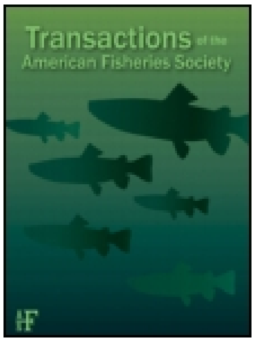

Transactions of the American Fisheries Society

ISSN: 0002-8487 (Print) 1548-8659 (Online) Journal homepage: http://www.tandfonline.com/loi/utaf20

Comparison of Visual Survey and Mark–Recapture Population Estimates of a Benthic Fish in Hawaii

Ernie F. Hain, Bradley A. Lamphere, Michael J. Blum, Peter B. McIntyre, Stacy A.C. Nelson & James F. Gilliam

To cite this article: Ernie F. Hain, Bradley A. Lamphere, Michael J. Blum, Peter B. McIntyre, Stacy A.C. Nelson & James F. Gilliam (2016) Comparison of Visual Survey and Mark–Recapture Population Estimates of a Benthic Fish in Hawaii, Transactions of the American Fisheries Society, 145:4, 878-887, DOI: 10.1080/00028487.2016.1159610

To link to this article: http://dx.doi.org/10.1080/00028487.2016.1159610

Published online: 29 Jun 2016.

Transactions of the American Fisheries Society 145:878–887, 2016

ISSN: 0002-8487 print / 1548-8659 online
DOI: 10.1080/00028487.2016.1159610

ARTICLE

Comparison of Visual Survey and Mark–Recapture Population Estimates of a Benthic Fish in Hawaii

Ernie F. Hain*
Center for Geospatial Analytics, North Carolina State University, Box 7106, Raleigh, North Carolina 27695, USA

Bradley A. Lamphere
Department of Biology, North Carolina State University, Box 7617, Raleigh, North Carolina 27695, USA

Michael J. Blum
Department of Ecology and Evolutionary Biology, Tulane University, 400 Lindy Boggs Building, New Orleans, Louisiana 70118, USA

Peter B. McIntyre
Center for Limnology, University of Wisconsin, 680 North Park Street, Madison, Wisconsin 53706, USA

Stacy A.C. Nelson
Center for Geospatial Analytics, North Carolina State University, Box 7106, Raleigh, North Carolina 27695, USA

James F. Gilliam
Department of Biology, North Carolina State University, Box 7617, Raleigh, North Carolina 27695, USA

Abstract
Visual surveys are conducted to rapidly estimate population densities of stream fishes, often without calibration against more established or more widely used methods to determine precision and accuracy or to correct for potential biases. We compared population density estimates from a visual survey (VS) point quadrat method widely used in Hawaii with estimates from "in hand" individual and batch mark–recapture (BMR) methods. Visual survey sampling and individual mark–recapture (IMR) sampling were conducted in three watersheds that represent gradients of land use and prevalence of nonnative poeciliid fishes on the Island of Hawaii. Focusing on adult O'opu Nākea *Awaous stamineus*, VSs were conducted prior to IMR events to allow direct comparisons of results independent of location and time. Density estimates of O'opu Nākea from VS and IMR samplings were strongly correlated, although VS estimates were generally higher and underrepresented exceptionally large fish. Batch mark–recapture estimates of O'opu Nākea densities were conducted for comparison with VSs at 13 sites across the archipelago. Estimates of VSs were not significantly different from BMR estimates. Estimates of VSs also exhibited less variance than did BMR estimates across sites. General linear models showed that the relationship between VS and IMR estimates varied significantly among watersheds but not seasons and that land use was associated with a greater mismatch between VS and BMR estimates of population density. These findings indicate that visual surveys using a point quadrat method are an efficient and accurate approach for estimating the abundance of small benthic fishes, such as O'opu Nākea, in wadeable streams and that obtaining absolute densities or size distributions from VS methods would benefit from a calibration with IMR not BMR estimates.

*Corresponding author: ernie_hain@ncsu.edu
Received July 15, 2015; accepted February 23, 2016

Estimating population density and assemblage composition is fundamental to the management and conservation of stream fishes. Logistical constraints sometimes force a compromise between sampling effort (i.e., speed and extent) and accuracy (i.e., bias and repeatability) of fish density estimates. As an alternative to traditional "in-hand" methods to estimate density, a visual survey (VS) is often conducted to rapidly obtain estimates in wadeable streams, especially for characterizing populations of small benthic species difficult to capture, yet readily observable via snorkeling (McIntyre et al. 2008).

Traditional approaches for estimating population densities and other attributes require catching fish for data collection. Depletion electrofishing has become the most common "in-hand" sampling method for freshwater fish (Dolloff et al. 1996; Snyder 2003) because it can generate reliable population estimates with little time investment per fish captured. However, logistical and regulatory constraints sometimes limit the use of electrofishing. For instance, depletion sampling can be negatively biased due to reduced capture efficiencies during successive passes (Peterson et al. 2004; Rosenberger and Dunham 2005). Electrofishing capture efficiency often suffers in habitats with deep water or boulder substrates, or when the target species are benthic fish that lack swim bladders (Polacik et al. 2008). Electrofishing also requires specialized training and equipment that limit broad application (e.g., implementation by nonprofessionals). Additionally, electrofishing can impose stress on target and nontarget organisms (Snyder 2003), which has resulted in some jurisdictions, including the state of Hawaii, placing a moratorium on its use. Alternative in-hand methods typically require greater time investment. Individual mark–recapture (IMR) sampling, for example, can yield more accurate and less biased estimates of population attributes than depletion electrofishing and other common nonlethal methods like batch mark–recapture (BMR) sampling (Rodgers et al. 1992; Thurow et al. 2006; Carrier et al. 2009)—especially at low capture rates (Peterson et al. 2004; Carrier et al. 2009)—but it requires greater investment of time per fish and considerable specialized expertise. For BMR sampling, all individuals are given an identical mark during the first capture event. A second capture event allows for a simple point-in-time population estimate, assuming that the population is closed. In contrast, IMR methods require each fish to be given an individual identifying mark and at least three capture events. With IMR data, one can relax the assumption that the population is closed, and therefore estimate demographic rates (e.g., apparent recruitment and survival) as well as population density.

Rapid, noninvasive VS methods are sometimes used in lieu of in-hand methods for population estimation of stream fish. Methods using VSs involve minimal expenses beyond field time, require limited training, and can be implemented in habitats where other methods are not effective (Dolloff et al. 1996; McIntyre et al. 2008; Albanese et al. 2011). Prior studies suggest that population estimates from VS methods compare favorably with estimates from in-hand methods like depletion electrofishing (Mullner et al. 1998; Wildman and Neumann 2003; Jordan et al. 2008; Korman et al. 2010), but VS methods can have systematic biases that can go undetected without calibrating them against at least one other well-constrained method. Some of these biases can still go undetected if both sampling methods are affected by the same biases. For instance, poor water quality may bias VS and depletion methods in the same direction. Calibration using an independent method of population estimation with different sources of bias and where model assumptions are met (i.e., "dual gear" approach) enables a correction for bias and other limitations (Hankin and Reeves 1988), which can enable broader implementation of VS approaches in fisheries management.

