USE OF DUAL FREQUENCY IDENTIFICATION SONAR TO ESTIMATE SALMONID ESCAPEMENT TO REDWOOD CREEK, HUMBOLDT COUNTY CALIFORNIA

By

Matthew D. Metheny

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Committee Membership

Walter G. Duffy, Committee Chair

Margaret A. Wilzbach, Committee Member

Darren M. Ward, Committee Member

Rob Van Kirk, Natural Resources Graduate Coordinator

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ABSTRACT

Use of dual frequency identification sonar to estimate salmonid escapement to Redwood Creek, Humboldt County, California

Matthew D. Metheny

I used dual frequency identification SONAR (DIDSON) to estimate escapement of adult coho salmon, Chinook salmon, steelhead and coastal cutthroat trout entering Redwood Creek to spawn. Effective estimates of salmonid escapement include a quantifiable error associated with the number of fish. The errors associated with DIDSON estimates were described and computed to assess whether or not the technology is appropriate for monitoring salmonid escapement in Redwood Creek. DIDSON counts of unidentified fish were assigned a species using models developed from spawning survey observations in the Redwood Creek watershed.

The DIDSON deployment on Redwood Creek worked well during flows below 3000 cubic feet per second. Multiple regression of environmental variables showed no clear relationships with daily fish passage rates. Between 17 November 2009 and 18 March 2010, I estimated that 2,435 Chinook salmon, 375 coho salmon, 775 steelhead and 400 coastal cutthroat trout entered Redwood Creek to spawn. Calculation of sampling variance and a census of 88 hours suggested that a sample of 10 minutes to represent the hour resulted in a 9-13% confidence interval around the point estimate.

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INTRODUCTION

Populations of California salmonids are in a state of decline (Katz et al. 2012). In California, multiple stocks of salmon and steelhead are listed under the Endangered Species Act (ESA). California has seven Evolutionarily Significant Units currently listed as endangered, three listed as threatened, and one is a species of concern. Only two Evolutionarily Significant Units of anadromous salmonids are considered not warranted for listing, and a petition to list one of these is currently being reviewed.

Information on population trends is needed to manage these species, including documenting the response to recovery actions, harvest, and progress toward recovery and delisting goals (McElhany et al. 2000). California has adopted a monitoring plan for coastal rivers that emphasizes gathering data on trends in abundance of adults returning to spawn or escapement (Adams et al. 2011). Gathering escapement data has, however, historically presented challenges.

The total length of streams used by spawning fish is immense, amounting to more than 20,000 km in the range of coho salmon (*Oncorhynchus kisutch*) in California alone (National Marine Fisheries Service 2010, 2012). Much of this area is remote and difficult to access. Furthermore, the hydrology of most of the streams in coastal California is flashy and they are located in unstable geology, contributing to turbidity that makes ground-based surveys unreliable. Taken together, the features of California's coastal rivers makes monitoring adult salmonid escapement with walking surveys costly, if at all possible, and the resulting data questionable.

Weirs can provide high quality escapement data for river systems with favorable conditions (Cousens et al. 1982), as well as valuable biological data on fish age, species, and length (Zimmerman and Zabkar, 2007). As with walking surveys, remote areas with flashy hydrology complicate the use of weirs in northern California. High debris loads can clog weirs and cause collapse of weir structures (Hubert 1996). In addition, weirs can be overtopped (Wright 2011), or alter the migratory behavior of threatened salmonids.

Recent technology offers promise in gathering data needed to estimate escapement in coastal rivers. The acronym DIDSON stands for dual frequency identification SONAR. It provides high resolution underwater video and has been used for a wide variety of fisheries applications (Tiffan and Rondorf 2004, Belcher 2005, Johnson et al. 2005, Mueller et al. 2006). Among its many applications, DIDSON has been effectively used by management agencies to count migrating salmon in rivers (Holmes et al. 2005, Cronkite et al. 2006, Maxwell et al. 2007, Melegari 2008, Johnson et al. 2009). In a study of Fraser River sockeye salmon in Alaska, Holmes et al. (2005) compared results from a counting fence census to DIDSON fish counts and concluded that DIDSON "can deliver escapement estimates whose accuracy, precision and scientific defensibility is consistent with or better than existing escapement techniques and at a lower operating cost to assessment programs."

Redwood Creek provided a good setting for evaluating the capabilities of DIDSON in estimating escapement to northern California rivers. The watershed is of moderate size and supports four species of salmonids. It has a flashy hydrograph, with discharge often increasing from less than 1000 f^3/s to more than 6000 f^3/s over a 24-hour period during winter. Suspended sediment concentration in the river is high during moderate and higher flows, limiting visibility when adult salmonids are migrating.

Estimates of escapement require a measure of certainty to be informative, and the errors associated with DIDSON escapement estimates have been identified and quantified (Maxwell and Gove 2004, Cronkite et al. 2006, Holmes et al. 2006, Kucera and Orme 2007, Kerkvliet et al. 2008). The consensus is that errors in DIDSON counts arise from accuracy, precision, equipment downtime, and sampling regimes. Errors in the species apportionment of the DIDSON counts presents further challenge where multiple runs overlap temporally. Given these multiple influences, the nature of the error structure for any DIDSON escapement estimate will depend on aspects of the deployment and how the video is interpreted. I assessed the error structure for the Redwood Creek DIDSON in order to provide instructive escapement estimates.

The timing of salmonid migrations into freshwater is an important population trait, affected by both genetic and environmental factors. Riverine and estuary conditions such as discharge and tidal stage may influence the time when salmonid spawning migrations occur (Quinn 2005). The hourly and daily estimates of fish passage at the DIDSON site provide an opportunity to investigate the environmental cues which may prompt upstream movements in Redwood Creek salmonids.

The primary objective of this study was to estimate escapement for four species of anadromous salmonids in Redwood Creek. The average run timing and body length of three of these four species differs, but each also overlaps with at least one other species

(Figures 1, 2). Use of DIDSON to estimate escapement has proven challenging on rivers supporting multiple species of anadromous salmonids. While the image resolution of the DIDSON is impressive, salmonid species which overlap in size cannot be distinguished with the video it produces (Faulkner and Maxwell 2008). Melegari and Osborne (2008) were unable to use DIDSON images to differentiate chum salmon (*O. nerka*) from Chinook salmon (*O. tshawytscha*), which overlapped in size and run timing. In a review of salmonid escapement monitoring methods, Parsons and Skalski (2010) recommended the use of DIDSON over other escapement estimation methods, but only for single species runs.

Apportionment of species with overlapping run times and sizes for DIDSON escapement estimates has typically been derived from sampling with seines (Pfisterer 2002, McKinley 2003, English et al. 2011) or fish wheels (Westerman and Willette 2006). Video methods have also been used to identify species in conjunction with DIDSON technology (Johnson et al. 2009), but optical cameras require water clarity uncharacteristic of Redwood Creek.

A basin-wide regime of spawning surveys commenced on Redwood Creek in 2009-2010. Observations of fish on ground surveys offer a means of modeling the species apportionment within Redwood Creek. I investigated using run timing and species size distributions to assign species probabilities to observations of individual fish from the DIDSON. Additionally, escapement assessments from redd expansion methods provide an opportunity to compare estimation techniques for agreement.

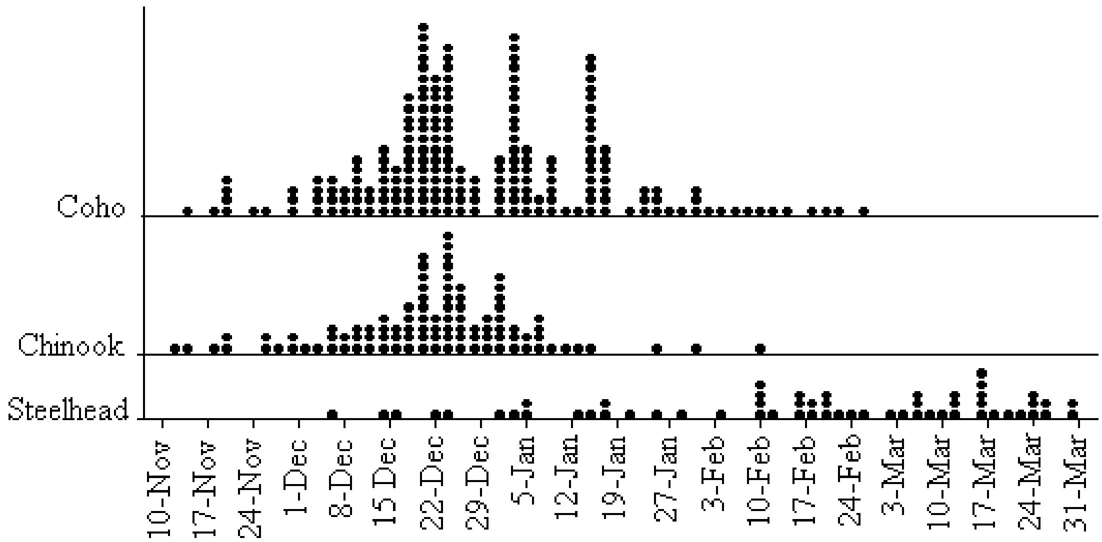

Figure 1. Distributions of run times for coho and Chinook salmon and steelhead in the Redwood Creek Basin (n=1209). Data are from fish captured at the Prairie Creek Weir 2005-2009 (385) as well as observations of live fish from spawning surveys on Prairie Creek 2004-2008 (654) and Redwood/Prairie Creeks 2009-2010 (170). Each dot represents up to four observations.

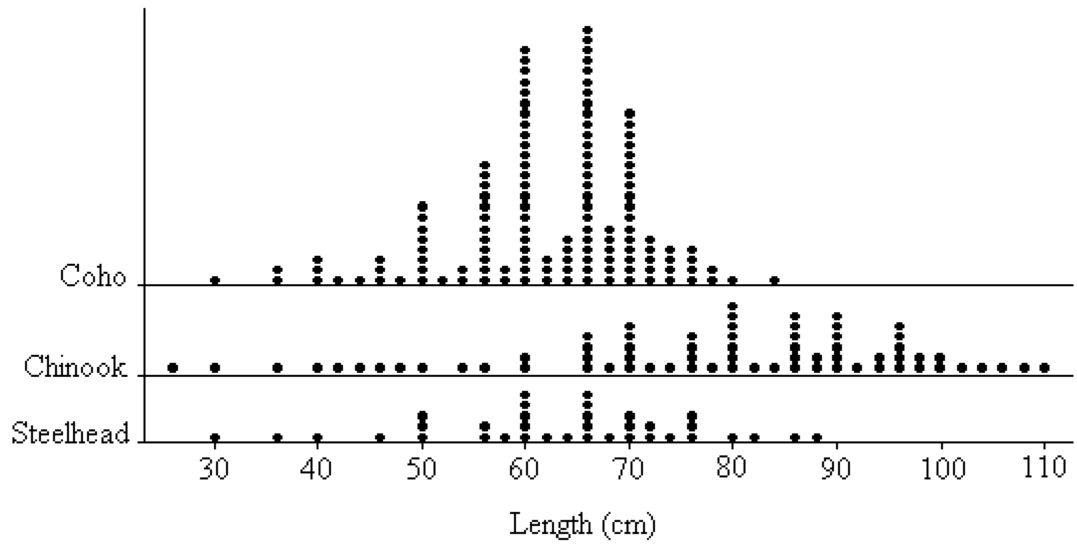

Figure 2. Distributions of lengths for coho and Chinook salmon and steelhead in the Redwood Creek Basin (n=1209). Data are from fish captured at the Prairie Creek Weir 2005-2009 (385) as well as observations of live fish from spawning surveys on Prairie Creek 2004-2008 (654) and Redwood/Prairie Creeks 2009-2010 (170). Each dot represents up to six observations.

Video from DIDSON must be reviewed and interpreted to produce estimates of fish passage, which can be time consuming. The DIDSON software has features intended to speed up the review process. The convoluted-samples-over-threshold (CSOT) feature processes video files and retains moving objects larger than a certain threshold size, while video that has no moving objects is discarded. The resulting video is often a fraction of the duration of the original video.

The echogram software feature is the most automated method for reviewing DIDSON video files. This produces a time-space plot of all moving objects detected by the camera. An output table is generated which lists the time, size, range and direction of each moving object, and more.

Successful use of these software features has been demonstrated (Kucera and Orme 2007, Melegari 2008, Faulkner and Maxwell 2008, Pipal et al. 2010). A semi-automated technique for the review of DIDSON data is described by Boswell et al. (2008), and fully automated review methods are described by Meuller et al. (2008) and Rakowitz (2009). I explored the use of these methods on Redwood Creek DIDSON data, attempting to reduce the effort required for video review.

SITE DESCRIPTION

Redwood Creek flows into the Pacific Ocean near the town of Orick about 56 km north of Eureka, California. The watershed covers an area of 738 km^2, is long, narrow and oriented northwest-southeast. Redwood Creek is about 108 km long, but with tributaries contains 192 km of habitat accessible to anadromous fish. The largest tributaries to Redwood Creek are Prairie Creek, located just upstream of Orick and Lacks Creek, located in the middle part of the watershed. The lower 6 km of Redwood Creek is contained within flood control levees. The watershed has been identified as a high priority for restoration activities to improve water quality and recover anadromous salmonid populations (Canata et al. 2006).

The Redwood Creek watershed supports four species of anadromous salmonids, of which Chinook salmon, coho salmon, and steelhead (*O. mykiss*) are listed under the ESA (United States Office of the Federal Register 1997, 1999, 2000). Coastal cutthroat trout (*O. clarkii clarkii*) and Pacific lamprey (*Lampetra tridentata*) also migrate into Redwood Creek, and resident fish species also inhabit the watershed (Redwood National and State Parks 1997). Sacramento suckers *(Catostomus occidentalis*) are among resident fish species, and may overlap in size with smaller anadromous salmonids.

Redwood Creek watershed has documented water quality problems that are believed to limit salmonid populations including the following: excess sediment (California North Coast Regional Water Quality Control Board 2001), high summer water temperatures (California State Water Resources Control Board 2003), a shortage of in-channel large woody debris, and poor riparian conditions (Canata et al. 2006). Restoration actions have been proposed and implemented throughout the watershed to address these water quality concerns (Canata et al. 2006).

Mean annual basin-wide rainfall is about 200 cm and falls mostly as rain between November and March (Janda et al. 1975). The mouth of Redwood Creek is closed to the ocean during dry months, typically late July through October. Winter storm events breach the bar between the ocean and river and drive a flashy hydrograph throughout winter.

I selected a study site in the community of Orick, immediately downstream of the U. S. Geological Survey gauging station 11482500 located 5.9 km from the Pacific Ocean (lat 41^{o} 17’ 58” long 124^{o} 03’ 00” NAD83). This site was about 100 m downstream of the confluence of Prairie Creek, the first major spawning tributary in the watershed (Figure 3). The landowner adjacent to the site on the east side of Redwood Creek, Orick Rodeo Association, allowed the use of a secure trailer with electricity to power the unit and to house the topside computer components. At this site, the deepest part of channel is against the west bank, which is nearly vertical and consists of rip-rap. On the east bank, a gravel bar slopes gradually down from the levee toe to the channel thalweg. Approximately 100 m of channel is contained between the two levees at the site.

Selecting the site from which to operate a DIDSON is critical in gathering reliable data (Maxwell 2007, Pipal et al. 2010). The ideal location for deploying a DIDSON is a secure site, downstream of spawning areas at a natural constriction of the river, having

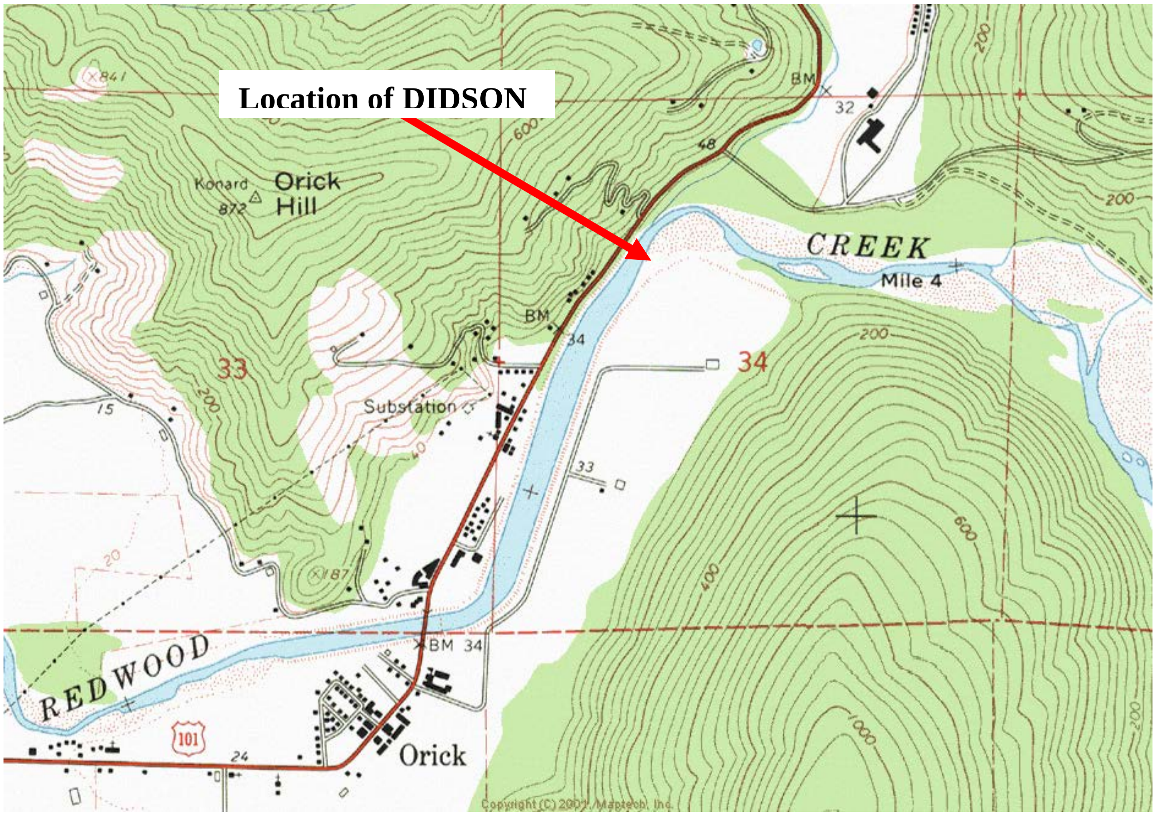

Figure 3. Location of DIDSON deployment site on Redwood Creek.

medium velocity that minimizes milling behavior, sloped/steep sided, and few air bubbles in the water column (Cronkite et al. 2006). While the lower 6 km of Redwood Creek are accessible, few sites offer 120 volt AC power, the necessary security and the proper channel configuration.

