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Comparison of selected population characteristics of adult Chinook salmon during upstream passage through a resistance board weir and during carcass surveys

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We compared population characteristics of adult Chinook salmon (*Oncorhynchus tshawytscha*) during 2003–2006 in the lower Stanislaus River, Stanislaus County, California, by counting and measuring live fish moving past a resistance board weir and dead fish counted and measured by the California Department of Fish and Wildlife (CDFW) during annual carcass surveys. The comparison of annual escapement was extended to 2007–2009 by including unpublished data. Although annual salmon passage counts at the weir were significantly correlated with estimates of carcass survey escapement, size estimates of live fish passing the weir were smaller on average than dead fish measured during carcass surveys. Sex ratios also differed for fish counted at the weir compared to those counted during carcass surveys. In general, females outnumbered males in both datasets, except in 2004 when more males than females were counted at the weir. Ratios of clipped to unclipped adipose fins differed significantly between fish from the weir and from the carcass surveys during 2005–2006, but not during 2004. These results suggest that population characteristics of adult salmon returning to the Stanislaus River may be better represented by the relatively high numbers of live fish examined during their concentrated passage through the weir than by the lower numbers of widely dispersed dead fish examined during carcass surveys.

Key words: Central Valley, Chinook salmon, *Oncorhynchus tshawytscha*, resistance board weir, carcass survey, annual escapement

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Accurate measures of salmonid escapement are critically important to fisheries managers for regulating fishing seasons, monitoring habitat enhancement programs, and supporting the reestablishment of suppressed populations (e.g., Hatch et al. 1998, Dauble and Mueller 2000, Merz and Merz 2004, Keefer et al. 2005, Gallagher et al. 2010). Escapement of adult Pacific salmon (*Oncorhynchus* spp.) can be estimated with a variety of techniques. In California's Central Valley, traditional methods for estimating Chinook salmon (*Oncorhynchus tshawytscha*) and steelhead (*O. mykiss*) escapement include visual counts of live fish (Clark 1929, Fry 1961, Hillborn et al. 1999), live trapping (Whelan et al. 1989), carcass mark-recapture surveys (Cousens et al. 1982, Shardlow et al. 1987, Boydstun 1994, Law 1994, Crawford et al. 2007), redd surveys (Gallagher and Gallagher 2005, Courbois et al. 2008), and hatchery counts (Brown et al. 1994, Mills and Fisher 1994, Williams 2006).

Despite the widespread use of traditional survey methods, they are inherently variable and inaccurate, resulting in uncertainty when making temporal or spatial comparisons of escapement estimates. For example, sampling bias is well documented for carcass surveys (Sykes and Botsford 1986, Rajwani and Schwarz 1997, Zhou 2002, Miyakoshi et al. 2003, Murdoch et al. 2009, Murdoch et al. 2010) due to difficult-to-satisfy assumptions when computing estimates. Furthermore, steelhead are iteroparous (multiple reproductive cycles over the course of an individual's lifetime), making traditional survey methods inappropriate for estimating escapement (Evans and Beaty 2004, Narum et al. 2008). Surveyor bias in identifying redds and superimposition of redds are also known to affect the accuracy of escapement estimates based on redd counts (Fukushima et al. 1998, Dunham and Rieman 2001). Adult escapement estimates from hatchery counts are also problematic because hatcheries are typically located at or near the upper extent of salmonid spawning areas, and the counts are strongly influenced by proportions of naturally produced (natural) versus hatchery fish (Fleming and Gross 1993, Banks et al. 2000).

Technological advances in recent years have allowed development of new and improved methods to estimate escapement and overcome some of the challenges associated with traditional survey techniques. Contemporary methods include video monitoring (Hatch et al. 1994, Davies et al. 2007, Killam 2008, Palmer et al. 2008) and electronic counters (Shardlow and Hyatt 2004, Tiffan et al. 2004, Garcia de Leaniz et al. 2006, Santos et al. 2008). Often, video monitoring and electronic counter systems require discrete passage areas to adequately detect fish movement. In these instances, passage can be constrained by natural channel features or artificial structures (e.g., fish ladders or weirs) to constrict passage and guide fish past monitoring equipment. As a result, advancements in weir design and applications have greatly increased the efficacy of these remote monitoring systems.

