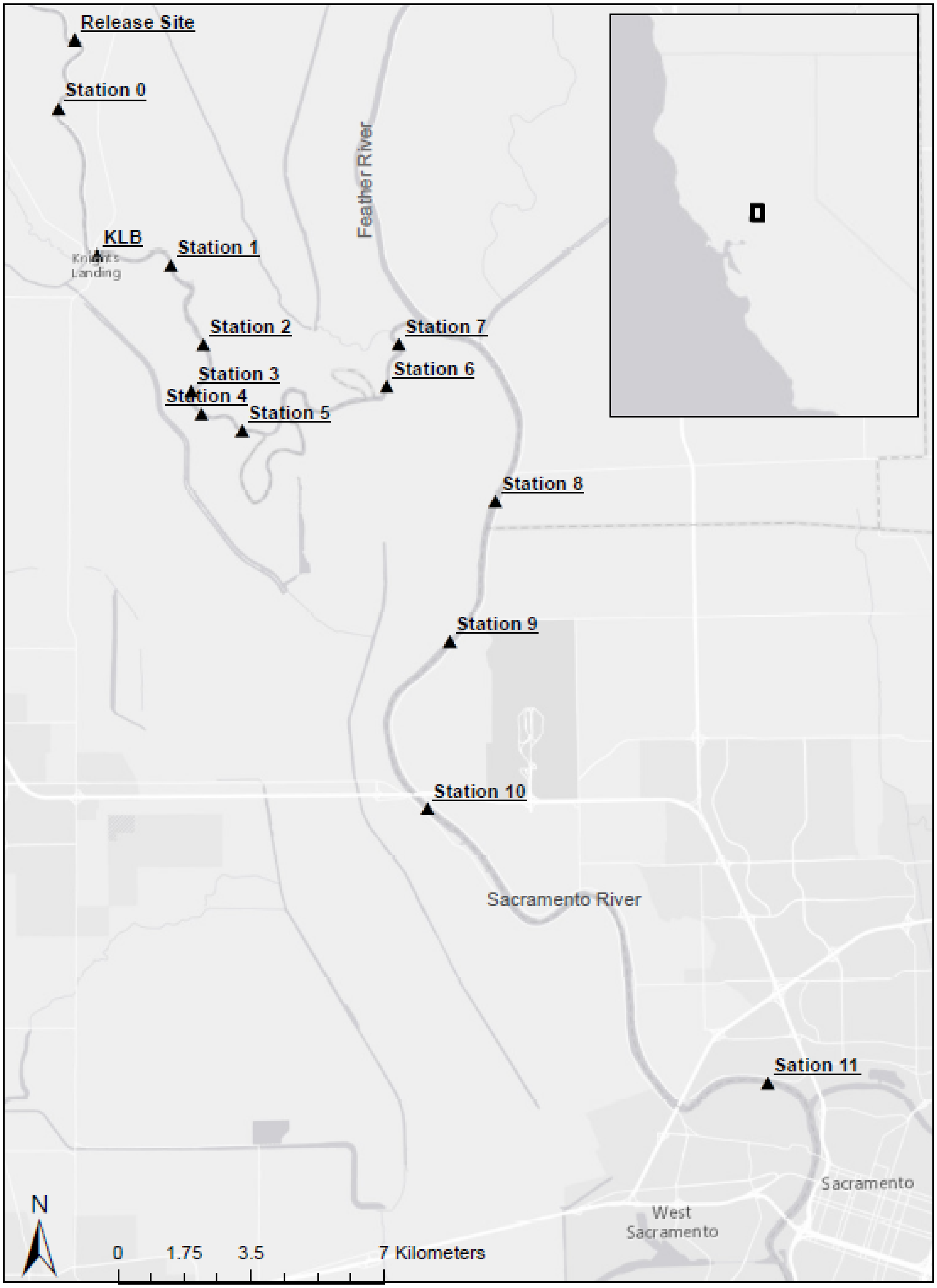


Figure 1. The study area of the Sacramento River, Knights Landing to Sacramento, California.