The DIDSON was operated at the Orick deployment site for two consecutive salmon migration seasons in 2009-2010 and 2010-2011. Data was recorded from 20 November 2009 to 3 June 2010 and from 1 November 2011 to 3 June 2011. Data and analysis presented here focuses on the 2009-2010 migration season.

MATERIALS AND METHODS

Deployment of the DIDSON

A DIDSON system consists of the camera body, a camera cable, a topside control box, software and a computer with a Windows operating system (Figure 4). The topside control box supplies power to the camera and links the computer to the camera cable with an Ethernet cable. The topside control box requires a 24-volt DC power supply and includes an AC adapter.

I used a standard model DIDSON, which can detect salmon at distances of up to 30 m (Burwen et al. 2007, Matthews and Baillie 2007). The DIDSON was deployed in typical side-facing position, described by Maxwell (2007), and mounted on an adjustable H-frame constructed of 5.08 cm aluminum tubing (Figure 5). The DIDSON was housed in a custom-made aluminum enclosure to protect it from damage. The enclosure fit snugly around the camera with only the lens and camera cable exposed.

When deployed, I stabilized the H-frame mount and camera with T-posts driven into the river bottom and lashed to the mount with 1 cm diameter nylon line. For security, 1 cm diameter nylon line was attached to the camera box, mount, and to T-posts anchored on shore. To protect from abrasion, the DIDSON data cable was strung through 2.5 cm diameter PVC conduit where it crossed the levee and wrapped with vinyl tubing between the levee and camera.

Figure 4. Components of a DIDSON system including: (clockwise from top right) DIDSON camera, black camera cable, gray topside box, blue Ethernet cable and laptop computer. AC power adapter for topside box is shown in the center. Source: Sound Metrics Corporation.

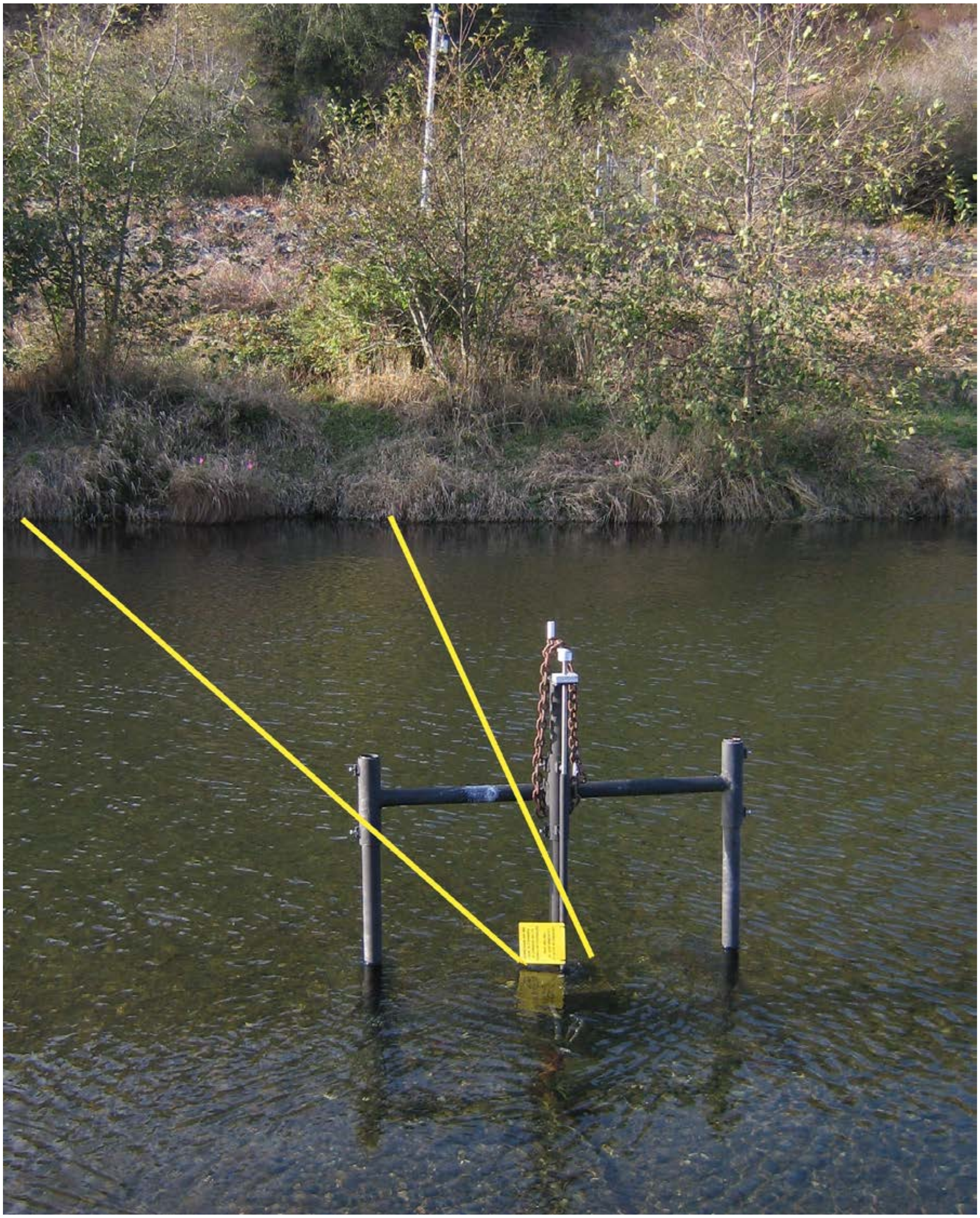

Figure 5. DIDSON deployed from H-frame mount on Redwood Creek in typical side-facing fashion. The yellow lines show the approximate field of view. Source: author.

The channel cross section was surveyed, and a scale drawing was used to determine the best vertical angle to aim the DIDSON at the onset of the study. The channel cross section changed frequently, so I used visual aiming methods similar tothose described by Maxwell and Gove (2007), who recommend positioning the DIDSON close to bottom substrate and angling the beam along the angle of the river bottom. This angle was typically between -2° and -6°.

The camera stand was positioned in 0.5 to 1 m deep water with the camera lens facing the deeper water of the thalweg. I situated the camera lens about 30 cm above the bottom substrate and visually determined an angle perpendicular to the flow to aim the camera horizontally. The objective of aiming was to ensonify as much of the channel as possible, as recommended by Maxwell (2007). At moderate to high flows, the camera stand was positioned as close to the deepest part of the channel as flows allowed, about 25 m from the west bank. At flows less than 1000 f^3/s, I kept the camera in the shallow water close to the east bank to keep fish from swimming behind the camera, about 18 m to the west bank.

The DIDSON was programmed to record 24 hours a day, in 10-minute increments. The 10-minute file length was selected to minimize data loss in the event of a corrupt file, and to facilitate a systematic sampling method for data analysis. The DIDSON video files were stored on external hard disk drives at the study site. I switched hard drives every two to four weeks and made a backup copy of all DIDSON data. Two copies of all DIDSON video files were archived to minimize the risk of data loss from potential hard disk drive failure.

To keep the camera stand in the appropriate water depth, the study site was checked at least once a week and the camera was moved if discharge had changed from the previous week. During rain events, I monitored stage height from the nearby USGS gage to ensure I was able to move or remove the camera before flows increased to hazardous levels. The camera was checked after storms or every two weeks for silt and algal buildup, and was rinsed as needed, since the accumulation of either can diminish video quality.

Estimating escapement to Redwood Creek

A non-replicated systematic sample of the first 10 minutes of each hour was employed to estimate escapement into Redwood Creek. For each 10-minute file, net movement was defined as the sum of positive upstream movements and negative downstream movements (Xie et al. 2002). Net movement over 10 minutes was multiplied by a factor of six to derive hourly estimates of fish passage. Net movement of fish for a day was treated as the sum of hourly net movements.

Unprocessed video files played back at one to eight times faster than recorded speed were reviewed to estimate escapement. Increasing fish densities required slower playback rates, as described by Faulkner and Maxwell (2008). I investigated using condensed video footage and echogram auto-counting, but I did not utilize these methods when estimating escapement due to excessive image noise. A regression of manual counts versus auto-counts in 10-minute increments was used to assess the effectiveness of automated review methods.

I initially recorded details of every fish target, including: direction of movement, length, distance from camera, duration present, exact time and the frame number where the length measurement was taken. Recording information at this level of detail proved to be impractical, due to milling behavior, large numbers of fish, and the inability to determine direction of movement for some fish. Subsequently, the review process was simplified to increase speed of video data analysis and gather the data necessary to estimate escapement. Using the simplified approach, a tally of fish was kept, and only the net movement and corresponding lengths for each 10-minute file were recorded.

Milling behavior was not quantified with the simple approach, and a file having many fish visible during review may have resulted in a calculated net movement of zero. Length was not measured for downstream moving fish, fish for which the direction of movement was unknown, or fish that move back and forth. The length of downstream-moving fish was only recorded when the net movement for a file was downstream. In summarizing movement for a 10-minute file, a best guess was used to determine the net movement for a file and the fish lengths to record which reflected the net movement.

When measuring the length of fish, I used a method similar to the one described by Pippal et al. (2010). With this method, footage is replayed after a fish is observed, and a frame showing the entire length of the fish is selected. The software is then used to obtain a minimum of two length measurements, and the average is recorded. This length is assumed to represent the fish’s total length.

A cutoff of 40 cm was used to differentiate adult salmonids from jacks, cutthroat trout, and resident fish. This cutoff was based on the 40.64 cm minimum length for adults used by the California Department of Fish and Game Steelhead Report Card. For each day, the proportion of observed fish above and below the 40 cm cutoff was applied to the daily escapement estimate. All fish over 40 cm were assigned to a species using models based on spawning survey observations. It was assumed that DIDSON targets were non-fish when length exceeded 120 cm during the salmon migration and 90 cm when only steelhead were present. Maximum fish sizes were based on measurements taken from a weir on Prairie Creek 2005-2009 and spawning survey observations (Figure 1, 2).

Since the jack component of salmonid runs varies greatly within and between watersheds (Quinn 2005), an arbitrary value of was chosen. The assumption that jack salmon were present as a fixed proportion (5%) of the adult population was not based on any evidence specific to Redwood Creek. I used anecdotal evidence to model non-jacks under 40 cm as cutthroat trout before 15 December and steelhead after that date. I first estimated jack abundance over the two time periods: 21 November – 15 December and 16 December – 23 January, then classified remaining fish as cutthroat or steelhead.

Kelts can be confused with milling fish and can distort population estimates (Kerkvliet and Booz 2012). To deal with the kelt problem, I used the technique outlined by Pipal et al. (2010). After the date of peak upstream steelhead passage had passed, daily escapement estimates with negative values were not subtracted from the season's steelhead population estimate, as illustrated in Table 1. The estimated number of kelts returning to the ocean after spawning was the sum of negative daily escapement estimates after the date of peak migration.

Table 1. Example of estimating escapement over different time scales. Escapement is estimated as the sum of positive upstream movements and negative downstream movements, except during kelt season. Kelt season is defined as the period after the peak of the steelhead spawning migration has occurred. When summing the daily estimates for kelt season, escapement is equal to the number of fish passing upstream.

Scale	Upstream tally	Downstream tally	Escapement estimate
Hour	3	2	1
Day	3	2	1
Salmon season	3	2	1
Steelhead season	3	2	1
Kelt season	3	2	3

Milling steelhead were presumed to be encountered and accounted for when calculating net movement for hourly and daily escapement estimates during kelt season. I assumed that changes in total upstream or downstream flux would be apparent when summing the daily escapement estimates for the season.

No adjustments were made to seasonal counts of fish for days when the DIDSON malfunctioned or days on which video quality was too poor to provide a count. Net passage for un-sampled hours and days was assumed to equal to zero. Using the average of counts from nearby days to interpolate for missing days is risky due to the fluctuations in daily fish passage rates. Since more days had net upstream counts than downstream counts, the estimate of unapportioned fish is more likely to be biased high than low.

Two potential sources of error were assumed to be present in the DIDSON escapement estimate: reviewer error, and sampling error. The assumption was made that all fish passing the DIDSON site are detected by the camera and that counts are unbiased.

The error arising from using a sample to represent the hour was assessed by conducting a census of 87 hours in 10 minute increments. A regression of hourly expanded counts versus the census values was used to infer how well a single 10-minute file predicts hourly passage rate. For each hour, the error between the census escapement estimate and the escapement estimates derived from the six 10-minute samples per hour was calculated as follows:

$$error_{10\ minute\ count\ i} = \frac{|expanded\ count_{10\ minute\ count\ i} - \ census\ count|}{census\ count}$$

The mean error was then calculated as the mean of the six individual errors.

I assessed the sampling error over five sampling rates (10, 20, 30, 40 and 50 minutes per hour) to identify the appropriate sample rate needed to achieve a desired error level. The mean error for all levels of sampling effort from six combinations of 10 minute files was calculated. It was assumed that a census of 60 minutes an hour resulted in zero sampling error.

I used the V5 estimator to calculate the variance $\hat{V}(\bar{y})$ associated with using a ten minute sample to represent each hour. The V5 estimator accounts for autocorrelation and nonlinear trends (Wolter 1984, 1985) and is the best choice for salmon escapement estimates based on non-replicated systematic sampling (Reynolds et al. 2007). The V5 estimator is calculated as follows:

$$\hat{V}(\bar{y}) = (1-f)(1/n)\sum_{j=5}^{n} a_j^2/(3.5(n-4)), \text{where}$$

$$a_j = y_j/2 - y_{j-1} + y_{j-2} - y_{j-3} + y_{j-4}/2$$

where the estimated variance of the total escapement, $\hat{V}(\hat{Y})$ from *n* observations, is the product of $\hat{V}(\bar{y})$ and the square of the expansion factor: $6 * 24 * number\ of\ days$, where *j* indexes observation sequence and *f* is the proportion of observations collected (1/6). I constructed 95% confidence intervals for the escapement estimate $\hat{Y}$ as follows, assuming a normal error structure: $\hat{Y}$ +/- $1.96\sqrt{\hat{V}(\hat{Y})}$.

Reviewer error was assessed by comparing the repeatability of counts from two reviewers over the same 210 minute files. Correlation and regression were used to infer the level of precision between the two reviewers, based on sample units of 10-minute increments. Reviewer error was not included in total confidence intervals for escapement.

Multiple linear regression was used to explore the influence of environmental factors on the timing of salmonid migration into Redwood Creek. Daily escapement estimates of unspecified fish of all sizes was the response while date, discharge, and tides were used as explanatory variables (Table 2). I modeled fish movement into Redwood Creek over the first 58 days of continuously gathered data, and again over all available days, reasoning that the relation between environmental conditions and movement may be different between salmon considered alone versus salmon and steelhead pooled together. The variables for tides were highly correlated (R^2=0.56 – 0.92). Models having more than one parameter for tide were not considered, due to the difficulty in interpreting the effects of their multicollinearity.

Table 2. Definitions, symbols, and explanation of environmental variables used in multiple linear regression models of salmonid escapement to Redwood Creek based on conditions during the 2009-2010 migration season.

