IDENTIFICATION OF THE INSTREAM FLOW REQUIREMENTS FOR ANADROMOUS FISH IN THE STREAMS WITHIN THE CENTRAL VALLEY OF CALIFORNIA

Annual Progress Report
Fiscal Year 2003

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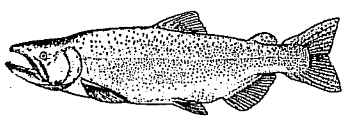
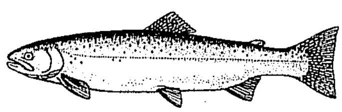
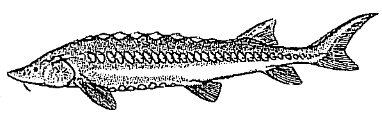

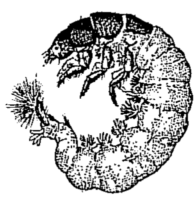
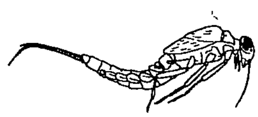

PREFACE

The following is the second annual progress report prepared as part of the Central Valley Project Improvement Act Instream Flow Investigations, a 6-year effort which began in October, 2001.[1] Title 34, Section 3406(b)(1)(B) of the Central Valley Project Improvement Act, P.L. 102-575, requires the Secretary of the Interior to determine instream flow needs for anadromous fish for all Central Valley Project controlled streams and rivers, based on recommendations of the U.S. Fish and Wildlife Service (Service) after consultation with the California Department of Fish and Game (CDFG). The purpose of this investigation is to provide reliable scientific information to the Service's Central Valley Project Improvement Act Program to be used to develop such recommendations for Central Valley streams and rivers.

The field work described herein was conducted by Ed Ballard, Mark Gard, Bill Pelle, Rick Williams, Jonathan Foster and Rich DeHaven.

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[1] This program is a continuation of a 7-year effort, also titled the Central Valley Project Improvement Act Instream Flow Investigations, which ran from February 1995 through September 2001.

INTRODUCTION

In response to substantial declines in anadromous fish populations, the Central Valley Project Improvement Act requires the doubling of the natural production of anadromous fish stocks, including the four races of chinook salmon (fall, late-fall, winter, and spring), steelhead trout, and white and green sturgeon. In June 2001, the Sacramento Fish and Wildlife Office (Service), Energy Planning and Instream Flow Branch prepared a study proposal to use the Service's Instream Flow Incremental Methodology (IFIM) to identify the instream flow requirements for anadromous fish in selected streams within the Central Valley of California. The proposal included completing instream flow studies on the Sacramento and Lower American Rivers and Butte Creek which had begun under the previous 7-year effort, and conducting instream flow studies on other rivers, with the Yuba River selected as the next river for studies.

The Sacramento River study was planned to be a 7-year effort originally scheduled to be concluded in September 2001. Specific goals of the study are to determine the relationship between streamflow and physical habitat availability for all life stages of chinook salmon (fall, late-fall, winter-runs) and to determine the relationship between streamflow and redd dewatering and juvenile stranding. The study components include: 1) compilation and review of existing information; 2) consultation with other agencies and biologists; 3) field reconnaissance; 4) development of habitat suitability criteria (HSC); 5) study site selection and transect placement; 6) hydraulic and structural data collection; 7) construction and calibration of reliable hydraulic simulation models; 8) construction of habitat models to predict physical habitat availability over a range of river discharges; and 9) preparation of draft and final reports. The first five study components were completed by September 2001. The Fiscal Year (FY) 2003 Scope of Work (SOW) identified study tasks to be undertaken. These included: construction of hydraulic models (study component 7), construction of habitat models (study component 8), and preparation of draft and final reports (study component 9).