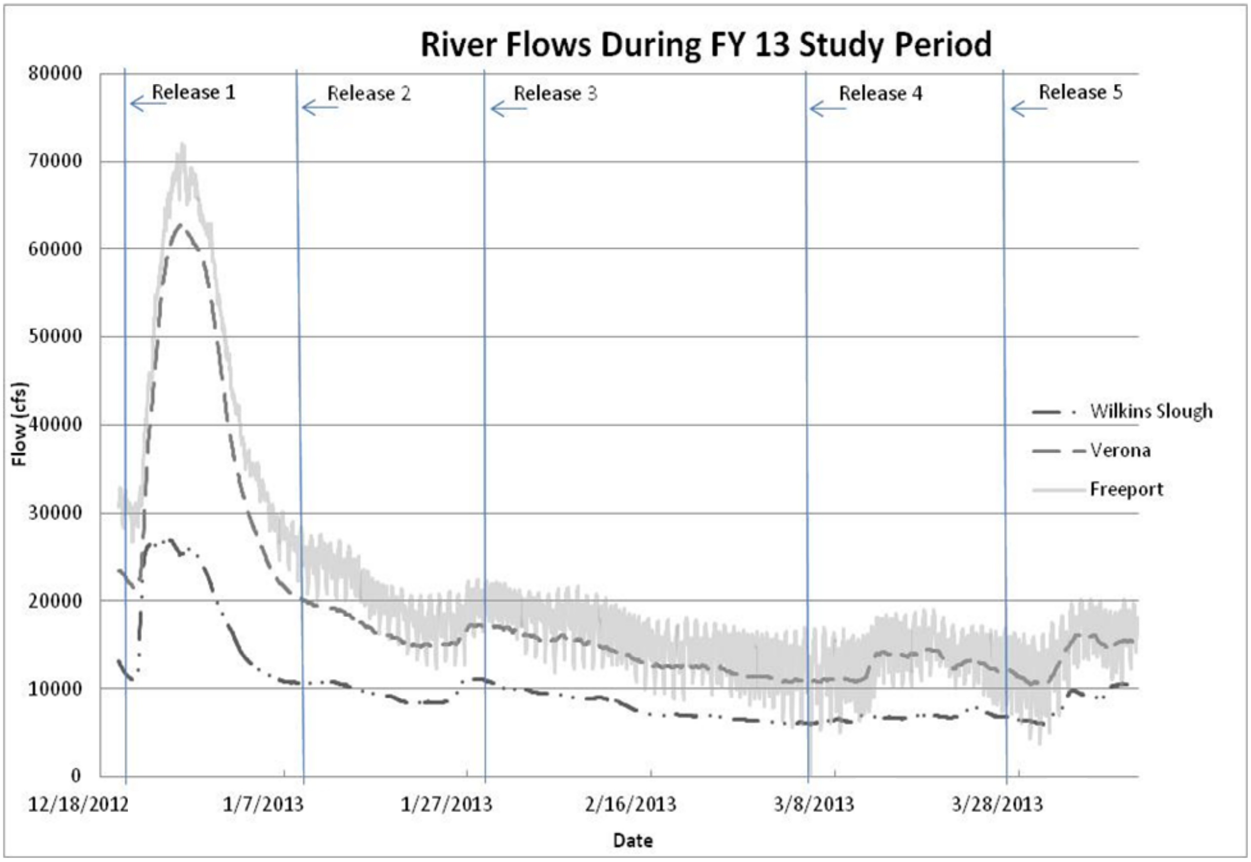
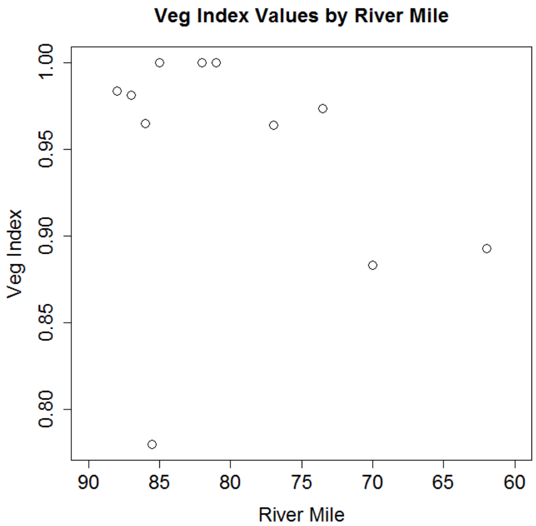
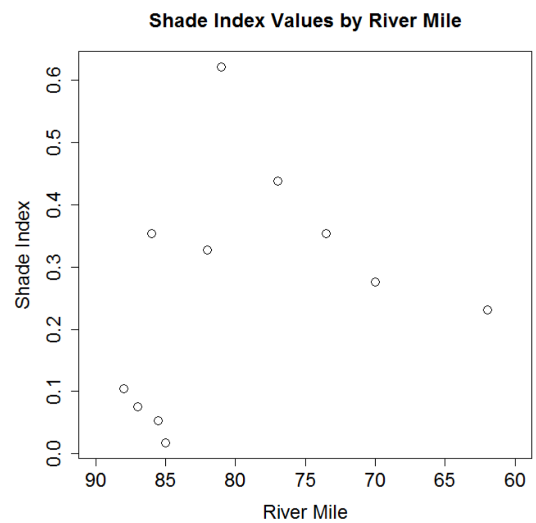