Here we compare population estimates from VSs of a small-bodied, native benthic fish in Hawaiian streams to estimates derived from IMR and BMR methods. Unlike prior calibration studies that have primarily focused on large-bodied game species in coldwater streams (e.g., Slaney and Martin 1987; Orell and Erkinaro 2007; Pink et al. 2007), our objective was to assess the accuracy, precision, and bias of a rapid VS method for estimating population densities and demographic characteristics of a small benthic species in warmwater streams. Focusing on Oʻopu Nākea *Awaous stamineus*, an at-risk, amphidromous goby endemic to Hawaii, we structured comparisons between VS and in-hand methods according to land use, fish community structure, longitudinal position, and habitat type to determine whether covariates may influence estimated population density and other demographic attributes. This study thus offers a quantitative framework for use of VS methods in lieu of traditional in-hand census methods for the management of native stream fishes in Hawaii.

METHODS

Our comparisons focused on a VS point quadrat approach that is the standard method for estimating abundance and geographic distributions of stream fishes in the Hawaiian archipelago (Higashi and Nishimoto 2007). The point quadrat method generates more quantitative and consistent density estimates than do transect methods (Baker and Foster 1992). As implemented in Hawaii, the point quadrat method involves snorkelers conducting a visual census of all fish at random points within a stream survey reach. For each point, two random numbers between one and eight are obtained using a random number generator. The first number represents the distance upstream in meters, and the second represents the horizontal position in the stream, where the stream width is divided by eight. Census counts are made at 30 points to obtain a representative sample of microhabitats in the reach. At each point, the species and relative size of all fish are recorded within an observation area of 1 × 1 m; the small quadrat size ensures that all fish can be counted nearly instantaneously, including those in smaller size-classes (Baker and

Foster 1992). Fish sizes are estimated, and population densities are calculated as the number of fish recorded in quadrats divided by the number of quadrats surveyed. Observers are trained to estimate fish sizes by first estimating the size of known objects under water using a hand-held metric ruler. When measuring O‘opu Nākea, observers determined size estimates from a distance of no more than 1 m. Brewer (2013) demonstrated that the size of small fish can be accurately estimated by trained observers.

We compared VS to IMR population estimates of adult O‘opu Nākea (TL > 40 mm) in nine 60-m reaches within three watersheds on the Island of Hawaii (Figure 1). The 60-m length represented a compromise between habitat diversity and logistic restraints. For these streams, this length allowed us to select study sites that contained at least two pools and two riffles, but were small enough to capture a large percentage of the resident fish. O‘opu Nākea is one of five species of stream fish endemic to Hawaii (Lindstrom et al. 2012). Like the other four species, O‘opu Nākea is a benthic gobioid with an amphidromous life history (Hogan et al. 2014) that is afforded protection by the state of Hawaii as a species of conservation concern (Walter et al. 2012). The study sites were chosen to capture gradients in land use and fish communities. The three watersheds, Hi‘ilawe, Hanawī, and Maili, exhibited little, moderate, and heavy development, respectively (Table 1; Figure 1). While all three watersheds supported high densities of native fishes, only the Maili watershed contained introduced poeciliids at all three sites. Poeciliids, which are indicators of invasive fish assemblages in Hawaiian streams (Blum et al. 2014), were only observed at the lowest site in the Hi‘ilawe watershed, and were absent from all sites in the Hanawī watershed. At each site, we conducted a point quadrat VS following Higashi and Nishimoto (2007). Individual O‘opu Nākea were then caught with hand nets, temporarily anesthetized with tricaine methanesulfonate (MS-222), given