The Lower American River study was a 1-year effort which culminated in a March 27, 1996, report detailing the methods and results of this effort. This report was submitted to CDFG for enclosure in their final report on the Lower American River. Subsequently, questions arose as to which of the chinook salmon spawning HSC used in the March 27, 1996, report would be transferable to the Lower American River. As a result, additional field work was conducted in FY 1997, culminating in a supplemental report submitted to CDFG on February 11, 1997. As a result of substantial changes in the Lower American River study sites from the January 1997 storms, a second round of habitat data collection and modeling was begun in April 1998. Data collection for this effort was completed in February 1999 and a final report on the Physical Habitat Simulation (PHABSIM) portion of the study was completed on September 29, 2000. A final report on the 2-D modeling portion of the study was completed in February 2003.

The Butte Creek study is a 2-year effort which started with collection of spring-run chinook salmon spawning HSC data during September 1999. In May 2000, field work was begun to determine the relationship between habitat availability (spawning) and streamflow for spring-run chinook salmon. This fieldwork included study site selection, transect placement and hydraulic and structural data collection. This data collection was completed in March 2002. Collection of spring-run chinook salmon spawning HSC data was completed in September 2000. A final report on the study was completed in September 2003.

The Yuba River study is a 4-year effort, the goals of which are to determine the relationship between stream flow and physical habitat availability for all life stages of chinook salmon (fall- and spring-runs) and steelhead/rainbow trout and to identify flows at which redd dewatering and juvenile stranding conditions occur. The study started with the location and counting of spring-run chinook salmon redds during September 2001 and the collection of fall-run chinook salmon spawning HSC during November-December 2001. Spawning criteria data was collected in February and April 2002 for steelhead/rainbow trout and in September 2002 for spring-run chinook salmon. Field work to determine the relationship between habitat availability (spawning) and streamflow for spring-run and fall-run chinook salmon and steelhead/rainbow trout continued in FY 2003. This field work included hydraulic and structural data collection. Mesohabitat mapping of the Yuba River between Englebright Dam and the confluence with the Feather River was completed. Using the information on habitat types gathered during the mesohabitat mapping, sites for studying the relationship between habitat availability (juvenile rearing) and streamflow for spring-run and fall-run chinook salmon and steelhead/rainbow trout were selected and the process of gathering HSC data for juvenile rearing was begun.

The following sections summarize project activities between October 2002 and September 2003.

SACRAMENTO RIVER

Hydraulic Model Construction and Calibration

Juvenile chinook salmon stranding areas

Stranding flows have been determined for 88 of the 108 stranding sites. Stranding areas have been determined for 102 of the 108 stranding sites. The stranding flows and areas for the remaining sites will be determined in FY 2004, and a final report on juvenile chinook salmon stranding sites will be completed by September 2004.

Chinook salmon spawning habitat

The topographic data for the 2-D model (contained in bed files) is first processed using the R2D_Bed software, where breaklines are added to produce a smooth bed topography. The resulting dataset is then converted into a computational mesh using the R2D_Mesh software, with mesh elements sized to reduce the error in bed elevations resulting from the mesh-generating process to 0.1 foot where possible, given the computational constraints on the number of nodes. The resulting mesh is used in River2D to simulate depths and velocities at the flows to be simulated.

The PHABSIM transect at the bottom of each site is calibrated to provide the Water Surface Elevation's (WSEL) at the bottom of the site used by River2D. The PHABSIM transect at the top of the site is calibrated to provide the water surface elevations used to calibrate the River2D model. The initial bed roughnesses used by River2D are based on the observed substrate sizes and cover types. A multiplier is applied to the resulting bed roughnesses, with the value of the multiplier adjusted so that the WSEL generated by River2D at the top of the site match the WSEL predicted by the PHABSIM transect at the top of the site[2]. The River2D model is run at the flows at which the validation dataset was collected, with the output used in GIS to determine the difference between simulated and measured velocities, depths, bed elevations, substrate and cover.

