Coastal Management, 34:339–349, 2006

ISSN: 0892-0753 print / 1521-0421 online
DOI: 10.1080/08920750600686711

Towed-Diver Surveys, a Method for Mesoscale Spatial Assessment of Benthic Reef Habitat: A Case Study at Midway Atoll in the Hawaiian Archipelago

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We thank more than two dozen fellow NOAA-certified divers for building the safety record of towed-diver surveys, the officers and crew of the NOAA ship *Townsend Cromwell* for logistic support and field assistance, and Greta Aeby for sharing belt-transect data. Permission to work at Midway Atoll National Wildlife Refuge was granted by the Pacific Remote Islands Wildlife Refuge Complex, U.S. Fish and Wildlife Service, Department of the Interior. Will Smith, of the Hawaii Coral Reef and Monitoring Program of the University of Hawaii's Hawaii Institute of Marine Biology, and Michael Coyne, of the Biogeography Program of NOAA's National Ocean Service, assisted with surveys from which a layback model was derived. Funding from the Office of Habitat Conservation at NOAA Fisheries as part of the NOAA Coral Reef Conservation Program has supported this work since 2001, with particular encouragement and facilitation from Tom Hourigan.
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An integrated method for benthic habitat assessment is described, in which divers maneuver boards equipped with digital video, temperature, and depth recorders while being towed behind a small boat. The tow path is concurrently recorded by a GPS receiver, and a layback model is applied to more accurately map the data. Percent cover of salient benthic categories is quantified by whole-image analysis of still frames sampled at 30-s intervals. The results of 15 towed-diver surveys at Midway Atoll in the Hawaiian Archipelago during a mass coral bleaching event are presented to exemplify the method and are compared to results derived from conventional methods. Towed-diver surveys bridge a gap between large-scale mapping efforts using satellite data and small-scale, roving diver assessments, providing a mesoscale spatial assessment of reef habitats. The spatial coverage of towed-diver surveys provides comprehensive data to managers concerning the extent, intensity, differential taxonomic response, and bathymetric correlates of bleaching.

Keywords benthic assessment, coral bleaching, Midway Atoll, towed diver

Introduction

Coastal managers require information on the composition and condition of benthic communities to effectively manage resources. The choice of assessment method depends on multiple factors including the biological and physical variables to be measured, the level of detail (e.g., taxonomic resolution) required, the spatial scale of the communities involved, and the availability of resources such as personnel, equipment, and time. Large-scale assessments using satellite imagery or aerial photographs and GIS technology can generate spatially referenced maps showing the location and size of major habitat types (e.g., NOAA, 2003). Detailed data suitable for mapping bathymetry can be collected with single- or multi-beam sonar (e.g., Miller et al., 2003), and are particularly valuable for constructing habitat maps when coupled with visual data from towed-camera systems (e.g., Rooney et al., 2004). In coral reef ecosystems, managers frequently use percent coral cover as an important indicator of reef status, and rely on data collected *in situ* by divers using a number of accepted methods (e.g., point-intercept transect, video transect, visual quadrat, permanent photo quadrat; reviewed in Hill & Wilkinson, 2004).

The manta tow technique, in which snorkel divers are towed behind a small boat, is a versatile method that has been adapted to census-specific benthic targets including crown-of-thorns starfish *Acanthaster planci* (e.g., Chesher, 1969; Moran & De'ath, 1992), introduced algal species (Rodgers & Cox, 1999), and derelict fishing gear (Donohue et al., 2001). Manta tows have also proved useful for broader benthic habitat characterization (e.g., Kenchington, 1978; Miller & Müller, 1999; Lopez Victoria et al., 2000). A primary advantage of the manta tow technique in habitat characterization is that it enables efficient survey coverage of large areas of reef benthos; a disadvantage is the lack of fine taxonomic resolution that can be observed and recorded compared to surveys conducted by free-swimming divers (Carleton & Done, 1995). The technique has not customarily included a photographic or videographic component (Bass & Miller, 1996) that provides a permanent record of the benthos and that is suitable for quantitative image analysis.