Figure 2. Hydrograph showing the average flows during the study period from Wilkins Slough (above the study area), Verona (near MS 7) and Freeport (after the study area in a tidally influenced zone) monitoring gauges. Each vertical line represents a release group. (Source: DWR 2013)





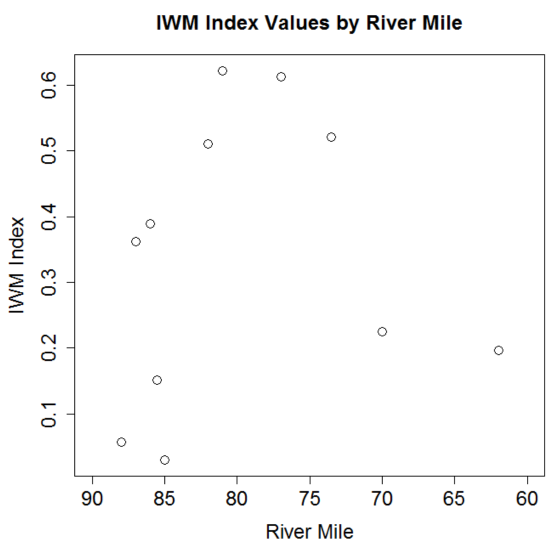


Figure 3. Habitat index value for vegetation, shade, and IWM by Sacramento River mile.

