Estimating Total Fish Abundance and Total Habitat Area in Small Streams Based on Visual Estimation Methods

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Hankin, D. G., and G. H. Reeves. 1988. Estimating total fish abundance and total habitat area in small streams based on visual estimation methods. Can. J. Fish. Aquat. Sci. 45: 834–844.

We present sampling designs for estimating total areas of habitat types and total fish numbers in small streams. Designs are applied independently within strata constructed on the basis of habitat unit type and stream reach. Visual methods for estimating habitat areas and fish numbers are used to increase sample sizes and thereby reduce errors of estimation. Visual estimates of area are made for all habitat units, and visual estimates of fish numbers are made for systematic samples of units within given habitat types. Use of systematic sampling circumvents the requirement for a preexisting map of habitat unit locations and simplifies selection of units. We adjust for possible proportional bias of visual estimation methods by calibrating visual estimates against more accurate estimates made in subsamples of those units for which visual estimates are made. In a test application of these sampling designs, correlations between visual estimates and more accurate estimates were generally high, $r > 0.90$. Calculated 95% confidence bounds on errors of estimation were 13 and 16% for total areas of pools and riffles, respectively, and were 17 and 22% for total numbers of 1+ steelhead trout (*Salmo gairdneri*) and juvenile coho salmon (*Oncorhynchus kisutch*), respectively. Our methods appear to offer a cost-effective alternative to more traditional methods for estimating fish abundance in small streams. In addition, visual estimation surveys can produce detailed maps of the areas and locations of all stream habitat units.

Les auteurs présentent des protocoles d'échantillonnage pour l'estimation de la superficie totale de types d'habitats et du nombre total de poissons de petits cours d'eau. Les protocoles sont appliqués indépendamment à l'intérieur de strates déterminées à partir du type unitaire des habitats et de la section des cours d'eau. Des méthodes visuelles d'estimation de la superficie des habitats et du nombre de poissons sont utilisées afin d'accroître la taille des échantillons et, ainsi, de réduire les erreurs d'estimation. Des estimations visuelles de superficie sont réalisées pour toutes les unités d'habitat et d'autres portent sur le nombre de poissons se trouvant dans des échantillons systématiques d'unités au sein de types d'habitats donnés. L'échantillonnage systématique permet de contourner la nécessité de disposer d'une carte précisant les emplacements des unités d'habitat et de simplifier leur choix. Les biais proportionnels éventuels des méthodes d'estimation visuelle sont corrigés par étalonnage à partir d'estimations plus exactes obtenues de sous-échantillons des unités ayant fait l'objet d'estimations visuelles. Les auteurs ont obtenu, au cours d'un essai de mise en application de ces protocoles, des corrélations entre les résultats d'estimations visuelles et ceux d'estimations plus exactes qui s'avéraient généralement élevées ($r > 0,90$). Les limites de confiance à 95 % calculées des erreurs d'estimation étaient de 13 et 16 % pour, respectivement, les superficies totales des fosses et des hauts-fonds et de 17 et 22 % pour le nombre total de truites arc-en-ciel (*Salmo gairdneri*) 1+ et de juvéniles de saumons cohos *Oncorhynchus kisutch*). Les méthodes présentées semblent constituer une solution de remplacement rentable aux méthodes plus classiques d'estimation de l'abondance des poissons dans les petits cours d'eau. De plus, les inventaires par estimations visuelles permettent de produire des cartes détaillées des zones étudiées et des emplacements de toutes les unités d'habitat d'un cours d'eau.

Received May 20, 1987
Accepted January 6, 1988
(J9293)

Reçu le 20 mai 1987
Accepté le 6 janvier 1988

Hankin (1984) showed that typical surveys for estimation of fish abundance in small streams are two-stage sampling designs. Errors of estimation arise from two sources: (a) extrapolation from a small number of sampled stream sections to an entire stream and (b) estimation of fish numbers within sampled sections. Hankin (1984) recommended that sampled sections should be made equivalent to natural habitat units and that independent samples should be drawn from within strata constructed on the basis of habitat unit type and location. He then proposed several alternative two-stage sampling designs and compared their performances in several plausible settings.

The most important conclusion of Hankin's research was that errors of estimation of fish numbers *within* selected units (second stage errors) are likely to be small compared with errors that arise due to variation in fish numbers or densities *between* sampled units (first stage errors). There are a variety of methods whereby first stage errors can be reduced through choice of sampling design. When fish numbers within habitat units are poorly correlated with auxiliary variables such as habitat unit size, however, errors of estimation can be substantially reduced only by increasing the number of sampled habitat units (increasing the first stage sampling fraction).

Budget limitations may rule out a large first stage sampling fraction if costly and time-consuming electrofishing/removal methods or mark–recapture methods are used to estimate numbers of fish within selected units. An alternative to these methods is visual estimation based on independent counts of fish by divers. Although visual estimates of abundance may be less accurate than those obtained using other methods, the average time and expense required to sample a given unit may be much less than for other methods so that the first stage sampling fraction may be substantially increased for a fixed total survey cost.

Diver counts have been previously used to assess fish abundance, principally in larger streams and rivers (Northcote and Wilkie 1963; Schill and Griffith 1984; Gardiner 1984; Hicks and Watson 1985). Reported variation between visual estimates of abundance by independent divers has been small (Northcote and Wilkie 1963; Schill and Griffith 1984), indicating that visual estimates may often be precise (have small variance). Bias of visual estimates has rarely been determined, however, usually because there has been no suitable method for making an extremely accurate estimate with which to judge bias of visual estimates. Northcote and Wilkie (1963) found that divers undercounted the number of fish actually present and that degree of negative bias appeared species dependent. (True numbers of fish present were determined by poisoning.) Diver counts may thus be quite precise but, because they are not unbiased, their use requires correction for bias in estimators for abundance and error of estimation.

The feasibility and accuracy of visual methods for estimation of fish abundance in small streams have not been previously assessed in the fisheries literature. One advantage of working in small streams is that more accurate population estimates can be made using alternative methods of estimation (such as removal or mark–recapture methods). If these more accurate methods generate estimates with very small errors, then these estimates may be assumed equal to the "true" numbers and they may be compared with diver counts to establish bias of visual estimates. If a consistent proportion of those fish actually present are counted (so that proportional bias is nearly constant), then one can calibrate or adjust diver counts by the ratio of true fish numbers to diver counts and obtain an approximately unbiased estimate of the true number of fish present. Errors of estimation of adjusted diver counts may then be calculated based on (a) between-diver variation and (b) the correlation between diver counts and "true" numbers of fish.