Technological advances in videography over the past decade have catalyzed the development and evaluation of protocols designed to quantitatively assess reef benthos using computer-assisted image analysis (Vogt et al., 1997; Osborne & Oxley 1997; Page et al., 2001; Bernhardt & Griffing, 2001). Most field studies have involved video surveys of multiple, short (10–50 m) transects by free-swimming divers (e.g., Aronson et al., 1994; Lybolt & Eaken, 2000; Ninio et al., 2000; Crabbe & Smith, 2002), from which randomly or regularly selected frames have been assessed for benthic composition and abundance by the projection of random points on the image (e.g., Carleton & Done, 1995; Miller & Müller, 1999). Although such surveys enable reliable, site-specific habitat description, they generally sample only a single habitat, and they do not capture the transitions by which habitat characteristics change over larger spatial scales.

Carleton and Done (1995) coupled the use of a manta tow with a camcorder mounted on the manta-board in an underwater housing so as to record a portion of the benthic survey area; the observer maneuvering the manta-board was equipped with SCUBA rather than snorkel gear. Although the authors report the potential of the technique for sampling on the scale of kilometers, the actual lengths of reported surveys were confined to 200 meters and, despite the SCUBA capacity of the observer, were conducted to maximum depths of three meters. No protocol by which the tow path could be georeferenced was described, an important procedure for linking image to position over large, geomorphic spatial scales.

In 1990, the Honolulu Laboratory of NOAA Fisheries began using SCUBA-diver-controlled towboards equipped with videographic equipment to assess benthic variables considered important to lobster habitat on three emergent banks in the Northwestern Hawaiian Islands (Parrish & Polovina, 1994). Since that time the Honolulu Laboratory has continued to develop an integrated towed-diver survey methodology in response to advances in videographic and georeferencing technology and has adapted the method for mesoscale assessment of coral reef benthic habitats. Our methodology differs from other techniques widely used and reported in that: (a) towed divers regularly survey the reef benthos to the accepted limit of conventional SCUBA, (b) the tow track is mapped through the concurrent recording of GPS positions and depth data, and (c) the data extraction and analysis regime includes percent cover quantification of all identifiable components within sampled frames rather than a point sampling strategy. In this article we present the main components of our integrated methodology, provide a case study of data collected and processed using this methodology during a mass coral bleaching event at Midway Atoll in the Hawaiian Archipelago (Aeby et al., 2003; Kenyon et al., 2004), and compare results with data derived from more conventional belt-transect surveys.

MATERIALS AND METHODS

Personnel Allocation

Four people conduct each towed-diver survey: two SCUBA divers, a coxswain to drive the surface boat, and an additional crew member to deploy and retrieve the towboards, operate GPS units, and record the time at which videorecording begins and ends. Efficiency is enhanced by the four people composing two teams of two divers, such that surface personnel and divers switch roles at the end of each tow survey. One member of each dive team maneuvers a towboard dedicated to recording observations concerning the benthic habitat (“habitat” towboard), whereas the other member of the dive team maneuvers an adjacent towboard dedicated to recording observations of ecologically and economically important fish taxa (“fish” towboard). This article focuses on protocols pertinent to benthic habitat characterization.

Towboards and Accessory Instruments

Constructed of marine-grade plywood and coated in epoxy resin, towboards are equipped with a digital video camera recorder inside an underwater housing with a wide-angle port and color-correction filter, mounted to maintain a viewing angle perpendicular to the bottom. The videocamera automatically records the date and time on the imagery. On each side of the camera bracket, a waterproof, battery-operated laser pointer is mounted, with the inter-laser distance calibrated to project two red dots in the field of view that are 20 cm apart. A depth gauge, digital watch, and alarm chronograph set to emit an auditory signal every 5 min after activation are mounted on a separate bracket. The camera clock and digital watch are synchronized with the clock of the GPS unit used onboard the towboat. Plexiglas strips affixed to the towboard allow insertion of a vinyl data sheet for recording written information pertinent to the overall tow as well as quantitative visual estimates of benthic composition integrated over 5-min periods. A SBE 39 temperature recorder (Sea-Bird Electronics, Inc.) mounted on the towboard electronically records depth, temperature, and time at 5-s intervals. While conducting the videotaped survey, the diver maneuvers the habitat towboard to maintain an estimated distance of 1 m above the substrate. A simple telegraph is operated by the diver who maneuvers the fish towboard to maintain communication with the tow boat, using several prearranged acoustic signals based on dots (short tones) and dashes (long tones).