Parameter	Symbol	Source, where day *n* corresponds to the same 24 hours as the daily escapement estimate
difference between highest and lowest tides for the day	Δ tide	difference between highest and lowest tides recorded at Trinidad harbor by NOAA over day *n*
highest tide of the day	max tide	highest tide recorded at Trinidad harbor by NOAA over day *n*
lowest tide of the day	min tide	lowest tide recorded at Trinidad harbor by NOAA over day *n*
discharge at Orick	cfs Orick	mean daily discharge at USGS gage in Orick for day *n*
change in discharge at Orick	Δ cfs Orick	(mean daily discharge at USGS gage in Orick for day *n)* - (mean daily discharge at USGS gage in Orick for day *n-1*)
discharge at Orick , 1 day lag	cfs Orick lag=1	mean daily discharge for at USGS gage in Orick for day *n-1*
change in discharge at Orick, 1 day lag	Δ cfs Orick lag=1	(mean daily discharge at USGS gage in Orick for day *n-1)* - (mean daily discharge at USGS gage in Orick for day *n-2*)
discharge at O'Kane	cfs O'Kane	mean daily discharge at USGS gage at O'Kane for day *n*
change in discharge at O'kane	Δ cfs O'Kane	(mean daily discharge at USGS gage at O'Kane for day *n)* - (mean daily discharge at USGS gage at O'Kane for day *n-1*)
discharge at O'Kane, 1 day lag	cfs O'Kane lag=1	mean daily discharge for at USGS gage in Orick for day *n-1*
change in discharge at O'kane, 1 day lag	Δ cfs O'Kane lag=1	(mean daily discharge at USGS gage at O'Kane for day *n-1)* - (mean daily discharge at USGS gage at O'Kane for day *n-2*)
water year day	date	number of days passed since 1 October
water year day squared	$date^2$	(number of days passed since 1 October)^2

Species models for overlapping runs

Observations of live fish made by the California Department of Fish and Game and the U. S. Geological Survey, Cooperative Fish and Wildlife Research Unit during spawning surveys in Redwood Creek during 2009-2010 were used to model species abundance of fish over 40 cm (Chinook salmon, coho salmon, and steelhead). Carcass observations were not considered, due to increased uncertainty in determining date of migration past the DIDSON into spawning reaches. I devised four methods of assigning Redwood Creek DIDSON counts to species: (1) logistic regression using individual assignment; (2) logistic regression using summed probabilities; (3) ratios of spawning survey observations and (4) normalized distributions of run times.

General Assumptions

Several assumptions were made in using live fish observations to inform models of species abundance. The first was that spawning survey observations reflected the true mixture of species present in the basin. Second, I assumed no effect of sub-basin upon the frequency of species observation. The third assumption was that there were no differences in probability of detection among the three species over all spawning reaches. It was assumed that the length measurements taken from DIDSON video files and spawning surveys were congruent. Finally, I assumed that fish were not observed on multiple surveys. The first survey was conducted on 24 November 2009, and the final survey was conducted on 16 March 2010 (Table 3).

Table 3. Spawning survey intervals, observations, locations and calculated species proportions from Redwood Creek watershed 2009-2010. Observations included fish for which length was not estimated (129 Chinook, 39 coho, and 48 steelhead. The spawning survey observations with length estimates consisted of 99 Chinook, 33 coho and 38 steelhead (n=170).

Interval		Observations			Proportions			Surveys	
Start date	End date	Chinook	Coho	Steelhead	Chinook	Coho	Steelhead	Prairie Cr.	Redwood Cr.
9/30/2009	11/25/2009	3	0	0	1	0	0	2	2
11/26/2009	11/27/2009	1	0	0	1	0	0	0	1
11/28/2009	12/3/2009	6	0	0	1	0	0	0	4
12/4/2009	12/8/2009	9	0	0	1	0	0	0	5
12/9/2009	12/10/2009	3	0	0	1	0	0	0	1
12/11/2009	12/14/2009	1	0	0	1	0	0	0	1
12/15/2009	12/19/2009	7	2	0	0.778	0.222	0	3	0
12/20/2009	12/24/2009	11	0	0	1	0	0	0	4
12/25/2009	12/27/2009	4	2	0	0.667	0.333	0	3	0
12/28/2009	12/31/2009	34	0	0	1	0	0	2	5
1/1/2010	1/7/2010	18	13	0	0.581	0.419	0	7	1
1/8/2010	1/10/2010	7	0	2	0.778	0	0.222	1	0
1/11/2010	1/16/2010	3	14	0	0.176	0.824	0	6	0
1/17/2010	1/23/2010	0	2	0	0	1	0	1	0
1/24/2010	4/18/2010	0	0	42	0	0	1	7	6

For species modeling, I divided the study into two sub-seasons: 1) when both salmon and steelhead were migrating and 2) when only steelhead were migrating. The first spawning survey with no observations of live salmon was assumed to signify the end of the salmon migration for the season. After that date, all fish moving past the DIDSON site were assigned as steelhead.

Logistic Regression

Logistic regression was used to estimate the possibility of a fish target being Chinook salmon, coho salmon, or steelhead, based on fish length and date. I used a two-phase binary logistic regression, first between salmon and steelhead, and then a second phase to differentiate Chinook salmon from coho salmon. Multinomial logistic regression of the three species considered simultaneously was also used. The models are expressed as follows: $logit = \beta_0 + \beta_1 * Date + \beta_2 * Fork\ Length$, where the inverse link function is: $f(logit) = \frac{1}{1+e^{-(logit)}}$. Model parameters β_0 of intercept, β_1 of date and β_2 of length were estimated using a generalized linear model assuming a binomial error structure.

Dates were transformed to 'water year day' representing the number of days since the start of the water year, 1 October. I adjusted date values, assuming that fresh fish migrated past the DIDSON site 10 days prior to the date of observation on the spawning grounds and spawned-out fish 15 days prior for all species. Adjustments were based on residency times calculated for Prairie Creek salmon (Wright 2011).

For binary logistic regression, individual fish observed for a day were classified as salmon or steelhead using a 50% cutoff value. The proportion of steelhead for a day was calculated as:

$$proportion\ steelhead_{day} = \frac{number\ predicted\ steelhead_{day}}{total\ number\ fish_{day}}.$$

Daily steelhead escapement was calculated as:

$proportion\ steelhead_{day} * daily\ escapement\ estimate$. Remaining fish for the day comprised the daily salmon escapement estimate. The salmon were then classified as coho or Chinook salmon with a second phase of binary logistic regression, using the same methods outlined above. Seasonal species escapement estimates were treated the sum of daily estimates.

The multinomial logistic regression was interpreted in two different ways. For one method, the highest predicted probability was used to classify individual fish as coho or Chinook salmon or steelhead. The number of predicted fish for each species was used to calculate daily estimates of species proportions, as follows:

$proportion\ coho_{day} = \frac{number\ predicted\ coho_{day}}{total\ number\ fish_{day}}$. The daily estimates of species proportions, $proportion\ coho_{day}$, were applied to daily escapement estimates to derive seasonal estimates of species abundance. Alternatively, the predicted species probabilities from multinomial logistic regression for all observed individuals were summed to derive species proportions for the season, as shown in Table 4.

Table 4. Example of summed probabilities versus individual assignment interpretation of multinomial logistic regression. Individual assignment based on highest probability results in one coho and four Chinook, while using summed probabilities results in two coho, two Chinook, and one steelhead.

		Probability			
Date	Length	Coho	Chinook	Steelhead	Highest Probability
1/25/2010	78	0.420	0.432	0.149	Chinook
1/26/2010	79	0.391	0.457	0.152	Chinook
1/27/2010	55	0.654	0.029	0.318	Coho
2/2/2010	86	0.240	0.619	0.140	Chinook
2/3/2010	82	0.291	0.471	0.238	Chinook
Summed	Probabilities	2	2	1	

Spawning survey observations by interval

Spawning survey observations were used to calculate the species ratio of fish observed over a given time interval as follows:

$proportion\ coho_{interval\ i} = \frac{coho\ observed_{interval\ i}}{total\ observered_{interval\ i}}$. Observations from surveys performed on consecutive days were combined for ratio calculations. The calculated species ratio over *interval i* was applied to the corresponding escapement estimate as follows:

$$coho\ escapement_{\ interval\ i} = proportion\ coho_{interval\ i} * \ escapement_{interval\ i}$$

Species ratios from a single survey or surveys conducted on consecutive days were applied to all preceding days extending back in time to the previous survey (Table 3).

Normalized distributions of run times

Finally, I considered the seasonal migration pattern of each species as normally distributed over time. A normal distribution was fit to the spawning survey observation dates for each species, and probability distributions were generated for each of the three normal distributions (Figure 6). The areas of the probability distribution curves were then scaled to the number of observations of that species (Figure 7).

For each distribution, a single observation was added representing the onset of the spawning migration for that species. This pseudo-observation for coho and Chinook salmon on 1 October lengthens the leading tail of the distribution and prevents division by zero. Addtition of this extra data point was based on sightings of salmon in Redwood Creek upstream of the DIDSON site on 6 October 2009, immediately following the first

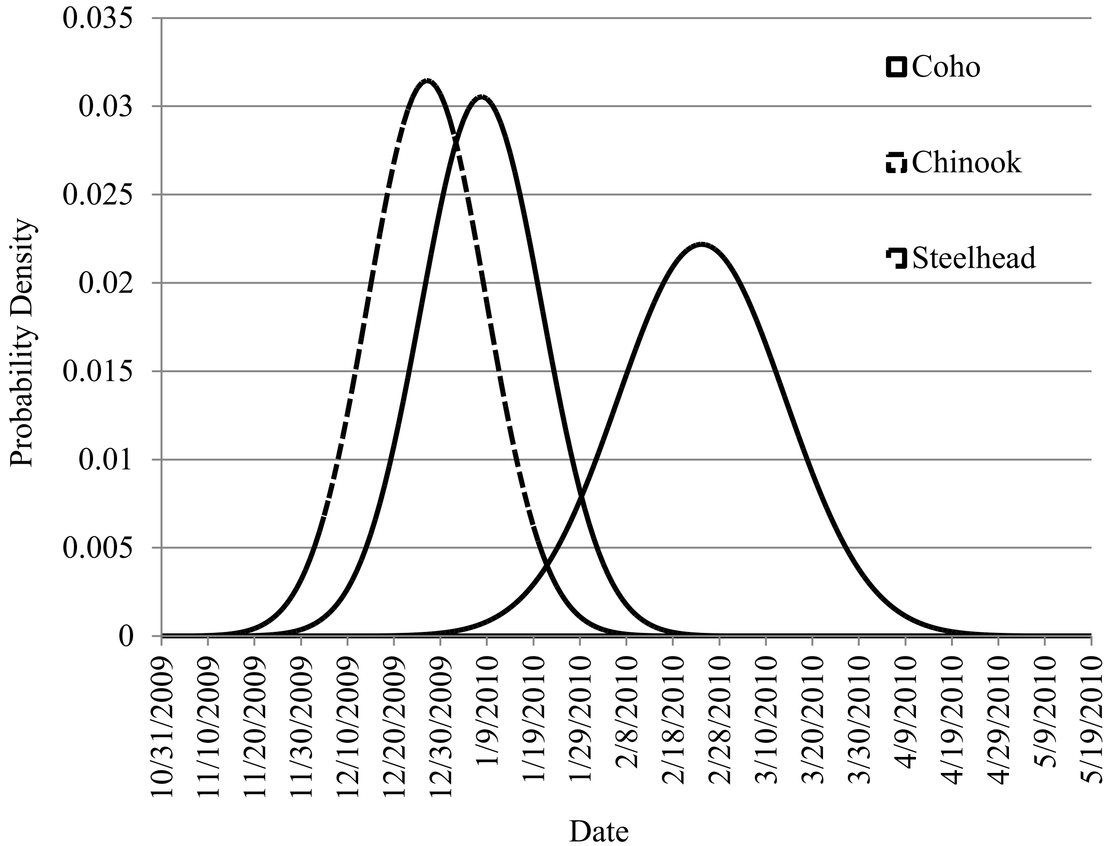

Figure 6. Normalized distributions of steelhead and coho and Chinook salmon observations from California Department of Fish and Game and the U. S. Geological Survey, Cooperative Fish and Wildlife Research Unit spawning surveys in Redwood Creek during 2009-2010.

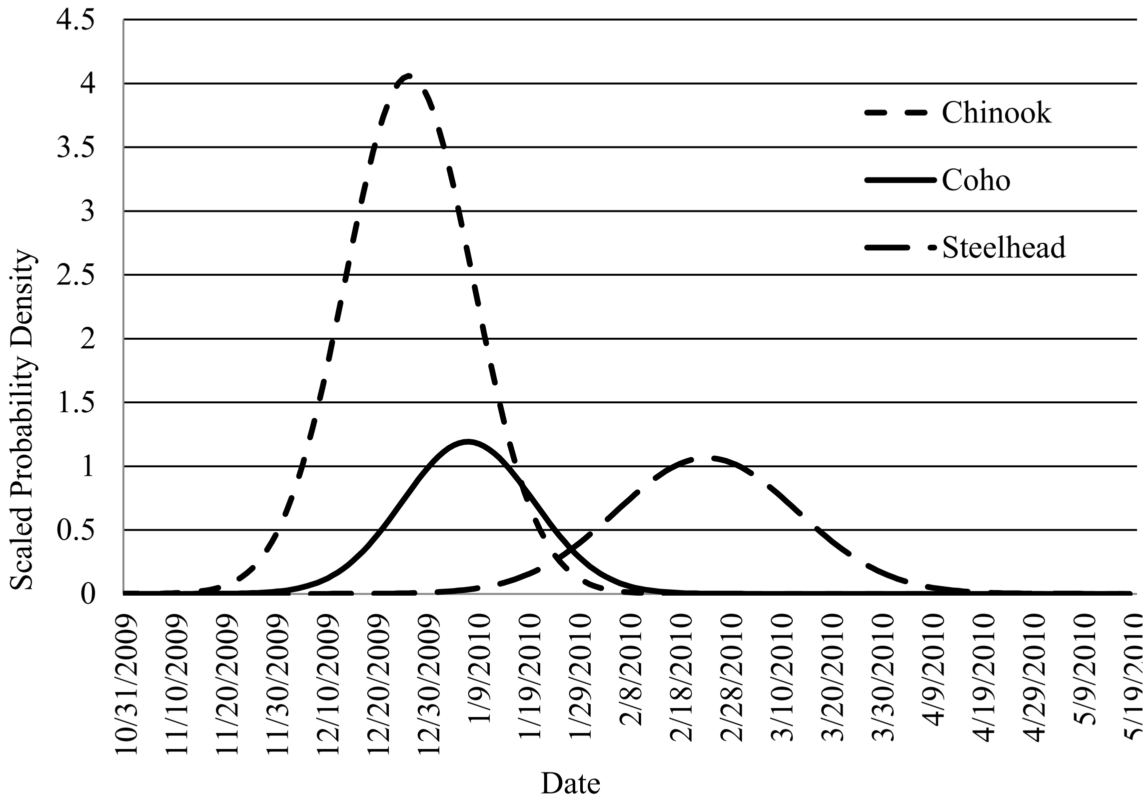

Figure 7. Normalized distributions of steelhead and coho and Chinook salmon observations from California Department of Fish and Game and the U. S. Geological Survey, Cooperative Fish and Wildlife Research Unit spawning surveys in Redwood Creek during 2009-2010, where the area of each curve has been scaled to the number of observations of each species. Number of observations were 129 Chinook salmon, 39 coho salmon, and 48 steelhead.

breach of the lagoon. For steelhead, the addition of a single observation on 20 December was based on data from the Prairie Creek weir, 2005-2009.

The three scaled probability curves were used to predict the expected species ratio for each day as follows:

$proportion\ coho(day\ i) = \frac{p(coho)_{day\ i}}{p(coho)_{day\ i}+p(Chinook)_{day\ i}+p(steelhead)_{day\ i}}$ where

$p(coho)_{day\ i} = probability(coho)_{day\ i} *\ p_{coho}$ and $probability(coho)_{day\ i}$ is the value from the normal coho probability distribution for day i and p_{coho} is the total number of coho observed on spawning surveys.

RESULTS

Deployment of the DIDSON

The DIDSON deployment worked well on Redwood Creek at flows less than 3000 f^3/s. At higher flows, the camera deployment accumulated debris, increasing the downstream force exerted on the components. The strength of the current pulled the T-post anchors out of the bottom substrate when the camera mount was left near the thalweg at higher flows. The DIDSON mount had to remain in water less than 1 m deep, and was not able to image out to the thalweg at flows greater than 3000 f^3/s, which occur about 24 days per year on average (Figure 8).

During 2009-2010, the DIDSON did not function properly on 12 days. The DIDSON did not acquire images during four days due to computer malfunctions or hazardous flows on Redwood Creek. The thalweg was out of range with video quality too poor to identify fish targets on eight days (Figure 9, 10).

During 2010-2011, the DIDSON deployment was inoperable during 79 days. Damage to the camera cable and subsequent repairs accounted for 40 days of downtime and 39 days were missed due to high flows and computer malfunctions (Figure 11, 12). While daily estimates of escapement are presented, no seasonal estimate of escapement for 2010-2011 is available due to missed days.

