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Applications of New Technologies to Instream Flow Studies in Large Rivers

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Abstract.—An acoustic Doppler current profiler, underwater video system, hand-held laser range finder and global positioning receiver were used to collect data for instream flow studies on the Sacramento and lower American rivers in California. The use of the equipment decreased the time required to collect spawning criteria data for Chinook salmon *Oncorhynchus tshawytscha* in deep water in a given area by a factor of 3.4 and doubled the number of transects that could be modeled with the same budget. With the application of quality control criteria, discharges could be measured with an average accuracy of 2.7% versus gauge data with an accuracy of 5%. The total time required to collect data for two-dimensional habitat sites varied with the length and complexity of the sites, and was equivalent to the total time required for physical habitat simulation (PHABSIM) data collection for shorter sites, and less for longer sites.

The data collection for studies that use a physical habitat simulation system (PHABSIM, a component of the instream flow incremental methodology [IFIM]) on large rivers (defined here as those which are not wadeable) has historically involved a considerable investment of time and resources, with safety as a possible factor. Due to the cost of obtaining data, the number of transects selected may be low, which, in turn, may result in large degrees of uncertainty in the subsequent flow–habitat relationships (Williams 1996), depending on the channel character and complexity and the type of information needed.

By applying life-stage-specific habitat suitability criteria for depth, velocity, substrate, and cover, PHABSIM predicts depth and velocity across channel transects and combines them with substrate or cover into a habitat index known as weighted useable area (WUA) (Bovee 1982; Milhous et al. 1989). The WUA output is generally simulated for river reaches over a range of streamflows. Alternatively, two-dimensional (2-D) hydraulic and habitat models can be used to predict depth and velocity laterally and longitudinally throughout a length of river channel at a range of streamflows, and they can be combined with substrate or cover to predict the WUA for the site. Recent advances in technology—including acoustic Doppler current profilers (ADCP), hand-held laser range finders, global positioning system (GPS) receivers, and underwater video cameras—provide the opportunity to reduce the per-transect and per-site time and cost of flow–habitat data collection, and thus potentially increase the number of transects or sites that can be modeled.

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In this paper, we present results using the technologies noted above to conduct instream flow studies on the Sacramento and lower American rivers in California. The mention of specific equipment or manufacturers should not be viewed in any way or manner as an endorsement of such equipment or manufacturers by the U.S. Fish and Wildlife Service.

Description of the Technologies

We have been using a 600 kHz broadband ADCP with a 20° transducer beam angle mounted on the side of a jet boat to measure depths, velocities, and distance across the channel in portions of the channel deeper than 1 m. The ADCP is mounted so that the transducer faces are located 0.25 m below the water surface. Depths are determined by the time taken for an acoustic signal to return to the ADCP from the channel bottom (RD Instruments 1995). Distance across the channel is determined from the Doppler frequency shift of the signal from the channel bottom, while velocities are determined from the Doppler shift of acoustic signals returning to the ADCP from particles in the water column. Water column velocities are measured in cells going down through the water column, starting from as shallow as 0.46 m below the water surface and ending as close as 0.12 m from the river bottom. The ADCP can be set to operate in a variety of configurations, corresponding to different depth and velocity characteristics of the river channel. The data from the ADCP are transmitted to a laptop computer.

We have been using a hand-held laser range finder to measure the slope distance to an object, such as a person or a boat. The laser range finder measures slope distance by the time taken for a laser signal to return to the range finder. Without using a prism, the range finder can measure distances of up to 300 m with an accuracy of 0.03 m.

We used a GPS receiver to measure and record the global position (latitude and longitude or northing and easting) of redds. The global positioning system receivers determine global position by measuring the time taken to receive radio signals from semisynchronous satellites (U.S. Fish and Wildlife Service 1997). The GPS unit which we have used can have a 95% confidence limit horizontal accuracy of 3–7 m. The data from the GPS receiver was downloaded to a laptop computer.

We used underwater video equipment to observe the substrate and cover in deep water. The underwater video equipment consists of two waterproof remote cameras mounted on an aluminum frame with two 14-kg sounding weights. The frame was modified slightly from the design presented in Groves and Garcia (1998) to allow for the use of different underwater remote cameras (Micro-SeaCam 1050, Deep Sea Power and Light, San Diego, California). The cameras have a 98° diagonal field of view in water and a scene illumination of 0.27 lux at f 2.8. One camera was mounted facing forward, depressed at a 45° angle from the horizontal, and the second camera was mounted such that it faced directly down at a 90° angle from the horizontal. The frame was attached to a cable/winch assembly, while a separate cable from the remote cameras was connected to two TV monitors on the boat. The two monitors were used by the winch operator to distinguish changes in substrate size-classes and to determine the substrate size. Substrate size could be visually assessed using a calibrated grid on the monitor connected to the 90° camera. The grid was calibrated so that, when the camera frame was 0.3 m off the bottom, the smallest grid corresponded to a 5-cm substrate, the next largest grid corresponded to a 10-cm substrate, and so on.