In this paper we present practical sampling designs for estimation of fish abundance and total habitat area in small streams based on visual estimation of fish numbers and habitat areas. The effectiveness of these sampling designs depends on the correlations between visual estimates and corresponding true habitat areas and fish numbers. True habitat areas and fish numbers are assessed using more accurate methods of measurement or estimation in a subset of those units in which visual estimates are made. Systematic sampling is used for selection of units, where unit ordering is the natural stream location sequence, thus circumventing the requirement for a preexisting map of habitat units (Hankin 1984) and simplifying selection of sample units.

Results of applications suggest that the increased first stage sampling fraction achievable with diver counts will usually more than compensate for increased errors of estimation within selected units by substantial reduction in first stage variance and in total errors of estimation. When compared with more expensive traditional methods for estimating fish abundance and habitat area, visual estimation methods offer a cost-effective alternative in small streams.

Sampling Designs

In this section we present brief developments of sampling designs and estimators that can be used for estimation of total habitat area and total fish abundance in small streams based on visual estimates. Sampling designs assume that habitat units are first stratified according to habitat type (e.g. riffles, pools, glides) and location (e.g. lower, middle, upper reaches) so as to generate a finite set of habitat type/location strata (e.g. the upper pool stratum; see Hankin 1984). Primary units within strata are of unequal sizes, equivalent to the natural habitat units, and each habitat type/location stratum is sampled independently. Because strata are sampled independently, estimates of fish abundance or habitat area (and their respective estimated variances) can simply be added across strata to give estimates of total fish abundance or habitat area (and estimated variances) for specific habitat types (e.g. total number of fish in all riffles) or for the entire stream (Hankin 1984). In the development that follows, stratum-specific notation has been avoided for simplicity.

Estimation of Total Habitat Area

Visual estimates of habitat areas are made for all habitat units within a given habitat type/location stratum. A systematic (1 in k) sample of units is drawn from this stratum and accurate estimates of habitat unit areas are made for each unit appearing in the sample based on uniformly spaced measurements of stream width. We assume that these accurate estimates of habitat area have negligible errors so that they can be equated with the true habitat area.

Definitions

m_i = true area of unit i; $i = 1,2,\ldots,N$
$M = \sum^N m_i$ = true total area of all units
x_i = visual estimate of area of unit i
$T_x = \sum^N x_i$ = total of visual estimates across all units

It seems reasonable to assume that

(1) $m_i = Qx_i + \epsilon_i; E(\epsilon_i) = 0$

(2) $E(\epsilon_i^2) = x_i\sigma^2$.

Equations (1) and (2) state that the true habitat unit area, m_i, may be regarded as a random variable with expected value Qx_i and variance $x_i\sigma^2$, proportional to the magnitude of the visual estimate of unit area, x_i. They thus incorporate the reasonable notion that possible discrepancies between visual estimates of habitat area and true habitat area will increase as habitat area increases. If these assumptions are met, then the standard ratio estimator is model-unbiased (Cochran 1977, p. 158) and has the form

(3) $\hat{M} = T_x\hat{Q}$

where

$\hat{Q} = \sum^{n} m_i / \sum^{n} x_i$

with sampling variance approximately estimated from a sample by (Cochran 1977, equation 6.9):

$$(4) \quad \hat{V}(\hat{M}) = \frac{N\,(N-n)}{n\,(n-1)} \sum_{i=1}^{n} (m_i - \hat{Q}x_i)^2.$$

If the model assumptions are not met, then the ratio estimator is not model-unbiased, but bias will be small if the relation between m_i and x_i is linear and passes through the origin.

Estimation of Fish Abundance

Within a given habitat type/location stratum, a systematic sample of n units is selected for which paired independent diver counts of fish numbers are made for each unit in the sample. In a random subsample of these selected units, some more accurate method of estimating fish numbers is also used to allow calibration or adjustment of diver counts and calculation of errors of estimation within selected units. We assume that this more accurate method of estimation has sufficiently small errors that estimates obtained by this method may be regarded as equal to the true numbers of fish actually present in selected units. Estimates of total fish abundance, and estimated variances for these estimates, are calculated based on adjusted diver counts using an estimator appropriate for two-stage sampling designs with equal probability selection of unequal sized primary units (see Hankin 1984).

Definitions

y_i = true number of fish in unit i; $i = 1,2,\ldots,N$

$Y = \sum^{N} y_i$ = true total number of fish in all units

d_{ij} = count of fish by diver j in unit i; $j = 1,2$

$d_i = \sum_{j=1}^{2} d_{ij}/2$ = mean diver count in unit i

n' = number of units for which both diver counts and more accurate estimates of fish numbers are made

n = total number of units for which diver counts are made; $n > n'$

The first step in calculations involves obtaining adjusted estimates of fish numbers within selected units (those that appear in n but do not appear in n') and computing associated within-unit errors of estimation. (For those units that appear in n', the more accurate estimates for y_i should be used.) It seems reasonable to assume that $d_i = y_i$ when $y_i = 0$ (i.e. if no fish are present, then diver counts will be zero) and that diver counts become progressively less reliable as the number of fish present increases. Then, given the above definitions, the true number of fish in habitat unit i can be estimated by

$$(5) \quad \hat{y}_i = d_i\hat{R} \text{ (for } i \text{ not in } n')$$

where

$$\hat{R} = \sum_{i=1}^{n'} y_j \Big/ \sum_{i=1}^{n'} d_i \text{ (for } i \text{ in } n').$$

$\hat{R}$ is a sample-based ratio estimator for R, the true ratio of numbers of fish present to mean counts by divers. $\hat{R}$ will be the best linear unbiased estimator of R if the relationship between y_i and d_i is the same as that specified for m_i and x_i in equations (1) and (2).

Error of estimation of y_i using equation (5) will depend on (a) variation between diver counts within a unit and (b) error of estimation of R. An estimated variance for $\hat{y}_i$, that incorporates both kinds of errors, may be calculated using Goodman's (1960) result for the exact variance of a product of independent random variables (d_i and $\hat{R}$ will be statistically independent for i not in n'):

$$(6) \quad \hat{V}(\hat{y}_i) = \hat{R}^2\hat{V}(d_i) + d_i^2\hat{V}(\hat{R}) - \hat{V}(d_i)\hat{V}(\hat{R}).$$

If between-diver variation ($\hat{V}(d_i)$) is small, then $\hat{V}(\hat{y}_i)$ will be approximately proportional to the square of the mean diver count, a result consistent with the assumption that diver counts become less reliable as the number of fish present increases. If $\hat{V}(d_i)$ is not small, then the first term in equation (6), reflecting between diver variation, may make a substantial contribution to error of estimation.