Historically, fish weirs were designed as fixed or rigid structures (Anderson and McDonald 1978, Baxter 1982, Hill 1991) that directed fish into a more confined area for sampling or collection (Gobalet and Wake 2000). Rigid picket weirs have been used for many years and work well in smaller streams with relatively low flow and debris levels; however, in larger river systems, they are prone to failure due to fluctuating flows and high debris loads. Subsequent repair and replacement costs are expensive and time-consuming, and data lost during downtimes are irreplaceable. A design variant, the resistance board weir (RBW), has received significant use over the past few decades, primarily in Alaska (e.g., Wiswar 1997, Harper and Watry 2001, Gates and Harper 2003). Rigid weirs and RBWs share the same fundamental concept, but a flexible design allows the RBW to operate under a broader range of river conditions. Under high water pressure, an RBW is designed to collapse, whereby its panels are forced down to lay on the river bottom, effectively allowing high flow and debris to freely pass over it. After river flows subside, the panels can be reset and quickly restored to operation.

Resistance board weir technology was originally developed in 1986 by Daishin Kogyo Co., Ltd. (Tobin 1994), and has been used only recently in California. The RBW uses the hydrodynamic force of flow against boards set to create resistance and lift to elevate integrated polyvinyl chloride (PVC) panels above the water surface, creating a fence-like barrier across the channel. As with most fish structures, passage is restricted to allow for species identification, enumeration, live trapping and sampling and, in some instances, to completely impede passage. Although recent technologies have increased the application of RBWs for monitoring fish stocks (e.g., Anderson et al. 2007, Zimmerman and Zabkar 2007), we are not aware of any published reports that compared RBW accuracy with those of more traditional methodologies for estimating adult spawning escapement or characterizing their population structure.

The purpose of this paper was to determine if population characteristics of adult Chinook salmon measured as they passed through an RBW were similar to those measured by the California Department of Fish & Wildlife (CDFW) during carcass surveys. Specifically, we compared selected measurements of salmon—i.e., escapement estimate, fork length (FL), sex ratio, and adipose fin clip ratio—as they returned during fall and early winter to spawn in the Stanislaus River.

Materials and Methods

Study area.—The snow-fed Stanislaus River is one of three major east-side tributaries of the lower San Joaquin River system in California. Headwaters originate in Alpine and Tuolumne counties at an elevation of 3,675 m and drain approximately 240,000 ha of the western slope of the Sierra Nevada (Kondolf et al. 2001). The Stanislaus River flows in a westerly direction to its confluence with the San Joaquin River (elevation, 30.5 m), approximately 14.5 km west of Ripon in Stanislaus County. Goodwin Dam (37º 51' N, 120º 37' W), located at river km (rkm) 93.9 (measured from the confluence of the Stanislaus and San Joaquin rivers), is the upstream migration barrier to anadromous fish and demarks the upstream extent of the lower Stanislaus River (Figure 1).