Methods

The ADCP, underwater video equipment, and GPS receiver were used to collect habitat suitability criteria data for Chinook salmon *Oncorhynchus tshawytscha* spawning in deep areas (greater than 1 m), while the ADCP, underwater video equipment, and hand-held laser range finder were used to collect data for modeling habitat availability using both PHABSIM and 2-D hydraulic and habitat modeling. The habitat suitability criteria data were collected during the period of November 1997 through June 2001 for 49 deep fall-run Chinook salmon redds, 16 deep late fall-run Chinook salmon redds, and 110 deep winter-run Chinook salmon redds in the Sacramento River. The habitat availability data were collected during the period of June 1997 through December 1998 for 34 PHABSIM transects for Chinook salmon spawning in the Sacramento River, 27 PHABSIM transects for fall-run Chinook salmon and steelhead *O. mykiss* spawning in the lower American River, and 24 PHABSIM transects (located at the top and bottom of 2-D habitat modeling sites) for Chinook salmon rearing in the Sacramento River. Habitat availability data were collected during the period of April 1998 through February 2000 for five 2-D habitat modeling sites for fall-run Chinook salmon and steelhead spawning in the lower American River and for fifteen 2-D habitat modeling sites for Chinook salmon rearing in the Sacramento River. We used the ADCP at flows ranging from 172 to 1,264 m^3/s on the Sacramento River and 86–314 m^3/s on the lower American River. The configurations used for the ADCP data collection are given in Table 1.

Habitat suitability criteria.—When searching for redds in deep water using underwater video, a series of parallel upstream traverses were made with the boat. The main feature used to identify redds was the clean substrate present in the redd, compared with the algal-covered substrate surrounding the redd. The camera mounted at a 45° angle was used to look for topographic features of the redds (such as the rise of the tailspill or the depression at the pit), while the camera mounted at 90° was used to look for differences in algal growth on the substrate and the cut at the head of the pit. After locating a redd in deep water, the jet boat held position over the redd, and the substrate size was measured using the underwater video directly over the redd. Depth and water velocity were measured over the redds using the ADCP, with at least 12 measurements made at each redd. The location of all redds was recorded with the GPS receiver, so we could ensure that redds were not measured twice. An American standard code for information interchange (ASCII) file of the ADCP data from each redd was produced using the playback feature of the transect program (RD Instru-

TABLE 1.—Acoustic doppler current profiler (ADCP) configurations used for ADCP data. Configuration (CFG) files were used by the ADCP software to set the values of the parameters in this table. There is no consistent naming convention for the CFG files: for the files that begin with MD, the third character is the mode and the fourth character increases with the depth range of the mode (A works best for the smallest depths while H works best for the largest depths); for the CFG files starting with S (indicating shallow) or D (indicating deep), the second character is the number of pings and the third character indicates a water track transmit length (WT) value of 5 cm. Number of transects is the number of transects for which each configuration file was used.

CFG file	Mode	Depth cell size (cm)	Number of depth cells	Max bottom track (m)	Pings	WT	First depth cell (cm)	Blanking distance (cm)	Number of transects
MD8A	8	20	15	8	4	5	49	10	28
S45D	8	20	15	8	4	5	59	20	6
S85D	8	20	15	8	8	5	59	20	3
MD4A	4	20	15	8	8	5	56	10	4
MD4C	4	10	30	8	4	5	46	10	26
MD4E	4	20	30	8	4	5	56	10	4
MD4G	4	20	45	12	4	5	56	10	2
MD4H	4	20	60	16	4	5	56	10	1
D45D	8	20	30	8	4	5	59	20	7
D85D	8	20	30	8	8	5	59	20	1

ments 1995), the software used to receive, record, and process data from the ADCP. Each ASCII file was then imported into the riverine habitat simulation software (RHABSIM) Version 1.18 (Payne and Associates 1997) to produce the depths and mean water column velocities measured at each redd. The averages of the depths and water column velocities were used as a single characteristic depth and velocity for each redd. Redd measurements which were within 2 m of each other (based on the GPS measurements) and which had depths and velocities which did not differ by more than 0.3 m and 0.5 m/s were categorized as duplicate measurements of the same redd.

We tested the horizontal accuracy of the GPS unit by recording the position of the pit of 33 shallow winter-run Chinook salmon redds with GPS on June 4–7, 2001, and by installing numbered metal tags (painted red) in the tailspill of each redd. The tags were held in place with a 20-cm carriage bolt. We navigated to the GPS location of each redd on June 19–22, 2001, and measured the distance from the location indicated by the GPS to the pit of the marked redd.

Physical habitat simulation transects.—For the PHABSIM transects, the hand-held laser range finder was used to measure the stations for dry ground elevation, shallow-water depth and velocity (using a wading rod and velocity meter), and the starting and ending point of the ADCP traverses. At the location of the last depth and velocity measurement made while wading, a buoy was placed to serve as a starting point for the ADCP. The boat was then positioned so that the ADCP started operation at the buoy, and water depth and velocity data were collected across the transect up to the location near the opposite bank where water depths of approximately 1 m were reached. A buoy was placed at the location where ADCP operation ceased, and the procedure used for measuring the depths and velocities in shallow water was repeated until the far bank water's edge was reached. Typically, three ADCP traverses were made across each transect at each flow. For sites where the discharge was not known, at least four ADCP traverses were made.

The hand-held laser range finder was used to measure the stations on the transects at which substrate or cover changed on dry land and in shallow water (where substrate and cover were visually assessed) and in the deepwater portion of the transects (where the underwater video equipment was used to asssess substrate and cover). A buoy was placed at each location where visual assessment stopped. Assessment from that point was continued across the transect by boat using the video camera assembly, with the distances where substrate size and cover changed again measured with the hand-held laser range finder. The camera mounted at a 45° angle was used for distinguishing any changes in substrate size-classes, while the camera mounted at 90° was used for assessing substrate size. A buoy was again dropped at the location along the transect near the opposite shore where shallow-water depth prevented further progress by boat.