$\hat{V}(d_i)$ is calculated empirically (Som 1976, p. 30) from between-diver variation as

$$(7) \quad \hat{V}(d_i) = \tfrac{1}{2} \sum_{j=1}^{2} (d_{ij} - d_i)^2$$

and $\hat{V}(\hat{R})$ is calculated using a standard ratio estimation approximation (Cochran 1977, equation 6.13):

$$(8) \quad \hat{V}(\hat{R}) = \frac{(N - n')}{Nn'\,\bar{d}^{\,2}} \sum^{n'} (y_i - \hat{R}d_i)^2/(n' - 1)$$

where

$$\bar{d} = \sum^{n'} d_i / n'.$$

Results from equation (7) and (8) are then substituted in equation (6) to generate estimates of errors of estimation within selected units (for i not in n'). If y_i and d_i are highly correlated, then the squared differences between y_i and $\hat{R}d_i$ should be small, so that $\hat{V}(\hat{R})$ will also be small. If, instead, y_i and d_i are poorly correlated, then the squared differences between y_i and $\hat{R}d_i$ will be large so that $\hat{V}(\hat{R})$ will also be large. The form of equation (8) thus points out the importance of consistency in the proportional bias of visual estimates as compared with true numbers of fish present.

The total number of fish within a habitat type/location stratum can now be estimated as

$$(9) \quad \hat{Y} = \frac{N}{n} \sum^{n} \hat{y}_i$$

where n equals the number of units in the systematic sample (drawn from N) for which diver counts are made. Although equation (9) is statistically unbiased only when N/k = n, we recommend its general use even when $N/k \neq n$ (see Appendix). Note that if the y_i are highly correlated with visual estimates of habitat unit areas, x_i, then a two-stage ratio estimator may be preferable to equation (9) (see Hankin 1984, his equations (4) and (6)).

An estimate of the variance of this estimated total can be calculated as (Hankin 1984, his equation (3))

$$(10) \quad \hat{V}(\hat{Y}) = \frac{N\,(N-n) \sum^{n} (\hat{y}_i - \hat{\bar{y}})^2}{n\,(n-1)} + \frac{N \sum^{n} \hat{V}(\hat{y}_i)}{n}$$

where

$\hat{\bar{y}} = \sum^{n} \hat{y}_i / n.$

In practice, it may be more practical to estimate the ratio (R) of true numbers of fish present to (mean) diver counts based on a random sample of units drawn from several habitat/location strata of the same habitat type. For example, one may be willing to assume that R is a constant for *all* pools, or for all pools within upper and middle pool strata. In that case, N in equation (8) would refer to the sum of the numbers of pools located in all such strata, and n' would refer to the total number of units within these strata for which visual estimates and more accurate estimates of abundance were made. We have followed this practice in the example application presented below.

Assessment of the Relative Performance of Visual Estimation

Equation (10) is a sample-based estimator for the true two-stage sampling variance of $\hat{Y}$ (Hankin 1984, his equation (2)):

$$(11)\quad V(\hat{Y}) = \frac{N(N-n)\sum^{N}(y_i - \bar{y})^2}{n(N-1)} + \frac{N\sum^{N} V(\hat{y}_i)}{n}$$

$$= \frac{N(N-n)}{n} S_1^2 + \frac{N\sum^{N} V(y_i)}{n}$$

where

$$S_1^2 = \sum^{N}(y_i - \bar{y})^2/(N-1)$$

and is unaffected by sample size, and $\bar{y} = Y/N$. The true sampling variance of $\hat{Y}$ can thus be separated into two terms. The first term in equation (11) reflects variation between unit totals (first stage variance) and measures error of estimation that arises in single stage sampling (as if the unit totals were all measured without error). The second term reflects an additional contribution to variance due to "subsampling" (estimating y_i) within selected units (second stage variance). Total sampling variance is the sum of the contributions from the two stages of sampling. As the first stage sampling fraction increases, contributions from both the first and second stages of sampling are reduced. In contrast, use of a more accurate method of estimation at the second stage will only reduce the contribution from the second stage.

Raj (1968, p.119) showed that the expected value of the first term in equation (10) equals $V(\hat{Y}) - \sum^{N} V(\hat{y}_i)$, the true total sampling variance of $\hat{Y}$ less the contribution from the second stage when all units are sampled. $\sum^{N} V(\hat{y}_i)$ can therefore be estimated from a sample as the second term in equation (10), and a sample-based estimate of the second term in equation (11) (the contribution from the second stage of sampling) can be obtained as (Murthy 1977, p. 323)

$$(12)\quad \hat{V}_2 = \frac{N^2}{n^2}\sum^{n} \hat{V}(\hat{y}_i).$$

Given $\hat{V}_2$, the contribution from the first stage of sampling (the first term in equation (11)) can be estimated from a sample as $\hat{V}(\hat{Y}) - \hat{V}_2$. Finally, S_1^2 may be estimated as

$$(13)\quad \hat{S}_1^2 = n\,\frac{[\hat{V}(\hat{Y}) - \hat{V}_2]}{N(N-n)}.$$

The estimate for S_1^2 from equation (13) can be used to calculate expected sampling variances given alternative first stage sampling fractions, n/N (using equation (11) and a sample-based estimate of $\sum^{N} V(\hat{y}_i)$). Based on such calculations, one may compare the expected performances of alternative methods that could be used to estimate fish numbers within selected units. In particular, one may contrast the expected performances of visual estimation methods (with calibration) and more traditional methods such as electrofishing/removal method estimation.

To compare the probable performances of estimators based on visual estimation with those based exclusively on a more accurate method (such as electrofishing), we assumed that the total sampling-related costs of a visual estimation survey could be expressed as

$$(14)\quad C_V = n_V c_V + n_{E|V} c_E$$

where n_V is the number of units for which fish abundance is visually estimated, $n_{E|V}$ is the number of units (out of n_V) for which abundance is (also) estimated using a more accurate method (here, electrofishing), and c_V and c_E are the average costs per unit (in man-hours) of estimation using the two methods. If fish abundances were instead estimated using only the more accurate method, then total sampling-related costs would be

$$(15)\quad C_E = n_E c_E$$

where $n_E > n_{E|V}$. That is, the number of units in which the more accurate method could be used would be greater (for the same cost) if fish numbers were not visually estimated in additional units.

Because C_E and C_V are expressed in total man-hours, setting $C_V = C_E$ should result in approximately equal total survey costs for visual estimation (with calibration) and for a more accurate estimation method (e.g. electrofishing). Other survey costs (per diem, travel to study site, etc.) should be roughly proportional to the total man-hours expended in survey sampling. For example, let $c_E = 5$ and $c_V = 1$. If fish abundance were visually estimated in 10 units ($n_V = 10$) and were estimated using a more accurate method in 2 units ($n_{E|V} = 2$), then $C_V = (10)(1) + (2)(5) = 20$. Setting $C_E = C_V$ would give $n_E = 4$ if the more accurate method were the only method used to estimate fish abundance. Based on this alternative sample size, expected sampling variance for the more accurate method ($E[V_E(\hat{Y})]$) can be calculated as

$$(16)\quad E[V_E(\hat{Y})] = \frac{N(N-n_E)}{n_E}\hat{S}_1^2$$

where N is the total number of units in a particular stratum, $\hat{S}_1^2$ is based on sample data for that stratum, and second stage errors of estimation are assumed negligible.