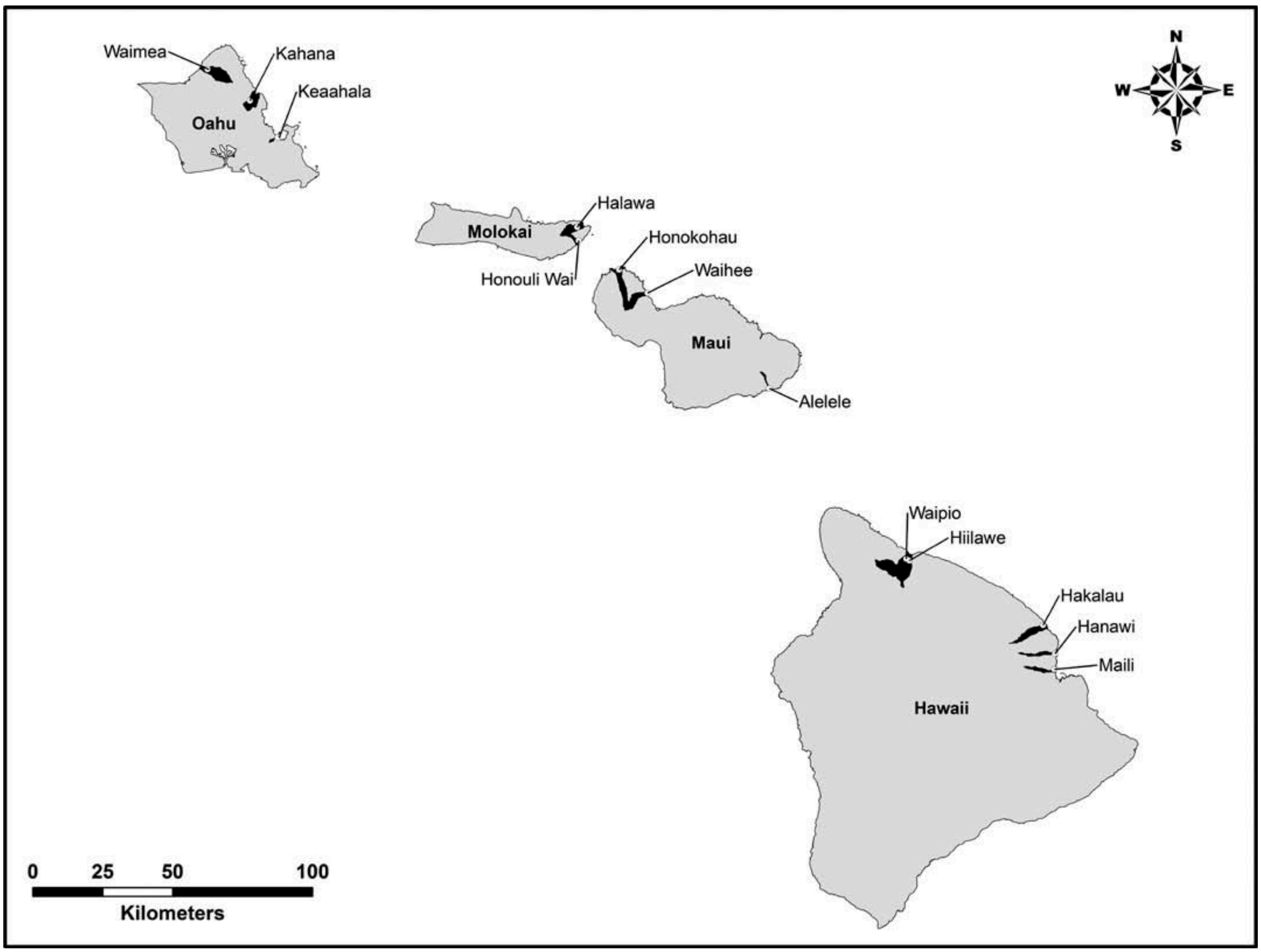

FIGURE 1. The location of visual survey, individual mark–recapture, and batch mark–recapture study sites throughout the Hawaiian Archipelago (except for Kauai) as listed in Table 1.

TABLE 1. Numbers of individual O'opu Nākea encountered in VSs (N_o = number of observed fish), batch mark–recapture (N_m = number of fish marked; N_c = number of captured fish; N_r = number of recaptured fish), and individual mark–recapture (N_{tm} = number of total marked fish; N_{tr} = number of total recaptured fish, including fish recaptured multiple times) per site. The percent of agriculture and urban land uses within the watershed (%AgUrb) was calculated from the 2001 National Land Cover Database, where AgUrb = the sum of all developed and planted or cultivated land use categories. See Figure 1 for location of individual mark–recapture and batch mark–recapture sites.

					Visual survey		Batch mark–recapture				Individual mark–recapture		
Site	Island	Latitude	Longitude	%AgUrb	Events	N_o	Events	N_m	N_c	N_r	Events	N_{tm}	N_{tr}
Hi'ilawe, low[a]	Hawaii	20.10716	–155.59639	45.41	7	30					7	115	95
Hi'ilawe, mid	Hawaii	20.10434	–155.59578	45.58	6	71					6	240	260
Hi'ilawe, high	Hawaii	20.09957	–155.59500	39.14	6	22	1	18	16	12	7	141	156
Hanawī, low	Hawaii	19.80502	–155.09163	27.17	7	22					7	71	70
Hanawī, mid	Hawaii	19.80522	–155.09358	26.14	6	12	1	37	26	21	6	109	104
Hanawī, high	Hawaii	19.80572	–155.09573	26.11	7	57					7	206	122
Maili, low[a]	Hawaii	19.75524	–155.09521	37.97	7	71	1	65	32	15	7	294	163
Maili, mid[a]	Hawaii	19.75397	–155.09642	37.54	7	62					7	227	73
Maili, high[a]	Hawaii	19.74825	–155.11227	30.95	7	47					7	171	106
Waipio, high	Hawaii	20.10473	–155.60442	18.54	1	8	1	35	35	5			
Hakalau, low	Hawaii	19.89755	–155.13340	5.25	1	3	1	20	13	2			
Alelele, low	Maui	20.64808	–156.08473	6.10	1	44	1	76	56	21			
Waihee, low[a]	Maui	20.94750	–156.50957	18.31	1	8	1	33	27	8			
Honokohau, low	Maui	21.02077	–156.60893	0.92	1	3	1	31	29	9			
Halawa, mid	Molokai	21.15497	–156.75615	2.51	1	28	1	121	121	77			
Honouli Wai, high[a]	Molokai	21.11246	–156.75009	17.07	1	13	1	30	24	9			
Keaahala, mid[a]	Oahu	21.41553	–157.81065	85.80	1	75	1	69	84	12			
Kahana, mid[a]	Oahu	21.53346	–157.89333	4.65	1	7	1	37	35	11			
Waimea, high	Oahu	21.63064	–158.04265	0.00	3	8	1	9	7	1			

[a] Indicates poeciliids present at site.

individual elastomer marks, and returned to their original position in the stream. A snorkel survey and recaptures were subsequently conducted at each site six to seven times at 4–6-week intervals from June 2010 to March 2011. Weight, length, and overall condition were recorded for each captured fish, and fish caught for the first time were marked. Over 1,500 individuals were marked over the course of the study (Table 1). Population densities for individual and aggregated IMR events at each site were calculated in the program MARK using the POPAN parameterization (White and Burnham 1999). Model parameters were selected to allow survival and capture probability to vary between the dry sampling period (June–October) and the wet sampling period (November–March).

In addition to IMR estimates, we compared population densities estimated by point quadrat snorkel surveys with BMR estimates of adult O'opu Nākea at 13 sites across the archipelago (excluding Kauai) from March to July 2011 (Table 1; Figure 2), which precluded direct comparisons between VS, IMR, and BMR estimates across study sites. At each site, we conducted a VS and then attempted to net all adult O'opu Nākea. Fish were temporarily held in sealable, labeled, storage bags. A small flag was placed in the stream channel where each fish was caught. Captured fish were temporarily anesthetized with MS-222, given an identical elastomer mark, and returned to their original position in the stream. Recaptures were conducted the following day. Over 500 individuals were marked over the course of the study (Table 1). We used the Lincoln–Peterson estimator with Chapman corrections to calculate densities per unit area from BMRs at each site (Chapman 1951).

To compare VS with mark–recapture density estimates, we first ran a geometric mean (GM) regression with no y-intercept and compared the regression slope with a 1:1 slope line. We used GM regression, rather than ordinary least squares, because it is more appropriate when the measurement error of each variable is expected to be of similar magnitude (McArdle 2003). We transformed all population density estimates as $\log(x + 1)$ values prior to analysis so that variances were homoscedastic.

We also undertook comparisons to determine what combination of VS data and environmental covariates best predicted the density estimates obtained from mark–recapture sampling.