The Redwood Creek DIDSON detected fish consistently out to approximately 27 m. Fish 27-35 m from the camera appeared intermittently as flickering images. Periods of high turbidity and debris diminished video quality. Swimming targets detected by the

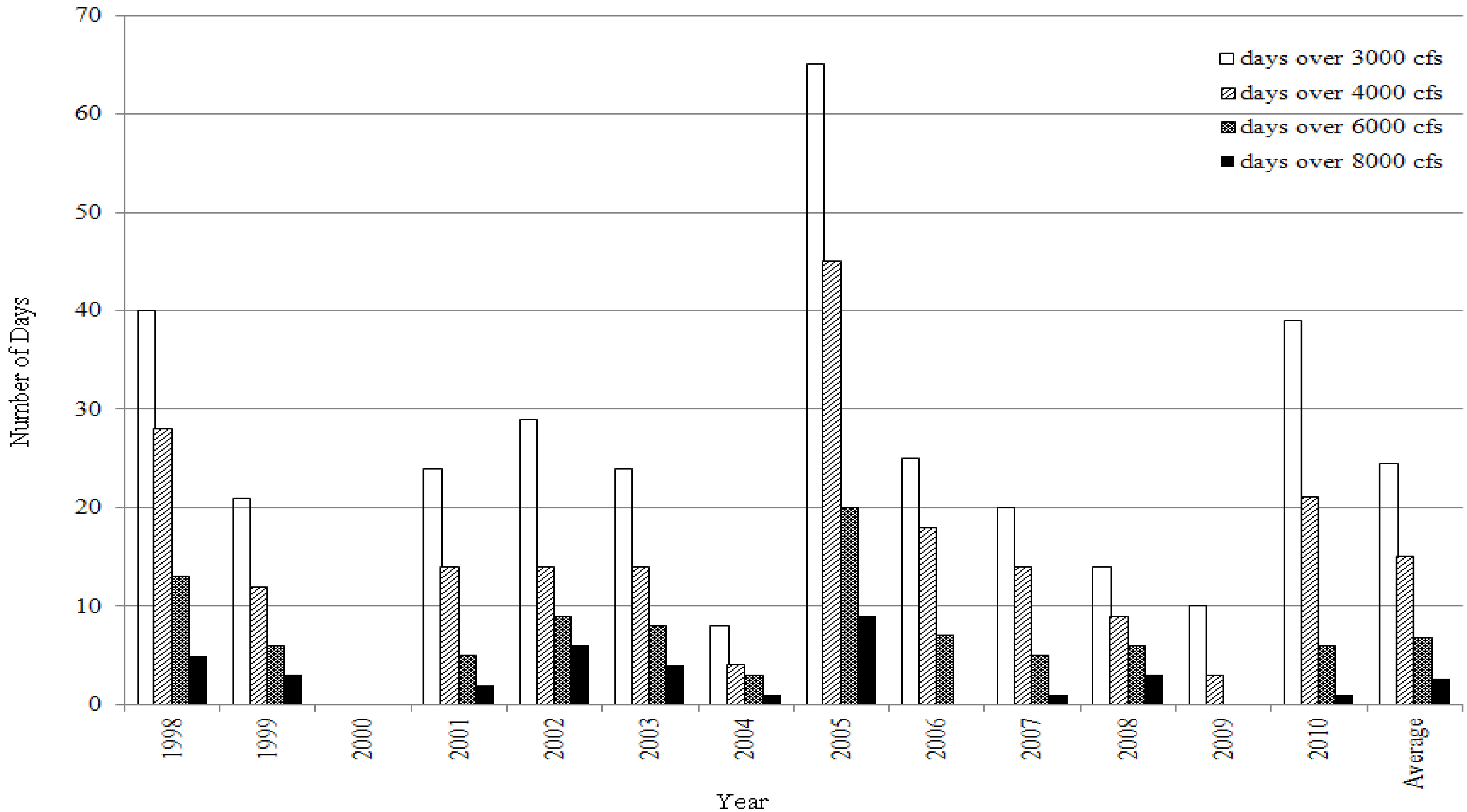

Figure 8. Days when Redwood Creek exceeded discharge levels where the DIDSON deployment was able to image the entire channel width for water years 1998 – 2011, and means based on 13 years of data.

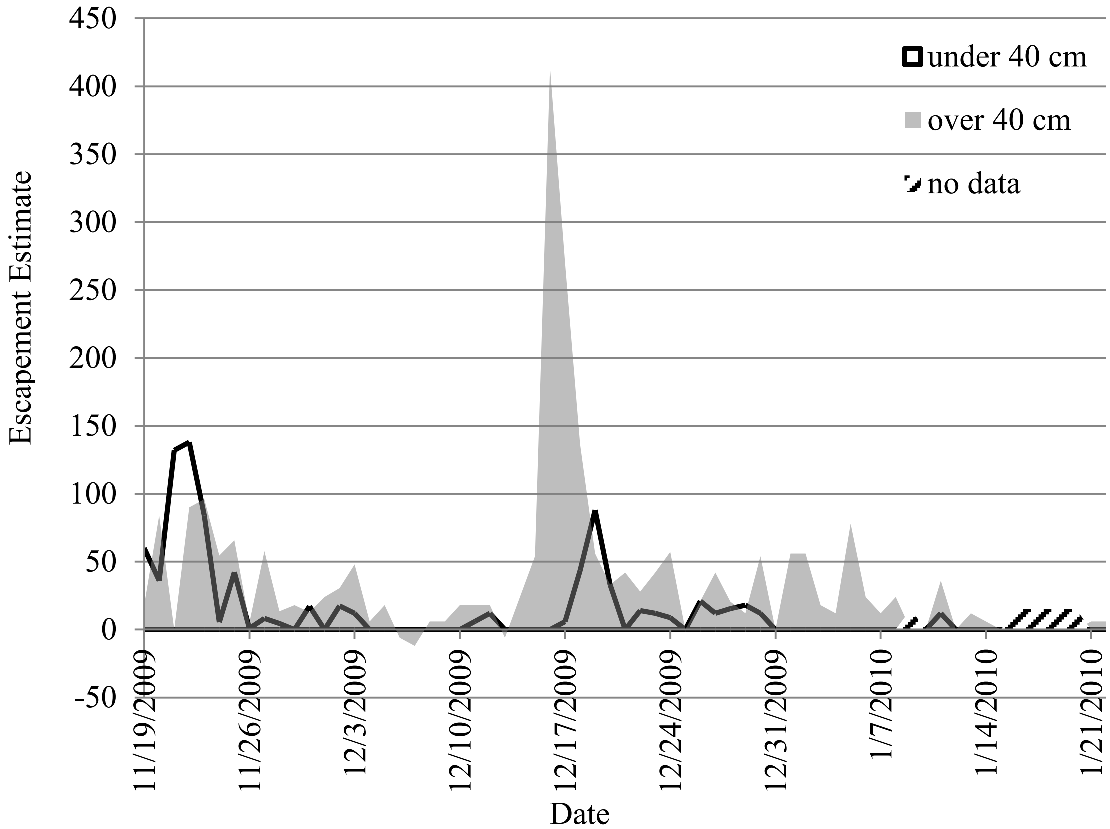

Figure 9. Distribution of daily escapement estimates of fish over and under 40 cm for the Redwood Creek salmon migration season, 19 November 2009- 23 January 2010. Steelhead passage is predicted to be six to 12 fish during this time period. Cross hatching indicates no data.

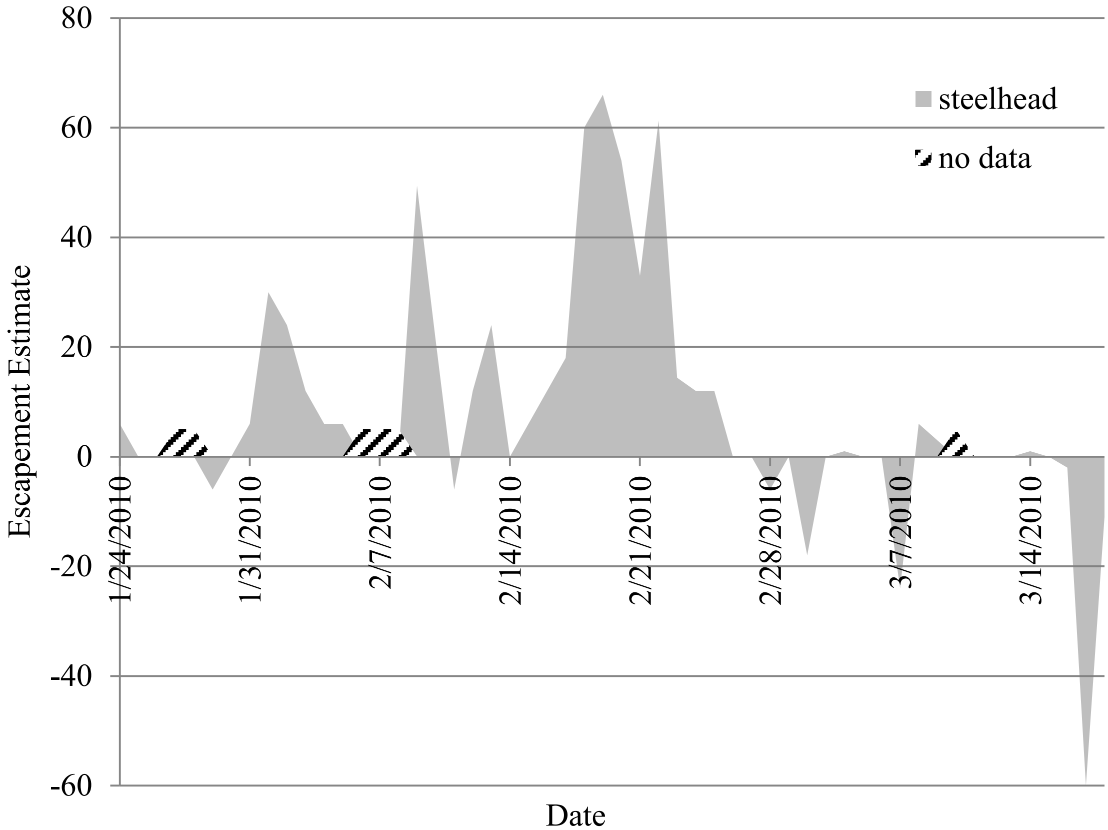

Figure 10. Distribution of daily steelhead escapement estimates for Redwood Creek, 23 January – 18 March 2010. Negative values after 28 February 2010 represent kelts returning to the ocean post-spawning. Cross hatching indicates no data.

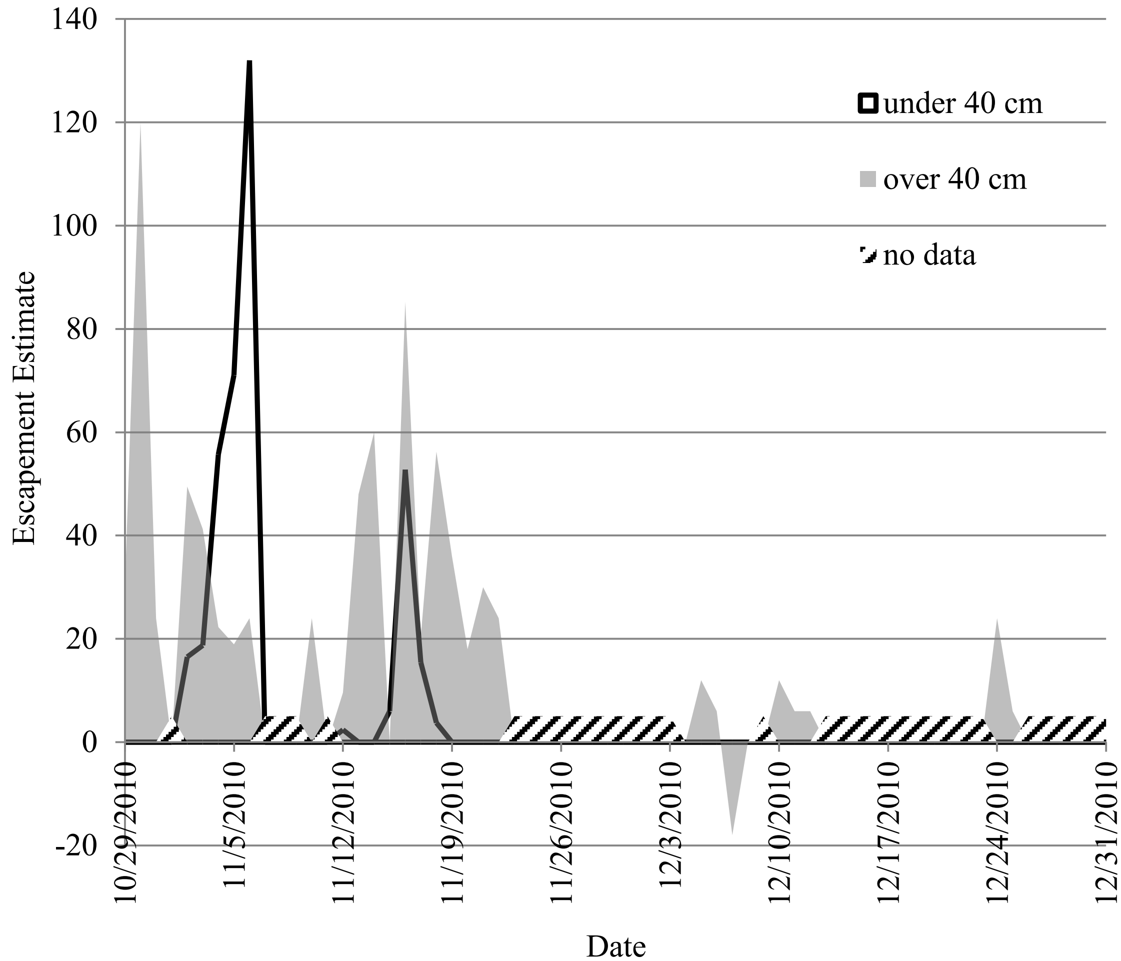

Figure 11. Distribution of daily escapement estimates of fish over and under 40 cm for Redwood Creek, 29 October 2010 – 31 December 2010. Cross hatching indicates no data.

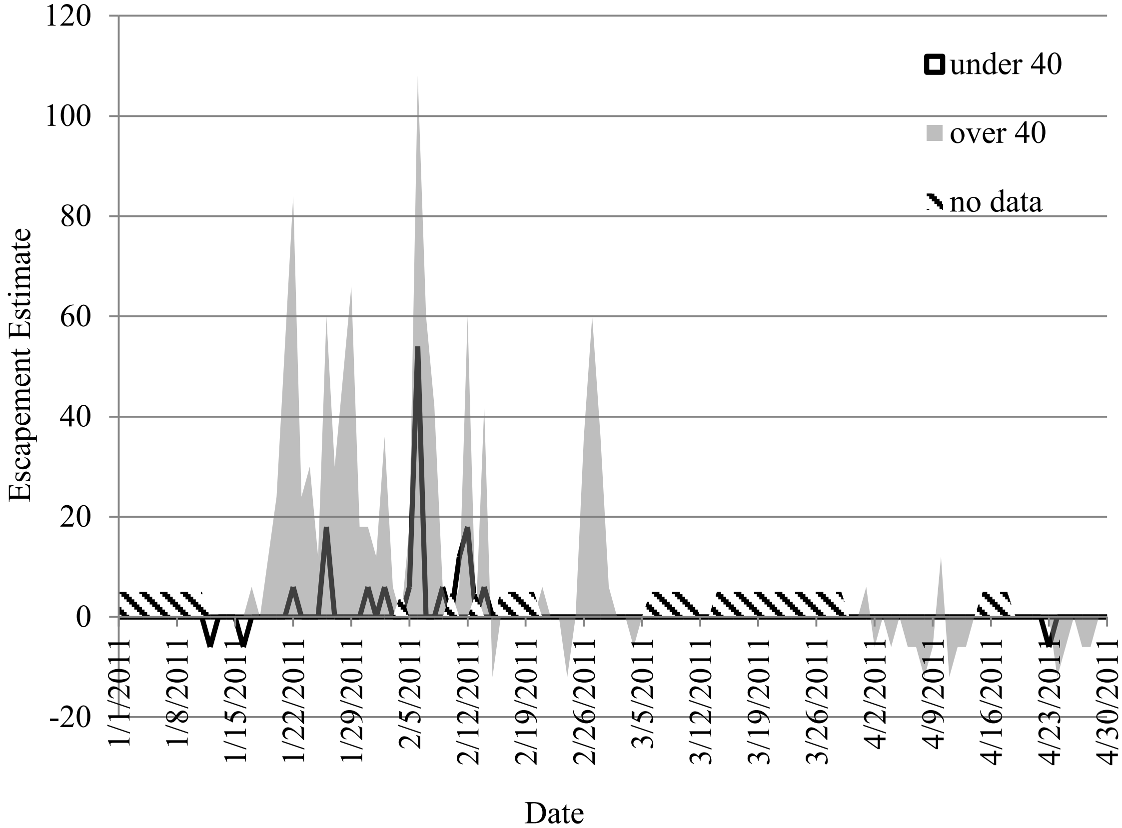

Figure 12. Distribution of daily escapement estimates of fish over and under 40 cm for Redwood Creek, 1 January – 28 April 2011. Cross hatching indicates no data.