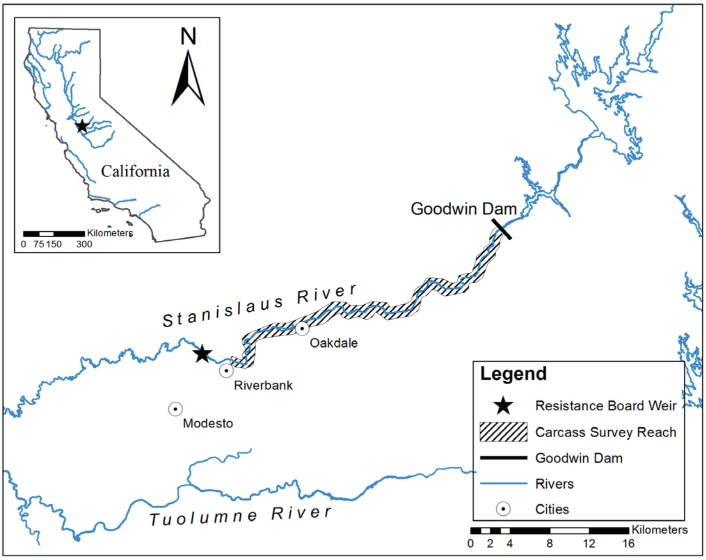

Figure 1.—Map of the study area showing locations of the resistance board weir at river km 50.6 (37° 44' N, 120° 58' W) on the Stanislaus River, California, and the reach where carcass surveys are conducted.

Historically, steelhead and several races of Chinook salmon inhabited the Stanislaus River watershed, including fall, late-fall, and spring runs (Yoshiyama et al. 2000). According to Fry (1961), approximately 35,000 adult fall-run Chinook salmon migrated up the Stanislaus River in 1953. The fall-run still predominates even though total adult escapement is only a fraction of its original abundance.

Site selection.—Site characteristics to consider for RBW operation include flow, velocity, water depth, channel width, substrate composition, channel profile, and seasonal timing of high water events (Larson 2001, Anderson et al. 2007, Zimmerman and Zabkar 2007). In general, laminar flows with slow to moderate water velocity, depths less than 1 m during normal flows, and substrates dominated by coarse gravel or cobble are ideal for RBW operation (Tobin 1994). During the present study, water depth in the 32 m-wide channel of the Stanislaus River ranged from 0 m to 1 m during normal flows. This locality was characterized by a relatively uniform (flat) river bottom dominated by sand and gravel, which allowed proper anchoring and sealing of the RBW to prevent uncounted fish escapement. Both banks had gradual slopes, enabling water to inundate the floodplain during high flow events and effectively reduce water velocities at the RBW.

Construction and installation.—Construction and installation of the RBW followed general techniques described by Tobin (1994) and Stewart (2002, 2003). Floating resistance board panels (0.91 m × 6.10 m) were constructed from electrical grade schedule 40 polyvinyl chloride (PVC) pipe (2.54 cm x 6.10 m) and 1.27-cm-thick ultra-high molecular weight polyethylene (UHMW). Modifications to general construction techniques detailed in Stewart (2002) were as follows: design and installation of a PVC "cap" to allow for recreational boat passage and to protect the RBW panels from damage; 3.18-cm stainless steel hose clamps were used as retaining sleeves instead of PVC to add stability to each panel; 3.81-cm-thick insulating sheet styrofoam was added to each resistance board to increase panel buoyancy; bulkheads were constructed from 2.54-cm square aluminum tubing and PVC pipe (2.54 cm) instead of wood to increase structural strength and RBW longevity; and ripped-in-half acrylonitrile butadiene styrene (ABS) plastic (7.62 cm) was placed over the substrate rail cable to reduce potential injuries to fish. We used stainless steel or aluminum hardware throughout in an effort to reduce corrosion.

Resistance board weir construction required four people to complete in approximately 8 weeks. Annual site installation and removal required 4–6 people and approximately 2 days. General in-season maintenance and trapping required two people for 1–4 hrs/day. Maintenance included cleaning the RBW and downloading passage data. We operated the RBW each season (late September to early January) from 2003 to 2007 to capture the fall-run Chinook salmon migration.

We designed and installed a trap (1.52 m high x 1.52 m wide x 4.88 m long) to periodically collect live fish each season, obtain biological samples (e.g., scales and tissue), and validate passive counts. The live-trap frame was constructed from 7.62-cm aluminum channel and tubing into which we drilled 2.54-cm diameter holes spaced 6.67 cm apart on center and fitted with 2.54-cm galvanized electrical conduit.