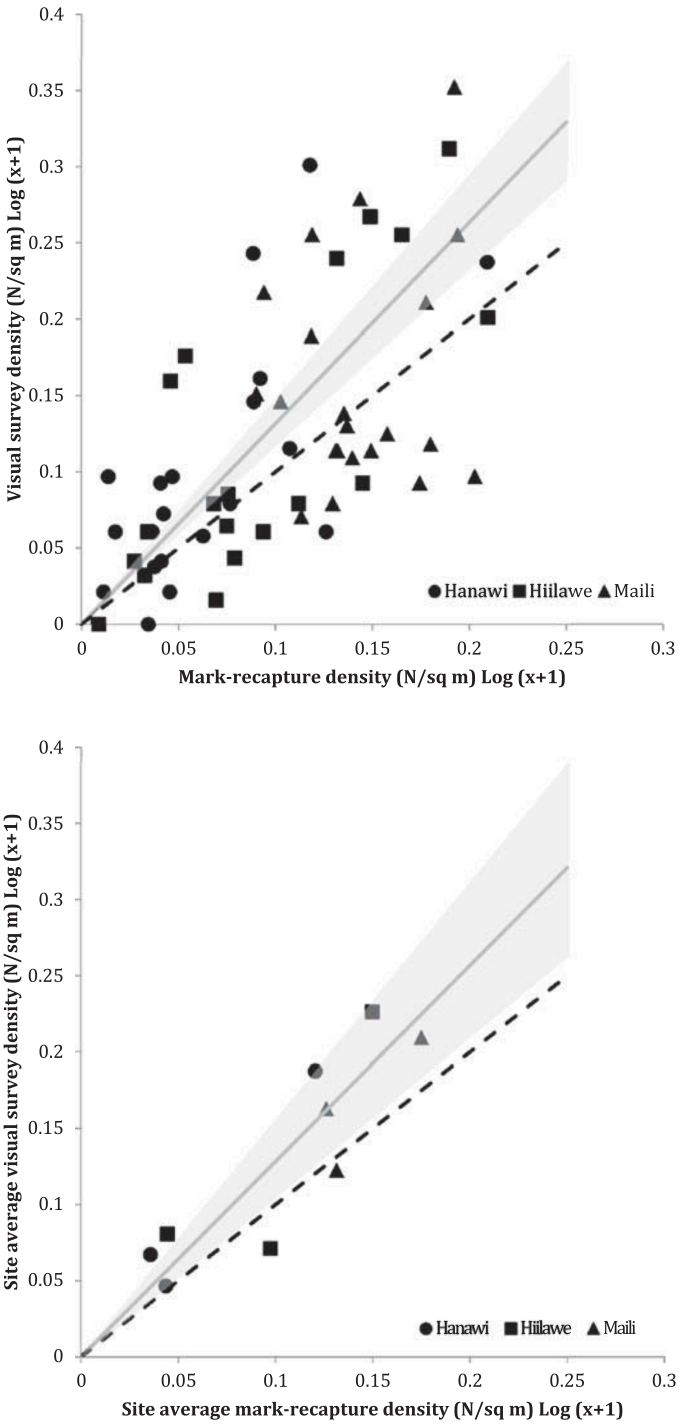

FIGURE 2. Geometric mean regression (solid gray line, gray area = 95% CI) of IMRs and VSs (individual sampling events) with 1:1 line (dashed black line) for reference (top panel). Geometric mean regression of IMRs and VSs averaged per site with 1:1 line for reference (bottom panel).

Predictor variables for the IMR density model (N = 60) included VS density, poeciliid presence (coded as 1 = present and 0 = absent), watershed, site position in watershed (coded as 1 = upstream, 2 = middle, and 3 = downstream), and sample month, which was coded as a categorical variable because we expected a nonlinear relationship between season and density. Predictor variables for the BMR density model (N= 13) included VS density, poeciliid presence, and percent agricultural and urban land cover in the watershed (as described in Blum et al. 2014). We used general linear models to assess the significance of each variable and their effect sizes (partial η^2). We also calculated the corrected Akaike information criterion (AIC_c) for subsets of the variables to obtain model-averaged estimates and SEs for each coefficient (Burnham and Anderson 2002). Significantly positive, model-averaged coefficients for a covariate would indicate that it tends to increase mark–recapture densities relative to the VS estimate at the site. Because the IMR and BMR data sets overlapped at only three sites, it was not possible to conduct a meaningful three-way analysis of density estimates.

We additionally used Kolmogorov–Smirnov tests to compare estimates of population size structure from VS versus IMR methods, and VS versus BMR methods (Sokal and Rohlf 1995). Kolmogorov–Smirnov tests were used to determine whether watershed identity, position in watershed, month of sample, and poeciliid presence altered the direction or magnitude of differences between the size distributions obtained from VS and mark–recapture sampling. All analyses were completed with SAS 9.3 software (SAS Institute, Rockville, Maryland).

RESULTS

Population density estimates from VS and IMR methods were significantly correlated whether the data were averaged for each site ($N = 9$, $R^2 = 0.77$, $\alpha < 0.05$) or whether each event was treated as an independent observation (N = 60, R^2 = 0.41, α < 0.05; Table 2). The slopes of the GM regressions of site-averaged (1.28 ± 0.09 [mean ± SD]) and per-observation (1.32 ± 0.09) data were each significantly greater than 1.0 (P < 0.02), reflecting higher overall density estimates from VSs in both analyses (Figure 2; Table 2). Population density estimates from VSs were also sig-

TABLE 2. Regression results for density estimates of Oʻopu Nākea from VS versus mark–recapture approaches (IMR, BMR). Regressions were performed on log(x + 1)-transformed densities. The slope is calculated without an intercept. Standard deviations (SD) were derived from bootstrap with replacement. The null hypothesis (H_0) states that the slope is not different from the 1:1 line. Significant P-values (α < 0.05) indicate that the slope is different from 1.

				95% CI		
Method	R^2	Slope	SD	Lower limit	Upper limit	P-value (H_0 = 1)
BMR	0.41	0.87	0.45	0.72	2.10	0.42
IMR event specific	0.40	1.32	0.09	1.14	1.49	<0.0001
IMR site average	0.77	1.28	0.09	1.07	1.48	0.02

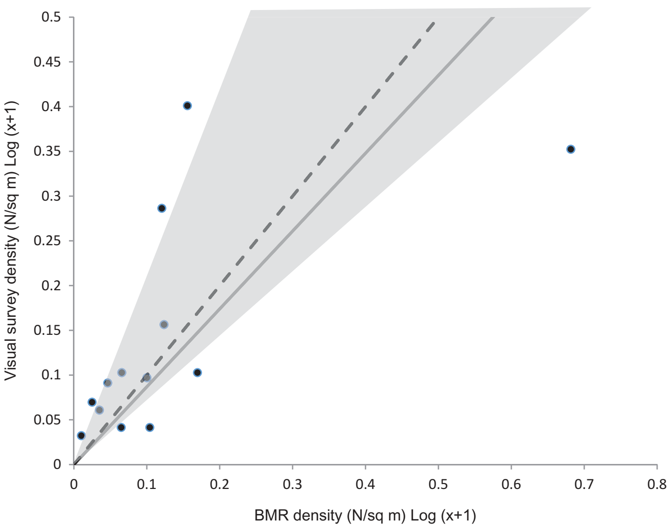

FIGURE 3. Geometric mean regression (solid gray line, gray area = 95% CI) of BMRs and VSs, derived from bootstrap with replacement, and 1:1 line (dashed black line) for reference. The CI is not symmetrical about the mean due to high leverage of the high-density samples.

nificantly correlated with BMR density estimates ($N = 13$, $R^2 = 0.42$, $\alpha < 0.05$; Table 2). Estimates from VSs were higher than Lincoln–Peterson BMR estimates at 8 of 13 sites (Figure 3), but the regression slope (0.87 ± 0.45) was not significantly different from 1.0 ($P = 0.42$; Table 2).