DIDSON ranged in size from 15 cm to 2 m (Figure 13). The DIDSON detected 35 swimming objects longer than the 120 cm maximum size for fish in 2009-2010.
The DIDSON successfully identified a cinder block test target at distances up to 25 m from the camera, which ensured the camera functioned properly. Test targets could not be safely deployed during periods of high discharge to test the limits of the cameras capabilities. The detection ability of the DIDSON has been well documented, so the assumption was made that the properly functioning DIDSON would detect fish on Redwood Creek.

Estimating escapement to Redwood Creek

A total of 650 fish were counted in 2009-2010 at the Redwood Creek DIDSON site from 17 November 2009 to 18 March 2010. The escapement estimate for fish over 40 cm was 3,000. The escapement estimate for fish under 40 cm was 900. Of fish below 40 cm in length, I estimated 150 were jacks, 525 were cutthroat trout, and 225 were steelhead.

Daily escapement estimates for fish over 40 cm varied from -60 to 400 fish, with a mean of 34 fish/day. Daily escapement estimates for fish under 40 cm varied from -30 to 138 fish, with a mean of eight fish/day. The distribution of counts across the 2009-2010 salmon season showed a distinct spike of up to 400 fish during December 16-18 and across steelhead season showed was variable with fewer than 50 fish on other dates (Figure 9). The distribution of counts several peaks in February, the strongest being

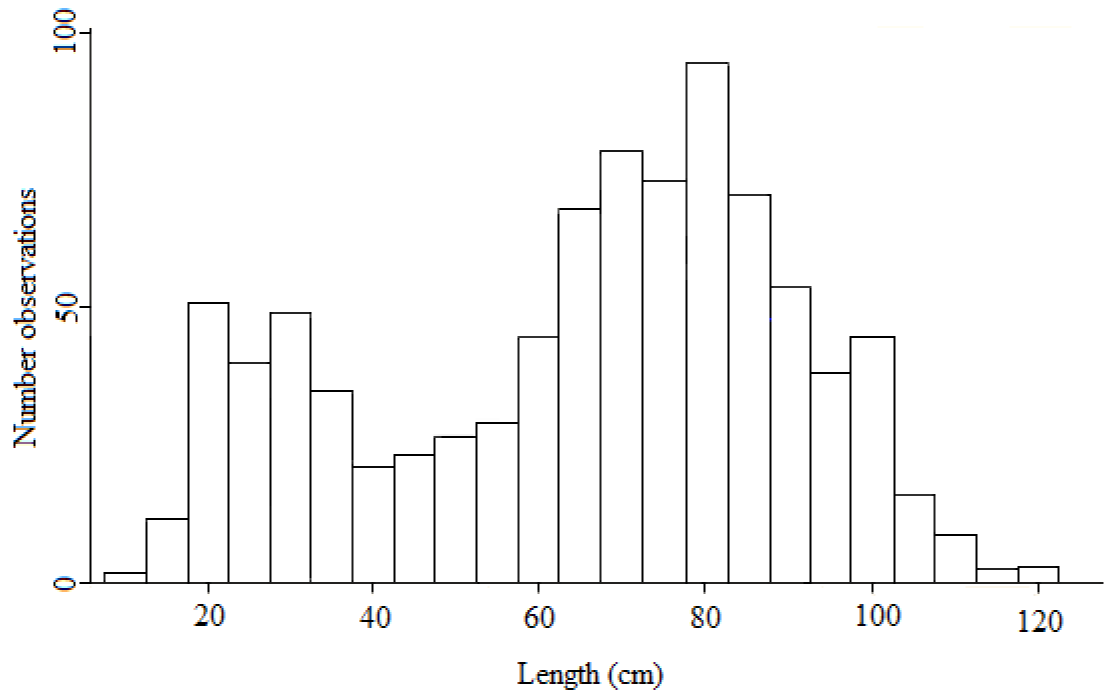

Figure 13. Distribution of fish lengths taken from Redwood Creek DIDSON video from 19 November 2009 - 5 March 2010 (N=1043). Non-fish targets are excluded.

during February 15-25 (Figure 10). After February, the net movement of fish was predominantly downstream. Values for observed and expected fish tabulated daily above and below the 40 cm cutoff are presented in Appendix A.

On average, hourly escapement rates were lowest at mid-day and highest at dusk. Observations from 11 am to 4 pm accounted for 10% of all fish, while 35% of all fish were counted fom 4 pm to 9pm (Figure 14). On the 35 days where both upstream and downstream counts were recorded, downstream moving fish accounted for 10-40% of all fish observations (except during kelt season).

Daily stream discharge did not explain most of the variation in fish passage (Figure 15). The day of peak fish passage on 17 December 2009 followed an increase of flow from 160 f^3/s to 1600 f^3/s on December 15-16. The movement analysis over the first 58 days yielded no clear relationships, with the saturated model ranking highest (adjusted $R^2 = 0.249$, Table 5). Analysis of all available days showed a slightly stronger relationship between fish passage and environmental conditions, with the top model incorporating parameters for high tide (p=0.0099) and date (p=0.0022) as follows: $fish\,passage = 118.653 - 25.683(maxtide) - 0.685(date)$. However, explanatory power for all models was low, with adjusted R^2 values no higher than 0.174. A complete list of all models considered is presented in Appendix B.

A total of 394 fish were counted going upstream in 2010-2011. Passage estimates based on available data were 2,292 total fish with 500 smaller than 40 cm and 1792 over 40 cm. Long periods of equipment downtime prevented effective estimation of

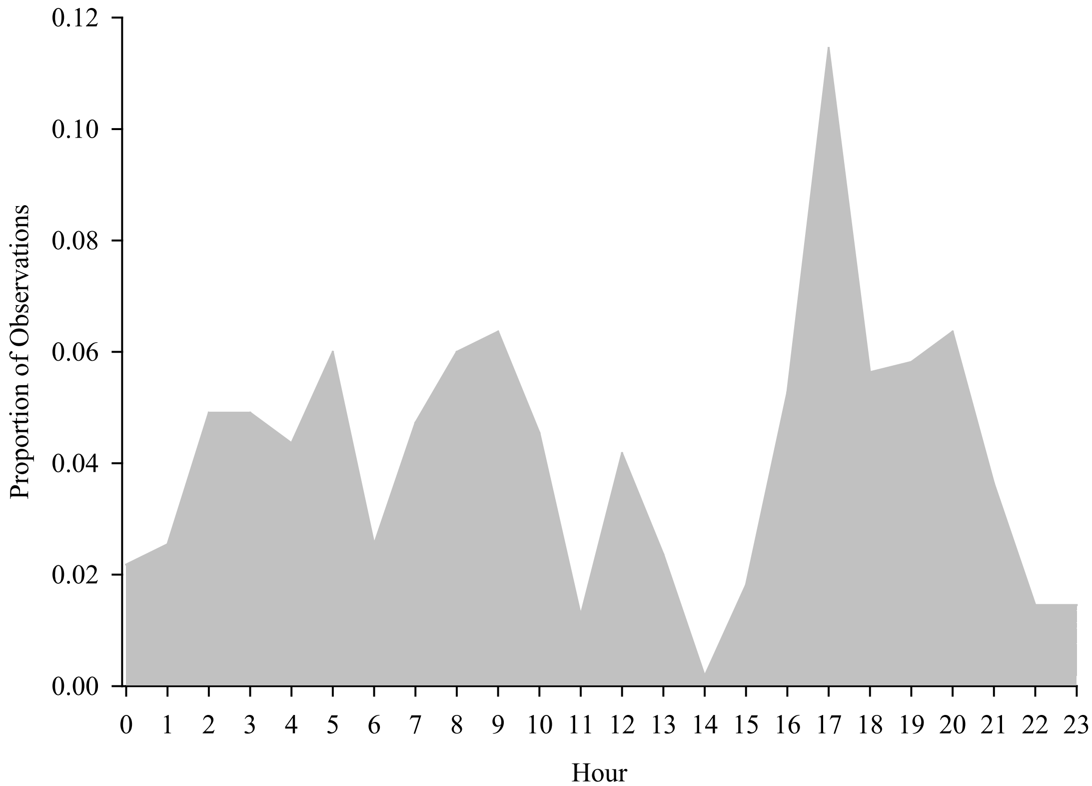

Figure 14. Hourly distribution of upstream moving fish throughout the day from 17 November 2009 – 18 March 2010 (n=1000). Days where less than 24 hours were recorded were not considered.

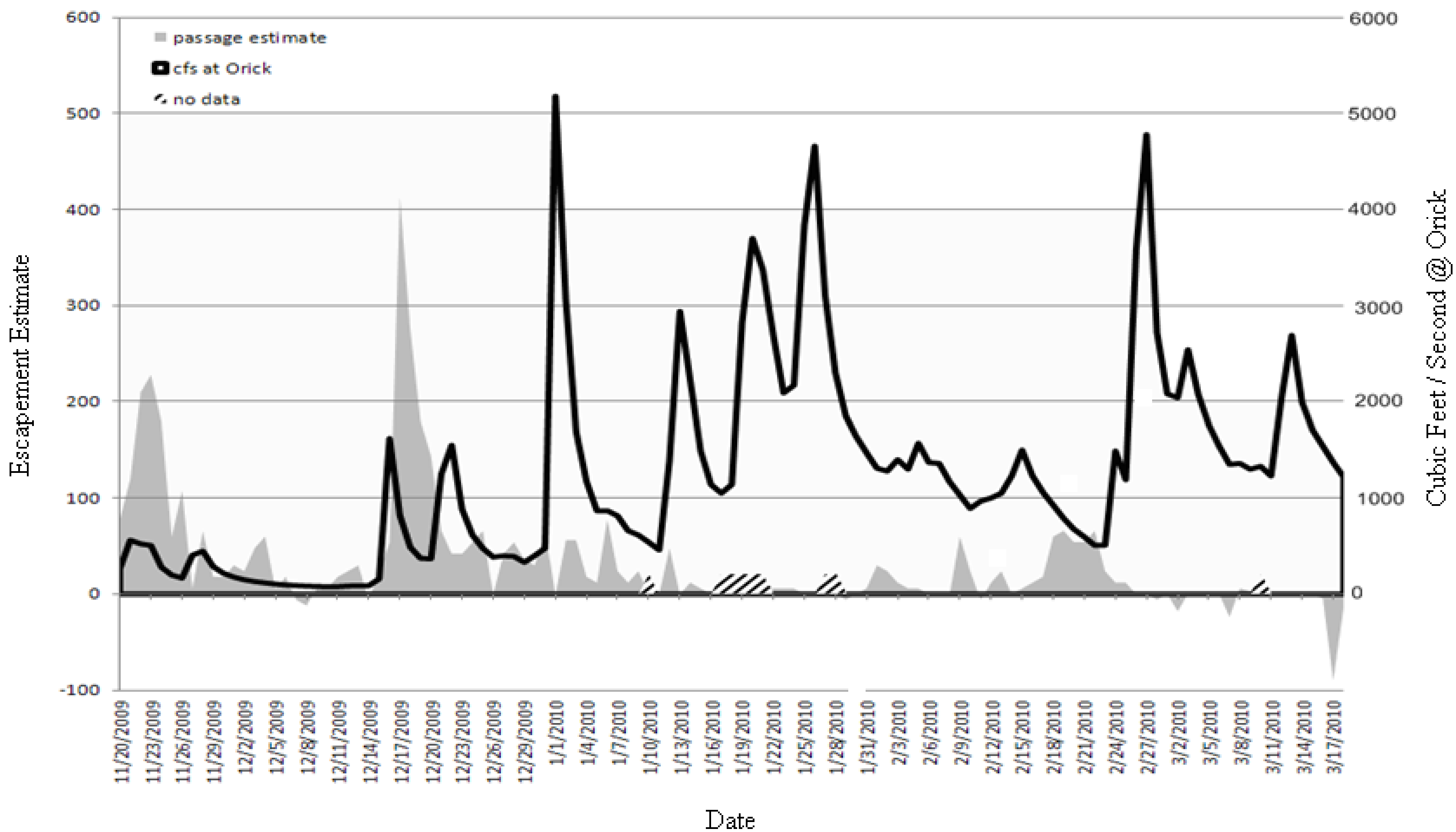

Figure 15. Mean daily discharge in cubic feet per second at the USGS gauging station in Orick and estimated passage of fish of all sizes from 17 November 2009 – 18 March 2010. Cross hatching indicates no data.

Table 5. Comparison of top movement models based on environmental conditions, where the response is daily passage estimate for fish of all sizes. Akaike's information criterion (AIC) and adjusted R-squared (Adj. R^2) are shown for each model. All models considered are shown in Appendix B.

Parameters	AIC	Δ AIC	Adj. R^2
First 58 days			
saturated model	653.508	0.000	0.249
maxtide, cfs Orick lag=1, date^2	655.254	1.746	0.140
All days			
maxtide, date	987.597	0.000	0.164
Δ cfs Orick, maxtide, date	987.77	0.173	0.172
maxtide, date^2	988.288	0.691	0.158
Δ cfs Orick, Δ cfs Orick lag=1, maxtide, date	988.402	0.805	0.174
maxtide, Δ cfs Orick, date^2	988.588	0.990	0.164
maxtide, Δ cfs Orick lag=1, date^2	988.733	1.136	0.162
maxtide, cfs Orick lag=1, date^2	989.763	2.166	0.153
maxtide, Δ cfs O'Kane, Δ cfs O'Kane lag=1, date^2	989.99	2.393	0.160
maxtide, cfs Orick, date^2	990.138	2.541	0.149
saturated model	993.482	5.885	0.177

escapement to Redwood Creek for 2010-2011 (Figure 11, 12). No attempts were made to model species apportionment for the 2010-2011 migration season.

The V5 estimate of variance resulted in 95% confidence intervals of +/- 406 fish, representing sampling error. Regression of hourly expanded counts versus census values over all available days and for 17 December 2009 are presented in Figures 16 and 17. The error between the census escapement estimate (496 fish) and the six escapement estimates (414-660 fish) from 10 minute samples ranged from 2-33%, with a mean error of 13% (Table 6). The assessment of differing sampling rates showed a clear relationship, where increased sampling effort resulted in reduced mean error, as low as 3% at a rate of 50 minutes per hour (Table 6).

The repeatability assessment revealed that one reviewer observed 73 fish while the other reviewer observed 97 fish over the same time period. Of 210 files compared, 176 had complete agreement, while 32 files had a difference of one fish, and 2 files had a difference of two fish. The correlation of counts for the two reviewer A versus reviewer B resulted in a Pearson correlation of 0.94. The regression of counts between reviewers yielded an R^2 of 0.889 (Figure 18).

I was unable to effectively use the DIDSON software to automate the review process. Condensed CSOT files were used to conduct a 24 hour census on five days with very low fish densities, and very clear water conditions. Raw video was not reviewed for days where a CSOT census was performed, thus assuming that the compression process did not discard fish passage events. I generated echogram auto count summaries using

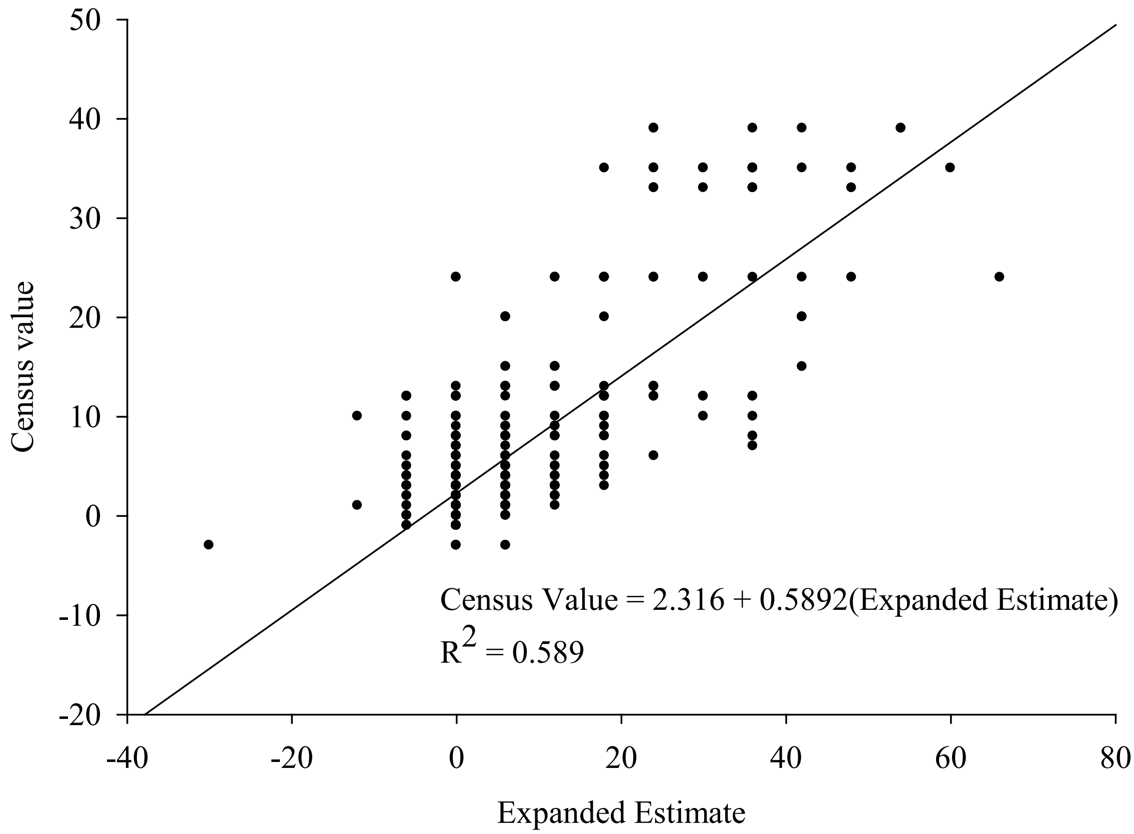

Figure 16. Relationship between number of fish counted in a census of 88 hours during 2009-2010 and expanded estimates derived from the 528 corresponding ten minute files at all levels of fish passage rate. The diagonal line represents a 1:1 relationship.