Each towboard is separately connected to the towboat transom by an adjustable-length (typically 60 m long), 3/8″ inch low-stretch buoyant line. Rather than being directly attached to the towboard, the tow line connects to a short bridle with a stainless steel swivel shackle that allows the diver to disconnect the towboard from the tow line if the towboard becomes grounded and cannot be quickly freed by the diver. Each towboard has a 5-m-long trailing line for the divers to grab if they become detached from the towboard. Divers receive special training in the risks associated with conducting surveys. A standard video survey ($<$ 21 m depth) is 50 min long. At greater depths (21–27 m) the time is adjusted according to no-decompression limits.

Coordination with Collection of GPS Tow Track Data

To georeference all data collected during a tow, a GPS receiver is programmed to record longitude and latitude coordinates every 5 s onboard the tow boat. When the divers are ready to begin videorecording, a prearranged acoustic signal is sent to the tow boat, where the crew member marks a waypoint indicating the start point of the videotape recording. The coxswain drives along a predetermined isobath using a bathymetric chart, depth sounder, and shoreline features (when present) as a guide while maintaining a speed of 2.5–3.5 km/h (1.7–2.5 knots). At the end of the benthic survey, before beginning an ascent to the safety stop, another coded signal is sent to the tow boat to record the time and place at which the video recording ended.

The primary GPS positioning error is the difference between the location of the GPS unit onboard the tow boat and the divers, typically some 55 meters behind the tow boat. To reduce this source of error, a series of tows were conducted in order to model the “layback” difference between the position of the videocamera and the position of the GPS unit on the tow boat. Normal survey protocols were conducted, with the addition of a surface snorkeler being towed directly above the towboard divers while wearing a backpack containing a GPS unit inside a waterproof bag. The coxswain maneuvered the tow boat over a series of courses that varied in frequency and amplitude of curvature to mimic the most conservative and the most extreme deviations of the divers’/snorkeler’s position from the coordinates recorded by the GPS unit on the tow boat during regular surveys.

Tape Processing and Data Extraction

The quantitative analysis of each benthic videotape begins with the capture of single, still frames as the tape is simultaneously played through a computer and a high-resolution monitor. The high-resolution monitor assists with identification of benthic characters that may be difficult to distinguish on the lower-resolution computer screen. If the frame is too blurry because of momentary excessive speed, or more than an estimated 5 percent of the benthos cannot be identified due to shadow, the analyst toggles forward frame by frame until the next frame that is suitable for analysis is reached. Based on preliminary analyses examining the cost/benefit of sampling at 15, 30, 60, or 150-s intervals, a sampling interval of 30 s was selected as best optimizing the joint interests of reproducible results, inter-frame distance, and time required to conduct the analysis.

Each captured still frame is next imported into SigmaScan® Pro (SPSS Science™), a software program that enables calculation of percent cover for each benthic category (e.g., corals) by tracing the outline of each category component (e.g., coral head) using a stylus and graphics tablet. The benthic area (cm^2) included within the frame is determined using the projected pair of red laser dots known to be 20 cm apart, and is used as the denominator in the percent cover calculations for benthic categories within that frame. For frames in which the dots have not been imprinted because of laser malfunction, the number of pixels composing the still image is used as the denominator in percent cover calculations. The number of benthic categories that can be identified from still frames varies according to the geographic localities surveyed; the variation is attributable to different coral faunas. Categories that are consistent among geographic localities include macroalgae, turf algae, coralline algae, invertebrates other than coral, sand, rubble, carbonate pavement, rock, and unencrusted (recently dead) coral. A spreadsheet called up within the SigmaScan® Pro program receives the computed area (in cm^2 or pixels) of each component of each benthic category as the analyst completes tracing it with the stylus. Tracing proceeds until only one category present within the frame remains. These values are then imported into a Microsoft® Excel spreadsheet that has been preformatted with formulas for the calculation of percent cover of each category of imported data. The percent cover of the remaining untraced category is computed by subtracting the sum of the other categories from 100. The time-stamp for the still frame is manually entered. The percent cover data and time stamp from each frame-specific Excel spreadsheet are then compiled into a master spreadsheet from which the quantitative habitat data can be summarized over whatever time/spatial interval is desired.