The general linear model for IMRs indicated that VSs were the strongest predictors ($\eta^2 = 0.401$), though watershed and poeciliid presence were also significant predictors (Table 3). The effect of watershed was stronger ($\eta^2 = 0.287$) than the effect of poeciliid presence ($\eta^2 = 0.105$). Model-averaged coefficients indicated that sites in the Hanawi watershed and other sites with poeciliids tended to have lower IMR estimates than estimates from the Maili watershed and other sites without poeciliids. In the BMR model VSs were also strong and significant predictors ($\eta^2 = 0.431$). We also found that anthropogenic land was a strong predictor in the BMR model ($\eta^2 = 0.557$); watersheds with higher levels of agricultural and urban use had relatively high BMR estimates (Table 3).

Across all sites, the size distributions of fish recorded by VSs differed from those collected by IMR methods ($P = 0.004$). Larger (>150 mm) individuals were particularly underreported by VSs relative to IMR methods (Table 4). As a result, the size distributions for IMR methods were more skewed (skew = 1.71), with a longer right tail, compared with the size distributions for VSs (skew = 1.47; Figures 4, 5). The difference in skew between the two sampling methods was consistent across the covariates tested, including watershed, poeciliid presence, and capture event. On the

TABLE 3. General linear models for density estimates of O'opu Nākea from mark–recapture (IMR or BMR) approaches versus VS estimates and environmental covariates. Values in bold italics are significant at α = 0.05; SS = sum of squares and MS = mean square.

	Model-averaged							
Variable	Coefficient	SE	SS	df	MS	*F*-value	*P*-value	Effect size (partial η^2)
			IMR versus VS comparison					
Intercept	***0.0923***	***0.0138***	***0.043***	1	***0.043***	***36.784***	***0.000***	***0.434***
Visual survey	***0.2953***	***0.0581***	***0.038***	1	***0.038***	***32.133***	***0.000***	***0.401***
Poeciliid presence	***–0.0547***	***0.0182***	***0.007***	1	***0.007***	***5.640***	***0.022***	***0.105***
Position	–0.0018	0.0035	0.001	1	0.001	0.867	0.357	0.018
Watershed (all)			***0.023***	2	***0.011***	***9.650***	***0.000***	***0.287***
Hanawi	***–0.0514***	***0.0109***						
Maili	***0.0623***	***0.0123***						
Month (all)			0.009	6	0.002	1.284	0.283	0.138
June	0.0015	0.0030						
July	–0.0007	0.0017						
August	–0.0002	0.0010						
September	0.0012	0.0025						
October	–0.0012	0.0025						
November	–0.0008	0.0018						
Error			0.057	48	0.001			
			BMR versus VS comparison					
Intercept	–0.0479	0.0426	0.011	1	0.011	1.200	0.302	0.118
Visual survey	***0.6154***	***0.2285***	***0.062***	1	***0.062***	***6.827***	***0.028***	***0.431***
Poeciliid presence	0.0034	0.0218	0.000	1	0.000	0.012	0.914	0.001
%AgUrb	***0.0045***	***0.0013***	***0.102***	1	***0.102***	***11.326***	***0.008***	***0.557***
Error			0.081	9	0.009			

TABLE 4. Comparison of the observed size distributions of O'opu Nākea from VSs and IMRs, as well as from VSs and BMRs. A significant *P*-value ($\alpha < 0.05$) in the Kolmogorov–Smirnov test (KS) indicates a difference in the distribution of size structures between the two sampling methods. KSa is the asymptotic Kolmogorov–Smirnov statistic and *D* is the two sample Kolmogorov–Smirnov statistic.

Method	*N*	Mean	SD	Minimum	Maximum	Skew	Kurtosis	KS	KSa	*D*	*P*-value
IMR	2,236	73	27	41	274	1.71	5.48	0.03	1.75	0.1	0.004
VS	394	70	23	42	180	1.47	2.36				
BMR	801	85	32	40	206	0.88	0.37	0.034	1.18	0.01	0.13
VS	167	87	33	40	180	0.95	0.44				

other hand, the size distributions of fish recorded by VS methods were not significantly different from those recorded by BMR methods ($P = 0.13$); a lower-size skew also was found in both VS (skew = 0.95) and BMR methods (skew = 0.88; Table 4; Figures 4, 5).

DISCUSSION

Visual surveys are appealing alternatives to in-hand census methods, especially in areas like Hawaii where noninvasive approaches are favored for monitoring and managing native species of conservation concern. Our results have provided quantitative evidence of both the efficacy and limitations of VS relative to mark–recapture approaches for a small benthic species in Hawaiian streams. We found that density estimates from the visual survey point quadrat method, which is widely used in Hawaii, were significantly correlated with estimates from two effort-intensive, well established, and widely used mark–recapture methods (Table 2). However, the point quadrat method overestimated population densities (Figure 2) and undersampled large size-classes ($P = 0.004$) relative to the IMR method. Thus, while VS data are an effective estimate of relative densities, estimating absolute densities from VS data may require calibration against an in-hand method. Our data further support using IMR rather than BMR methods, as BMR methods exhibited biases in density and size distribution comparable with VS biases (Table 4; Figures 3, 4, 5).

Close correlation of density estimates generated by VS and mark–recapture approaches is consistent with prior comparisons of VS versus other widely used in-hand methods (Mullner et al. 1998; Wildman and Neumann 2003). Previous studies found VS methods underestimated density relative to depletion electrofishing (Mullner et al. 1998; Wildman and Neumann 2003) and rotenone censuses (Ackerman and