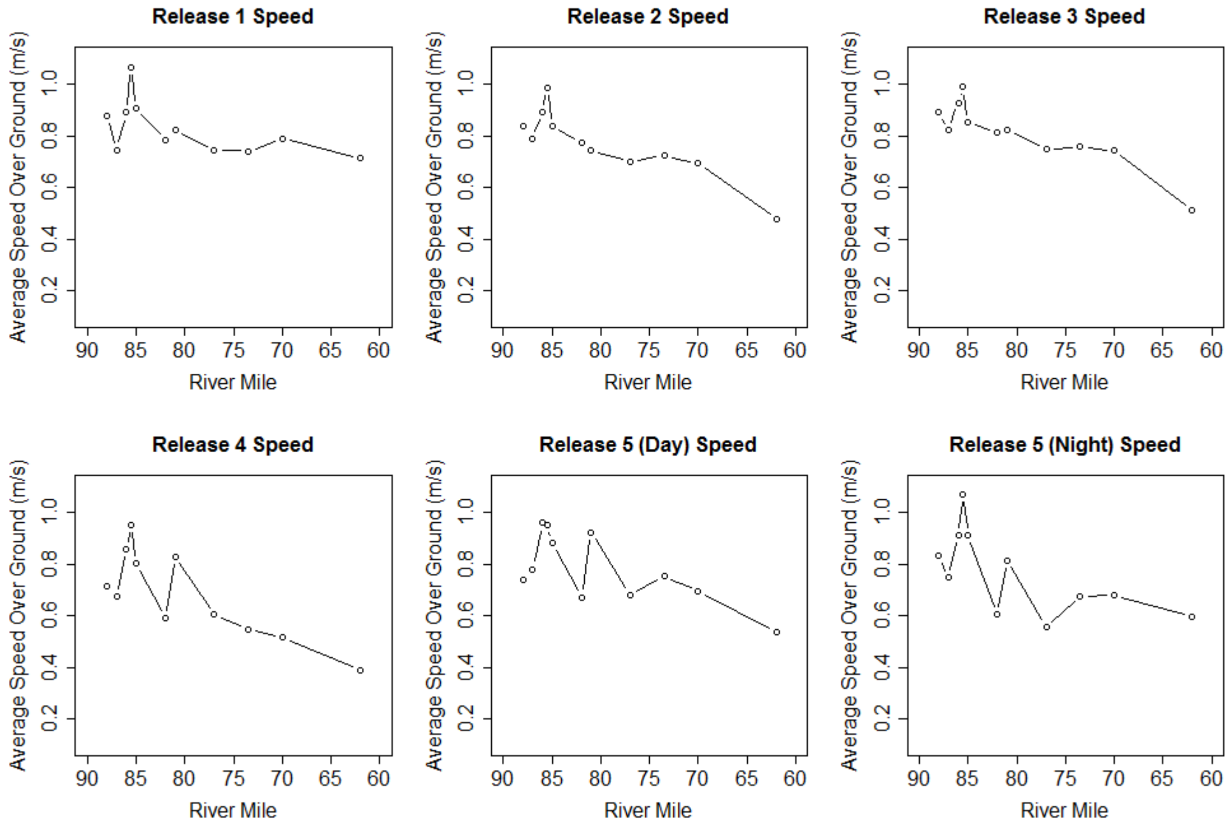


Figure 4. The reach specific average movement speed by river mile of migrating juvenile Chinook salmon in the Sacramento River, separated by release groups.