We used equation (13) and collected survey data to estimate a distinct S_1^2 for coho salmon and 1+ steelhead trout in each pool or riffle habitat type/location stratum. Given the total number of units in a particular stratum and the calculated n_E for that stratum, we then calculated an optimistic (i.e. lower than would in practice be achieved) expected total sampling variance for electrofishing ($E[V_E(\hat{Y})]$) using equation (16). This calculation gave an optimistic notion of sampling variance for electrofishing because the solution for n_E was always rounded up, and equation (16) includes no second stage errors. That is, equation (16) assumes that electrofishing would result in (perfect) enumeration of true unit totals.

Finally, we calculated the net relative efficiency (see Hankin 1984) of the visual estimation survey as compared with a survey based exclusively on electrofishing. For each fish species and habitat type/location stratum, net relative efficiencies (NRE) were calculated as

$$(17) \quad \text{NRE (visual electrofishing)} = \frac{E[V_E(\hat{Y})]}{\hat{V}(\hat{Y})} .$$

An Application

Study Site Description

Sampling designs were applied to estimation of habitat areas and abundances of juvenile anadromous salmonids in Cummins Creek, a third-order pristine stream on the central Oregon coast near Yachats. The Cummins Creek basin is 14 km^2 and the stream drains directly into the Pacific Ocean. All work was conducted during July 1985 in the lower 9.6 km of Cummins Creek; a debris jam prevents movement of anadromous salmonids beyond 9.6 km. Flow during the study averaged 0.8m^3/s at the mouth, and water temperatures averaged about 15°C. Stream width ranged from 2 to 16 m and mean depth of individual habitat units ranged from 0.1 to 1.3 m. Gradient averaged 2.5% and exhibited little variation. Stream substrate was cobble with gravel and some sand and small boulders. Debris torrents and beaver dams were common and well-developed side channels and flood terraces occurred throughout the study reach.

Field Survey Methods

Cummins Creek was first stratified into three contiguous reaches (upper, middle, lower) of about the same length based on distribution patterns of juvenile anadromous salmonids (from previous sampling) and large woody debris. The survey began at the mouth and proceeded upstream to the apparent barrier to upstream migration of anadromous salmonids.

Within a given reach, a first team of two individuals classified habitat units as either (1) riffle, (2) pool, (3) glide, or (4) side channel following Bisson et al. (1981). One individual made a visual estimate of the area of each identified habitat unit, and both individuals jointly made accurate measurements of habitat unit areas in systematic samples of 1 out of 10 units in the lower reach and 1 out of 20 units in the middle and upper reaches (for each habitat type, using independent random starts for each habitat type/location stratum). For accurate area measurements, unit widths were measured at 1- or 2-m intervals along the length of the unit and the mean of these measurements was used to estimate mean width. Total unit area was then calculated as the product of unit length times mean width. Estimates of total habitat areas, and estimated variances for these estimates, were calculated for each habitat type/location stratum using equations (3) and (4). Point estimates and variance estimates were then summed across all three reaches to obtain estimates for the entire stream for a particular habitat type.

The first team also marked (with flagging) units in which fish numbers were to be counted by divers approximately 2–5 h later. This delay minimized disturbance to units immediately prior to estimation of fish abundance. Independent counts of fish were made by a team of two divers, using mask and snorkel, for each unit that appeared in a systematic sample of one in five units drawn from each distinct habitat unit type (using independent random starts for each habitat type/location stratum). Divers did not make counts in all units that appeared in these systematic samples, however. Divers occasionally

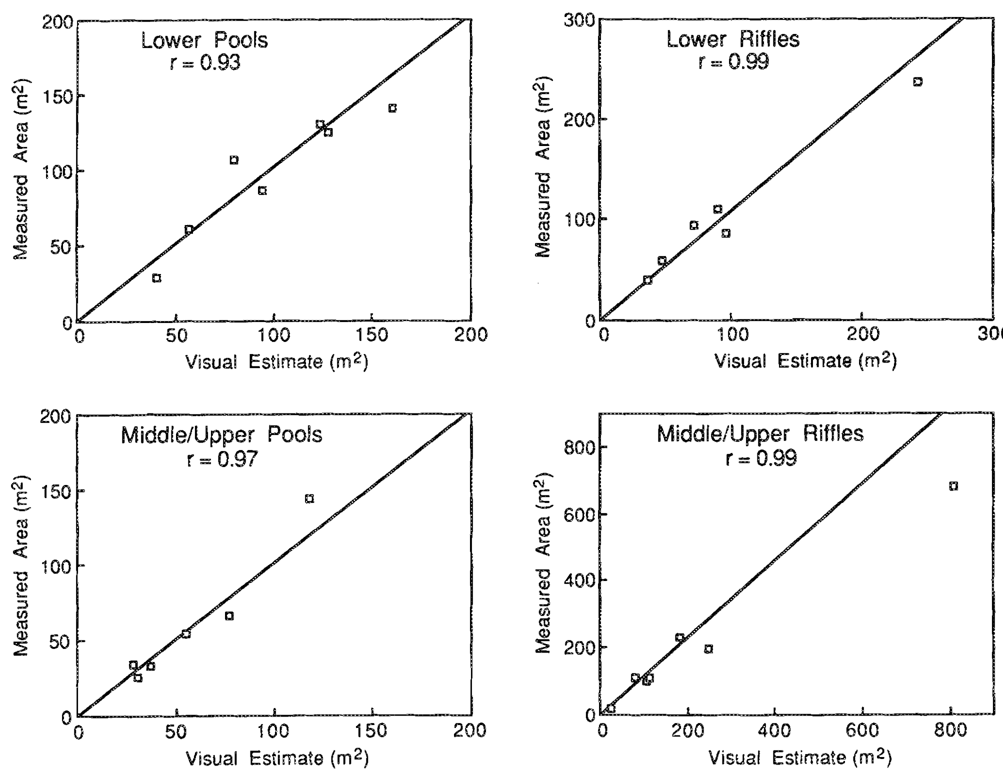

FIG. 1. Plots of accurate measurements against visual estimates of areas for pools and riffles in lower and middle/upper reaches of Cummins Creek in July 1985. Plotted lines are forced through the origin with slopes equal to the estimated ratios of measured areas to visually estimated areas.

