Key Strategies for Estimating Population Sizes of Emigrating Salmon Smolts with a Single Trap

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ABSTRACT: The decline of salmonid populations in many locations has resulted in the increased use of traps to estimate the number of juvenile salmonid smolts emigrating from streams. To provide direction to biologists who are planning and conducting such studies, we discuss key strategies to be considered when estimating population sizes of emigrating smolts using a single trap, including selection of the trap and its operation, the marking, release and recapture of fish for estimating trap efficiencies, evaluating trap selectivity, and population estimation procedures. To improve the quality of the sampling design, we recommend that investigators (1) operate traps daily if possible; (2) mark only migrating fish; (3) release marked fish so that most move past the trap within several days of release; (4) use and locate traps such that their potential capture efficiencies exceed 10%; (5) determine trap efficiencies independently for species, rearing strategy (hatchery versus wild), age-group, and time periods; and (6) consider the assumptions that are implicit to mark-recapture population estimation and how they may apply to each specific situation and location.

KEY WORDS: Migration, salmon population estimation, sampling design.

INTRODUCTION

Estimating numbers of emigrating salmon smolts with traps or weirs has long been an important tool in understanding and managing anadromous salmonid populations (Shapovalov and Taft 1954; Salo and Bayliff 1958; Willis 1962). The capture of smolts as they emigrate from a river or stream can provide information on abundance (Macdonald and Smith 1980; Seelbach et al. 1985; Dempson and Stansbury 1991), age, size, (Irvine and Ward 1989), migration timing (Hartman et al. 1982; Irvine and Ward 1989), egg-to-smolt survival, smolt-to-adult survival (Ward and Slaney 1988), as well as information on environmental cues that trigger movement (Wagner 1974; Grau et al. 1981; Zaugg et al. 1986).

As many stocks of anadromous salmonids decline in the Pacific Northwest (Nehlsen et al. 1991; Frissell 1993), an improved understanding of survival through a variety of life stages will be necessary for stock maintenance and recovery (Peterman 1987; Hicks et al. 1991; McIntosh 1992). One prominent piece of information needed is production of juvenile salmon, which may often be most practically derived from estimates of the number of smolts leaving a watershed (Power 1985; Dempson and Stansbury 1991).

To accurately and precisely estimate the number of smolts leaving a stream with a single trap, at least seven aspects must be consid-

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ered: (1) choosing the trap, (2) operating the trap, (3) marking fish, (4) releasing and recapturing marked fish, (5) estimating trap efficiency, (6) assessing trap selectivity, and (7) estimating population size. In this paper, we discuss important aspects of sampling smolts and estimating their population size for small streams and rivers. Examples are drawn from the literature and from recent investigations in Oregon's South Umpqua River basin.

TRAPS

A variety of methods can be used to capture or enumerate smolts, including fyke nets (Craddock 1959; Davis et al. 1980; Milner and Smith 1985), stake nets (Hare 1973), wolf nets (Lister et al. 1969), incline screen traps (Seelbach et al. 1985; McMenemy and Kynard 1988; Dubois et al. 1991), video cameras (Irvine et al. 1991), fences (Clarke and Smith 1972; Dempson and Stansbury 1991), perforated pipes (Menchen 1975), and rotary or augur traps (Dambacher 1991; Cramer et al. 1992; Harkleroad and La Marr 1993; Kennen et al. 1994).

Traps are usually placed within the thalweg (Dambacher 1991; Harkleroad and La Marr 1993) or used in combination with a second structure that diverts fish from the thalweg into the trap (Seelbach et al. 1985; Dempson and Stansbury 1991; Cramer et al. 1992). In situations where smolts (or fry) migrate along the shoreline, however, it may be necessary to locate traps in a position other than the thalweg (Mains and Smith 1964), or to span a trap across the entire channel (Zafft 1992). The trap used and its location within the stream will be dictated by species and size of target fish, and the size of the stream. For example, species or sizes of fish known to emigrate nearer the bottom of the river rather than at the surface, or nearer the bank rather than in the thalweg, may not be susceptible to capture with traps positioned in the thalweg and sampling near the surface. Larger streams may require larger traps to ensure adequate efficiency of sampling.