The playback feature of the ADCP transect program was used to produce ASCII files of each ADCP traverse. Each ASCII file was then imported into RHABSIM Version 2.0 (Payne and Associates

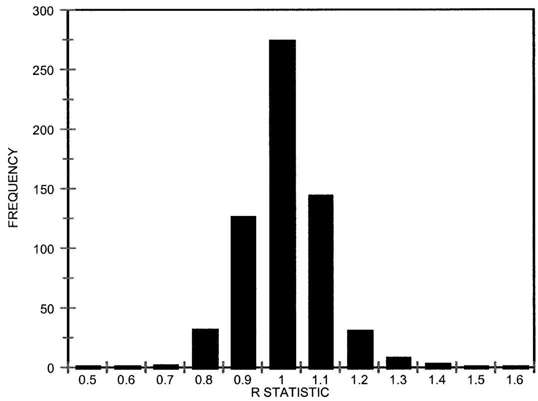

FIGURE 1.—Frequency distribution of R (velocity quality control statistic) for data collected in 1995 on the lower American River with a Price AA velocity meter; $R = \text{Vel}_i/(\text{Vel}_{i-1} + \text{Vel}_{i+1})/2$ at station i, where $i - 1$ refers to the station immediately before station i, $i + 1$ refers to the station immediately after station i, and Vel is velocity ($n = 618$). Values of R were computed for all of the velocity measurements made with the Price AA velocity meter where Vel_i, Vel_{i-1}, and Vel_{i+1} were all greater than 0.3 m/s.

1998) to produce the bed elevations, mean water column velocities, and stations (relative to the start of the ADCP traverse). The RHABSIM software was then used to produce a second ASCII file containing this data. The second ASCII file was input into a QuattroPro spreadsheet and combined with the velocity, depth, and station data collected in shallow water. Substrate and cover data values were assigned to each vertical based on the distances measured with the hand-held laser range finder.

We defined a statistic (R) to provide a quality control check of the velocity (Vel) measured by the ADCP at a given station n:

$$R = \text{Vel}_i/[(\text{Vel}_{i-1} + \text{Vel}_{i+1})/2] \text{ at station i,}$$

where $i-1$ refers to the station immediately before station I, and $i + 1$ refers to the station immediately after station i. R was calculated for each velocity where Vel_i, Vel_{i-1} and Vel_{i+1} were all greater than 0.30 m/s for each ADCP data set. Based on data we collected in 1995 on the lower American River using a Price AA velocity meter, the acceptable range of R was set at 0.5–1.6; this was the range of R values in the 1995 dataset (Figure 1). All verticals with R values less than 0.5 or greater than 1.6 were deleted from each ADCP data set. We also deleted verticals where Vel_i was less than 0.30 m/s and Vel_{i-1} and Vel_{i+1} were greater than 0.61 m/s, and where Vel_i had one sign (negative or positive) and Vel_{i-1} and Vel_{i+1} had the opposite sign (when the absolute value of all three velocities were greater than 0.30 m/s); these criteria were also based on the 1995 dataset since there were no velocities in the 1995 dataset which met these criteria.

Flows were calculated for each ADCP traverse, including the data collected in shallow water. The traverse for each cross section which resulted in a flow closest to the actual flow (determined from gauge readings) was selected for use as a velocity set or to measure discharge. However, for split channels which had a small percentage of the total discharge or sites which did not have the total river discharge, the split channel or site discharge was calculated by using the average of the discharge from all of the ADCP traverses.

2-D habitat modeling sites.—For the 2-D habitat modeling sites, the ADCP was used in concert with a total station to obtain bed elevation and horizontal location data for the portions of the sites with depths greater than 1 m. The ADCP was traversed across the channel at 15–46 m intervals, with the initial and final horizontal location of each traverse measured by the total station. Prior to each ADCP traverse, buoys were placed at the initial and final locations of the traverse, and water surface elevation was measured with a level at the initial location of the traverse. The underwater video equipment and hand-held laser range finder were used to determine the substrate and cover along the ADCP traverses in the same manner described above for the PHABSIM transects, with the video equipment used between the buoys placed at the initial and final locations of each traverse. A total station was used to collect bed elevation, horizontal location, substrate, and cover data for the shallow and dry portions of the sites. All of this data for the American River sites and a majority of the data for the Sacramento River sites were collected with a total station where the slope distance, horizontal angle, and vertical angle had to be manually recorded, while the rest of the Sacramento River data were collected with a second total station where these parameters were electronically recorded. Electronic recording increased efficiency as noted below.

The playback feature of the ADCP transect program was used to produce ASCII files of each ADCP traverse. Each ASCII file was then imported into RHABSIM version 2.0 to produce the bed elevations, mean water column velocities, and stations (relative to the start of the ADCP traverse). The RHABSIM software was then used to produce a second ASCII file containing this data. The second ASCII file was input into a QuattroPro spreadsheet. The water surface elevation of each ADCP traverse was then used—together with the depths from the ADCP—to determine the bed elevation of each point along the traverse. The horizontal locations of the initial and final locations of each traverse were used with the station of each point on the traverse to determine the horizontal location of each point. Substrate and cover data were assigned to each point on the ADCP traverses based on the distances along the ADCP traverses measured with the hand-held laser range finder. The quality control criteria presented above for the PHABSIM transects were applied to the velocity data from the ADCP traverses, with velocities not meeting the above criteria being deleted. The remaining velocities at each point measured by the ADCP were used to validate the velocity predictions of the 2-D model.