TABLE 1. Total number of units (N), number of units accurately measured (n), sample-based estimates of ratios of accurately measured areas to visually estimated areas ($\hat{Q}$), estimated total areas (m²) of all units ($\hat{M}$), estimated variances for estimated total areas ($\hat{V}(\hat{M})$), and 95% confidence bounds for estimated total areas (95% C.I.) for pools and riffles in lower, middle/upper, and all reaches combined of Cummins Creek in July 1985. Visual estimates of habitat unit areas were made for all units.

Reach	N	n	$\hat{Q}$	$\hat{M}$	$\hat{V}(\hat{M})$	95% C.I.
Pools						
Lower	65	7	0.990	6 141	119 827	±875
Middle/upper	134	6	1.029	8 284	448 315	±1721
All reaches				14 425	568 142	±1938
Riffles						
Lower	62	6	1.066	12 556	159 155	±1026
Middle/upper	124	7	0.926	19 208	3 846 554	±4799
All reaches				31 764	4 005 709	±5146

TABLE 2. Estimated total area (m²) of all habitat units ($\hat{M}$), unadjusted totals of visual estimates (T_x), total number of habitat units (N), estimated average areas ($\hat{\bar{m}}$), and unadjusted average areas from visual estimates ($\bar{x}$) for pool and riffle habitat type units in lower, middle, and upper reaches of Cummins Creek in July 1985.

Habitat type/ location stratum	N	$\hat{M}$	T_x	$\hat{\bar{m}}$	$\bar{x}$
Lower pools	65	6 141	6 200	94.4	95.4
Middle pools	67	5 925	5 758	88.4	85.9
Upper pools	67	2 358	2 292	35.2	34.2
Lower riffles	62	12 556	11 782	202.5	190.0
Middle riffles	67	11 598	12 525	173.2	187.0
Upper riffles	57	7 670	8 283	134.5	145.3

failed to observe flagging before walking past or through a unit. In all such instances but one, the divers proceeded to the next unit (of a particular habitat type) and made counts in that unit. They then reverted to the original unit sampling sequence. In addition, some selected riffle units in the upper reach of Cummins Creek were very shallow and were extremely difficult to sample by snorkeling. These units were sampled by divers but, because we were unsure of the effectiveness of such efforts, we later electrofished selected areas within these units to verify diver observations. We assumed that these minor departures from true systematic samples did not substantively affect the essential randomness with which sampled units were selected.

Divers entered the water downstream from a selected unit and proceeded slowly upstream, identifying species and/or age-class of fish and counting fish. The two divers positioned themselves near the midline of a selected unit and moved through the unit parallel to one another, using hand signals to coordinate movements. Species and numbers of fish counted were recorded on Plexiglas slates that had surfaces roughened with sandpaper. All observations of fish were made between 0900 and 1600 when visibility was very good, averaging 4–5 m. Species identified and counted included juvenile coho salmon (*Oncorhynchus kisutch*), 0+ and 1+ steelhead trout (*Salmo gairdneri*), and cutthroat trout (*S. clarkii*).

Diver counts were calibrated for each fish species and for each habitat type against a more accurate method of estimation in one out of three pools and riffles (of those snorkled) in the lower and middle reaches and in one out of four pools and riffles (of those snorkled) in the upper reach. These calibration units were a systematic subsample drawn from those units previously snorkled.

As a more accurate method of estimation, we used the Moran–Zippen equal effort (electrofishing) removal method estimator (Seber 1982), applied separately to each species or species/age-class. A five-member team made successive timed removals (passes), using two electrofishing units, in a selected unit until the numbers of fish of each species removed on a particular pass were either zero or less than 10% of those removed during the previous pass. The large size of the electrofishing crew was deemed necessary in order to obtain population estimates with narrow confidence bounds. Many of the sampled units, particularly in the lower and middle reaches, were too large and complex to be sampled effectively with a single electroshocker. Mean numbers of passes per unit were 2.9 for pools (range 2–4) and 2.2 for riffles (range 2–3).

If calculated bounds on errors of estimation of fish abundance based on removal method estimation were ≤3 fish for a given unit, then we regarded the estimated number present as sufficiently close to the true number of fish present to warrant use of this datum in calibration of diver counts. If calculated confidence intervals did not meet this criterion, then we omitted such data from those used for calibration. We assumed that the relation established between this more accurate method and diver counts held for all stream reaches for a given habitat type and fish species. We also assumed that those units actually used for calibration constituted an essentially random sample of all units of that habitat type (with respect to the correspondence between diver counts and more accurate estimates).

Diver counts of steelhead trout and coho salmon were often zero in many large upper reach riffles that were difficult to snorkel effectively. To check the validity of these counts, we later electofished many of these units and did not find fish. These units were not included in those used for calibration, however, because their selection was purposive.

Estimated total numbers of fish, by species and/or species/age-class, and variances of these estimates were calculated using equations (5)–(10) for each habitat type/location stratum. Estimates were then summed across all three reaches to generate separate estimates, by species, of the total number of fish in all units of a particular habitat type. Estimates were summed across habitat types to generate estimates of fish abundance, by species, for the entire stream.

Results

We restrict our presentation of survey results to estimation of habitat areas and total abundances of 1+ steelhead trout and coho salmon in the two principal habitat unit types: riffles and pools. Side channels and glides constituted less than 20% of the total number of identified units and less than 5% of the estimated total area of all habitat unit types. Snorkeling was judged not effective for estimation of the numbers of 0+ steelhead trout, and cutthroat trout were present in very small numbers compared with 1+ steelhead trout or coho salmon.

Habitat Areas

Correlations between visually estimated habitat unit areas and accurately measured areas exceeded 0.93 for all riffle and pool habitat/location strata (Fig. 1). Estimated total area of pool habitat was 14 425 m², with 95% confidence bounds of ±1938 m²,