TRAP OPERATION

Whenever possible, traps should be operated all day every day. If traps are not operated daily then it will be necessary to estimate the number of fish migrating when traps are not in operation.

In general, linear regression methods, with time as the dependent variable, have been used to estimate the number of fish that would have migrated on the days the trap was not operated (Zafft 1992; Seelbach1993). In streams where a high percentage of the total smolt population can migrate out of the basin in a short time, the accuracy of the linear regression method is suspect since the number of smolts migrating daily is likely autocorrelated (i.e., related among adjacent days). In Figure 1, for example, if linear regression estimates of the population were made using the four days prior to and after the period 23 June to 25 June, the point estimate of the total population of age-0 coho salmon (*Oncorhynchus kisutch*) migrating from 1 May to 15 July would have been underestimated by one-third (4,642 versus 3,110). If traps are operated only on weekdays, for example, the accuracy of estimates of smolts may suffer. Reliance on linear regression methods can thus seriously affect the accuracy of smolt population estimates.

MARKS

A variety of marks has been used to identify fish for mark-recapture trials (Chart and Bergersen 1988; Emery and Wydoski 1987). Because marks need only be retained by smolts for the short time (usually less than one week) between release and the time they pass the trap used for recapture, permanent marks or tags are not necessary to obtain population estimates of emigrating smolts. Retention of marks should be evaluated, as well as persistence of mark recognition (Thedinga et al. 1994). This evaluation may involve the use

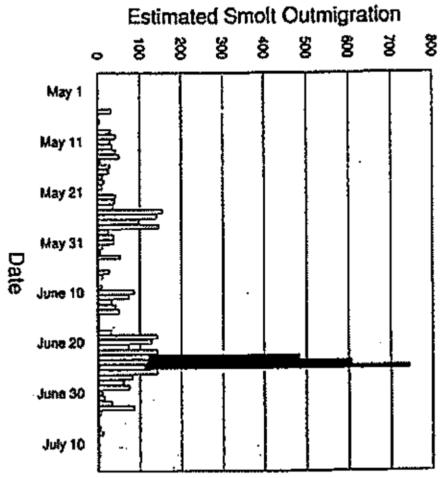

FIGURE 1. *Example of a smolt migration for which linear regression estimation procedures are inadequate. For the three days of highest catch, the darker shaded areas correspond to actual, direct estimates of smolts and the light areas below correspond to indirect estimates from regression methods using the four days prior to and after the period 23 June to 25 June.*

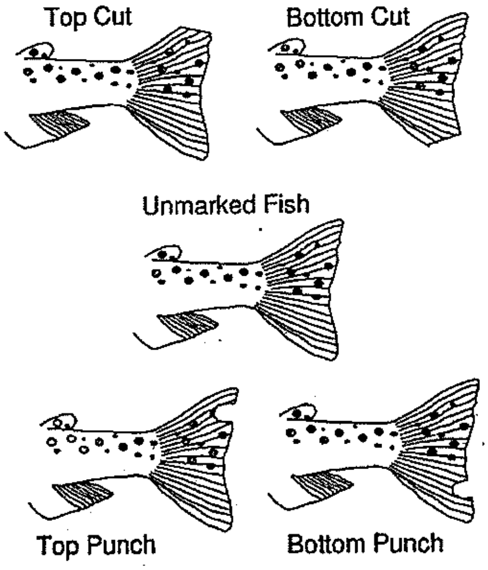

FIGURE 2. *Partial removal of the caudal fish for estimating trap efficiencies.*

of multiple marks per fish or the retention of fish in holding facilities to assess mark retention and recognition.

Marks commonly employed in mass marking of smolts include branding (Fay and Pardue 1985; Giorgi and Sims 1987; Cramer et al. 1992), fin clipping or removal (Dambacher 1991; Vincent-Lang 1993), staining (Beacon 1961; Mundie and Traber 1983), fluorescent marks (Pitcher and Kennedy 1977; McAfee and Louchs 1986), coded-wire tags (Chart and Bergersen 1988) and PIT (transponder) tags.