Monitoring technology.—The 32-m wide RBW was coupled with a passive monitoring system that used infrared detection and digital image technology (RiverWatcher, Vaki Aquaculture Systems, Ltd., Kopavogur, Iceland) to record fish as they passed the RBW. The system was composed of a pair of infrared scanner plates (20 cm × 60 cm, spaced 30-cm apart), an underwater color digital camera, and a computer (PC) to run the software program and store collected data. Each scanner plate had two vertical rows containing 96 infrared diodes. As an object moved through the scanner, it obstructed the infrared light beams and a silhouette of the object was generated. After the PC sensed that an object had broken the scanner plane, the digital camera was triggered to record the silhouette and capture up to five digital photographs. Date, time, direction of travel (upstream or downstream), maximum body depth (mm), and water temperature were also recorded. Maximum fish body depth was used to calculate total length (TL) using a length:depth ratio of 4.2:1 for Chinook salmon; this ratio is an average for all Chinook salmon trapped and handled at the RBW over the sampling period (Cramer Fish Sciences, unpublished data), and possibly overestimates the lengths of females and underestimates the lengths of males (Mesick et al. 2009). Total length was then converted to fork length (FL) with conversion equations provided by Conrad and Gutmann (1996). Data collection and live fish handling methods complied with all applicable state and federal permitting requirements.

The monitoring system operated continuously following installation each season. The scanner was positioned at the rear entrance and the camera on the side of the trap to record fish as they swam past the RBW. A clear acrylic panel (1.27-cm thick) was used to create a viewing window for the camera to capture images. White acrylic (1.27-cm thick) was used as a background to photograph fish as they passed through the trap. White light-emitting diodes (LEDs) illuminated the viewing window at night to capture clear digital images (Anderson et al. 2007).

Two 0.61-m × 0.91-m photovoltaic panels mounted to a 6.10-m-tall stainless steel pole (to reduce shading from riparian vegetation) were used to power the system. Panels were connected to a 20A/12V photovoltaic system controller (MorningStar Corporation, Model SS-20L), which were used to charge a bank of eight 6V deep-cycle batteries (Trojan Battery Company, Model T-125 6V), two sets of four batteries joined in a series, and then joined in parallel to create a 12V DC power source.

Statistical analyses.—Annual counts of Chinook salmon passing the RBW during 2003–2009 were compared with estimates of spawning escapement derived from the CDFW carcass surveys. Summary counts of salmon passage from 2007 to 2009 were obtained from FishBio (Oakdale, California), a firm that took over operation of the RBW in 2007 (FishBio 2013). Escapement estimates from carcass surveys during the same time period were retrieved from GrandTab (CDFG 2013), a database maintained by the CDFW. Other data from the carcass surveys (i.e., fish lengths, sex ratios, and adipose fin presence) were obtained from Guignard (2004, 2005, 2007a, 2007b).

All statistical tests were performed with SAS version 9.2 (SAS Institute Inc. 2009). Relationships between total fish counts from the RBW and escapement estimates from carcass surveys were assessed using Pearson product-moment correlation analysis. Mean FL of salmon measured at the RBW and during carcass surveys were compared with two-way analysis of variance (ANOVA), where "method" (RBW and carcass survey) and "year" (2003–2006) were categorical variables representing the main effects. Length-frequency distributions were compared between the two methods within years using the Kolmogorov-Smirnov two-sample test. Sex ratios (males versus females) and adipose fin clips (present versus absent) were also compared between the two methods within years by using the chi-square (X^2) test for homogeneity. Unless specified otherwise, the level of significance for rejecting null hypotheses of statistical tests was α=0.05.

Results

Annual counts of adult Chinook salmon moving upstream past the RBW during 2003–2009 were significantly correlated with annual escapement estimates computed by CDFW from carcass surveys (r_5 = 0.802, P = 0.0300; Figure 2). In general, as counts of live salmon passing the RBW increased, so did the counts of salmon carcasses several days or weeks later in upstream locations surveyed by CDFW.