All data for the six fall-run chinook salmon spawning sites between Battle Creek and Deer Creek has been compiled and checked. PHABSIM data decks and hydraulic calibration have been completed for the upstream and downstream transects for all six sites. The initial bed files have been developed for all six sites. Construction and calibration of the 2-D models of these sites and production runs for all of the simulation flows will be completed in FY 2004.

Juvenile chinook salmon rearing habitat

All of the data for the rearing sites between Keswick Dam and Battle Creek have been compiled and checked. PHABSIM data decks have been created and hydraulic calibration has been completed for the upstream and downstream transects for all of the rearing sites between Keswick Dam and Battle Creek. Bed files, computational meshes for the 2-D modeling program, calibration of the two-dimensional hydraulic models, and production runs for all of the simulation flows have been completed for all of the 17 rearing sites between Keswick Dam and Battle Creek.

Habitat Suitability Criteria Development

Juvenile chinook salmon rearing

Data collection for fry and juvenile rearing criteria was completed in FY 2001. Fry and juvenile rearing criteria were completed in FY 2003.

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[2] This is the primary technique used to calibrate the River2D model.

Chinook salmon spawning

HSC data were not collected for the six study sites on the Sacramento River between Battle Creek and Deer Creek. HSC previously developed by the Service on the Sacramento River for fall-run chinook salmon spawning (FWS 2003) will be used in FY 2004 to predict the amount of fall-run chinook salmon spawning habitat present over a range of discharges.

Macroinvertebrate Criteria

We are developing a second set of juvenile chinook salmon HSC - one based on food supply rather than physical habitat. Specifically, we are developing HSC for macroinvertebrate biomass and diversity. The criteria we develop will be run on the juvenile rearing site habitat models to predict the relationship between flow and habitat area for macroinvertebrate biomass and diversity. We completed our sampling for macroinvertebrate criteria in FY 2001, with a total of 75 macroinvertebrate samples (22 in riffles, 20 in runs, 13 in pools and 20 in glides). Having completed our sampling, we are now working on sorting, identifying and enumerating the samples. To date, we have completed initial processing of 25 of the 75 samples, separating macroinvertebrates from detritus. These samples are ready to have their biomass measured. We will then determine the relative biomass and diversity represented by each sample. HSC will be developed for macroinvertebrate production and diversity as determined by depth, velocity, and substrate size based on the relative biomass and diversity determined for the samples. Given the stratification of the sampling by depth, velocity and substrate, the 75 samples collected should be sufficient to generate HSC. Lack of sufficient personnel and funding precluded completing this work in FY 2003. We have obtained sufficient funding to complete this work and have selected a contractor to finish the work described above in FY 2004.

Habitat Simulation

Juvenile chinook salmon rearing

Using the Sacramento River juvenile chinook salmon rearing criteria developed in FY 2003, rearing habitat will be computed over a range of discharges in FY 2004. A draft report on the 2-D analysis of the fall, late-fall and winter-run chinook salmon rearing sites between Keswick Reservoir and Battle Creek will be completed in FY 2004.

Chinook salmon spawning

The same Sacramento River fall-run chinook salmon spawning criteria that were used to compute the spawning habitat for study sites between Keswick Dam and Battle Creek (FWS 2003) will be used in FY 2004 to compute the amount of spawning habitat present over a range of discharges. A draft report on 2-D modeling for spawning between Battle Creek and Deer Creek should be completed by September 2004.

LOWER AMERICAN RIVER

As a result of the 115,000 cfs (cubic feet per second) flood releases made into the Lower American River in January of 1997, considerable morphological changes have occurred in many areas of the river including some of our previous study sites. Consequently, CDFG requested that we collect additional hydraulic and structural data, and develop new spawning habitat models for fall-run chinook salmon on the Lower American River.