Although freeze branding can provide a variety of mark types permitting daily mark-recapture trials, considerable equipment is needed and not all marks are retained (Raleigh et al. 1973; Cramer et al. 1992). Heat branding (Hargreaves 1992) may be more convenient and require less specialized equipment.

Fin clipping or removals also provide a variety of marks and require minimal equipment to administer. We have found that the partial removal of fins (Figure 2) results in a large variety of marks and requires little time to administer. These marks are easy to identify on recaptured fish. We believe the long-term effects of these marks are probably minimal, although the effects have not been documented. Clipping of different fins on different days is also an option.

Vital stains are useful for the rapid marking of a large number of individuals (Thedinga et al. 1994) but this method does not provide distinctive daily marks. The injection of fluorescent pigments allows a variety of daily marks but can be time-consuming to administer (Fay and Pardue 1985).

The use of more costly, longer-term tags such as coded-wire tags (batch coded or individually numbered) and PIT tags is best incorporated into longer-term studies on survival rates and contribution to fisheries. These tags provide longer-term marks than needed for merely estimating smolt numbers, but individually-numbered tags will provide potentially useful data on individual fish.

Selection of the appropriate method of marking fish will depend on individual needs and circumstances. For example, one may choose permanent, individually-identifiable marks such as PIT tags for rare or endangered species, coded-wire tags in situations where long-term recovery of adults in fisheries is possible, or inexpensive batch tagging or fin clipping if only short-term marks are needed. Some care must be exercised in selection because marking and tagging have been shown to affect fishes. Removal of fins has been shown to reduce the long-term survival of marked fish (Vincent-Lang 1993). Tagging has been shown to affect fish movements (Hughes 1998).

RELEASE AND RECAPTURE OF MARKED FISH

Regardless of the methods by which smolts are sampled, most population estimates with a single trap rely on capturing fish, marking captured fish, and then transporting them above the trap site and releasing them so that a portion are recaptured as they again move past the trap. This approach allows the estimation of trap efficiency if the marked fish soon move past the trap a second time.

Nonsmolting fish may not be actively migrating, however, and only a small fraction of marked fish may move past the trap a second time. Kruzic (1998) found that less than 15% of marked age-0 coho salmon in the South Umpqua River passed the trap a second time.

Because smolt traps typically capture emigrating fish (Bjornn 1971), however, fish captured in smolt traps usually move rapidly downstream once released (Macdonald and Smith 1980). If marked fish are released just upstream of the trap site, most marked fish will move past the trap a second time within one or two days. If fish are released too close to the trap, however, capture probabilities of marked fish may differ from unmarked fish (Ricker 1975). An appropriate intermediate distance upstream from the trap should thus be sought.

In our mark-recapture trials (Roper and Scarnecchia 1996), for example, approximately 90% of the fish were captured one day after release when fish were released 300-400 m upstream from the trap. The other 10% of the captures exhibited a nearly exponential decline through the following days. Less than 0.05% of the age-0 chinook salmon (*O. tshawytscha*) or age-0 coho salmon in these trials were captured five or more days after release. Only about 2% of the age-1 or older age steelhead (*O. mykiss*) were captured five or more days after release.

To determine if 91.4 m was a sufficient distance for marked fish to have the same capture probability as unmarked fish (and to determine trap avoidance), Seelbach et al. (1985) compared captures from electrofishing to those with a smolt trap. Their research indicated that both marked and unmarked fish were equally vulnerable to capture when fish were released at this distance.

One secondary benefit of releasing marked fish close to the trap used for recapture is that mortality of marked fish between the point where they are released and the trap site will probably be low. Release of marked fish at a consistent location, however, can habituate predators to the release site so that high rates of predation can ensue.

If marked fish are released too far above the trap, mortality of smolts or aborted emigrations may bias results. In this case, models that include travel time as a variable may produce the best available estimates of smolt numbers (Schwarz and Dempson 1994).