GIS Data Ingestion, Processing, and Display

GPS data are downloaded directly into GIS using a custom-designed (Hoeke, unpublished) ArcView® extension. Data are downloaded as (1) track data files, containing a position and time stamp every 5 s, and (2) waypoint data files, defining locations of the start and end of the videotaped survey. The customized extension then performs a number of calculations and allows for editing and quality control of the data including (1) a layback calculation to rectify the position of the towboard, (2) merging all track files for a single day, (3) sorting and trimming track files based on waypoint files, interpolating for lost GPS data if necessary, (4) calculating sequential dive numbers, local time, and other attribute fields, (5) adding temperature and depth data, matching SBE 39 and GPS time stamps, and (6) calculating sequential segments for each tow, using segment lengths of 30 s and 5 min to correlate with the intervals over which analytical and *in situ* data are compiled, respectively. The

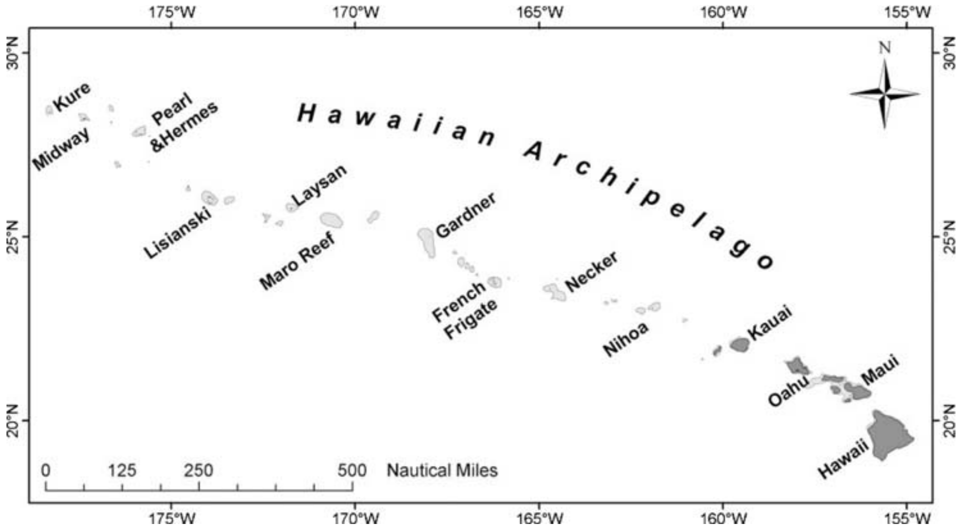

Figure 1. The Hawaiian Archipelago. Midway Atoll is located toward the northwestern end of the archipelago. Lightly shaded areas represent 100-fathom isobaths.

extension then adds video analysis data (30-s segments) and *in situ* observational benthic data (5-min segments) as separate files. These separate files are spatially represented as polyline files, where each segment of analysis/observation data is a separate polyline. The nodes of these polylines match the nodes in the track file. The attribute tables (*.dbf) of the analysis/observation tables are tied to the track file's attributes by the dive number and the respective segment number. The resulting georeferenced observations can be mapped in conjunction with IKONOS-acquired imagery and viewed on spatial scales of resolution varying from 33 m (the average separation between sequential frames) to the entire length of a tow (i.e., several kilometers).

Case Study, Midway Atoll

Midway Atoll (28°15′N, 177°20′W) is one of the northwestern-most atolls in the Hawaiian Archipelago (Figure 1). Between September 20 and 25, 2002, 15 towed-diver surveys were conducted at Midway Atoll to assess a mass coral bleaching event (Aeby et al., 2003; Kenyon et al., 2004) (Figure 2). Video analysis was conducted by a single analyst. The categories of live coral that could be recognized in recorded videotapes were *Pocillopora*, massive/encrusting *Porites*, *Porites compressa*, *Montipora*, and other live coral (e.g., *Pavona*, *Fungia*). For each category, percent cover of bleached and unbleached coral was separately quantified. Incidence of bleaching was computed as the percentage of coral cover that was bleached. To examine the correlation between depth and incidence of bleaching, video frames were matched with depth records using the time stamps.

Between September 19 and 25, 2002, belt transects enclosing 50 m^2 or 100 m^2 at each of 20 sites were conducted according to the methods of Maragos et al. (2004) (Figure 2), in which the number of colonies as well as the number with bleached tissue was tallied by genus. Incidence of bleaching was computed as the percentage of colonies with bleached tissue. To examine the correlation between depth and incidence of bleaching, for each site the percentage of all colonies with bleached tissue was paired with that site's depth.