Two PHABSIM transects are required for each 2-D site. The PHABSIM transects are not used to model habitat, but are used to provide inputs to the 2-D model. Specifically, the PHABSIM transect at the downstream end of the site is used to define the bed topography at the downstream boundary, and to provide water surface elevations at the simulation flows to the 2-D model. The PHABSIM transect at the upstream end of the site is used to define the bed topography at the upstream boundary, and to provide water surface elevations which are used to calibrate the 2-D model. The velocities measured on the PHABSIM transects are also used to validate the velocities predicted by the 2-D model.

Previous technology.—Prior to the use of ADCPs, distance, depth, and velocity measurements in large rivers were typically made with a velocity meter, sounding weight, and reel on a boat attached to a cable (Buchanan and Somers 1969). The California Department of Water Resources used this technology on an earlier instream flow study on the Sacramento River (California Department of Water Resources 1993). Depth and velocity measurements were made on 22 transects in the same reach of the Sacramento River as in our study.

Prior to the use of underwater video equipment, scuba techniques were used to locate redds and to observe substrate and cover in areas which were too deep to observe redds, substrate, and cover from above the water's surface. Specifically, divers grasping Plexiglas planing boards were towed behind a jet boat and relayed their observations of substrate and redds to personnel on the surface using radio gear (U.S. Fish and Wildlife Service 1992). The U.S. Fish and Wildlife Service used this technique from 1988 to 1996 to observe substrate and locate Chinook salmon redds in the same reach, and in many of the same sites, of the Sacramento River that we sampled in this study (U.S. Fish and Wildlife Service 1996a). We also used this technique in June 1996 to search for winter-run Chinook salmon redds in the Sacramento River (U.S. Fish and Wildlife Service 1996b). The previous instream flow study on the Sacramento River did not use this technology to observe substrate and cover on transects, but instead assumed that the substrate and cover in portions of the transect that could not be observed from above the water's surface were the same as for the last location that could be observed from above the water's surface (California Department of Water Resources 1993).

Data analysis.—Analysis of variance (ANOVA; Wilkinson 1990) was used to test for differences in the number of wetted cells (locations at which depth and velocity measurements were made), depth, velocity, percent of cells with a depth greater than 1 m, and wetted width for three categories of transects: (1) California Department of Water Resources transects; (2) Sacramento River spawning PHABSIM transects from this study; and (3) PHABSIM transects for 2-D modeling of Sacramento River rearing habitat. For parameters where there were significant differences, Fisher's least-significant-difference test (Wilkinson 1990) was used to determine which categories of transects were signficantly different.

We used simple regression with the 10 Sacramento 2-D modeling sites that were not also modeled with PHABSIM to determine if a relationship could be developed between the length of the site and the total time required to collect field data. The time for the remaining five Sacramento 2-D habitat modeling sites would not have been representative of the effort to collect data on 2-D habitat modeling sites as described above, since much of the data were previously collected to model Chinook salmon spawning on PHABSIM transects. For these sites (where there were up to 10 transects) much of the bed topography data for the sites came from the PHABSIM transect data by determining the location of the headpins and tailpins of the PHABSIM transects with a total station.

Results

The depths of Sacramento River Chinook salmon redds found with underwater video averaged

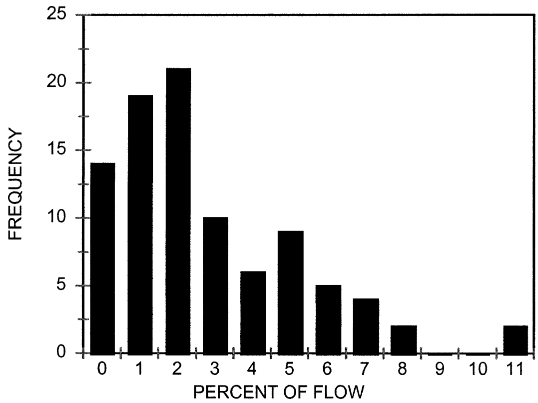

FIGURE 2.—Frequency distribution of errors in acoustic Doppler current profiler (ADCP) flow measurements. The *x*-axis is the percentage difference between the flow measured with the ADCP and the actual flow, based on gauge records. The average error was 2.7% (n = 93).

2.1 m (range = 0.9 to 4.8 m). The mean water column velocities of Sacramento River Chinook salmon redds found with underwater video averaged 1.14 m/s (range = 0.37 to 2.58 m/s). We were able to sample an average of 999 m/d (n = 18 d) of river channel with a three-person crew using the underwater video equipment. The length of river channel sampled with the underwater video equipment ranged from 596 to 1,690 m/d, with a standard error of 76 m/d. Sampling for redds with underwater video equipment required water visibility of at least 1.7 m. We determined that there were duplicate measurements of one deep fall-run redd based on the GPS data.

We were able to find 15 of the 33 tags that we placed on shallow winter-run Chinook salmon redds. For the 15 tags that we were able to find the second week, the distance from the location indicated by the GPS unit to the pit of the marked redd ranged from 0 to 4.6 m, averaging 2.1 m. The distance was only greater than 3 m for 3 out of 15 redds.