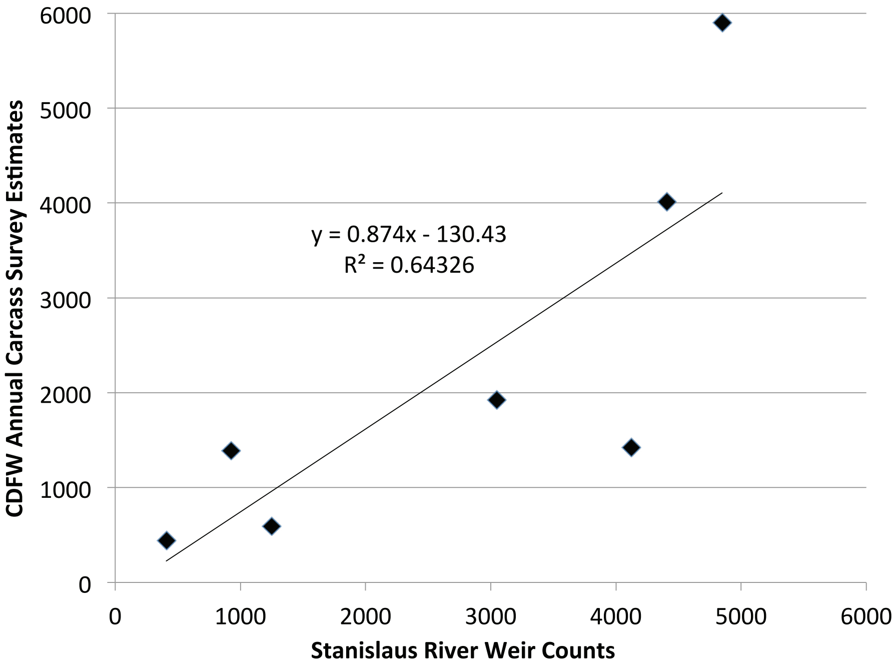

Figure 2.—Relation between Chinook salmon escapement estimated from resistance board weir counts and from carcass survey counts on the Stanislaus River, California, 2003–2009.

During 2003–2006, length-frequency distributions of live fish passing the RBW were significantly different from length-frequency distributions of dead fish recovered during carcass surveys (Figure 3; Kolmogorov-Smirnov two-sample test of FL measurements in 2003, D = 0.444; in 2004, D = 0.519; in 2005, D = 0.417; and, in 2006, D = 0.247; for all years, P <0.0001). According to two-way ANOVA, mean FLs exhibited significant method*year interaction (Table 1). As a result, we computed separate one-way ANOVAs within each year to compare mean FLs of fish from the two methods. On average, live fish passing the RBW were significantly shorter than dead fish recovered during carcass surveys for each of the four years: in 2003, $F_{1,14632}$ = 1,146.00; in 2004, $F_{1,14632}$ = 1,299.72; in 2005, $F_{1,14632}$ = 258.23; and in 2006, $F_{1,14632}$ = 34.97; for all years, P <0.0001.