ESTIMATING TRAP EFFICIENCIES

The estimation of trap efficiencies is, for several reasons, often the best approach for obtaining estimates of numbers of emigrating smolts, especially in small populations. These reasons include (1) the simplicity of estimating trap efficiencies, (2) the similarity of the estimates to those of more complex models (Darroch 1961; Dempson and Stansbury 1991), (3) the applicability with a single trap, (4) the yielding of computable confidence intervals that are always zero or positive, and (5) the ability to make estimates of the daily number of smolts.

Trap efficiency is the proportion of the total number of smolts that are captured as they move past the trap. If the majority of marked fish move past the trap the day after they are released (as described in the previous section), then an approximate estimate of trap efficiency for that day will be

$$u_j = \frac{\sum_{i=1}^{n} R_{ji}}{M_j} \qquad (1)$$

(Ricker 1975; Seelbach et al. 1985; Zafft 1992); where u_j is the trap efficiency for the day when the most fish are recaptured, even though recaptures are made through several (n) days, R_{ji} is the number of recaptured fish from the j^{th} release group on the i^{th} day, and M_j is the number of marked fish released. For example, a group of 100 marked fish (M_j=100) is released on 1 June. A total of 20 fish is recaptured from this release group (ΣR_{ji}=20), 15 on 2 June (i=1), three on 3 June (i=2), one on 4 June (i=3), and one on 5 June (i=4, n=4). The estimate of trap efficiency for this release group (u_j) then is 20% (20/100). This approximation of trap efficiency will be exact if trap efficiency does not change among days that marked fish are recaptured, or if all marked fish move past the trap the day after they were released. Other assumptions are that (1) all released fish must continue their downstream migration after release, (2) handling and marking does not affect fish behavior, (3) mortality rates from release to recapture are zero, and (4) marked and unmarked fish mix randomly in the population.

A large-sample approximation for the confidence interval (C.I.) for trap efficiency is

$$C.I. = u_j \pm z_{\alpha/2}\left[\frac{u_j(1-u_j)}{M_j}\right]^{1/2} \qquad (2)$$

(Hollander and Wolfe 1973; Kennen et al. 1994).

Estimates of trap efficiencies are often applied to a variety of time scales (Seelbach et al. 1985; Harkleroad and La Marr 1993). The estimates, whether over a week or a year, assume that trap efficiency does not change through that period. As stream conditions change, however, trap efficiencies can also change (Dambacher 1991, Seelbach 1993). For example, in one instance, higher water may result in a smaller volume of water being sampled and may reduce efficiency; in another instance, lower water may allow more fish to detect and avoid the trap, also reducing efficiency.

Because it is impossible to evaluate trap efficiencies without the capture of marked fish, marking and releasing fish on as many days as possible improves the understanding of how trap efficiencies change during the migration period. We suggest that marked fish be released daily even if results of adjacent days are later combined.

An evaluation of daily trap efficiencies for age-0 chinook salmon from the South Umpqua River (Table 1) illustrates how point estimates of efficiencies can differ over a short time period. In this example, estimates of trap efficiencies ranged from 14.6% to 30.8% within one week. Although point estimates of trap efficiencies differed among days, pair-wise comparisons of trap efficiencies were not significantly different (comparisons of binomial proportions; $P<0.05$; Table 2). Failure to reject the null hypothesis that trap efficiencies were different has been used as justification to combine data so that a single estimate of efficiency results (Peterman 1990; Thedinga et al. 1994).

We suggest that estimates of trap efficiencies be computed daily except when the number of recaptured fish is less than about seven fish. In cases of very few recoveries, daily confidence intervals will be wide and probably biased (Robson and Regier 1964; Jensen 1981; Warren and Dempson 1995). Bias can be minimized if the total number of recaptures used

TABLE 1

Daily estimates of trap efficiencies of age-0 chinook salmon in the South Umpqua River based on recaptures up to four days after release.