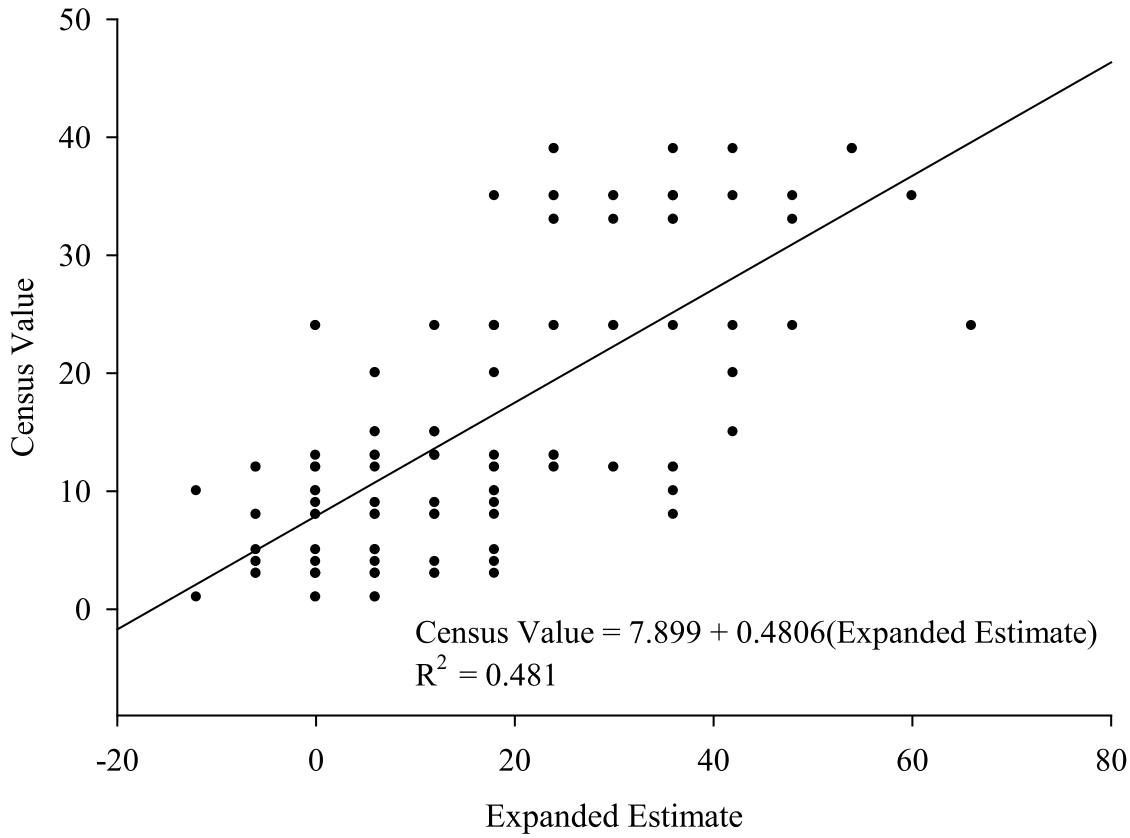

Figure 17. Relationship between number of fish counted in an hourly census of 24 hours and expanded estimates derived from the 144 corresponding ten minute files from 17 December 2009, day of peak fish passage. The diagonal line represents a 1:1 relationship.

Table 6. Census values, expanded escapement estimates and associated errors at sampling levels from 10 to 50 minutes per hour, based on the review of 87 hours of Redwood Creek DIDSON video data from 2009-2010. File "0" represents minutes 0:00 - 9:59 of the hour, file "10" refers to minutes 10:00 - 19:59 of the hour, etc.

Files sampled	Error	Mean Error
0	0.3306	
10	0.0766	
20	0.0806	
30	0.1653	
40	0.0202	
50	0.1411	0.1357
0,10	0.2036	
10,20	0.0020	
20,30	0.1230	
30,40	0.0927	
40,50	0.0806	
50,0	0.0948	0.0995
0,10,20	0.1089	
10,20,30	0.0565	
20,30,40	0.0887	
30,40,50	0.1089	
40,50,0	0.0565	
50,0,10	0.0887	0.0847
0,10,20,30	0.0403	
10,20,30,40	0.0474	
20,30,40,50	0.1018	
30,40,50,0	0.0010	
40,50,0,10	0.0615	
50,0,10,20	0.0464	0.0494
0,10,20,30,40	0.0282	
10,20,30,40,50	0.0661	
20,30,40,50,0	0.0153	
30,40,50,0,10	0.0161	
40,50,0,10,20	0.0331	
50,0,10,20,30	0.0040	0.02715

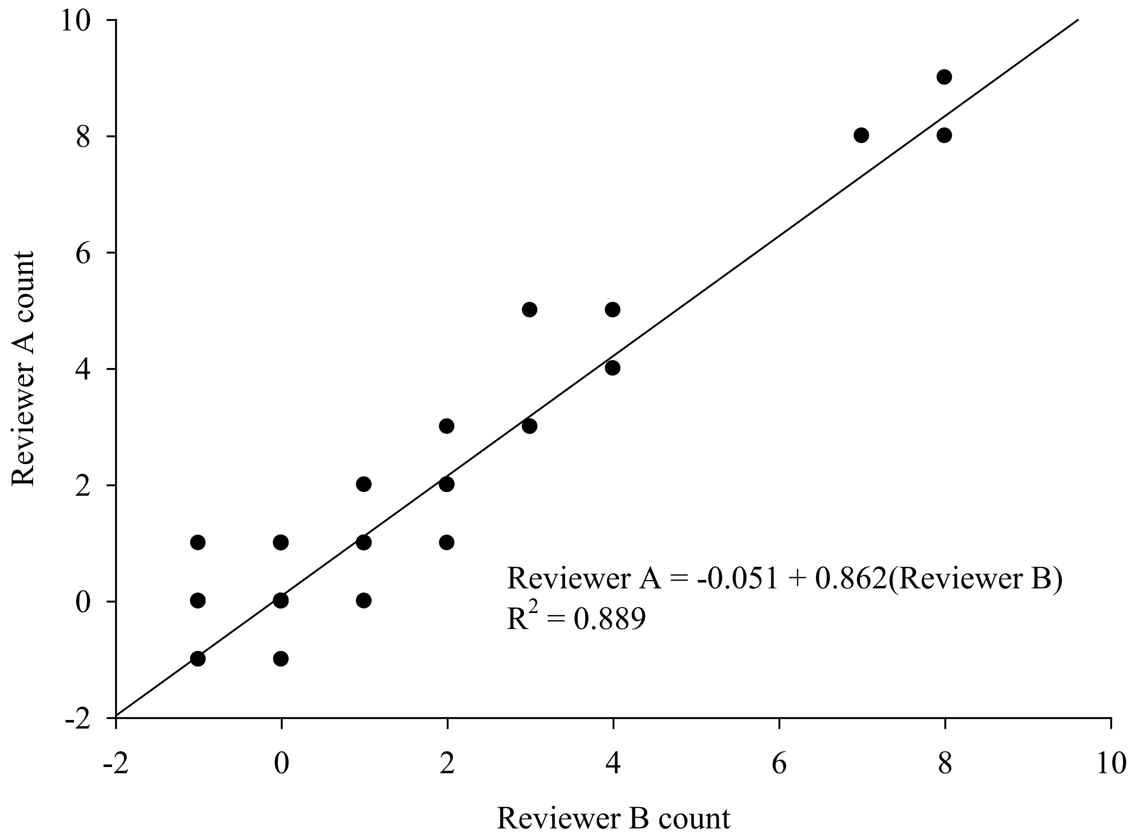

Figure 18. Regression comparing the counts of two reviewers over the same 210 files of Redwood Creek DIDSON video data 2009-2010. The diagonal line represents a 1:1 relationship.

default software settings for 45 days and compared the total upstream count from the echogram output to the corresponding estimates from human review (Figure 19).

Results of the echogram auto-counting, 6,804 upstream targets, were not consistent with human reviewers, who estimated 2,738 fish for the same time period. The echogram detected 32,578 downstream targets, which were not confirmed to be fish or debris. Assuming upstream targets detected by the software have a greater probability of being fish, and non-fish represent a constant level of noise in the upstream count, analysis of the echogram suggests that a 10 minute sample will result in a mean error of 9% (Table 7).

Species models for overlapping runs

Models yielded a mixture of Chinook salmon, coho salmon and steelhead during 19 November 2009 - 22 January 2010. For Chinook salmon, the four models predicted a minimum escapement of 2,318 and a maximum of 2,500 (Table 8). During this same period, coho salmon escapement was estimated to range from 315 to 490. Escapement of steelhead, six to 12 fish, entering Redwood Creek was predicted to be low before 23 January 2010.

All fish after 23 January 2010 were modeled as steelhead. I estimated that 550 steelhead migrated into Redwood Creek from 23 January 2010 to 18 March 2010. Of these 550 steelhead, 100 were estimated to have returned to the ocean after spawning. An estimated 225 steelhead under 40 cm migrated into Redwood Creek during 2009-2010 in addition to the 550 fish over 40 cm in length, for a total of 775 steelhead.

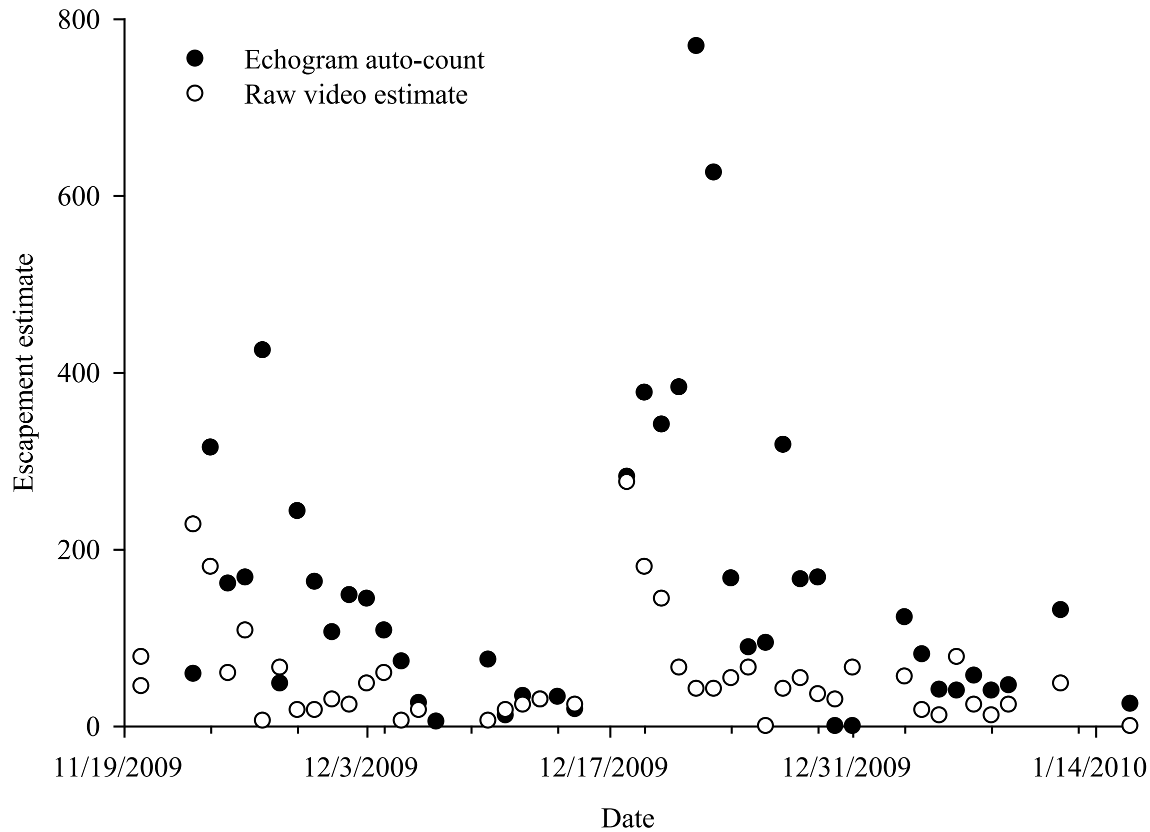

Figure 19. Echogram auto-count, expressed as total upstream targets for a day compared to human-derived escapement estimates from a 10 minute/ hour sample of unprocessed video.

Table 7. Sampling analysis of echogram auto-count results over 318 hours, showing expanded escapement estimates, census values, errors and mean error. Estimates and census values refer to total upstream count from the echogram. File "0" represents minutes 0:00 - 9:59 of the hour, file "10" refers to minutes 10:00 - 19:59 of the hour, etc.

Files sampled	Estimate	Census	Difference	Error	Mean error
0	2148	2057	91	0.04	
10	2220	2057	163	0.08	
20	2382	2057	325	0.16	
30	1932	2057	-125	0.06	
40	1758	2057	-299	0.15	
50	1902	2057	-155	0.08	0.094

Table 8. Comparison of results from four methods of species classification for DIDSON escapement estimates 17 November 2009 to the day of the last salmon observed on Redwood Creek spawning surveys, 23 January 2010. Note that steelhead counts below do not represent the full run.

Method	Coho	Chinook	Steelhead
Logistic regression – individual assignment	321	2488	12
Logistic regression - summed probabilities	490	2318	12
Survey intervals	368	2444	8
Normalized distributions	314	2500	6

Logistic regression species models which included both *Date* and *Length* (AIC = 74.05) performed better than models which included either *Date* (AIC = 115.54) or *Length* (AIC = 215.77). Due to the similarity of the underlying processes of the models, only the estimates derived from the multinomial logistic regression of both *Date* and *Length* have been presented. For coho versus Chinook salmon the probability of coho $= 1/(1 + e^{-x})$ where x =*294.268 -2.671(Date) +0.023(Length)*. For coho versus steelhead the probability of coho $= 1/(1 + e^{-x})$ where x = *290.131 -2.728(Date) +0.167(Length)*. A complete list of logistic equations is presented in Appendix C.

DISCUSSION

Escapement to Redwood Creek

The DIDSON was a viable method of escapement estimation in 2009-2010, but was not viable in 2010-2011, due to missed days. When the Redwood Creek DIDSON was deployed properly in low to moderate flows, the resulting estimates and confidence intervals were reasonable. Other studies have found that DIDSON was an improvement over estimates from older sonar systems (Maxwell and Gove 2004, Xie et al. 2005, Cronkite et al. 2006, Holmes et al. 2006), and that DIDSON was as accurate as visual counts from enumeration fences (Cronkite et al. 2006, Holmes et al. 2006).

Other escapement estimation methods have been used concurrently with DIDSON, presenting an opportunity to compare results. Counts from DIDSON can be significantly higher than estimates derived from area under the curve methods (Matthews and Baillie 2007) and Bendix sonar deployments (Fair et al. 2009). The DIDSON counts of Chinook salmon on the Anchor River, Alaska were considerably higher than aerial counts, and were used to justify changes to the management status of that stock (Kerkvliet et al. 2004). Closer agreement was found between redd survey estimates (362 fish) and DIDSON counts (382) on Mill Creek, California (Johnson et al. 2009). The DIDSON escapement estimate of sockeye salmon to the Horsefly River, British Columbia was nearly identical to high precision estimates from mark-recapture and counting fences (Welch et al. 2007).

The echogram auto count of total fish resulted in a mean error of 9% (3000 +/- 270 fish) when sampling 10 minutes per hour over 318 hours, similar to the mean error of 13% (3000 +/- 390 fish) from the human-based census of 87 hours. Calculation of sampling variance using the V5 estimator (3000 +/- 430 fish) resulted in similar magnitudes of error. General agreement between these three assessments of sampling error at 10 minutes per hour indicates that the estimated error rates of 9-14% are reasonable.