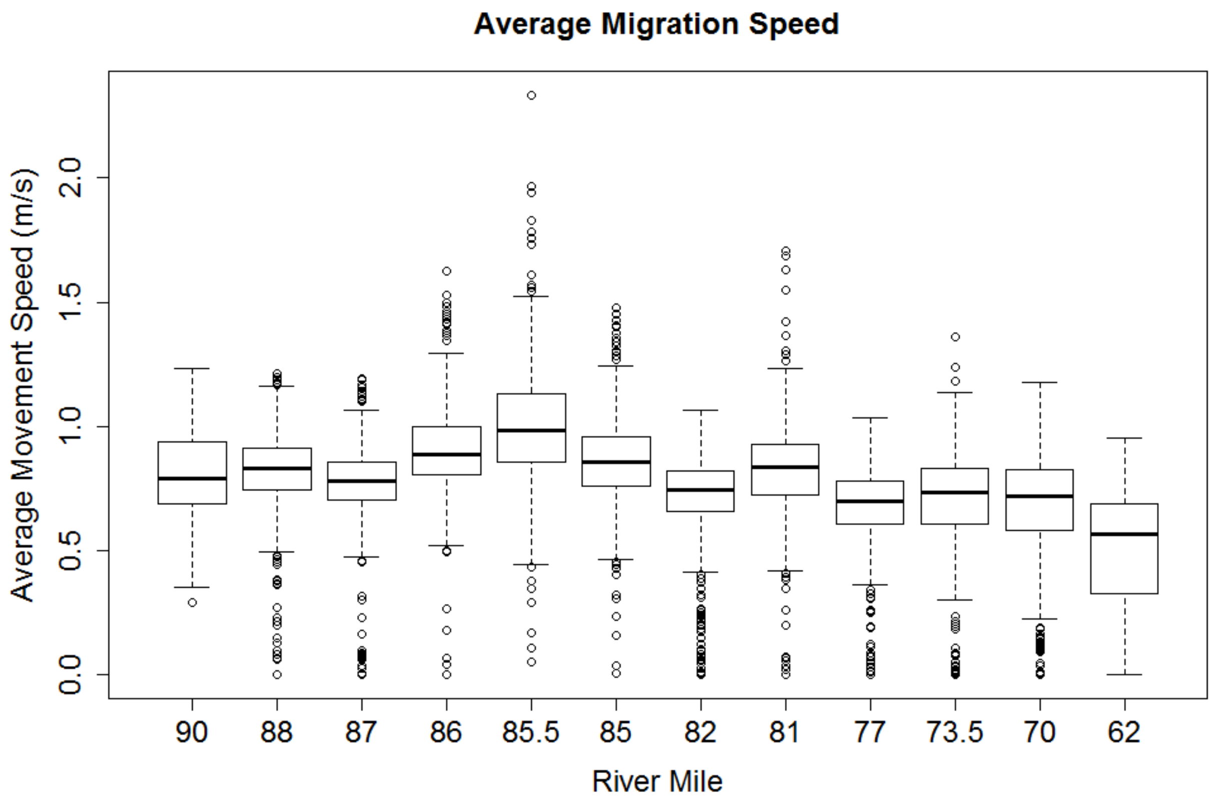


Figure 5. Boxplot showing the average juvenile Chinook migration speed by migration station in the Sacramento River.