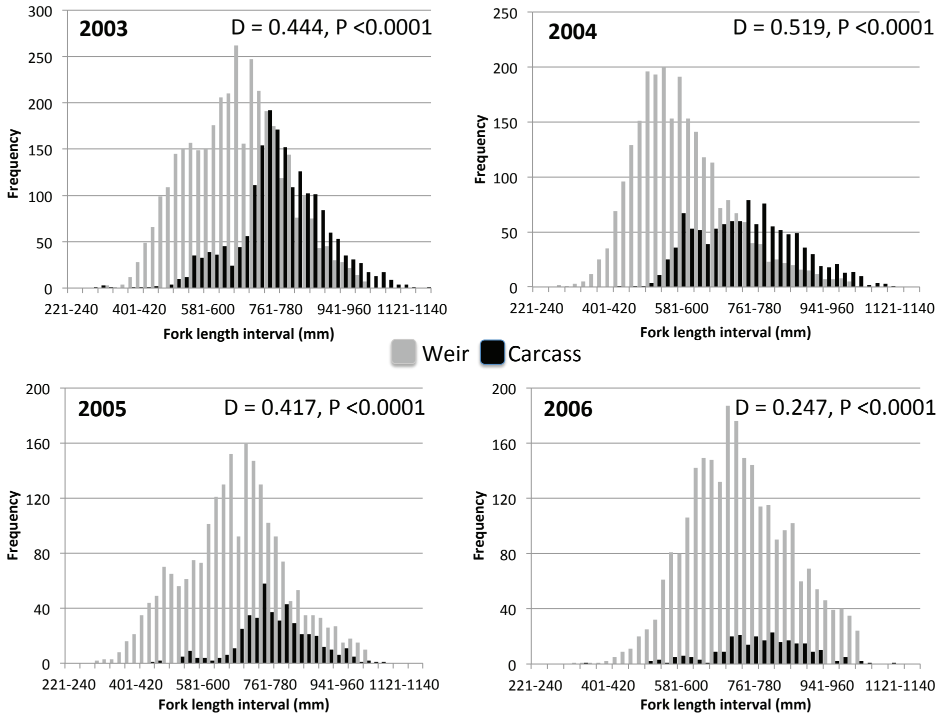

Figure 3.—Length frequency distributions of Chinook salmon measured at the resistance board weir and during carcass surveys on the Stanislaus River, California, 2003–2006.

Table 1.—Results of two-way analysis of variance for mean fork lengths of adult Chinook salmon measured by two "methods" (resistance board weir and carcass survey) over four "years" (2003, 2004, 2005, and 2006) on the Stanislaus River, California.

Source	*df*	Mean square	*F*-statistic	*P*-value
Model	7	8,663,258.00	548.50	<0.0001
Method	1	20,928,848.03	1,325.08	<0.0001
Year	3	2,824,839.60	178.85	<0.0001
Method*Year	3	886,210.14	56.11	<0.0001
Error	14,632	15,794.40		

Sex ratios differed significantly between live fish counted at the RBW and dead fish recovered during carcass surveys (in 2004, $X^2_1 = 186.0$, P <0.0001; in 2005, $X^2_1 = 22.2$, P <0.0001; in 2006, $X^2_1 = 12.2$, $P = 0.0005$; Figure 4). With one exception, females predominated over males at the RBW and during carcass surveys. The exception occurred at the RBW in 2004 when a larger proportion of the population consisted of males (67%) rather than females (33%). During each of the remaining three years, higher percentages of males were documented at the RBW (41%–67%) than during carcass surveys (29%–40%).

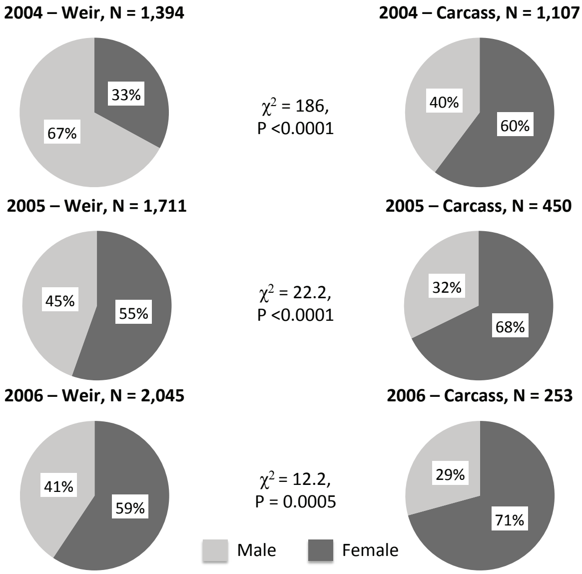

Figure 4.—Sex ratios of Chinook salmon measured at the RBW and during carcass surveys on the Stanislaus River, California, 2004–2006.