		Recaptured marked fish				
Day	Marked fish released	Day 1	Day 2	Day 3	Day 4	Trap efficiencies (%)
1	41	4	0	2	0	14.6
2	39	11	1	0	0	30.8
3	142	37	3	0	0	28.2
4	161	30	0	0	0	18.6
5	130	25	0	0	0	19.2
6	49	11	0	0	0	22.4
7	27	5	0	0	1	22.2

TABLE 2

Trap efficiencies, population estimates, variances (Var), and confidence intervals (lower(LCI)) and upper(UCI)) of age-0 chinook salmon smolts within the South Umpqua Basin based on daily captures and combined captures for one week in 1991. Data are the same as those in Table 1

	Unmarked fish captured (C_j)	Marked fish released (M_j)	Recaptures next day	Total recaptures (R_j)	Trap efficiencies (U_j)	Var (U_j)	Population estimate ($\hat{N}_j$)	Var ($\hat{N}_j$)	LCI	UCI
	51	41	4	6	0.146	0.003047	311.00	10462.61	110.52	511.48
	219	39	11	12	0.308	0.005462	675.92	30705.36	332.47	1019.36
	226	142	37	40	0.282	0.001425	790.73	12198.21	574.26	1007.40
	162	161	30	30	0.186	0.000942	850.81	18318.84	585.53	1116.09
	65	130	25	25	0.192	0.001195	331.54	2467.29	234.18	428.89
	32	49	11	11	0.224	0.003553	136.50	912.07	77.30	195.69
	20	27	5	6	0.222	0.006401	83.00	574.08	36.04	129.96
Totals	775	589		130			3,179.50 (added)	75,638.46	2,641	3,718
							3,493 (combined)		2,949	4,036

for an estimate of trap efficiency is seven or more (Seber 1973), although Ricker (1975) suggested that as few as three or four fish may be satisfactory.

In cases where efficiencies can be estimated only weekly or monthly, efficiencies may be estimated by releasing a predetermined number of marked fish (e.g., the first 200 fish captured each week) or by releasing a maximum number of fish each day during the time period (e.g., all fish are marked each day if the total number of fish is less than 50, but only 50 are marked when more than 50 are captured). Differences in how marked fish are released, however, can yield different estimates of smolt populations (Table 3). If trap efficiencies are determined by marking a preset number of fish, estimates of smolt numbers will reflect trap efficiencies at the time marked fish are recaptured. In contrast, if no more than a preset number of fish are released each day, overall estimates of smolt numbers over periods of several days will reflect the near equal weighting of daily efficiencies. Differences in point estimates suggest that care should be exercised when using any strategy other than marking all or the same proportion of the fish each day.

In other cases (e.g., for an endangered species), it may be desirable or necessary to estimate trap efficiency from a single group of marked fish during the emigration (Seelbach et al. 1985). In these cases, smolt population estimates will only be as accurate as that single estimate of trap efficiency, which may or may not be a good estimate of the average annual trap efficiency. If an estimate of trap efficiency is to be made only once during the season, we suggest that it be made near the peak of emigration so that the estimate reflects trap efficiency when the most fish are emigrating.

Because wide confidence intervals will result from low trap efficiencies, we suggest that trap efficiency be at least 10% if estimates of smolt populations are to be reliable. Even more efficient traps may be needed to estimate very small populations. For a given confidence interval around the efficiency estimate, Figure 3 shows the relation between trap efficiencies and the number of fish that must be marked.

Highly efficient traps, however, create logistical drawbacks. The time needed to process fish accurately increases as the number of fish handled increases. Also, since more fish are handled when using more efficient traps, total handling mortality may be higher. In streams with small populations of smolts, or endangered stocks, additional mortality resulting from handling may be unacceptable.

TABLE 3

Comparisons of population estimates based on trap efficiencies estimated daily, weekly, and over the first two days of the week.