The total discharge for the ADCP traverses selected for use differed from the actual flow by an average of 2.7%, with a 95% upper confidence limit of 7.6%, and never differed by more than 11.4% (Figure 2). Based on 19 of the Sacramento River spawning PHABSIM transects where both mode 4 and 8 were used, mode 8 resulted in a discharge closer to the actual flow when the average velocity on the transect was less than 1.78 m/s (13 transects), while mode 4 resulted in a discharge closer to the actual flow when the average velocity on the transect was greater than 1.78 m/

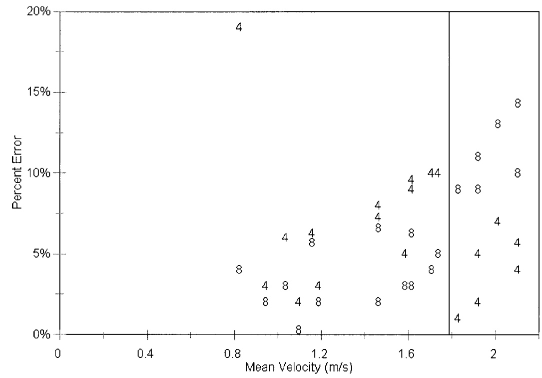

FIGURE 3.—Error relative to gauge flows for discharge measurements made on 19 Sacramento River physical habitat simulation (PHABSIM) Chinook salmon spawning transects with ADCP modes 4 (points labeled 4) and 8 (points labeled 8). The *x*-axis is the mean of all of the velocity measurements made on each transect. The vertical line represents a mean velocity of 1.78 m/s.

s (6 transects; Figure 3). The largest average depth on these 19 transects was 4.3 m.

We were able to collect velocity sets on PHABSIM transects in 1.4 h/transect using the ADCP and hand-held laser range finder with a two- to three-person crew, and were able to collect the substrate and cover data on PHABSIM transects in 1.3 h/transect using the underwater video equipment and the hand-held laser range finder with a three-person crew. Overall, we were able to collect all of the data for PHABSIM transects in an average of 9 h per transect, ranging from 4.3 to 18 h/transect (Figure 4). The time required for col-

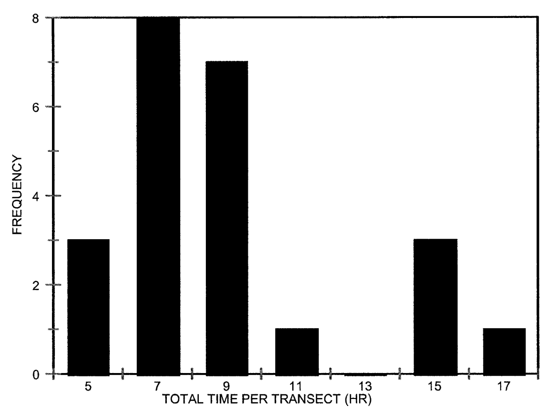

FIGURE 4.—Frequency distribution of total time per PHABSIM transect for lower American River and Sacramento River Chinook salmon spawning sites and for Sacramento River Chinook salmon rearing sites. The *x*-axis is the midpoint of the interval of the total time per transect. The average time was 9 h (n = 23 sites).

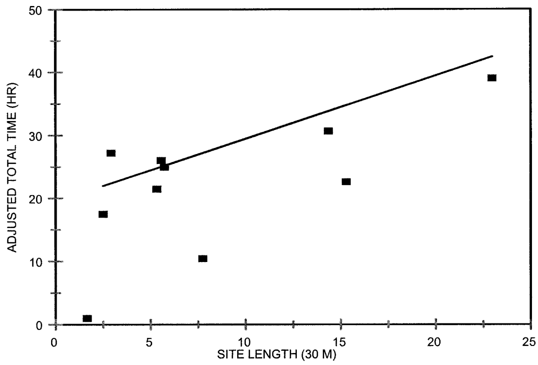

FIGURE 5.—Estimated relationship between adjusted total time and site length; adjusted total time = 19.5 h + site length (30 m; $r = 0.53$, $P = 0.017$, $n = 10$).

lecting deep-bed data with the ADCP for 2-D habitat modeling sites ranged from 1 to 14 h/site with a three-person crew, with the time required being proportional to the length and complexity of the site. The time required for collecting deep substrate and cover data with the underwater video equipment for 2-D habitat modeling sites ranged from 2 to 23 h/site with a three-person crew, with the time required being proportional to the length and complexity of the site.

The underwater video equipment was used to collect substrate and cover data in water up to 12.5 m of depth, and in water with velocities of up to 2.83 m/s when the depth was less than 2.3 m. We were able to use the underwater video equipment to collect substrate and cover data on habitat modeling sites when the water visibility was at least 1 m.

For the manually recording total station, we collected data at an average rate of 11 points/h; for the electronically recording total station, we collected data at an average rate of 29 points/h in the dry and shallow portions of the 2-D modeling sites. To evaluate the relationship between the total time for collecting data for 2-D modeling sites and the length of the sites, we first reduced the time for data collected with the manually recording total station to the equivalent time to collect that data with the electronically recording total station by multiplying the time by the ratio of the above average points per hour. Using the 10 Sacramento 2-D modeling sites that were not also modeled with PHABSIM, we found a statistically significant relationship between the length of the site and the total time required to collect the field data (Figure 5).

The time required for collecting velocity sets on the California Department of Water Resources' Sacramento River PHABSIM transects averaged 3.8 h/transect ($n = 22$ transects). The time per transect for velocity sets ranged from 2.0 to 6.2 h/transect, with a standard error of 0.2 h/transect.

The scuba dive-planing from 1988 to 1996 sampled an average of 294 m/d ($n = 25$ d) of river channel for substrate and redds. The length of river channel sampled with scuba ranged from 152 to 533 m/d, with a standard error of 20 m/d. We sampled about a 450-m length of channel in 3 d with scuba in June 1996 to search for winter-run Chinook salmon redds in the Sacramento River.