Chinook salmon with unclipped adipose fins greatly predominated over salmon with clipped adipose fins at both the RBW and during carcass surveys (Figure 5). Excluding

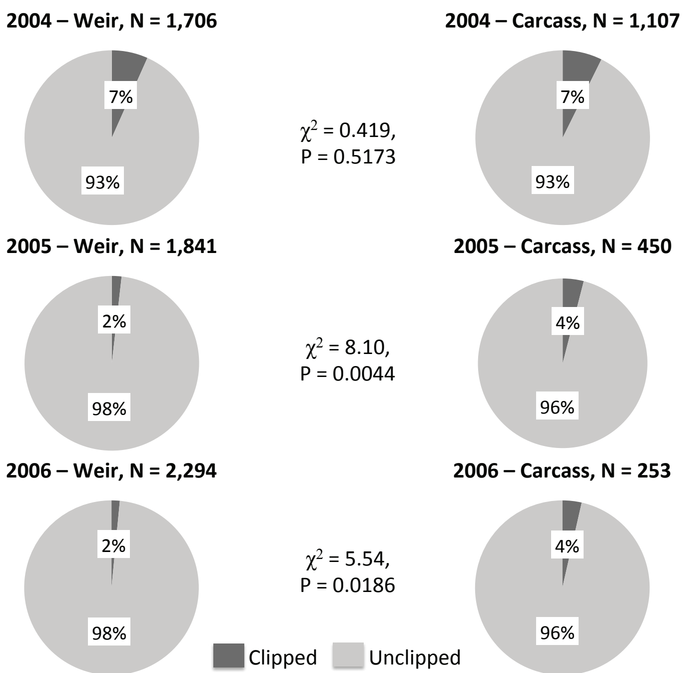

Figure 5.—Clipped to unclipped adipose fin ratios of Chinook salmon measured at the RBW and during carcass surveys on the Stanislaus River, California, 2004–2006.

2004 when the comparison was not significant ($X^2_1 = 0.419$, $P = 0.5173$), lower proportions of fin-clipped fish were encountered at the RBW than during carcass surveys (in 2005, $X^2_1 = 8.10$, $P = 0.0044$; in 2006, $X^2_1 = 5.54$, $P = 0.0186$).

Discussion

Since 1953, the CDFW has documented escapement of Chinook salmon on the Stanislaus River by conducting carcass surveys over a 40-km reach from Goodwin Dam (37º 51' N, 120º 37' W), downstream to Riverbank (37º 44' N, 120º 56' W) (Guignard 2004, 2005, 2007a, 2007b). These surveys typically began in October and continued through December or early January, depending on fish abundance and river flow conditions (Mesick et al. 2009). Estimates of escapement were usually generated using the Schaefer and Jolly-Seber mark-recapture methods, whereas the Peterson mark-recapture method was used whenever carcass numbers were low (Mesick et al. 2009). The escapement estimate judged to be most accurate based on the number of carcasses tagged and recovered was then reported by CDFW in their GrandTab file (Mesick et al. 2009).

Although the database for Chinook salmon escapement in the Stanislaus River extends back roughly 60 years, the accuracy of estimates generated by carcass surveys has not been critically assessed (CDFG 2013). Nevertheless, in an effort to improve escapement estimates, carcass mark-recapture methods have been coupled with live visual counts and redd surveys (Guignard 2004, 2005, 2007a, 2007b), but even these methods require major assumptions that have not been tested (for partial listings of assumptions, see Duffy 2005).

The present study provided an opportunity to compare selected population characteristics generated at the lower Stanislaus River RBW with those derived from carcass surveys. Available evidence suggests that nearly all fish are detected when they pass through a properly operating RBW. Fewings (1994) tested the RiverWatcher in Iceland and found it to be 98.9% accurate, whereas Eatherley et al. (2005) reported the RiverWatcher to be 100% accurate when counting returns of Atlantic salmon (*Salmo salar*) in a Scottish river. According to Shardlow and Hyatt (2004), accuracy of the RiverWatcher exceeded 95% when migration rates of adult Pacific salmon were <500 fish/hour. To our knowledge, migration rates in the lower Stanislaus River never approached that level (maximum fish count, 764 fish/day; Pyper et al. 2006). During the 2004 trapping season, Pyper et al. (2006) determined that average detection probability of the lower Stanislaus River RBW was 97% (95% confidence interval, 89%–105%), suggesting a slight undercount of fish. Nevertheless, the significant correlation between annual fish counts at the RBW and escapement estimates determined from the CDFW carcass surveys over a seven-year period (2003–2009) suggests a strong association between these two methods (Figure 2).