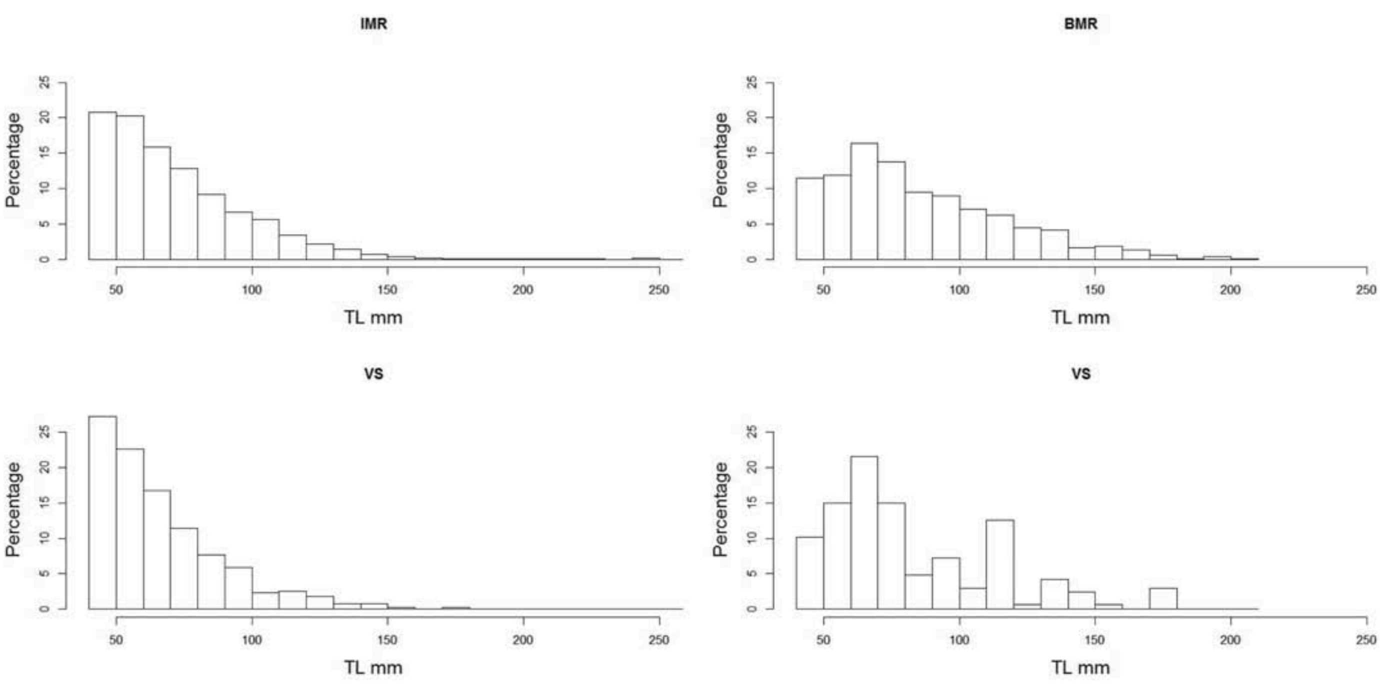

FIGURE 4. Histogram of TLs of observed O'opu Nākea from IMRs ($N = 2{,}236$; upper left panel) versus VSs ($N = 394$; lower left panel) and BMRs ($N = 801$; upper right panel) versus visual ($N = 167$; lower right panel) shown as percent of total observed population from individual size bins. See Table 4 for summary and comparison.

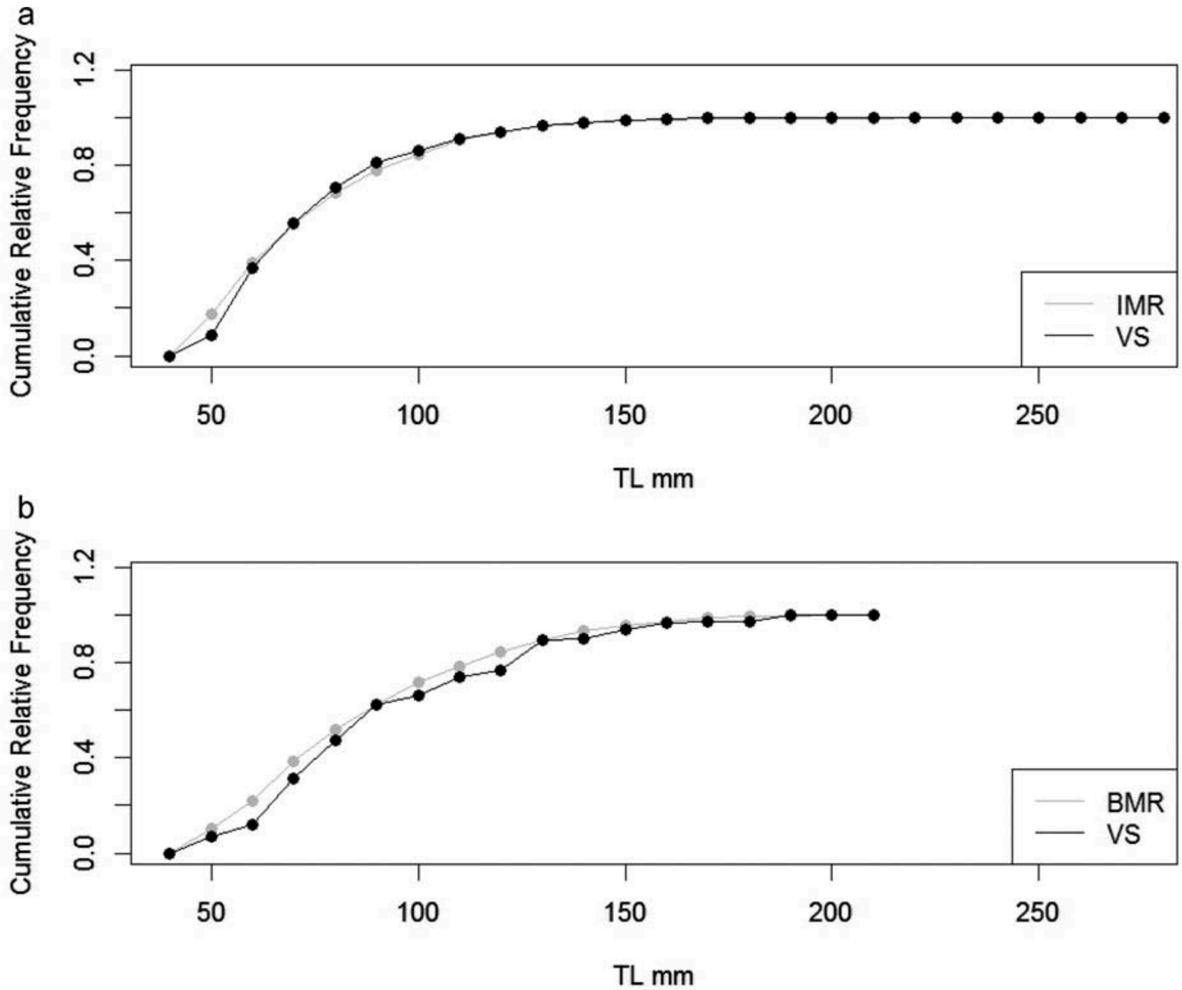

FIGURE 5. Cumulative frequency plots of TLs of observed fish from IMRs versus VSs (upper panel) and versus VSs (lower panel). See Table 4 for summary and comparison.