Day	Unmarked fish captured	Marked fish available	Total recaptures	Daily estimate
1	164	62	20	496
2	75	152	46	248
3	41	72	15	191
4	35	37	7	170
5	52	32	5	291
6	79	51	10	377
7	15	74	4	239
Total daily				2,008
Total weekly	461	480	107	2,057
First 2 days (214 total fish)	461	214	66	1,482

TRAP SELECTIVITY

Specific stream conditions may result in trap efficiencies being differentially affected by fish size, species, and rearing history. For example, at low stream velocities larger fish

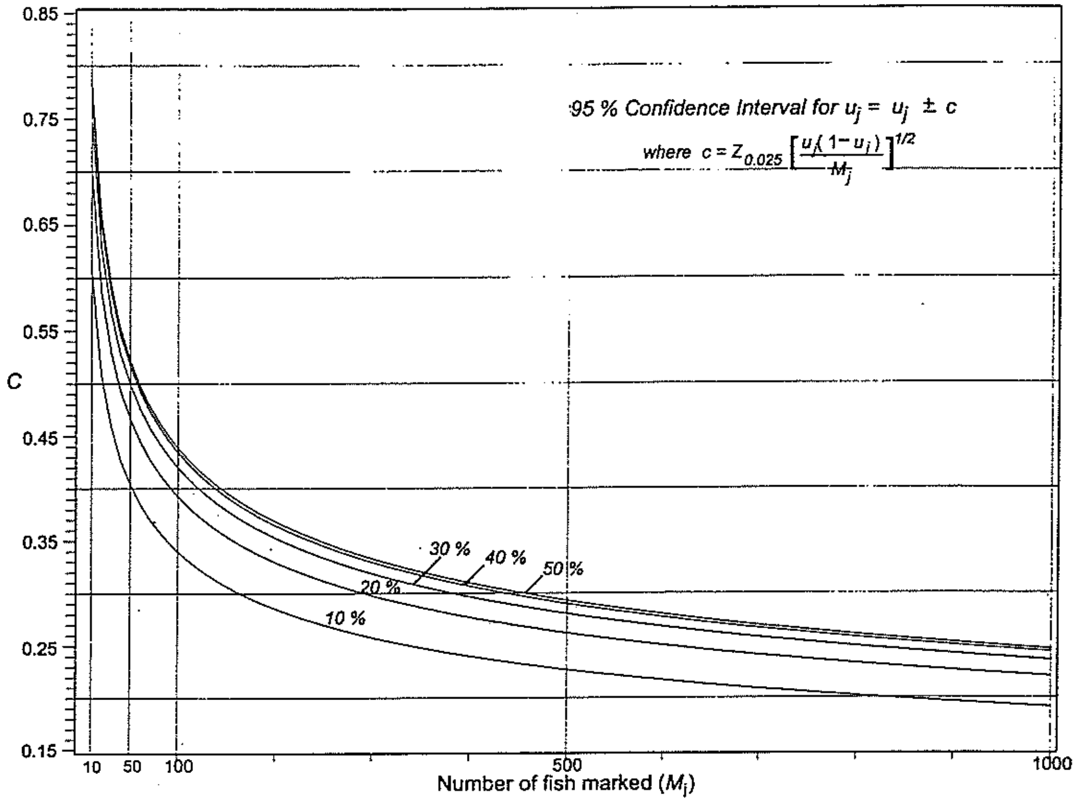

FIGURE 3. *Relation between confidence interval width, trap efficiencies, and the number of fish that must be marked.*

may be able to actively avoid capture. In another case, smaller fish may migrate along the shoreline and avoid capture by a trap located in the thalweg. Because selective capture may affect the accuracy of trap efficiency estimates, it is important to determine if a trap is selective (Seber 1973; Ricker 1975).

One method used to determine if a trap is size selective is to compare the size distribution of the initial captures to that of the recaptured marked fish. A chi-square goodness-of-fit test is then used to compare the size distributions (Seber 1973). In Table 4, for example, the size of recaptured age-0 chinook salmon was not significantly different from the size of fish originally released, at least through the range of conditions under which the trap was operated. Dambacher (1991), however, found trap efficiencies for smaller steelhead (70-105 mm) were almost twice that of larger steelhead (106-165 mm). This difference led him to make separate trap efficiency estimates for the two size groups.