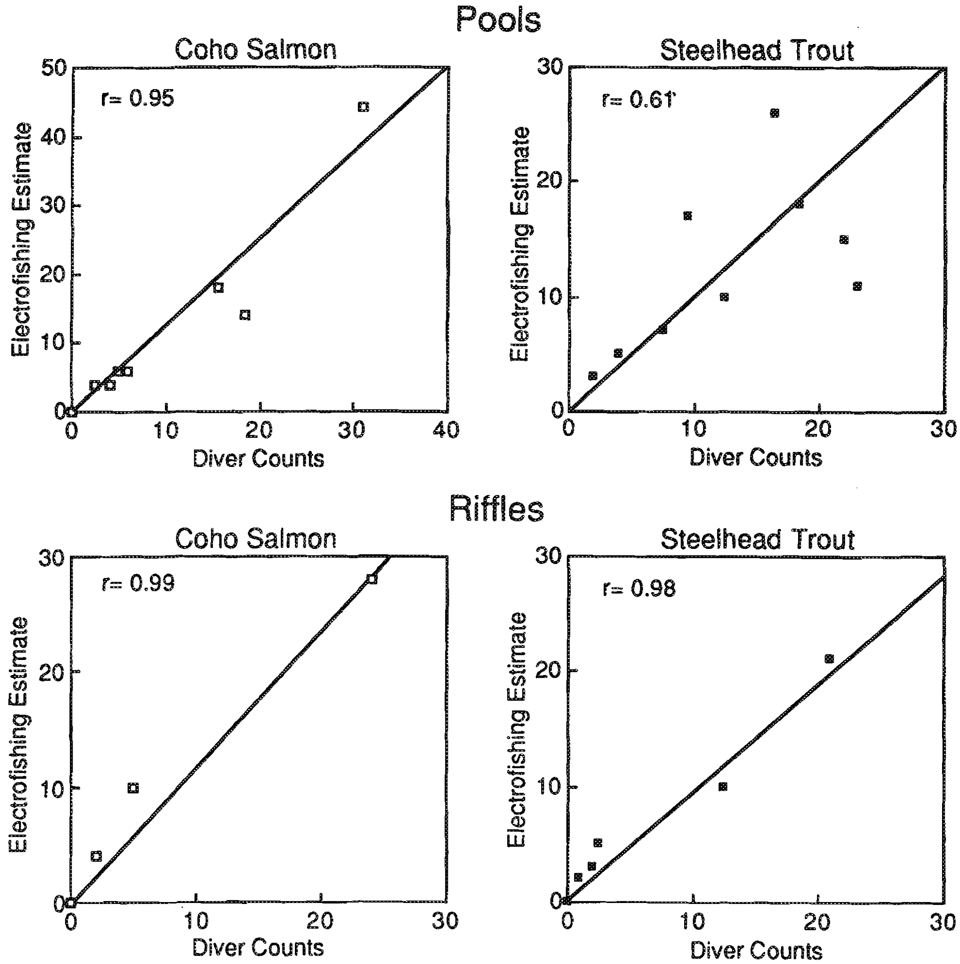

FIG. 2. Plots of numbers of juvenile coho salmon and 1+ steelhead trout estimated present (based on multiple pass removal method estimates) against numbers counted by divers (means of two independent counts) for pools and riffles in Cummins Creek in July 1985. Plotted lines are forced through the origin with slopes equal to the estimated ratios of accurately estimated numbers to visually estimated numbers.

TABLE 3. Independent counts by divers (d_{i1} and d_{i2}) of 1+ steelhead trout in pools in lower, middle, and upper reaches of Cummins Creek in July 1985.

Lower pools		Middle pools		Upper pools	
d_{i1}	d_{i2}	d_{i1}	d_{i2}	d_{i1}	d_{i2}
16	21	6	9	3	3
11	14	5	4	1	1
21	16	33	29	3	3
57	54	21	20	1	1
45	51	23	24	5	7
59	61	17	19	3	2
26	24	8	8	0	0
41	43	8	11	0	0
31	29	15	16	0	0
39	46	19	16	0	0
5	5	13	13	0	0
		4	4	0	0
		10	9		

TABLE 4. Sample correlations between visual estimates of numbers of fish (1+ steelhead trout and juvenile coho salmon) and visual estimates of habitat unit areas for pools and riffles in lower, middle, and upper reaches of Cummins Creek in July 1985. Sample sizes are in parentheses and significant correlations are denoted by superscript "a" ($P < 0.05$) or "b" ($P < 0.01$). No fish were observed in any of the sampled upper riffle habitat units.

Habitat type/ location stratum	Coho salmon (*n*)	Steelhead trout (*n*)
Lower pools	0.420 (11)	0.345 (11)
Middle pools	0.515 (13)	0.177 (13)
Upper pools	0.487 (12)	0.780[b] (12)
All pools	0.538[b] (36)	0.533[b] (36)
Lower riffles	0.419 (10)	0.633[a] (10)
Middle riffles	0.108 (13)	0.132 (13)
All riffles	0.206 (32)	0.277 (32)

and estimated total area of riffle habitat was 31 824 m^2, with 95% confidence bounds of ±5146 m^2 (Table 1). Confidence bounds were thus from 13 to 16% of estimated total habitat areas. Accurate measurements of habitat unit areas were made in about 7% of the identified pools and riffles.

Average estimated areas of pools and of riffles were similar between lower and middle pool and riffle strata, but average unit sizes were smaller in the upper reach (Table 2). Average area of riffles was about twice that of pools within lower and middle reaches and about four times that of pools within the upper reach.

TABLE 5. Estimated abundances ($\hat{Y}$) of 1+ steelhead trout and juvenile coho salmon, total number of habitat units (N), sample sizes for diver counts (n), and estimated variances of abundance estimates ($\hat{V}(\hat{Y})$) in lower, middle, and upper pools and riffles and in all pools, all riffles, and all pools and riffles in Cummins Creek in July 1985.

Habitat type/ location stratum	N	n	Coho salmon $\hat{Y}$	Coho salmon $\hat{V}(\hat{Y})$	Steelhead trout $\hat{Y}$	Steelhead trout $\hat{V}(\hat{Y})$
Lower pools	65	11	2111	112 769	1480	21 185
Middle pools	67	13	1088	36 024	738	17 205
Upper pools	67	12	101	1 266	428	13 943
All pools			3300	150 059	2646	52 333
Lower riffles	62	10	576	40 407	527	24 505
Middle riffles	67	13	230	5 588	236	4 967
Upper riffles	57	9	0	0	0	0
All riffles			806	45 995	763	29 472
All pools and riffles			4 106	196 054	3409	81 805

TABLE 6. Estimated mean numbers of fish per habitat unit ($\hat{\bar{Y}}$) and mean densities per unit of habitat area ($\hat{\bar{Y}}/\hat{\bar{X}}$, in fish/m²) for 1+ steelhead trout and juvenile coho salmon in lower, middle, and upper pool and riffles in Cummins Creek in July 1985.

Habitat type/ location stratum	Coho salmon $\hat{\bar{Y}}$	Coho salmon $\hat{\bar{Y}}/\hat{\bar{X}}$	Steelhead trout $\hat{\bar{Y}}$	Steelhead trout $\hat{\bar{Y}}/\hat{\bar{X}}$
Lower pools	32.5	0.344	22.8	0.241
Middle pools	16.2	0.184	11.0	0.125
Upper pools	1.5	0.043	6.4	0.182
Lower riffles	9.3	0.046	8.5	0.042
Middle riffles	3.4	0.020	3.5	0.020
Upper riffles	0.0	0.000	0.0	0.000

Calibration of Diver Counts

Figure 2 portrays data used to calibrate diver counts of steelhead trout and coho salmon in riffles and pools. Correlations between diver counts and exhaustive removal method estimates of abundance exceeded 0.94 for steelhead trout and coho salmon in pools and for coho salmon in riffles, but diver counts and accurate estimates were less highly correlated for steelhead trout in pools ($r = 0.61$). Estimated ratios of fish present to mean diver counts ($\hat{R}$) were 1.010 and 1.355 for coho salmon in pools and riffles, respectively, and 0.970 and 1.051 for steelhead trout. Thus, on average, diver counts were similar to accurate estimates for coho salmon and steelhead trout in pools and steelhead trout in riffles, but were less than accurate estimates of coho salmon in riffles.