Bellwood 2000), whereas we found that VSs overestimated densities relative to those determined by IMR methods. Orell et al. (2011) found visual counts to be similar to mark–resight estimates of Atlantic Salmon *Salmo salar*, though visual counts were still lower than known population sizes, particularly when performed by an inexperienced crew (Orell et al. 2011). Differences in VS methods likely contributed to the discrepancy between our results and previous work. While each of the previous studies estimated densities via visual counts of large areas, the point quadrat method relies on randomized subsamples. Consequently, while visual counts can only underestimate densities (unless the same individual is counted multiple times), the point quadrat method can overestimate or underestimate true densities. These results suggest that snorkel surveys using a point-quadrat method may be a more robust method for estimating densities by VSs than estimating by other survey methods, though more work is needed to better determine whether there are habitat and biological conditions that limit the approach.

Differences in the size distributions of fish observed by each method highlight potential biases. Though both VS and IMR methods found that large fish (<150 mm) were rare, they were underrepresented in VS samples relative to those from IMR samples, which indicates that large fish were more likely to be captured at the site than observed within a quadrat (Table 4; Figures 4, 5). This contrasts with previous comparisons, which found that larger fish were overrepresented in visual surveys relative to depletion electrofishing (Wildman and Neumann 2003; Thurow et al. 2006), even though sampling via electrofishing can exhibit size selectivity favoring large individuals (Peterson et al. 2004). For instance, Korman et al. (2010) found capture probabilities of larger juvenile steelhead *Oncorhynchus mykiss* (>60 mm) to be higher for VSs than for electrofishing. However, the reverse was true for smaller, juvenile steelhead (40–60 mm) (Korman et al. 2010).

McClendon and Rabeni (1988) found visual counts and electrofishing counts to be similar for larger centrarchid individuals, but electrofishing underestimated smaller individuals (<100 mm). Mark–recapture studies are also prone to size selectivity if samplers preferentially pursue and capture conspicuous, large fish, though some models can account for sampling bias via size-specific capture probabilities (Schofield et al. 2009). In contrast to visual and in-hand methods that encompass the entire site, the fine grain and limited extent of the subsamples in the point quadrat method facilitate detecting smaller individuals, which helps mitigate or eliminate size selectivity. As all nondestructive sampling methods (i.e., visual counts, point quadrat surveys, depletion electrofishing, and mark–recapture) carry some risk of size selectivity, and therefore bias, size distribution estimates should be considered as an index of size without comparison to a known "true" distribution (i.e., established from exhaustive sampling).

Differences between density estimates from VS and mark–recapture data varied with land use, watershed, and the presence of poeciliids. Shifts in water quantity, turbidity, and substrate arising from agricultural and urban land use (Walsh et al. 2005) can reduce the detection of fish in VSs (Peterson and Rabeni 2001). Consistent with this, the positive coefficient for land use in the BMR model indicated that BMR estimates at impacted sites were greater than would be expected from corresponding VS density estimates, suggesting that VS is more sensitive to human activity than is BMR. Though similar characteristics that influence detectability also correlate with season (Mullner et al. 1998; Ackerman and Bellwood 2000; Wildman and Neumann 2003; Orell et al. 2011), we found no evidence for seasonal effects on the relationships between VS and mark–recapture estimates. And, notably, the watershed effect detected in the IMR model did not parallel land use (Table 3). The IMR model suggests, however, that the presence of poeciliids elevates VS estimates, which could be a consequence of poeciliids distracting observers or influencing goby behavior in a manner that influences conspicuousness.

Evidence that covariates influence VS density estimates indicates that the use of well-supported calibration methods such as IMR on a subset of sites could produce population estimates superior to those derived from other methods (Peterson and Rabeni 2001) with a modest increase in time investment. However, the benefit of investing effort in calibrating site-specific correction factors should be weighed against the added field and analytical effort required. The need for calibration could be reduced, for example, by controlling for effects by scheduling sampling so that each field effort contains a representative number of sites at a targeted treatment level (e.g., developed versus undeveloped sites).

Though further work will be necessary to identify the operative factors that underlie variation in the bias of VS methods, our findings indicate that it is an efficient approach for estimating population density and size structure of O'opu Nākea in Hawaii. Additional advantages, including minimal handling of at-risk study organisms, low survey costs and time demands, and minimal training requirements, provide further justification for use of VS methods in lieu of in-hand methods, particularly in areas where depletion electrofishing is not possible. While an IMR method remains the more reliable and informative means to assess population density and structure, especially if process-oriented demographic data (e.g., recruitment) are of interest, VSs can serve as a robust alternative to in-hand methods to meet management objectives in Hawaii that require reliable indices of native fish abundance in wadeable streams. Dual-gear calibration of VSs using IMR at a subset of sites also appears to be a promising approach for achieving a broader range of management outcomes that require quantitative accuracy and precision, with the understanding that the operational advantages of VSs can be balanced against the need for calibration. Further comparisons between VSs and in-hand methods should examine the accuracy and biases of other common methods, including transect-based VS (Kido 2002; Young and Young 1998) and depletion sampling. Additionally, efforts to quantify the minimum number of area-count survey quadrats necessary to produce accurate estimates of fish density, as well as presence or absence, would facilitate broader application of VSs for research, monitoring, and management of benthic fishes in wadeable streams.

ACKNOWLEDGMENTS

We thank E. Childress, J. Fenner, R. B. Gagne, J. D. Hogan, D. P. Lindstrom, K. Moody, D. Oele, B. D. Policky, R. P. Walter, and A. G. Zajac for assisting with data collection, the Hawaii Division of Aquatic Resources for providing special activity permits and guidance, and the individual and agency land owners who provided access to study sites. The study was funded by the U.S. Department of Defense Strategic Environmental Research and Development Program through project RC-1646, the North Carolina State University College of Natural Resources, and the Southeast Climate Science Center.

REFERENCES

Ackerman, J., and D. Bellwood. 2000. Reef fish assemblages: a re-evaluation using enclosed rotenone stations. Marine Ecology Progress Series 206:227–237.

Albanese, B., K. A. Owers, D. A. Weiler, and W. Pruitt. 2011. Estimating occupancy of rare fishes using visual surveys, with a comparison to backpack electrofishing. Southeastern Naturalist 10:423–442.

Baker, J. A., and S. A. Foster. 1992. Estimating density and abundance of endemic fishes in Hawaiian streams. Department of Land and Natural Resources, Division of Aquatic Resources, Honolulu, Hawaii.

Blum, M. J., J. F. Gilliam, and P. B. McIntyre. 2014. Development and use of genetic methods for assessing aquatic environmental condition and recruitment dynamics of native stream fishes on pacific islands. Strategic Environmental Research and Development Program, Report RC-1646-FR, Alexandria, Virginia.

Brewer, S. K. 2013. Groundwater influences on the distribution and abundance of riverine Smallmouth Bass, *Micropterus dolomieu*, in pasture landscapes of the Midwestern USA. River Research and Applications 29:269–278.