The National Oceanic and Atmospheric Administtration recommends that adult spawner data for the Pacific Northwest have a coefficient of variation (CV) of no more than 15% on average for ESA populations (Crawford and Rumsey 2011). Using a 10-minute subsample, the 2009-2010 Redwood Creek DIDSON escapement estimate appears to meet this benchmark, with a CV of 6%, and 95% confidence intervals representing +/- 14% of the point estimate. However, while tight 95% confidence intervals are the scientific norm, Crawford and Rumsey (2011) point out that having 80% certainty that an estimate is within +/- 20% of the true value for salmonid escapement may be reasonable, given conditions and funding.

For Redwood Creek, the southern Oregon / northern California coast coho salmon recovery plan calls for 4,900 adult spawners / year for ESU viability (National Marine Fisheries Service 2012). The estimate of Redwood Creek escapement in 2009-2010 was 3,000 (+/- 15%) unspecified fish with 300-400 fish modeled as coho (2200 Chinook salmon, 500 steelhead). When considering de-listing, abundance of coho salmon remains well below the target for recovery, so the present level of error is acceptable. On the other hand, the minimum viable spawning population for Redwood Creek coho salmon is 150 fish, so it is vital to develop confidence intervals around the species estimates.

Challenges in estimating escapement

A distinction should be made between escapement and actual spawner abundance whenever possible (Crawford and Rumsey 2011). Pre-spawning mortality has been observed in Redwood Creek salmonids as un-spawned female carcasses with predation wounds. The proportion of adults that die from predation prior to spawning has not been determined on Redwood Creek. The Redwood Creek recreational steelhead fishery is another potential source of pre-spawning mortality.

A telemetry study of Fraser River sockeye salmon revealed that only 36.3% of fish captured by angling and immediately released eventually reached their natal sub-watershed (Donaldson et al. 2011). Angler information specific to Redwood Creek is available starting in 2012. Redwood Creek counts of steelhead could be adjusted downward to account for angling mortality.

Identification of species where multiple runs overlap remains a significant challenge to producing DIDSON escapement estimates. In a study on Alaska's Susitna River, DIDSON grossly underestimated the number of sockeye salmon returning to spawn in years of high pink salmon abundance (Fair et al. 2009). Mark-recapture methods revealed that the fish wheels used for species apportionment in the study were underestimating sockeye by a factor of 2.4 on average. The assumption that spawning survey observations of live fish represent the true proportion of species present in the

Redwood Creek watershed is suspect. Chinook salmon are more likely to be sighted during ground surveys than steelhead, due to differences in size and behavior.

All species apportionment models in this study assumed no effect of sub-basin on observed species compositions. Yet, Prairie Creek has a unique species assemblage, with more coho salmon and cutthroat trout smolts than the rest of the basin (Sparkman, 2012). In fact, no adult coho salmon were observed outside of Prairie Creek in 2009-2010, and populations of fewer than 100 0+ and 1+ coho were estimated for the 2009-2010 cohort outside of Prairie Creek (Sparkman, 2012). In addition, Prairie Creek clears faster after storms and was surveyed more frequently than the remainder of the Redwood Creek basin (32 versus 30 surveys). However, the dataset may be small enough to favor the use of simple models over more complex ones which include an effect of sub-basin. As a result of including Prairie Creek, it is possible that the coho estimate might be biased high, even though the the un-apportioned run estimate may be biased low, due to days when the camera was not recording.

Incongruent fish lengths taken from DIDSON and lengths observed on walking surveys may skew the results of species models based on length. The DIDSON software provides unbiased length measurements of free swimming fish; however, the lengths taken in low frequency mode are only accurate to +/- 5 cm (Burwen et al. 2007). The accuracy of fish length estimates from spawning surveys has not been determined in the Redwood Creek basin.

Species models for Redwood Creek had good agreement, but the dataset used to create the models was relatively small, at 170 total observations of fish. Results from the logistic regression using summed probabilities differed from the other models, allowing cases where fish are classified with lower certainty to have more effect on the outcome of the species composition. This method effectively increased the proportion of coho salmon predicted when compared to other models (Table 8).

Using logistic regression for species classification offers the advantage of considering both run timing and fish size in prediction compared to methods that use dates of observation alone. Of the four models described in this study, the survey interval model, where species apportionment is calculated over consecutive spawning surveys, is the most similar to existing methods. When seining or fish wheels are used to assign species, fish may be collected daily until a desired sample size is reached (five to 100 fish), and the proportion of species in that sample is applied to the corresponding time interval of sonar data (McKinley 2003). An alternative is pulsed sampling, where intense sampling is performed over one or two days, followed by several days off (McEwen 2008). Using walking surveys for species apportionment amounts to pulsed sampling, since reaches are generally surveyed twice each month.

I did not attempt to calculate confidence intervals for species apportionment on Redwood Creek. Matthews and Baillie (2007) calculated standard errors and 95% confidence intervals for species proportions, but their formula becomes unreliable when proportions are above 0.9 and below 0.1 (Fowler and Jarvis 1999). Species proportions from Redwood Creek spawning surveys were often 0 and 1, so this approach could not be used.

A shortcoming of using species models based on fish size and run-timing is that they cannot be tested for concordance. The California Coastal Salmonid Monitoring Plan calls for species apportionment of DIDSON data to be validated before it is accepted (Adams et al. 2011). However, the drawback of uncertainty in species identification is outweighed by the benefits of having a measure of all fish migrating into Redwood Creek for trend data and measuring responses to restoration activities.

An increase in the number of samples used to derive species apportionment could improve the performance of the models. More frequent spawning surveys or the use of seines are two ways to accomplish this. A seining regimen, along with a Passive Integrated Transponder (PIT) tag or acoustic tag array at the DIDSON site could determine whether fish pass the DIDSON site undetected. Tagged fish of known species could also be used identify unique morphologies and swimming patterns between species in DIDSON images, as Mueller (2011) did with chum versus coho salmon.

The emphasis on identifying species in this study made it necessary to measure the length of as many fish as possible. The video review process can be greatly accelerated by recording only counts, while ignoring fish lengths (Zack Larson, Smith River Advisory Council, personal communication). Considering the potential reduction in sampling error, a higher sampling rate combined with a subsample of fish lengths may be a viable approach. A future study could analyze how well a sample of lengths represents the population of fish lengths for a day.

Review of DIDSON video was time consuming and repetitive. It took one to four hours to review one day's worth (four hours of video) of DIDSON video data. It took longer to review files with more fish activity since reviewers must stop playback to record fish lengths, or re-watch portions of the video to determine fish origin or direction.

The use of CSOT condensed video data can greatly speed up the review process, especially at low fish densities. This allows for data to be reviewed at a much faster pace than manually viewing all the video, much of which shows nothing happening. However, the DIDSON detects downstream drifting debris and bubbles, which appear as noise or static during review. Image noise generally increases with discharge and turbidity. In contrast, reviewers can easily identify fish as objects that move differently from the smooth downstream motion of the background noise.

Excessive noise in the video image compromises the ability of the DIDSON software to effectively condense video, resulting in files only slightly shorter than real-time. The computer process is also disrupted by the constant motion of the bottom substrate during bedload movement of the stream sediment. Furthermore, condensed video complicates determination of the direction of travel and origin of fish. The process can remove frames where the fish is only partially visible to the camera, or barely moving.

The DIDSON echogram software has shortcomings which limit its utility in Redwood Creek studies. The process cannot differentiate between debris floating downstream and fish swimming downstream, so net movement of fish cannot be determined without human verification. Bedload movement and noise in the image are also mistaken for fish targets. Finally, slight changes to user controlled parameters can have drastic effects on the outcome of echogram processing. Conditions on California's

Smith River and Pudding Creek present similar challenges to automated review techniques as Redwood Creek, favoring the use of raw video files (Zack Larson, personal communication, Parker et al. 2012).

A census of all DIDSON video data provides the most accurate estimate possible, but is labor-intensive. A non-replicated systematic sample of 10 minutes per hour is commonly used for salmon escapement estimates derived from counting towers or hydroacoustic data (Siebel 1967, Reynolds et al. 2007, Woody 2007). Lilja et al. (2008) investigated the use of systematic sampling for DIDSON derived salmon escapement estimates. The study concluded that using a systematic hourly sample is an appropriate method when the timing of fish migration is not known a priori, and recommended using 10- to 20-minute hourly samples, based on cost-benefit analysis. Dividing the hour into smaller intervals is also desirable due to the 15-20 minute limit of a reviewer's attention span (Johnstone and Percival 1976, Woody 2007).

Results from this study suggest that a 10 minute sub-sample is adequate to detect coarse scale fluctuations of fish passage rates. A 10 minute sample reflects at least 50% of the variation in daily fish counts and could be used to identify periods when a more accurate count is desired, such as during the peak of the migration (Becker 1962, Siebel 1967, Lilja et al. 2008). For this study, a sample of 10 minutes per hour saved approximately 1000 hours of review time compared to performing a 24 hour census over a single migration season.

The relationship between sampling effort and the resulting error was approximately linear, similar to the findings of Lilja et al. (2008). The results of the

Redwood Creek DIDSON sampling analysis were nearly identical to those of Cronkite et al. (2006), where errors ranged from +/- 10% when 10 minutes were counted down to +/- 0% when the full hour was counted.

Sub-sampling of DIDSON data is more appropriate as the target population increases in size (Holmes et al. 2006). The precision and accuracy of sub-sampled DIDSON counts for runs of less than 100 fish has not been determined in published literature. Studies attempting to enumerate salmonid runs of less than 1000 fish generally perform a census of all hours either manually or using automated techniques (Kucera and Orme 2007, Johnson et al. 2009, Pipal et al. 2010).

Despite the clear bias demonstrated by the reviewer comparison, I assumed a negligible effect of precision on the outcome of the escapement estimate. In doing so, the sole error component was represented by the V5 calculation of sampling variance. I chose to ignore the differences between reviewers because of complications in the comparison. One set of files was reviewed using the aforementioned complex method, while the other reviewer used the simple approach to video interpretation. There was closer agreement between reviewers when both reviewers used the same review technique.

A comparison of more files and additional training of staff could result in closer agreement between reviewers. A larger sample of files with both reviewers employing the same review method may result in higher precision. Issues with repeatability could also be reduced by using a single reviewer.

Average percent error (APE) can be used to determine the precision among different DIDSON reviewers (Holmes et al. 2005, Cronkite et al. 2006). Cronkite et al. (2006) calculated an APE between reviewers of 6% and summed APE with sampling error to derive total error for the escapement estimate of sockeye salmon. Unfortunately, the APE equation cannot be used for Redwood Creek because all counts must be greater than zero.

When considering differences among DIDSON reviewers, Kucera and Orme (2007) considered upstream and downstream counts separately and treated the higher of the two reviewer's counts for a file as the true value. This structure essentially assumes that one reviewer failed to detect fish passage events. In contrast, disagreements between independent reviews of Redwood Creek DIDSON video are more likely to arise as a result of complex milling behavior. Thus, a better assumption for Redwood Creek DIDSON is that the true count for a given file lies between the two independent tallies, so reviewer error is negligible. One advantage of DIDSON technology is that video data can easily be archived and re-reviewed if a reviewer's estimates come into doubt.

In summary, the sources of uncertainty in DIDSON escapement estimates are relatively easy to measure or eliminate. Accuracy can be determined by using test targets; excessive sampling error can be addressed with a census. Incomplete channel coverage can be addressed by using a Long Range DIDSON model, multiple DIDSONs, or by monitoring smaller watersheds. Questions about reviewer errors can be answered by repeated viewing of the video.

In contrast, the sources of uncertainty of escapement estimates derived from redd surveys are more difficult to assess. Observer efficiency, number of fish per redd, number of redds per female, and sampling a subset of habitats must all be accounted for (Gallagher et al. 2007). The male- to -female ratio, test digs and redd superimposition are also of concern. The important assumptions that redds are counted correctly and represent the population status must be met, though they cannot be tested for (Dunham et al. 2001).

Technological limitations

Video recorded from DIDSON at high frame rates is desirable since fish targets are easier to identify when more frames are available. Objects moving close to the camera may be visible for as few as three frames. Having a series of images for a single fish target also aids in estimating length, since some frames may not show the complete extended length of the fish.

Frame rates for this study were limited by the use of a 150 m cable between the topside computer and the camera. The 150 m cable has a limited data transfer rate, which restricts the maximum allowable frame rate to around seven frames per second. Alternate study sites may allow for the use of a shorter DIDSON cable, and the resulting higher frame rates.

A pan and tilt rotator is available to remotely aim the DIDSON. The deployment would be heavier and less portable with the added rotator and the deployment was sufficiently easy to aim by hand. The camera was intentionally operated so that it was accessible by wading; thus there was no need for remote aiming.

The duration of a DIDSON deployment should coincide with the migration season of the species of interest. A lower threshold of counts in commonly used to determine when to stop collecting DIDSON escapement data. On Alaska's Nushagak River, when daily counts of sockeye represent less than 1% of the cumulative run for three consecutive days the sampling season is ended (English et al. 2011). An alternative for Redwood Creek could be to end sampling when kelt passage downstream is less than 1% of the cumulative kelt count to date.

Milling behavior complicates the review process and can distort estimates. Other studies have shown that downstream moving fish can make up from 3-95% of all fish targets detected (Cronkite et al. 2006, Kucera and Orme 2007, Pipal et al. 2010). Cronkite et al. (2006) found that milling in sockeye salmon was less likely on days of high fish passage and more likely at the start and end of the migration season in the Horsefly River, British Columbia. In contrast, Chinook salmon in the Secesh River, Idaho exhibited less milling behavior at the beginning of the migration season than later (Kucera and Orme 2007).

Patterns of milling on Redwood Creek could be determined by recording both upstream and downstream tallies for all days on Redwood Creek. Milling behavior captured by the DIDSON could be minimized by choosing an alternate deployment site, or using methods to alter fish behavior at the site. Unfortunately, a partial deflection weir is not an option for the Redwood Creek DIDSON site, due to permitting issues.

The main obstacles to the effective deployment of DIDSON on Redwood Creek were discharge levels above 3000 ft^3/s and equipment damage. Using the current deployment, high water years will yield poor results, since the thalweg is out of range at flows over 3000 ft^3/s (Figure 7). Other escapement estimation methods have similar shortcomings at high flows: weirs can be overtopped, redds and carcasses may be washed away, and observation of live fish can be obscured.

Equipment downtime due to damage was a major issue in 2010-2011, since the number of missed days prevented estimation of escapement (Figure 10, 11). The distribution of daily counts from 2009-2010 suggest that a large number of fish can pass the DIDSON site over a relatively short period of time (Figure 8). Interpolation techniques have limited utility when filling in long periods of missing data. Adequate staffing is required to respond to frequently changing stream conditions and to ensure the camera is functioning and sampling effectively at all times. An internet connection along with a remote desktop application could minimize downtime due to computer glitches.

A long-range DIDSON model on Redwood Creek could improve coverage when high flows increase stream width. Alternatively, the DIDSON could be deployed from the deep bank opposite the present site to sample sections of the thalweg during high flows. However, the 30 m range of the camera cannot provide samples from the entire water column (100 m across) when the channel is full to the base of the levees (flows exceeding 6000 ft^3/s, Figure 7). A method of sonar sub-sampling offshore areas in large rivers for fish passage was described by Xie et al. (2010), while the spatial sampling of smaller rivers to increase coverage was discussed by Matthews and Baillie (2007) and Enzenhofer et al. (2010).

Deployment of the DIDSON on Prairie Creek around the time of peak discharges could confirm if fish are migrating into spawning reaches during high flow events. Given the relative size of Prairie Creek (34 km^2) to Redwood Creek (738 km^2), one might assume that a lack of fish entering Prairie Creek indicates no movement up Redwood Creek over the same time interval.

Sparkman (personal communication) used radio telemetry to observe steelhead in the Mad River holding in stream margins during high flows, and migrating upstream under more moderate discharge conditions. Determination of whether fish moved up Redwood Creek at high, ascending flows was complicated by the fact that the camera was inoperable during 60% of times when discharge was increasing. Deployment times were constrained by safety concerns dictating that workers were not wading when stream discharge was at dangerous levels. Furthermore, travel during storm events which result in large increases of stream discharge can be hazardous in the study area, especially at night.

Biases in the Redwood Creek escapement estimate should be carefully considered, as NOAA recommends that estimation techniques for ESU consideration be un-biased (National Marine Fisheries Service 2012). The swimming undulations of fish moving upstream make them relatively easy for reviewers to detect. Fish travelling downstream may appear similar to debris if they drift downstream without exerting themselves. If upstream moving fish are more likely to be detected, the estimate will be positively biased. On the other hand, failure to detect fish in the water column could negatively bias the estimate. Moribund salmon may also bias estimates (Cronkite et al. 2006) but very few salmon carcasses were observed in lower Redwood Creek.

When viewing DIDSON video, fish may appear out of nowhere in the middle of the field and then disappear. This may be due to fish moving upward in the water column out of the sonar field, since the DIDSON cannot detect fish very close to the surface of the water. These fish were not counted. Fish at the far end of the DIDSON range (27-30 m) may only appear as a flicker, while fish very close to the camera may only appear as shadows; these fish were also not counted.