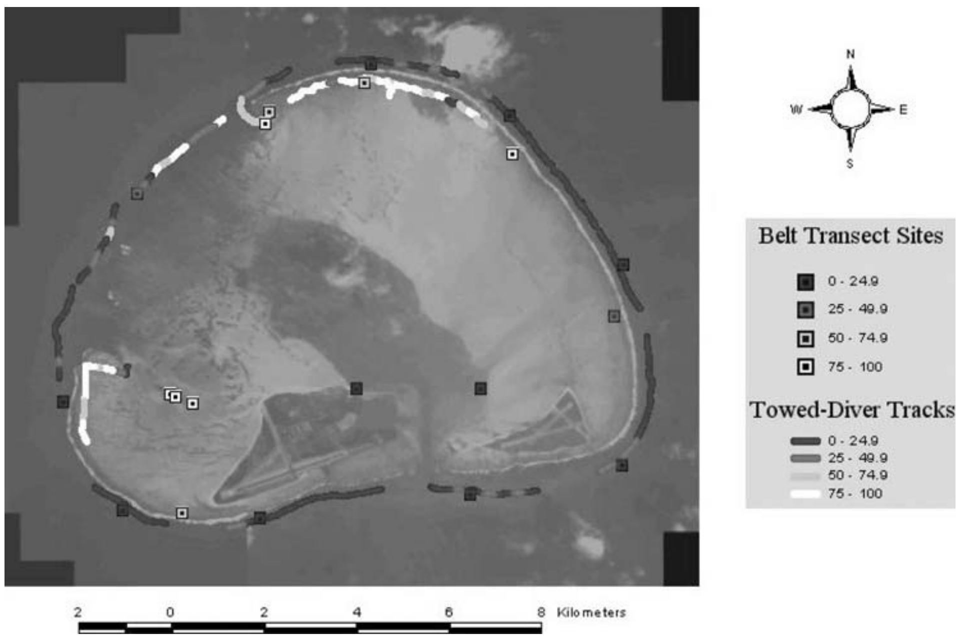

Figure 2. Locations of towed-diver and belt-transect surveys at Midway Atoll, using IKONOS-acquired imagery as a basemap. Sites and track segments are shaded according to incidence of bleached coral; values presented for towed-diver surveys are averages computed over sequential 5-min intervals.

RESULTS

Towed-Diver Surveys

The distance between sample frames captured at 30-s intervals depends on the tow speed; the average distance ranged from 19.2 m to 38.6 m (mean = 33.0, $n = 20$ tows). The average benthic area captured in laser-scaled frames was 10,907 cm^2 (SE = 119, $n = 700$). Towed divers surveyed 37.5 km of benthic habitat within three atoll zones (forereef, backreef, channel) (Table 1; Figure 2), from which 1129 frames were analyzed, for a total analysis area of 1231 m^2. The videotape from a standard 50-min tow over a habitat with a diversified benthos (e.g., backreef) requires approximately 16 h for complete analysis, from capturing still frames to summarization. Coral cover was low (<12%) in all 3 zones (Table 1). Incidence of bleaching was highest on the backreef, lowest on the forereef, and moderate in the broad channel along the northwest exposure (Table 1; Figure 2). Bleaching was most prevalent in *Pocillopora* and *Montipora*, with a lower incidence of bleaching in *Porites* (Table 1). There was a significant negative correlation between the incidence of bleaching and depth ($r_s = 0.50$, $n = 1129$, $p = 0.00$).

Belt-Transects

Belt-transect divers surveyed 1450 m^2 of benthic habitat in 4 zones (Table 1). Incidence of bleaching was highest on the backreef, lowest on the forereef, and moderate in the channel and on lagoon patch reefs (Table 1; Figure 2). Bleaching was most prevalent in *Pocillopora*

Table 1

Summary of towed-diver and belt-transect surveys conducted at Midway Atoll, Northwestern Hawaiian Islands, in September 2002 to assess coral bleaching. NS = not surveyed