Burnham, K. P., and D. R. Anderson. 2002. Model selection and multimodel inference: a practical information theoretic approach. Springer Science, New York.

Carrier, P., J. S. Rosenfeld, and R. M. Johnson. 2009. Dual-gear approach for calibrating electric fishing capture efficiency and abundance estimates. Fisheries Management and Ecology 16:139–146.

Chapman, D. G. 1951. Some properties of the hypergeometric distribution with applications to zoological sample censuses. University of California Press, Berkeley.

Dolloff, A., J. Kershner, and R. Thurow. 1996. Underwater observation. Pages 533–554 *in* B. R. Murphy and D. W. Willis, editors. Fisheries techniques, 2nd edition. American Fisheries Society, Bethesda, Maryland.

Hankin, D., and G. Reeves. 1988. Estimating total fish abundance and total habitat area in small streams based on visual estimation methods. Canadian Journal of Fisheries and Aquatic Sciences 45:834–844.

Higashi, G. R., and R. T. Nishimoto. 2007. The point quadrat method: a rapid assessment of Hawaiian streams. Bishop Museum Bulletin in Cultural and Environmental Studies 3:305–313.

Hogan, J. D., M. J. Blum, J. F. Gilliam, N. Bickford, and P. B. McIntyre. 2014. Consequences of alternative dispersal strategies in a putatively amphidromous fish. Ecology 95:2397–2408.

Jordan, F., H. L. Jelks, S. A. Bortone, and R. M. Dorazio. 2008. Comparison of visual survey and seining methods for estimating abundance of an endangered, benthic stream fish. Environmental Biology of Fishes 81:313–319.

Kido, M. H. 2002. The Hawaii stream bioassessment protocol, version 3.01. Hawaii Stream Research Center, Honolulu.

Korman, J., A. S. Decker, B. Mossop, and J. Hagen. 2010. Comparison of electrofishing and snorkeling mark–recapture estimation of detection probability and abundance of juvenile steelhead in a medium-sized river. North American Journal of Fisheries Management 30:1280–1302.

Lindstrom, D. P., M. J. Blum, R. P. Walter, R. B. Gagne, and J. F. Gilliam. 2012. Molecular and morphological evidence of distinct evolutionary lineages of *Awaous guamensis* in Hawai'i and Guam. Copeia 2012:293–300.

McArdle, B. 2003. Lines, models, and errors: regression in the field. Limnology and Oceanography 48:1363–1366.

McClendon, D. D., and C. F. Rabeni. 1988. Sampling stream centrarchids: comparing electrofishing and underwater observation. Proceedings of the Annual Conference of Southeastern Association of Fisheries and Wildlife Agencies 40(1986):92–101.

McIntyre, P. B., A. S. Flecker, M. J. Vanni, J. M. Hood, B. W. Taylor, and S. A. Thomas. 2008. Fish distributions and nutrient cycling in streams: can fish create biogeochemical hotspots? Ecology 89:2335–2346.

Mullner, S. A., W. A. Hubert, and T. A. Wesche. 1998. Snorkeling as an alternative to depletion electrofishing for estimating abundance and length-class frequencies of trout in small streams. North American Journal of Fisheries Management 18:947–953.

Orell, P., and J. Erkinaro. 2007. Snorkelling as a method for assessing spawning stock of Atlantic Salmon, *Salmo salar*. Fisheries Management and Ecology 14:199–208.

Orell, P., J. Erkinaro, and P. Karppinen. 2011. Accuracy of snorkelling counts in assessing spawning stock of Atlantic Salmon, *Salmo salar*, verified by radio-tagging and underwater video monitoring. Fisheries Management and Ecology 18:392–399.

Peterson, J., and C. Rabeni. 2001. Evaluating the efficiency of a one-square-meter quadrat sampler for riffle-dwelling fish. North American Journal of Fisheries Management 21:76–85.

Peterson, J., R. Thurow, and J. Guzevich. 2004. An evaluation of multipass electrofishing for estimating the abundance of stream-dwelling salmonids. Transactions of the American Fisheries Society 133:462–475.

Pink, M., T. C. Pratt, and M. G. Fox. 2007. Use of underwater visual distance sampling for estimating habitat-specific population density. North American Journal of Fisheries Management 27:246–255.

Polacik, M., M. Janac, P. Jurajda, M. Vassilev, and T. Trichkova. 2008. The sampling efficiency of electrofishing for *Neogobius* species in a riprap habitat: a field experiment. Journal of Applied Ichthyology 24:601–604.

Rodgers, J. D., M. F. Solazzi, S. L. Johnson, and M. A. Buckman. 1992. Comparison of three techniques to estimate juvenile Coho Salmon populations in small streams. North American Journal of Fisheries Management 12:79–86.

Rosenberger, A. E., and J. B. Dunham. 2005. Validation of abundance estimates from mark–recapture and removal techniques for Rainbow Trout captured by electrofishing in small streams. North American Journal of Fisheries Management 25:1395–1410

Schofield, M. R., R. J. Barker, and D. I. MacKenzie. 2009. Flexible hierarchical mark–recapture modeling for open populations using WinBUGS. Environmental and Ecological Statistics 16:369–387.

Slaney, P. A., and A. D. Martin. 1987. Accuracy of underwater census of trout populations in a large stream in British Columbia. North American Journal of Fisheries Management 7:117–122.

Snyder, D. E. 2003. Electrofishing and its harmful effects on fish. U.S. Geological Survey, Report USGS/BRD/ITR-2003-0002, Denver.

Sokal, R. R., and F. J. Rohlf. 1995. Biometry: the principals and practice of statistics in biological research. Freeman, New York.

Thurow, R., J. Peterson, and J. Guzevich. 2006. Utility and validation of day and night snorkel counts for estimating Bull Trout abundance in first- to third-order streams. North American Journal of Fisheries Management 26:217–232.

Walsh, C. J., A. H. Roy, J. W. Feminella, P. D. Cottingham, P. M. Groffman, and R. D. Morgan II. 2005. The urban stream syndrome: current knowledge and the search for a cure. Journal of the North American Benthological Society 24:706–723.

Walter, R. P., J. D. Hogan, M. J. Blum, R. B. Gagne, E. F. Hain, J. F. Gilliam, and P. B. McIntyre. 2012. Climate change and conservation of endemic amphidromous fishes in Hawaiian streams. Endangered Species Research 16:261–272.

White, G. C., and K. P. Burnham. 1999. Program MARK: survival estimation from populations of marked animals. Bird Study 46(Supplement): S120–S139.

Wildman, T., and R. Neumann. 2003. Comparison of snorkeling and electrofishing for estimating abundance and size structure of Brook Trout and Brown Trout in two southern New England streams. Fisheries Research 60:131–139.

Young, L. J., and J. H. Young. 1998. Statistical ecology: a population perspective. Kluwer Academic Publishers, Norwell, Massachusetts.