We decided to run both PHABSIM and the 2-D habitat modeling program used by the U.S. Geological Survey (USGS) office in Fort Collins, Colorado, to allow for additional comparisons of the 2-D model to PHABSIM. The 2-D model uses as inputs the bed topography and substrate of a site, and the water surface elevation at the bottom of the site, to predict the amount of habitat present in the site. We ran the 2-D model for each of the five study sites described in the FY 1998 annual report. The downstream-most PHABSIM transect was used as the bottom of the site, to provide WSEL as an input to the 2-D model. The upstream-most PHABSIM transect was used as the top of the site. To calibrate the 2-D model, bed roughnesses were adjusted until the WSEL at the top of the site matched the WSEL predicted by PHABSIM. The draft report underwent peer review and a final report was completed in February 2003.

BUTTE CREEK

The 2-D habitat modeling program described for the Lower American River study is being used for Butte Creek. Data collection for Butte Creek was completed in FY 2001. The final report for this study was completed in September 2003.

Hydraulic Model Construction and Calibration

All data for the spawning habitat sites were compiled and checked, and PHABSIM data decks, hydraulic calibration and final 2-D modeling files for the seven sites were completed for all sites in FY 2002. In FY 2003, production runs were completed for all seven study sites.

Habitat Suitability Criteria Development

Spawning

Data collection for spring-run chinook salmon spawning HSC was completed in FY 2001. Spring-run chinook salmon spawning HSC were completed in FY 2003.

Habitat Simulation

Using the Butte Creek spring-run chinook salmon spawning criteria developed in FY 2003, computation of spawning habitat over a range of flows was completed in FY 2003. A draft report on the 2-D modeling portion of the Butte Creek study was completed and underwent peer review. The final report was completed in September 2003.

YUBA RIVER

Habitat Mapping

The FY 2003 annual work plan called for mesohabitat mapping of the Yuba River in the reaches where juvenile salmonid rearing and macroinvertebrate habitat will be simulated. Our study plan called for this work to be done in two reaches: (1) upstream of Daguerra Dam which encompasses the river between Englebright Dam and Daguerra Dam, and (2) downstream of Daguerra Dam which encompasses the river from the dam to the confluence with the Feather River. The mesohabitat mapping in the annual work plan called for either using aerial photos or on-the-ground methods using an electronic distance meter and Global Positioning System (GPS) unit to determine the total length of each mesohabitat type (run, riffle, pool, glide) and the location of each mesohabitat unit.

The mesohabitat mapping was performed August 11-13, 2003. This work consisted of boating upstream from the confluence with the Feather River and delineating the mesohabitat units. Using habitat typing protocols developed by CDFG, the Yuba River was habitat mapped between the confluence with the Feather River and Englebright Dam. Aerial photos were used in conjunction with direct observations to determine the beginning and ending of each habitat unit. The location of the top and bottom of each habitat unit was recorded with GPS. The habitat units were also delineated on the aerial photos. The number of units for each habitat type were determined for each reach. A total of 130 mesohabitat units were mapped for the reach upstream of Daguerra Dam and 90 mesohabitat units for the reach downstream of Daguerra Dam. Table 1 summarizes the habitat types, area and numbers of each type recorded during the habitat mapping process.

Table 1
FY 2003 Yuba River Mesohabitat Mapping Results by Reach

Mesohabitat Type	Upstream of Area (1000 m^2)	Daguerra Dam Number of Units	Downstream of Area (1000 m^2)	Daguerra Dam Number of Units
Bar Complex Riffle (BCRi)	73.5	17	94.6	14
Bar Complex Run (BCRu)	631.8	19	379.3	24
Bar Complex Glide (BCG)	193.5	12	361.7	17
Bar Complex Pool (BCP)	159.6	15	120.5	14
Flat Water Riffle (FWRi)	1.6	2	0	0
Flat Water Run (FWRu)	49.0	6	6.2	1
Flat Water Glide (FWG)	18.6	1	73.4	4
Flat Water Pool (FWP)	78.7	8	173.9	6
Side Channel Riffle (SCRi)	11.0	12	1.5	1
Side Channel Run (SCRu)	46.8	19	11.3	5
Side Channel Glide (SCG)	5.5	3	2.1	2
Side Channel Pool (SCP)	34.5	15	1.4	2
Cascade (C)	1.1	1	0	0