For the Sacramento River data, there was a significant effect (at $P = 0.05$) of the three categories of transects on the number of wetted cells, average depth, average velocity, and wetted width, but no significant effect on the percent of wetted cells with a depth greater than 1 m ($P = 0.18$). Significant differences between means (at $P = 0.05$) are shown in Table 2. The Sacramento River PHABSIM transects had significantly more wetted cells than the 1985 Sacramento River transects or the Sacramento River 2-D transects. The 1985 transects were not significantly different from the PHABSIM transects for velocity, and were intermediate between the PHABSIM and 2-D transects for depth and wetted width.

Discussion

There was a bimodal distribution for the total time required per PHABSIM transect, with four

TABLE 2.—Characteristics of transects measured with old (Sacramento 1987) and new (American, Sacramento physical habitat simulation (PHABSIM) and Sacramento two-dimensional) technologies. Values are means ± standard errors. The values of n are the numbers of transects for each study. Values with the same letter are not significantly different at $P = 0.05$ (Fisher's least-significant-difference test).

Study	n	Number of wetted cells	Mean depth (m)	Mean velocity (m/s)	Percent of cells >1 m depth	Wetted width (m)
American	27	51 ± 2.6	0.95 ± 0.05	0.768 ± 0.045	45 ± 4.2	103 ± 5.2
Sacramento 1987	22	25 ± 1.4 z	2.15 ± 0.17 yz	1.361 ± 0.049 y	87 ± 2.6	123 ± 6.1 y
Sacramento PHABSIM	34	113 ± 5.8 y	1.67 ± 0.12 z	1.264 ± 0.044 y	78 ± 3.4	163 ± 4.3 x
Sacramento 2-D	24	31 ± 1.8 z	2.38 ± 0.28 y	1.085 ± 0.060 z	81 ± 4.3	95 ± 7.5 z

sites having times of greater than 11 h (Figure 3). Three of these sites were located over a 3.2 km reach above a dam, where the dam had a backwater effect throughout the reach. As a result, we had to tie together the vertical benchmarks for all three sites. The time required to tie together the benchmarks was 55% of the total time required for these three sites. The remaining site had split channels for all four transects. As a result, considerable time was required to measure the discharges on each split channel at different flows so as to be able to divide the total flow between the split channels. The average total time per transect for the remaining 19 sites was 7.5 h.

With scuba, a seven-person crew sampled an average of 294 m/d length of channel, versus the average of 999 m/d of channel that we were able to sample with the underwater video equipment with a three-person crew. Thus, using the underwater video equipment is 3.4 times faster than using scuba techniques, and substrate/cover data would require 30.9 person-hours per transect (1.3 h $\times$ 3.4 $\times$ 7 people) with scuba techniques, versus 3.9 person-hours per transect (1.3 h $\times$ 3 people) with underwater video.

Using the previous technology for velocity sets on the California Department of Water Resources' Sacramento River instream flow study, it took a nine-person crew an average of 3.8 h per two transects to collect velocity data. Thus, velocity data collection would require 34.2 person-hours per transect (3.8 h $\times$ 11 people per two transects) with the previous technology, versus 4.2 person-hours per transect (1.4 h $\times$ 3 people) with the ADCP.

Excluding the time required for collecting substrate/cover and velocity data, and considering only the 19 sites without the fairly unique factors of having to tie together benchmarks over a 3.2-km reach and having split channels for all transects, we spent 4.8 h/transect (7.5 $-$ 1.3 $-$ 1.4 h)—the equivalent of 14.4 person-hours per transect (4.8 h $\times$ 3 people)—to collect the field data for the PHABSIM transects. With the old technologies, the total time to collect field data for PHABSIM transects would have been 79.5 person-hours per transect (14.4 person-hours + 34.2 person-hours + 30.9 person-hours), versus 22.5 person-hours per transect (7.5 h $\times$ 3 people) with the ADCP and underwater video. While the techniques used to collect substrate and cover data on transects for the previous Sacramento instream flow study would have reduced this time to 48.6 person-hours per transect, the decrease in time would be at the sacrifice of accurate substrate and cover data. For the same field budget, 3.6 times as many transects (79.5 person-hours/22.5 person-hours) could be measured using the ADCP and underwater video than with the old technologies. If the analysis portion of the budget is 80% of the field budget, it would still be possible to have twice as many transects using the ADCP and underwater video than with the old technologies, for the same overall budget.

The equation in Figure 4 can be used to develop budgets for collecting field data for 2-D habitat modeling sites on rivers similar in size and complexity to the Sacramento and American rivers using the technologies discussed in this paper. The minimum time required for 2-D habitat modeling sites is approximately the same as for two PHABSIM transects since there is a PHABSIM transect at the top and bottom of each site. As a result, considerable cost savings may be possible by combining several habitat units into one 2-D habitat modeling site by reducing the number of PHABSIM transects needed. For example, three 2-D sites which were 300 m long would take a total of 88.5 h (3 $\times$ [19.5 h + 300 m/30 m]), while one 2-D site which was 900 m long (combining together the three sites into one site) would take a total of 49.5 h (19.5 h + [900 m/30 m]). However, this may not be (1) practical when habitat units are longer than 1 km due to practical distance limits and the logistics of obtaining accurate elevations over long distances, or (2) possible when there are intervening conditions that would prevent modeling as a single site. The number of PHABSIM transects needed to represent the habitat (in terms of the variation in depth and velocity profiles) in the 2-D habitat modeling sites would have ranged from around three transects for the shorter sites to at least six PHABSIM transects for the longer sites (Figure 6). Thus, for shorter sites the field time required for PHABSIM and 2-D habitat modeling is approximately the same, while the field time for 2-D habitat modeling for longer sites is less than for PHABSIM.