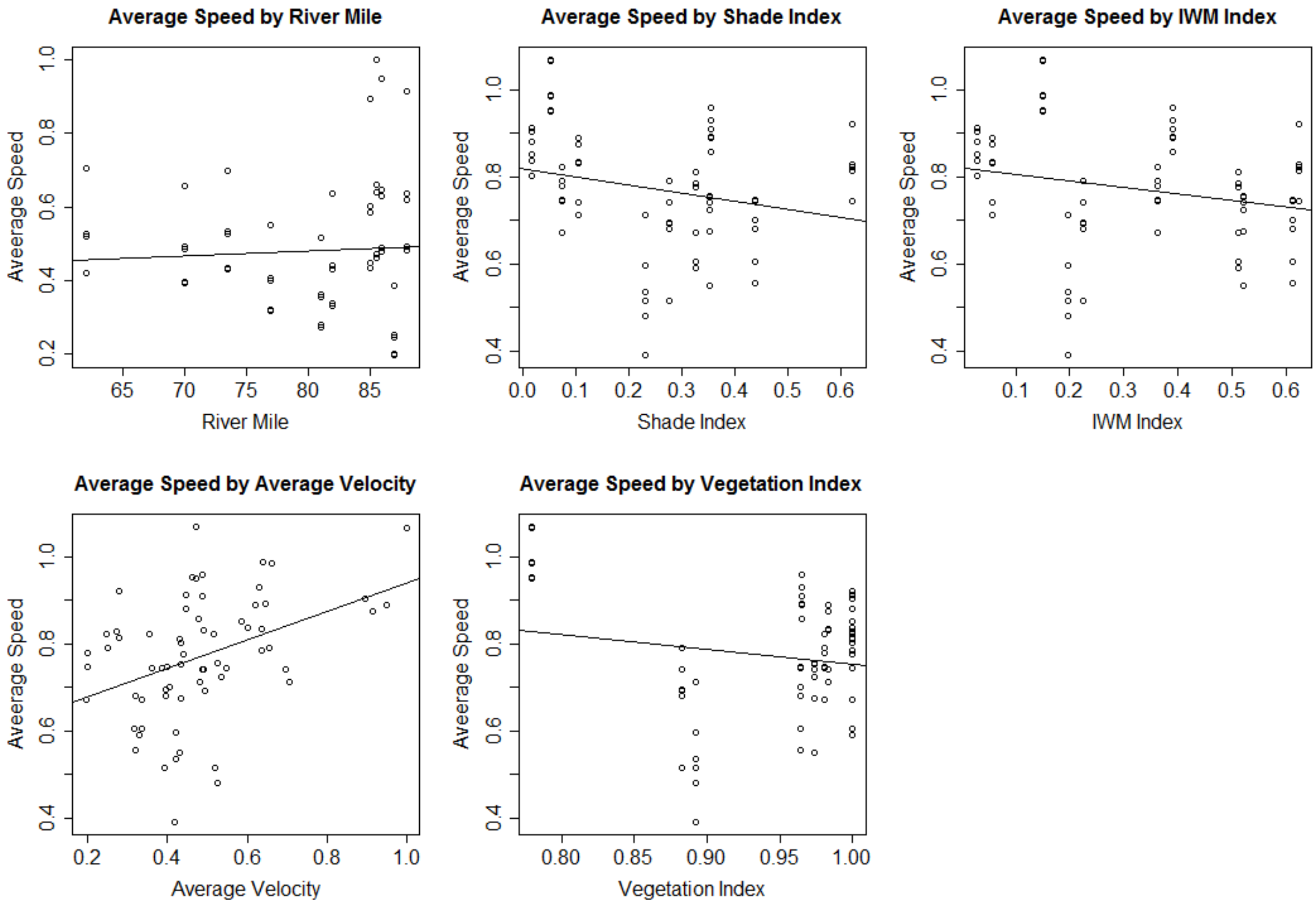


Figure 6. Linear regressions for average juvenile Chinook salmon migration speed by each habitat variable analyzed, including river mile, shade, IWM, average river velocity, and vegetation.

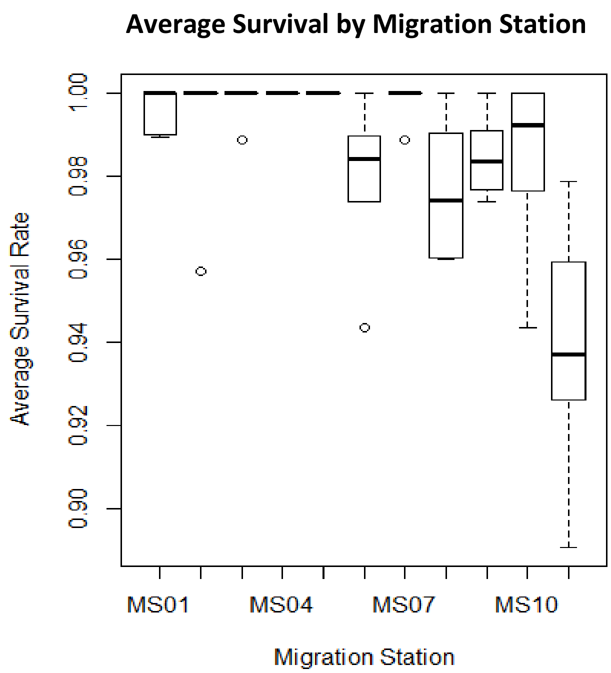


Figure 7. Boxplot showing the average juvenile Chinook salmon survival rate by migration station in the Sacramento River.

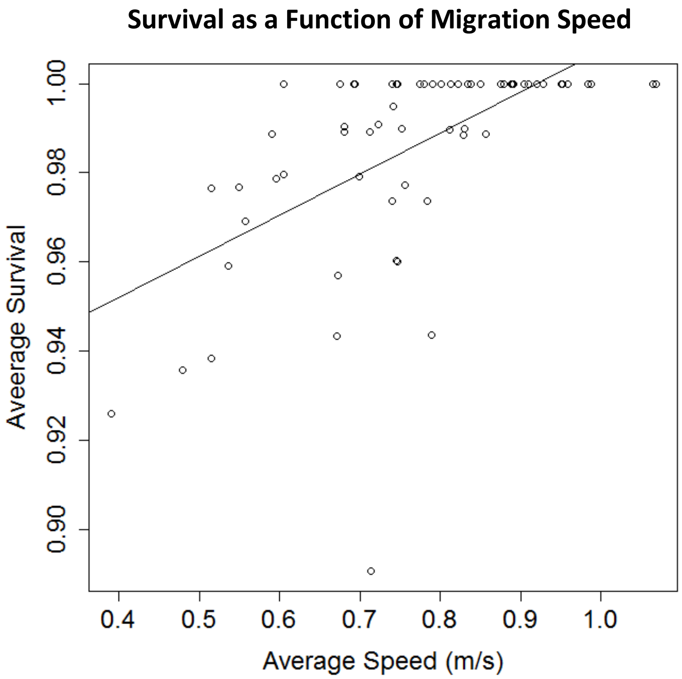


Figure 8. Migrating juvenile Chinook salmon survival as a function of migration speed (r=0.33, P<0.0001)

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