Comparisons of Chinook salmon length frequencies derived from the RBW and the carcass surveys indicated significant differences between these two methods. In general, the RBW yielded smaller fish than did the carcass surveys (Figure 3). Zhou (2002) determined that carcass recovery rates increased as fish size increased and as stream flow decreased. According to Zhou (2002), it makes intuitive sense for a carcass recovery rate to be size-dependent. Small carcasses are more likely to be consumed or carried away by scavengers, are more difficult for surveyors to detect, and are more readily washed away. Thus, it is probable that the CDFW carcass surveys were biased towards large-bodied fish, which would explain the larger average sizes of salmon measured during the carcass surveys.

Some populations of Pacific salmon are known to display persistent and often extreme sex ratio biases (Olsen et al. 2006). O'Brien (2006) reported the sex ratio of Chinook salmon passing a RBW in the Gisasa River, Alaska, as 67% males and 33% females. Gewin (2006) found nearly the same sex ratio for fish passing a RBW on the East Fork of the Andreafsky River, Alaska. In Cottonwood Creek, a tributary of the Sacramento River in California, results from carcass surveys by Austing and Null (2012) indicated a male:female ratio for hatchery-origin Chinook salmon of nearly 7:1 whereas the ratio for natural fish was nearly 1:1. By comparison, females generally outnumbered males at both the RBW and during carcass surveys (Figure 4), except in 2004 when males were roughly twice as numerous as females at the RBW. Nevertheless, the generally lower ratios of males to females are consistent with the notion that some genetic males in Central Valley rivers, including the Stanislaus River, have undergone sex reversal and have the appearance of females, as suggested by Williamson and May (2002, 2005). Although less numerous than females, higher percentages of male Chinook salmon were documented from the RBW (41%–67%) than during carcass surveys (29%–40%). Murdoch et al. (2009, 2010) recently demonstrated that carcass drift often differs between male and female Chinook salmon due to differences in post-spawning behavior (the redd-guarding behavior of females results in fidelity to their redds; by comparison, males are not known to display redd-guarding behavior). Moreover, dying males slowly drift downstream, with smaller males usually drifting longer distances than larger males (Murdoch et al. 2010). By drifting farther downstream, small males increase their exposure to potential scavengers or simply become less detectable as a result of drifting into logjams (Murdoch et al. 2010) or deep-water habitats. A systematic bias associated with poor detection rates of smaller males during carcass surveys could account for the somewhat higher percentages of males documented during upstream passage at the RBW.

Even though not statistically different in 2004, lower proportions of fin-clipped individuals were recorded during 2005 and 2006 among live fish passing the RBW than among dead fish recovered in carcass surveys (Figure 5). We found that high turbidity, heavy loads of floating debris, and simultaneous passage by several salmon adversely affected detection of morphological features such as presence or absence of an adipose fin in camera images taken at the RBW. We are not aware, however, if a reduction in detection probability would lead to an increase in false positives (i.e., that a missing adipose fin would be incorrectly scored as being present).

In conclusion, our results suggest that population characteristics of adult Chinook salmon can be more accurately quantified by using a strategically positioned RBW than by conducting manpower-intensive carcass surveys. Continued improvements in image recording, image processing, and computer analysis programs should further enhance the accuracy of automated imaging procedures employed at RBWs for fish species and sex ratio identification, and fish size measurements (Pippy et al. 1997, Hatch et al. 1998, Cadrin and Friedland 1999, Merz and Merz 2004). In addition, RBWs offer more versatility, and can be used in other applications such as segregating different runs of fish or blocking fish entry into a protected watershed.

Acknowledgments

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