Estimates of Total Fish Abundance

Agreement between diver counts was good for most sample units (Table 3); absolute differences between counts rarely exceeded four fish and were no more than two fish for most units. Estimated numbers of coho salmon and steelhead trout were largest in lower and middle pools and lower riffles whereas estimated numbers of fish were relatively small in middle riffles and upper pools. Diver counts were all zero for both species in upper riffles. Variation among estimated numbers of fish between habitat units was large in all habitat/location strata for both species (with the exception of upper riffles), and no clear trends of fish numbers with unit locations within habitat type/location strata were apparent.

TABLE 7. Estimated first and second stage contributions to estimated variances of the estimated total numbers of 1+ steelhead trout and juvenile coho salmon in Cummins Creek in July 1985. Estimated mean squared deviations between primary unit totals are indicated by S_1^2. No 1+ steelhead trout or juvenile coho salmon were found in the upper riffle habitat stratum.

Habitat type/ location stratum	First stage contribution	Second stage contribution	S_1^2
Steelhead trout			
Lower pools	14 720	6465	46.1
Middle pools	14 699	2506	52.8
Upper pools	13 352	591	43.5
Lower riffles	23 699	836	73.4
Middle riffles	4 462	505	16.0
Coho salmon			
Lower pools	104 914	7854	328.8
Middle pools	26 934	9089	87.7
Upper pools	1 237	28	4.0
Lower riffles	39 363	1043	122.1
Middle riffles	5 273	314	20.8

TABLE 8. Calculated net relative efficiencies of visual estimation surveys compared with surveys based exclusively on electro-fishing/removal method estimation for estimation of total numbers of 1+ steelhead trout and juvenile coho salmon in Cummins Creek in July 1985. Visual estimates of fish numbers were zero in the upper riffle stratum for both species.

Habitat type/ location stratum	Net relative efficiencies: Coho salmon	Net relative efficiencies: Steelhead trout
Lower pools	2.27	1.70
Middle pools	2.02	2.55
Upper pools	3.33	3.29
Lower riffles	2.72	2.69
Middle riffles	3.09	2.68

Estimated numbers of fish present in sampled habitat units were not significantly correlated with habitat unit areas for most habitat type/location strata. For habitat type/location strata where fish numbers and habitat areas were significantly correlated, correlations were relatively low (Table 4) and did not justify use of two-stage ratio estimation (see Hankin 1984).

Table 5 summarizes estimates of total abundance of coho salmon and steelhead trout by habitat type/location stratum. For both coho salmon and steelhead trout, estimated totals for lower pool and lower riffle strata were about twice those for middle pool and middle riffle strata. Within the same stream reach, totals for pools were about 3.5 times the totals for riffles. Estimated total abundance of coho salmon in all pools and all riffles were 3300 and 806, respectively, for a pool and riffle total of 4106. The 95% confidence bound for the pool and riffle total was ±886 fish (±21.6% of the estimated total). Analogous estimates for steelhead trout were 2646 and 763 for all pools and all riffles, respectively, giving an estimated 3409 fish for the pool and riffle total. The 95% confidence bound for the steelhead trout pool and riffle total was ± 572 fish (±16.8% of the estimated total).

The wisdom of stratification by habitat unit type and location was supported by strong differences in average fish densities among habitat type/location strata. Mean estimated densities of fish per unit area were much higher in pools and riffles from the lower and middle reaches than from the upper reach. Densities of fish per unit area in pools were 5–10 times those in riffles within a stream reach for both species (Table 6). Steelhead trout and coho salmon densities were similar within all habitat type/location strata with the exception of upper pools where steelhead trout densities averaged about four times those of coho salmon.

Relative Performance of Visual Estimation Methods

Contributions to estimated variance from the second stage of sampling (reflecting within unit errors of estimation only) were relatively small, in most cases, when compared with contributions from the first stage of sampling (Table 7). The majority of calculations thus supported the a priori contention that errors of estimation of fish numbers within units would be small compared with first stage errors.

From the total number of man-hours expended in various survey activities, we calculated that an average of 0.5 man-hours per unit were expended in visual estimation of fish abundance. Electrofishing/removal method estimation required an average of 10 man-hours per unit. Calculated net relative efficiencies for the visual estimation survey (with calibration) as compared with an electrofishing survey ranged from 1.70 to 3.33 across all species and habitat type/location strata and were at least 2.00 in all situations except for steelhead trout in lower pools (Table 8). The correlation between diver counts and accurate estimates of fish numbers were least strong for steelhead trout in pools.

Discussion

Visual methods proved extremely effective for estimation of habitat areas. Besides providing estimates with narrow 95% confidence bounds ($\pm$13–16% of estimated total areas of pools and riffles), survey results allowed construction of detailed maps of the locations and sizes of all habitat units. Such maps could be used to compare habitat unit sizes and/or sequences during different months of the year, or to evaluate the effects of various habitat alterations. We emphasize, however, that accurate estimation of habitat areas requires that a single experienced observer be responsible for all visual estimates. It is unlikely that visual estimates of habitat areas made by inexperienced observers will be highly correlated with accurate measured areas, and it is unlikely that several different experienced observers will share the same proportional bias of visual estimation.

In the Cummins Creek survey, estimated numbers of 1+ steelhead trout and juvenile coho salmon were not highly correlated with habitat unit sizes. More complicated sampling designs based on ratio estimation or unequal probability selection of habitat units would not have been effective in such a context (see Hankin 1984). It is exactly under such circumstances, however, that visual estimation of fish numbers may prove most effective. The total number of habitat units for which fish numbers could be estimated was dramatically increased through use of visual estimation. This increased first stage sampling fraction resulted in substantial reduction in first stage sampling errors and in total errors of estimation. As indicated by calculated net relative efficiencies, this reduction in first stage errors more than compensated for a modest increase in second stage sampling errors.

The potential for a large first stage sampling fraction offered by visual estimation is, of course, to some degree compromised by the requirement that the visual estimates be calibrated against more accurate estimates. The time and expense necessary to apply some highly accurate method in a subsample of those units within which visual estimates are made will necessarily limit the total number of habitat units that can be sampled for estimation of fish numbers. In the absence of such calibration, however, it is impossible to generate estimates of true fish abundance based on counts of fish made visually while snorkeling. The proportional bias of diver counts may vary among individuals in different surveys, and may also depend on survey conditions and habitat characteristics such as flow, depth, cover, turbidity, and water temperature (G. H. Reeves, unpubl. obs.; Gardiner 1984). Even under the most favorable conditions, diver counts by themselves are nothing more than rough indicators of true abundance.