TABLE 4

Results of test for size selectivity of age-0 chinook salmon trapped from 1 June to 3 June 1991 in the South Umpqua Basin. The observed distribution of marked fish is not significantly different from the distribution of recaptured marked fish.(P<0.05)

Length Class (mm)	No. fish marked	No. fish recaptured	No. expected recaptured	X^2
50-54.9	25	5	4.71	0.018
55-59.9	198	32	37.30	0.753
60-64.9	149	28	28.06	0.001
65-69.9	52	12	9.80	0.496
70-74.9	20	5	3.77	0.403
75-79.9	27	7	5.08	0.720
>80	28	5	4.77	0.014
Totals	499	94	94.00	2.404

In addition to size selectivity, trap efficiency may vary widely among species (Seelbach et. al 1985; Murphy et al. 1991; Kennen et al. 1994; Thedinga et al. 1994) as well as between wild and hatchery-reared fish (Roper and Scarnecchia 1996). Trap efficiency estimates should thus be made for each species or rearing strategy.

ESTIMATING POPULATIONS

Although methods of estimating smolt numbers have been established since the early 1950s (Schaefer 1951), many rely on large sample approximations (Darroch 1961; Macdonald and Smith 1980), an assumption often impractical when estimating numbers of smolts from populations having few smolts (Otis et al. 1978; Seber 1986; Nichols 1992). Some estimation methods may also rely on two traps, separated longitudinally within the same river (Schaefer 1951; Dempson and Stansbury 1991). The use of multiple traps to sample one smolt migration may, however, be prohibitively expensive and labor intensive for a single stream.

A simple method used to estimate smolt numbers with a single trap can be derived from an estimate of trap efficiency (Seber 1973; Ricker 1975; Seelbach et al. 1985). That is, $\hat{N}_j = u_j^{-1}C_j$ where $\hat{N}_j$ is the total number of smolts to move past the trap through time period (j), C_j is the total number of unmarked fish captured during time period j (from a day to a year) and u_j is the estimate of trap efficiency during that time period. However, Chapman's (1951) modification of this expression is preferable because of lack of bias:

$$\hat{N}_j = [(M_j+1)(C_j+1)/(R_j+1)]-1 \qquad (3)$$

Total captures (including marks) are not used because marked fish were included in a previous day's catch (when using a single trap). Confidence intervals (C.I.) for the population are calculated as

$$\text{C.I.} = \hat{N}_j + Z_{\alpha/2}\,[\mathrm{Var}(\hat{N}_j)]^{1/2} \qquad (4)$$

where

$$\mathrm{Var}(\hat{N}_j) = \hat{N}_j^{\,2}(C_j - R_j)/[(C_j+1)(R_j+2)] \qquad (5)$$

In the example depicted in Table 2, point estimates of the population size for combined data for the week (3,493) were similar to those for uncombined data added up over the week (3,179.5), and confidence intervals were of nearly the same width as well. The differences between the methods will depend on the specific data set.

FINAL RECOMMENDATIONS

We believe that estimates of smolt populations with smolt traps will play an increasingly important role in understanding declining anadromous salmonid populations. If the following six suggestions are implemented, estimates of smolt populations will likely be accurate and relatively precise: (1) operate traps daily if possible; (2) mark only migrating fish; (3) release marked fish so that most move past the trap within several days of release; (4) use and locate traps such that their potential capture efficiencies exceed 10%; (5) determine trap efficiencies independently for species, rearing strategy (hatchery versus wild), age-group, and time periods; and (6) remember the assumptions implicit to mark-recapture population estimation and how they may apply to each specific situation and location. These assumptions, listed in Ricker (1975; pages 81-82), include equal mortality of marked and unmarked fish, random mixing of marked and unmarked fish, and recognition and reporting of all marks. Adherence to these and related suggestions for study design will provide quality data for stock assessment.

Acknowledgments

We thank B. Dennis, C. Gowan and anonymous reviewers for helpful comments, and Y. Lim for assistance with computations.

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