The use of a 40 cm size cutoff to differentiate adult salmonids from jacks and cutthroat trout may not reflect the true of sizes non-adult fish in Redwood Creek. Cutthroat trout have been observed up to 45 cm in Redwood Creek. Jack salmon seined from the Mad River in 2002-2003 ranged from 44 to 48 cm for coho salmon and 42 to 58 cm for Chinook salmon. Chinook salmon jacks captured at the Prairie Creek weir from 2005-2008 were between 42 and 54 cm, while the distribution of lengths for Prairie Creek male coho salmon exhibited no break between size classes. Use of a 50 cm cutoff resulted in an escapement estimate of 119 fewer adult salmon (4% less) for 2009-2010.

The assumption that jacks are present as 5% of the adult population was not testable. The number of jacks relative to adults varies among years, as well as among watersheds. However it seemed necessary to apportion at least some of the fish in that size range as jacks. Apportionment of smaller fish among jacks, cutthroat trout and steelhead is complicated by a relative lack of information compared to larger fish, which are more easily observed on walking surveys (Zhou 2002).

The assumption that non-fish targets were not mistaken for fish could not be tested. Otters and beavers are of particular concern, since they overlap in size with the adult salmonid species present. I assumed that Sacramento suckers were not present at the site, although schools of 50 or more suckers have been personally observed just 2 km upstream of the study site. However, if non-salmonids (including mammals) move upstream and downstream at the same rate past the camera site, fish escapement estimates will not be affected.

On the other hand, migratory adult lamprey have the potential to positively bias estimates for Redwood Creek if they are mistaken for salmonids. The shape of acoustic shadows produced by DIDSON targets is currently being investigated as a means of differentiating mammals from fish (Nathan Cooley, personal communication) and identifying fish species (Langkau et al. 2012).

Results of the movement analysis on Redwood Creek indicate that more fish move when discharge is at moderate, dropping levels, though the analysis was complicated by missing values for escapement when the DIDSON was not operating. High tides may facilitate salmonid entry into the Redwood Creek estuary, and the influence of tide may be more pronounced during low water years. Similarly the effect of discharge will likely depend on the magnitude of the water year.

The effect of date on movement may reflect the genetic component of run-timing, rather than physical conditions arising from time of year. Consideration of multiple years of pooled data may reveal a stronger connection between tide, discharge, and daily passage rates of fish. The weak relationships observed here are not surprising, since the timing of salmon migrations is influenced more by genetics than by environmental conditions when compared to other freshwater fish (Quinn and Adams 1996).

In conclusion, DIDSON technology is a good candidate for monitoring populations of salmon and steelhead in coastal rivers of northern California. A DIDSON based escapement estimate does not require handling of threatened fishes and has the potential to be more accurate and less expensive than other methods. However, DIDSON does not provide species information, which is critical in northern California rivers where less abundant coho salmon overlap in distribution with other, more prevalent salmonid species. Species apportionment using various modeling techniques or aspects of the DIDSON images could address this limitation given further investigation.

RECOMMENDATIONS

- Future studies should use an internet connection to establish a remote desktop connection with the field computer controlling the DIDSON, so that the status of the camera can be checked remotely. This would help prevent downtime due to computer glitches, disturbance to the camera, or improper aim.
- Spatial sampling of the channel cross section should be instigated to address the DIDSON's range limitations and incomplete coverage of the river at higher flows.
- Determination of whether salmonids actively migrate upstream during high flows should be determined using either PIT or radio tags. Confirmation of a lack of movement at high flows would vastly simplify deployment of the DIDSON during storm-driven flow events.
- An analysis of fish lengths taken from DIDSON video should be performed to see if a sub-sample of lengths represents the true population of fish sizes. Taking fewer fish lengths can decrease the time needed to review DIDSON video.
- Independent observer counts from Redwood Creek DIDSON video should be compared in a more rigorous fashion to assess reviewer error and repeatability. The comparison used in this study was complicated by the use of different review techniques, and could be biased.
- Further investigation into species determination is essential if DIDSON is to be used to estimate escapement to California watersheds with multiple species overlapping in size and run-timing. Increasing the number of salmonid

observations in Redwood Creek with more frequent walking surveys or seining would strengthen species apportionment models.

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PERSONAL COMMUNICATIONS

Cooley, N. DIDSON Technician, Pacific States Marine Fisheries Council / California Department of Fish and Game, 306 East Redwood Drive, Fort Bragg, California 95437.

Larson, Z. 2011. Smith River Advisory Council, California Department of Fish and Game, 741 Cooper Avenue, Crescent City, California 95531.

Sparkman, M. 2012. Environmental Scientist, Anadromous Fisheries Resource Assessment and Monitoring Program, California Department of Fish and Game, 50 Ericson Court, Arcata, California 95521.

APPENDICES

Appendix A. Daily observations of fish over and under 40 cm from Redwood Creek DIDSON video 2009-2010 with expected numbers of fish based on an hourly expansion factor of 6. A dash indicates no data.

Date	Total observed	Observed < 40 cm	Observed > 40 cm	Total expected	Expected < 40 cm	Expected > 40 cm
11/21/2009	26	6	20	115	27	88
11/22/2009	35	22	13	210	132	78
11/23/2009	90	49	41	362	197	165
11/24/2009	79	27	52	248	85	163
11/25/2009	18	1	17	132	7	125
11/26/2009	18	9	14	108	42	66
11/27/2009	13	3	17	78	12	66
11/28/2009	11	2	14	66	8	58
11/29/2009	8	2	6	18	5	14
11/30/2009	10	0	10	18	0	18
12/1/2009	7	4	3	30	17	13
12/2/2009	7	0	7	24	0	24
12/3/2009	11	4	7	48	17	31
12/4/2009	10	2	8	60	12	48
12/5/2009	6	0	6	18	0	18
12/6/2009	12	1	11	18	2	17
12/7/2009	2	0	2	2	0	2
12/8/2009	0	0	0	0	0	0
12/9/2009	2	0	2	4	0	4
12/10/2009	0	0	0	0	0	0
12/11/2009	7	0	7	24	0	24
12/12/2009	8	3	5	24	9	15
12/13/2009	14	4	10	44	13	31
12/14/2009	8	1	7	24	3	21
12/15/2009	10	2	8	32	6	26
12/16/2009	-	-	-	-	-	-
12/17/2009	69	0	69	414	0	414
12/18/2009	47	1	46	276	6	270
12/19/2009	30	7	22	180	43	137
12/20/2009	32	22	14	144	88	56
12/21/2009	11	6	6	66	33	33
12/22/2009	7	0	8	42	0	42
12/23/2009	7	4	8	42	14	28
12/24/2009	9	2	7	54	12	42
12/25/2009	11	2	13	66	9	57
12/26/2009	0	0	0	0	0	0

Appendix A. Daily observations of fish over and under 40 cm from Redwood Creek DIDSON video 2009-2010 with expected numbers of fish based on an hourly expansion factor of 6. A dash indicates no data.

Date	Total observed	Observed < 40 cm	Observed > 40 cm	Total expected	Expected < 40 cm	Expected > 40 cm
12/27/2009	7	4	4	42	21	21
12/28/2009	27	5	22	100	19	81
12/29/2009	32	8	24	70	18	53
12/30/2009	33	16	17	70	34	36
12/31/2009	22	3	19	112	15	97
1/1/2010	0	0	0	0	0	0
1/2/2010	7	0	7	56	0	56
1/3/2010	7	0	7	56	0	56
1/4/2010	3	0	3	18	0	18
1/5/2010	2	0	2	12	0	12
1/6/2010	13	0	13	78	0	78
1/7/2010	4	0	4	24	0	24
1/8/2010	2	0	2	12	0	12
1/9/2010	4	0	4	24	0	24
1/10/2010	-	-	-	-	-	-
1/11/2010	0	0	0	0	0	0
1/12/2010	8	2	6	48	12	36
1/13/2010	0	0	0	0	0	0
1/14/2010	2	0	2	12	0	12
1/15/2010	-	-	-	-	-	-
1/16/2010	0	0	0	0	0	0
1/17/2010	-	-	-	-	-	-
1/18/2010	-	-	-	-	-	-
1/19/2010	-	-	-	-	-	-
1/20/2010	-	-	-	-	-	-
1/21/2010	-	-	-	-	-	-
1/22/2010	1	0	1	6	0	6
1/23/2010	1	0	1	6	0	6
1/24/2010	1	0	1	6	0	6
1/25/2010	0	0	0	0	0	0
1/26/2010	0	0	0	0	0	0
1/27/2010	-	-	-	-	-	-
1/28/2010	-	-	-	-	-	-
1/29/2010	-1	0	-1	0	0	0
1/30/2010	0	0	0	0		
1/31/2010	1	0	1	6	0	6
2/1/2010	5	0	5	30	0	30
2/2/2010	4	0	6	24	0	24
2/3/2010	2	0	2	12	0	12
2/4/2010	1	0	1	6	0	6
2/5/2010	1	0	1	6	0	6

Appendix A. Daily observations of fish over and under 40 cm from Redwood Creek DIDSON video 2009-2010 with expected numbers of fish based on an hourly expansion factor of 6. A dash indicates no data.

Date	Total observed	Observed < 40 cm	Observed > 40 cm	Total expected	Expected < 40 cm	Expected > 40 cm
2/6/2010	-	-	-	-	-	-
2/7/2010	-	-	-	-	-	-
2/8/2010	-	-	-	-	-	-
2/9/2010	10	3	14	60	11	49
2/10/2010	4	1	8	24	3	21
2/11/2010	-1	0	-1	0	0	0
2/12/2010	2	0	3	12	0	12
2/13/2010	4	0	7	24	0	24
2/14/2010	0	0	0	0	0	0
2/15/2010	1	0	1	6	0	6
2/16/2010	1	0	2	12	0	12
2/17/2010	3	0	3	18	0	18
2/18/2010	10	0	10	60	0	60
2/19/2010	11	0	10	66	0	66
2/20/2010	9	0	9	54	0	54
2/21/2010	9	7	11	54	21	33
2/22/2010	6	1	13	66	5	61
2/23/2010	4	2	3	24	10	14
2/24/2010	2	0	3	12	0	12
2/25/2010	2	0	3	12	0	12
2/26/2010	0	0	0	0	0	0
2/27/2010	0	0	0	0	0	0
2/28/2010	-1	0	-1	-6	0	-6
3/1/2010	0	0	0	0	0	0
3/2/2010	-3	0	-3	-18	0	-18
3/3/2010	0	0	0	0	0	0
3/4/2010	1	0	1	1	0	1
3/5/2010	0	0	0	0	0	0
3/6/2010	0	0	0	0	0	0
3/7/2010	-4	0	-4	-24	0	-24
3/8/2010	1	0	0	1	0	6
3/9/2010	0	0	3	3	0	3
3/10/2010	0	0	0	0	0	0
3/11/2010	0	0	0	0	0	0
3/12/2010	0	0	0	0	0	0
3/13/2010	0	0	0	0	0	0

Appendix A. Daily observations of fish over and under 40 cm from Redwood Creek DIDSON video 2009-2010 with expected numbers of fish based on an hourly expansion factor of 6. A dash indicates no data.

Date	Total observed	Observed < 40 cm	Observed > 40 cm	Total expected	Expected < 40 cm	Expected > 40 cm
3/14/2010	1	0	1	1	0	1
3/15/2010	0	0	0	0	0	0
3/16/2010	-5	-3	-2	-5	-3	-2
3/17/2010	-15	-5	-10	-90	-30	-60
3/18/2010	-15	-4	-11	-15	-4	-11

Appendix B. List of all models considered in movement analysis of fish detected by Redwood Creek DIDSON, 2009-2010. Explanatory variables are described in Table 2. Akaike's information criterion (AIC) and adjusted R-squared (Adj. R^2) are shown for each model considered over all days, and over the first 58 days of continually gathered data.

Model	Model parameters	All days		First 58 days	
		AIC	Adj. R^2	AIC	Adj. R^2
1	cfs Orick	998.926	0.040	662.706	-0.013
2	cfs Orick, maxtide	994.707	0.095	659.541	0.058
3	cfs Orick, Δ tide	999.845	0.041	663.460	-0.009
4	cfs Orick, Δ cfs, Orick	1000.259	0.036	663.327	-0.007
5	cfs Orick, date	993.979	0.102	660.322	0.005
6	cfs Orick, date^2	995.129	0.090	660.276	0.045
7	Δ cfs Orick, date	992.069	0.121	658.862	0.069
8	Δ cfs Orick, maxtide, date	987.770	0.172	658.093	0.096
9	cfs O'Kane	998.678	0.043	662.907	-0.017
10	cfs O'Kane lag=1, maxtide	996.904	0.072	656.839	0.101
11	Δ cfs O'Kane	1000.796	0.020	660.060	0.033
12	Δ cfs O'Kane lag=1	1003.508	-0.010	662.309	-0.006
13	Δ cfs Orick lag=1, maxtide	996.287	0.078	658.259	0.079
14	Δ cfs Orick, Δ cfs Orick lag=1, maxtide, date	988.402	0.174	659.194	0.093
15	Δ tide, Δ cfs Orick, Δ cfs Orick lag=1, Δ cfs O'Kane, Δ cfs O'Kane lag=1, date^2	998.392	0.095	663.440	0.053
16	maxtide, Δ cfs Orick, Δ cfs Orick lag=1, Δ cfs O'Kane, Δ cfs O'Kane lag=1, date^2	992.991	0.149	660.872	0.095
17	maxtide, Δ cfs Orick lag=1, date^2	988.733	0.162	658.155	0.095
18	maxtide, Δ cfs O'Kane, Δ cfs O'Kane lag=1, date^2	989.990	0.160	658.063	0.111
19	maxtide, Δ cfs Orick, date^2	988.588	0.164	657.964	0.098
20	Δ tide, Δ cfs Orick, date^2	993.756	0.114	660.347	0.060
21	maxtide, date	987.597	0.164	657.549	0.090
22	maxtide, date^2	988.288	0.158	657.428	0.092
23	maxtide, cfs Orick, date^2	990.138	0.149	658.926	0.083
24	maxtide, cfs Orick lag=1, date^2	989.763	0.153	655.254	0.140
25	Δ tide, cfs Orick, Δ cfs Orick lag=1, date	994.105	0.120	662.788	0.034

Appendix B. List of all models considered in movement analysis of fish detected by Redwood Creek DIDSON, 2009-2010. Explanatory variables are described in Table 2. Akaike's information criterion (AIC) and adjusted R-squared (Adj. R^2) are shown for each model considered over all days, and over the first 58 days of continually gathered data.

Model	Model parameters	All days		First 58 days	
		AIC	Adj. R^2	AIC	Adj. R^2
26	Δ tide, cfs Orick, Δ cfs Orick lag=1, $date^2$	994.920	0.112	662.696	0.036
27	Δ tide, cfs Orick, $date^2$	995.179	0.100	661.357	0.043
28	Δ tide, cfs Orick, date	994.104	0.110	661.479	0.041
29	Δ tide, cfs O'Kane, $date^2$	995.484	0.096	661.023	0.049
30	Δ tide, mintide, maxtide, cfs Orick, cfs O'Kane, cfs Orick lag=1, cfs O'Kane lag=1, Δ cfs Orick, Δ cfs Orick lag=1, Δ cfs O'Kane, Δ cfs O'Kane lag=1, date, date2	993.482	0.177	653.508	0.249

Appendix C. Logistic regression equations used to predict species of fish detected by Redwood Creek DIDSON based on observed dates and body sizes from California Department of Fish and Game and the U. S. Geological Survey, Cooperative Fish and Wildlife Research Unit spawning surveys. Akaike's information criterion (AIC) is shown for each model. A "*" indicates that the model did not converge. Multinomial probabilities are obtained by solving *x* for Pr(Chinook) and Pr(Steelhead), and the calculation for Pr(Coho) by making the three probabilities sum to 1.

	Parameters	Formula	AIC
Binary	Chinook vs. Coho	Pr(Coho) = $1/(1+e^{-x})$, where x =	
	Date + Length	*-4.136 -0.057(Date) +0.144(Length)*	74.052
	Date	*11.824 -0.130(Date)*	115.54
	Length	*-10.156 +0.163(Length)*	75.36
	Salmon vs. Steelhead	Pr(Salmon) = $1/(1+e^{-x})$, where x =	
	Date + Length	*-0.0043 +0.393(Date) -0.0061(Length)*	6*
	Date	*-439.292 + 3.964(Date)*	4*
	Length	*3.043 -0.0637(Length)*	151.5
Multinomial	Coho vs. Chinook	Pr(Coho) / Pr(Chinook) = $1/e^{x}$, where x =	
	Date + Length	*294.268 -2.671(Date) +0.023(Length)*	74.052
	Date	*290.185 -2.621(Date)*	115.54
	Length	*0.903 -0.019(Length)*	215.77
	Coho vs. Steelhead	Pr(Coho) / Pr(Steelhead) = $1/e^{x}$, where x =	
	Date + Length	*290.131 -2.728(Date) +0.167(Length)*	74.052
	Date	*302.010 -2.751(Date)*	115.54
	Length	*3.043 -0.0637(Length)*	215.77