The time-cost equations in this paper are based on the samples described herein and the different conditions in different rivers that could produce a different time-cost relationship. The times presented in this paper are valid for rivers with a wetted width ranging from 21 to 210 m. The time required to conduct instream flow studies on larger rivers, such as the Columbia or Mississippi river, would be greater. Time for such rivers could be conservatively estimated by scaling up the results of this study by the wetted width, although only

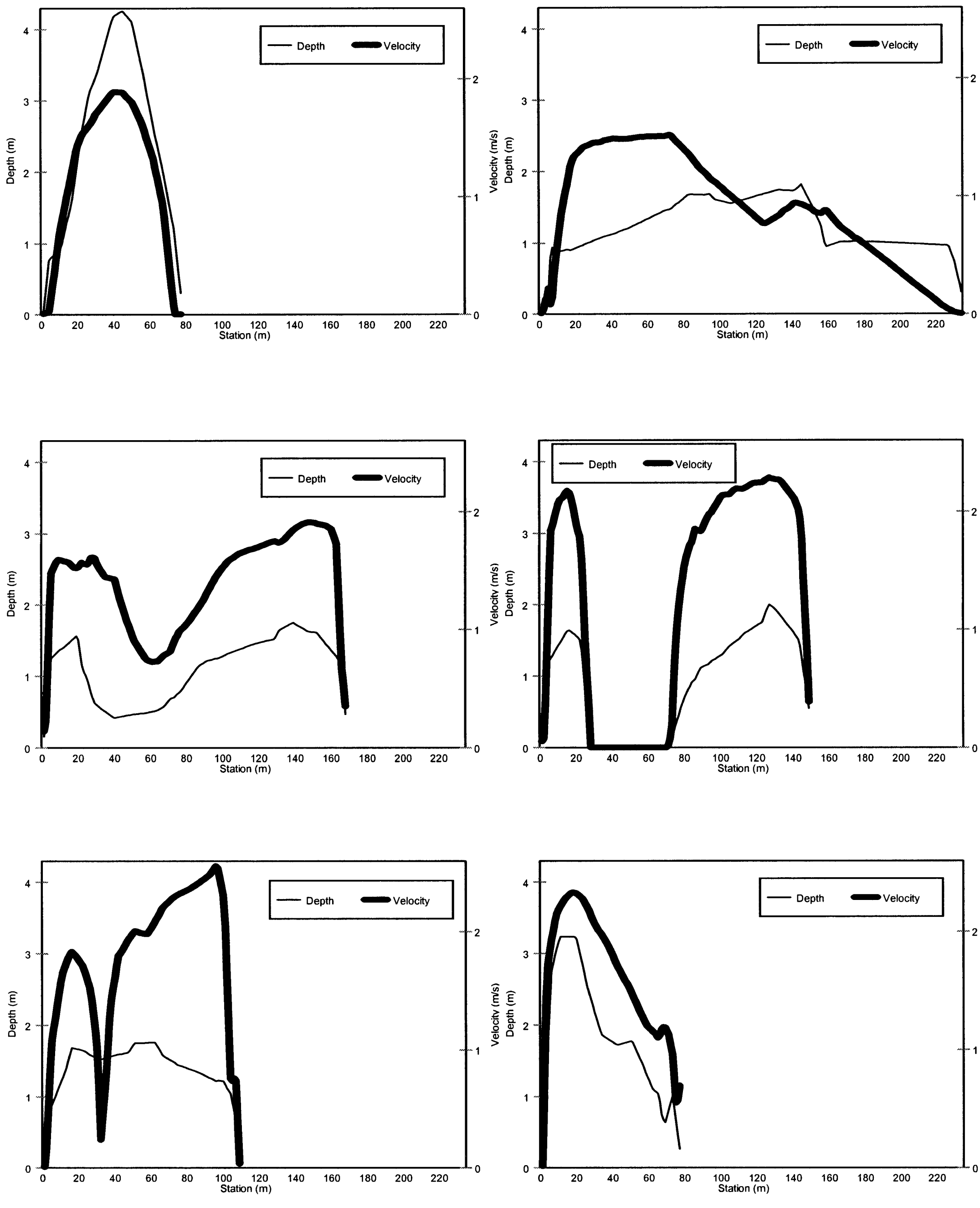

FIGURE 6.—Depth and velocity profiles, at a flow of 295.8 m^3/s, of transects that would have been needed to represent the habitat (in terms of the variation in depth and velocity profiles) for one of the longer two-dimensional (2-D) juvenile habitat modeling sites in the Sacramento River. Data were generated from the output of the 2-D model.

the time required for collecting velocities and substrate/cover data would likely increase directly as the ratio of the wetted widths. The time for other instream flow study field activities, such as measuring water surface elevations, would probably not increase dramatically with increased wetted widths.

The time savings for the new technologies discussed in this paper are likely conservative, since the number of wetted cells was greater for the Sacramento PHABSIM transects than for the Sacramento 1997 transects. In other respects, the Sacramento 1987 transects were comparable to the Sacramento PHABSIM and 2-D transects since the depths and wetted widths for the Sacramento 1987 transects were intermediate between the Sacramento PHABSIM and 2-D transects, and the velocities for the Sacramento 1987 transects were not significantly different from the Sacramento PHABSIM transects. The patterns of depths and wetted widths are consistent with the Sacramento 1987 transects and the combination of the Sacramento PHABSIM and 2-D transects representing all of the habitat present in the Sacramento River. The Sacramento 2-D transects did not require as many verticals as the Sacramento PHABSIM transects because the Sacramento 2-D transects only required enough verticals to capture the bed topography of the upstream and downstream boundaries of the 2-D sites, while the PHABSIM transects required enough verticals to capture the depth and velocity distribution of the transects.