We addressed the requirement for calibration by applying a multiple pass removal method estimator in a subsample of those units within which fish were counted by divers and by using only those removal method estimates that appeared to be highly accurate. This device was not entirely satisfactory because the true number of fish present in these units was not known with certainty and because certain units could not be used for calibration because of unreliable removal method estimates. Also, to obtain minimally adequate sample sizes for calibration, we had to assume that diver counts and true fish numbers were related in the same fashion across all reaches of the stream for a given habitat type. Although this method of calibration was less than ideal, it did provide an objective basis for judging the bias and reliability of diver counts of fish. We welcome any suggestions for alternative methods of calibration.

Correlations between diver counts and accurate estimates of fish abundance were quite high ($r \geq 0.94$), except for steelhead trout in pools ($r = 0.61$). The low correlation for steelhead trout may be attributable to the behavior and microhabitat utilization of juvenile trout in pools. Trout were closely associated with the bottom substrate and were often difficult to see. In contrast, coho salmon were more surface-oriented and were easier to observe, particularly when light intensity was reduced. Hartman (1965) reported similar differences in microhabitat distribution of coho salmon and steelhead trout. Everest and Chapman (1972) also found steelhead trout in pools to be closely associated with the substrate.

The behavioral responses of coho salmon and steelhead trout to the presence of divers also differed. Trout were more skitterish and moved to cover more quickly and frequently than salmon, especially in smaller units. Because of this difference in behavioral response to divers, the protocol used by divers was to scan the bottom immediately upon entering a pool and to count trout before salmon.

The patterns of distribution and abundance of habitat units and fish numbers that we found in Cummins Creek suggest that attempts to assess fish abundance based on so-called "representative reaches" are unlikely to provide meaningful notions of true fish abundance. We found substantial changes in size and composition of habitat units and in fish species composition and abundance along the length of this stream. About twice as many fish were found in pools in the lower section of Cummins Creek than in the middle or upper sections. Average fish densities (per unit area) in pools were from 4 to 15 times those in riffles. Essentially no 1+ steelhead trout or juvenile coho salmon were present in riffles in the upper section. Mean pool size was larger and pools made up a greater proportion of total habitat area in the lower section than in the middle and upper sections. These examples suggest that extrapolation from data collected in only one or several "representative" reaches could give a highly biased and very misleading picture of true fish abundance.

These changes in distribution of habitat unit sizes and fish numbers also support our construction of habitat type/location strata. Future abundance surveys could take further advantage of these changes in distribution of habitat unit sizes and fish numbers by allocating sampling effort according to estimates of first stage variation (S_1^2) within different habitat type/location strata. Estimates of S_1^2 for coho salmon and 1+ steelhead trout were 122.1 and 73.4, respectively, in lower riffles, 20.8 and 16.0 in middle riffles, and were both zero in upper riffles (no fish were present). For coho salmon in pools, estimates of S_1^2 were 328.8, 87.7, and 4.0 in lower, middle, and upper pools, respectively. According to rules for optimal (Neyman) allocation in stratified sampling (Cochran 1977, Section 5.5.), sample sizes per habitat type/location stratum should be proportional to the products of the stratum size (number of habitat units) and the square root of S_1^2. Thus, optimal allocation of the Cummins Creek survey would result in selection of a large sample size from the lower reach, an intermediate sample size from the middle reach, and a small sample size from the upper reach. Optimal systematic sampling intervals might be 1 in 3, 1 in 6, and 1 in 12 in lower, middle, and upper reaches, respectively.

We believe that the sampling designs we have presented in this paper will prove practical for estimating fish abundance and habitat areas in many small streams. The success of this kind of sampling design will depend, however, on the experience of field personnel and on accurate bookkeeping during survey activities. Divers must be experienced, and they must have established protocols for communicating with one another and for recording fish numbers by species and/or species/age-class. Individuals responsible for identifying habitat unit types and flagging units for later sampling by divers must maintain accurate independent numbering sequences for each habitat unit type. Any lapse of bookkeeping will result in failure to sample a unit or in sampling a unit that should not appear in a systematic sample. If such errors are frequent rather than rare, they may seriously compromise any valid statistical analysis of collected survey data using formulas presented in this paper. The solid performance of a stream survey based on visual estimation that we report in this paper can only be achieved with experienced divers and with careful attention to the details of bookkeeping.

Acknowledgements

We thank Frank Leone, Thomas Dewberry, Gary Susac, and Rob Hanneman for their assistance in collection of field data.

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Appendix. Some Comments on Our Use of Systematic Sampling

We have proposed the use of systematic selection of habitat units to circumvent the need for a preexisting map of all habitat unit locations, and to simplify selection of units in a practical field setting. Systematic selection of units will outperform simple random selection when there is a linear trend of fish numbers with unit location, and will perform as well as simple random selection when fish numbers are unrelated to habitat unit locations. Systematic selection will perform poorly when there is a regular periodic trend of fish numbers with unit locations, and when the systematic selection interval, k, coincides with such a trend (e.g. see Cochran 1977, Sections 8.6–8.8). We regard the possibility of this last situation as remote in the context of small stream surveys.

When systematic selection of units is used, however, equation (9) will give a statistically unbiased estimate of true total fish numbers only if $N/k = n$ (i.e. N/k gives an integer result), or if a circular systematic selection method is used to ensure that sample size is fixed (Murthy 1977, Section 5.2). In practice, it is unlikely that N/k will give an integer result. Also, the device of circular systematic selection may be impractical in a stream survey context.

A statistically unbiased estimator for the total number of fish within a habitat type/location stratum can be obtained using a simple modification of equation (9) (Murthy 1977, Section 5.1):

$$(9') \quad \hat{Y} = k \sum_{i=1}^{n} \hat{y}_i .$$

Equation (9′) compensates for the fact that, when $N/k \neq n$, the sample size n may take on one of two different values depending on the unit location of the original random start. We have not advocated routine use of this well-known unbiased estimator, however.

We have hesitated to recommend general use of equation (9′) because field experience in application of our proposed sampling designs suggests that one or more units that should appear in a systematic sample may be missed due to bookkeeping or other errors (see An Application). If a unit were missed, then the sum of estimated unit totals for sampled units would differ from the expected total (for a particular systematic sample) by the total for the missed unit. In such a situation, application of equation (9′) would therefore result in a very serious negative bias. If execution of the proposed design were flawless (i.e. no units were missed), however, use of equation (9′) would be preferred to use of equation (9).