				Average % of total coral cover/average % cover that is bleached				
Zone	Distance surveyed (km)	Average % total coral cover	Average % bleached	*Pocillopora*	Massive/ encrusting *Porites*	*Porites compressa*	*Montipora*	Other coral
			Towed-diver surveys					
Backreef	8.7	11.3	77.4	19.5/89.9	1.5/78.4	0.1/0.0	79.0/80.7	0.0/0.0
Forereef	21.9	1.6	15.0	23.1/63.7	76.0/8.5	0.8/0.0	0.0/0.0	0.2/0.0
Channel	6.9	1.5	32.4	11.2/88.6	83.1/17.9	0.5/35.0	0.4/61.8	4.8/67.7
Lagoon	NS	—	—	—	—	—	—	—
				Number of colonies /% with bleached tissue				
Zone	Area surveyed (m^2)	# coral colonies counted	% colonies bleached	*Pocillopora*	*Porites**	*Montipora*	Other coral	
			Belt transect surveys					
Backreef	400	408	56.1	74/83.8	59/0.0	266/61.3	9/44.4	
Forereef	550	1258	3.7	159/30.0	1065/0.0	2/0.0	32/0.0	
Channel	50	67	32.8	12/66.7	26/0.0	8/0.0	21/66.7	
Lagoon	450	303	39.0	128/92.2	132/0.0	0/0.0	43/0.0	

*Different growth forms/species of *Porites* were not separated using this method.

and *Montipora*, with no bleaching observed in *Porites* (Table 1). There was a significant negative correlation between the incidence of bleaching and depth ($r_s = 0.73$, $n = 20$, $p = 0.00$).

Discussion

Towed-diver surveys provide an efficient method for recording spatial variability in benthic communities on coral reefs when conducted by experienced divers trained in the safety considerations that pertain to this advanced diving technique. A primary strength of towed-diver surveys is their ability to assess the major benthic components and condition of reef habitats over spatial scales substantially greater than can be observed and documented by free-swimming divers. In the present study at Midway Atoll, belt-transect divers examined more benthic area than was analyzed from towboard videos (1450 m^2 vs. 1231 m^2, respectively); however, results from towed-divers were derived over a survey length of 37.5 km (Table 1), whereas results from belt transects were derived over transect lengths totaling 725 m. Because the samples (still frames) from towed-diver surveys are spread over a long curvilinear dimension, whereas belt- transect surveys are concentrated at specific sites (Figure 2), towed-diver surveys provide a broader spatial assessment of large reef systems with variable habitats. The primary conclusions generated from both methods are congruent: (1) incidences of bleaching were highest on the backreef, lowest on the forereef, and moderate in other atoll zones; (2) *Pocillopora* and *Montipora* were highly susceptible to bleaching whereas *Porites* evidenced little bleaching; and (3) there was a significant negative correlation between depth and the incidence of bleaching. Because they are corroborated by similar results generated through belt-transect surveys, towed-diver surveys allow extrapolation to broader spatial scales.

Powered by a surface boat, towed divers are able to survey in sea conditions that are too extreme for roving divers or their support skiff to safely work in, for example, high swell, strong current, or poor anchorage. They provide a permanent visual record that is amenable to re-sampling by different analysts, or to re-analysis when more automated, image-recognition technologies are developed. Inclusion of a GPS receiver on the towing boat allows georeferencing the survey path, and incorporation of a layback model improves the accuracy of positioning the recorded imagery, thereby providing a basis for ground-truthing satellite and aerial remote sensing imagery (e.g., Bainbridge & Reichelt, 1988; Andréfouët et al., 2002; Elvidge et al., 2004). The method is particularly useful for assessing remote areas that can only be visited infrequently and for short durations.

A primary limitation of interpreting visual information from a towed camera is the loss of taxonomic resolution compared to the capacity of free-swimming diver classifications. Field equipment as well as computer equipment needed to analyze imagery is expensive, realistically limiting this method to programs with large budgets. Image analysis is time-consuming, although recently developed point-count software that includes rapid calculation of percent cover (e.g., Coral Point Count with Excel Extensions (CPCe), http://www.nova.edu/ocean/cpce/) may reduce analysis time (J. Kenyon, unpublished data); point count and manual outline methods compared favorably in a study focusing on a single taxon (Bernhardt & Griffing, 2001). Field and computer personnel require special training, the former to ensure safety and accuracy, the latter to ensure consistency and reproducibility. Interested researchers should weigh the advantages and limitations of towed-diver surveys before investing in and implementing this method.

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