The new technologies discussed in this paper have additional advantages over old technologies apart from time and cost savings. There are significant safety advantages for the ADCP and underwater video since they do not require having cables crossing a river or having scuba divers. In addition, the ADCP and underwater video have the potential for producing a higher quality of data (specifically more measurements per transect with the ADCP and a more accurate assessment of substrates) in comparison with the methods used for transects on the previous instream flow study on the Sacramento River.

The primary disadvantage of the new technologies discussed in this paper is their relatively high capital costs. The ADCP and underwater video also require a highly skilled boat operator, someone who is capable of holding position in current and is able to maintain a straight course going perpendicular to the flow.

The main limitation of the ADCP unit we have used is that it cannot be used for depths less than 1 m. As a result, velocities and depths in portions of the transect shallower than 1 m must still be collected by wading with a wading rod and velocity meter, which takes considerably more time than collecting data with the ADCP. This limitation can be overcome to some extent by collecting velocity sets at higher flows, where more of the channel is deeper than 1 m. The primary limitations of the underwater video are the minimum water visibility required and the maximum velocity and depths where the video can be used. These limitations can be overcome, to some extent, by collecting substrate and cover data when flows are lower and when water visibility is better. Also, the maximum depth limitation might be overcome by using longer cables, but only under lower velocity (probably less than 1 m/s) conditions, and might require lighting. Finally, it should be noted that the minimum visibility and maximum velocities and depths for the scuba techniques are approximately the same as for the underwater video technique. The main limitation of the hand-held laser range finder is needing a clear line of sight. This limitation can be partially overcome by using the range finder at a location beyond any vegetation that might obstruct the line of sight.

The main limitation of the GPS receiver is being able to receive satellite signals. While this was not an issue for the studies discussed in this paper, it is likely to be a problem in locations in steep canyons or under dense tree cover. It is not likely that the resolution of the GPS would have any measurable effect on the outcome of the PHABSIM or 2-D modeling because the GPS was only used to determine if redds had been measured twice. The consequences of an error in GPS measurement would be either that a redd measurement was discarded where the measurement was not a duplicate measurement, or that two measurements of the same redd would be used to develop habitat suitability criteria. Thus, we do not feel that there would be any conditions (such as stream size) where such resolution would make a difference. We did not need to obtain elevation for redd locations because elevation was not needed to determine if two measurements were made at the same horizontal location. The 2-m threshold for rejecting redd measurements as duplicate measurements of the same redd was set equal to the average error in GPS measurement of 2.1 m that we found in our verification test, rounded to the nearest 0.3 m. Also, we felt that the 2-m threshold represented a balance between not rejecting measurements which were not duplicate and accepting duplicate measurements. With a smaller threshold, we would have increased the number of redd measurements which were erroneously accepted, but with a larger threshold, we would have increased the number of redd measurements which were erroneously rejected. Given that there is an adverse (though minor) effect of either error, we felt that it was best to balance the two potential errors.

Quality control is an important consideration for using an ADCP for instream flow studies. For PHABSIM transects, the two measures that we have found most successful for quality control are making at least three ADCP traverses for each transect, with the traverse that results in a discharge closest to the known (gauged) discharge used for the velocity set, and, applying the criteria given above to individual velocity measurements, eliminating those velocity measurements that do not meet the criteria. Since an individual ADCP traverse can be made in 5 to 10 min, making three ADCP traverses improves the quality of the data with little cost. Since ADCP measurements can be made with a spacing as small as 1 m, it is possible to throw out individual velocity measurements and still have enough measurements to characterize the velocity distribution across the transect. The spacing of ADCP measurements can be decreased by moving the boat across the channel at a slower speed. For habitat suitability criteria, the approach that we have found most successful for quality control is collecting at least 12 measurements per redd. Since the ADCP makes a measurement every 4–5 s, 12 measurements can be made in about 1 min.

Another important quality control measure for any ADCP application is to use mode 8 for velocities less than 1.78 m/s. While mode 8 appears to be more accurate than mode 4, it does not deliver as much power as mode 4 and thus stops working at higher velocities. Specifically, mode 8 sends two very short pulses (which have low power due to the short length), and both pulses need to be received to calculate the velocity (RD Instruments 1999). In contrast, mode 4 uses a single series of longer-length pulses (RD Instruments 1996). We generally select which mode to use by a visual estimation of the mean velocity for the transect. For example, with a mean velocity of greater than 1.78 m/s, our jet boat typically has to be up on-plane to stay in position. We generally first try mode 8 if we are not sure of the mean velocity, and if mode 8 fails to collect much data (more than one-third of the verticals are bad [no velocity data collected]), we then switch to mode 4. The remaining aspects of ADCP configurations (as shown in Table 1) are primarily tradeoffs of more cells per measurement versus more measurements per transect.

Future technological improvements may further decrease the time per transect and per site required for instream flow data collection. For example, more recent ADCP models will collect data in depths as shallow as 0.3 m, reducing the proportion of the channel where velocity measurements need to be made with a wading rod and velocity meter. For 2-D modeling, multispectral videography is capable of collecting bed topography data for dry areas as well as for inundated areas with low turbidity (Winterbottom and Gilvear 1997; Whited et al. 2002).

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