Field Reconnaissance and Study Site Selection

Juvenile Rearing

Field reconnaissance in FY 2003 investigated potential study sites where two-dimensional (2-D) habitat modeling will be undertaken for fall-run chinook salmon, spring-run chinook salmon, and steelhead/rainbow trout juvenile rearing. A total of 18 study sites will be used for this purpose. Ten of the 18 study sites are those used for fall-run chinook salmon, spring-run chinook salmon, and steelhead/rainbow trout spawning. Of the eight new study sites, three were selected in the reach upstream of Daguerra Dam and five were selected in the reach downstream of Daguerra Dam. The following section describes the methods employed and the results of FY 2003 reconnaissance and study site selection efforts for these species.

Following the completion of the mesohabitat mapping on August 13, 2003, the mesohabitat types and numbers of each habitat type were enumerated. Based on the results of this analysis, we selected eight habitat study sites in the reaches up and downstream of Daguerra Dam that, together with the 10 spawning habitat study sites, will adequately represent the various mesohabitat types in each reach. The process of designating the eight new habitat study sites relied on random selection to insure unbiased selection of the study sites. On August 14, 2003, we visited the various potential study sites that had been selected through this process to ascertain their suitability for 2-D modeling. Considering time and manpower constraints, the reconnaissance work narrowed the list of potential sites to the eight additional juvenile rearing sites that will be modeled.

Three of the new juvenile rearing study sites are located between the Narrows and Daguerra Dam and the remaining five are located downstream of Daguerra Dam between Daguerra Dam and the confluence with the Feather River (Table 2). Due to the logistical difficulties with accessing and transporting needed equipment above a large hydraulic barrier in the middle section of the Narrows, the study sites were confined to downstream of that barrier. For the sites selected for modeling, the landowners along both riverbanks were identified and temporary entry permits were sent, accompanied by a cover letter, to acquire permission for entry onto their property during the course of the study.

HSC Development

Spawning

<u>Methods</u>

On November 4-6, 2002, and November 18-21, 2002, we collected fall-run chinook salmon spawning criteria data in our study sites upstream and downstream Daguerra Dam. We sampled four sites upstream of Daguerra Dam (U.C. Sierra, Timbuctoo, Highway 20, and Hammond) and three sites downstream of Daguerra Dam (Upper Daguerra, Lower Daguerra, and Plantz). This data will be used for both HSC development and validation of the 2-D model's ability to accurately predict habitat suitability for spawning for each of the study sites. In each study site we collected habitat suitability data (depth, velocity and substrate) and counted the number of redds in each study site. The location of each redd found in our study sites was recorded with a total station. We sampled shallow areas by wading, and sampled deep areas within our study

Table 2
Sites Selected for Modeling Spring-Run, Fall-Run Chinook Salmon and Steelhead/Rainbow Trout Rearing

Site Name	Reach	Site Mesohabitat Types[3]
Narrows	Above Daguerra	FWP, FWRu
Rose Bar	Above Daguerra	BCP
U.C. Sierra	Above Daguerra	BCRi, BCG, BCP, SCRi (2), SCRu, SCP
Timbuctoo	Above Daguerra	BCRu (2), BCRi (2), BCG, BCP, SCRu (3), SCRi, SCG, SCP (2)
Highway 20	Above Daguerra	BCRi, BCP, BCG, SCRu, SCRi
Island	Above Daguerra	BCRu, BCG, BCP (2), SCRu, SCRi
Hammond	Above Daguerra	BCRu
Diversion	Above Daguerra	BCRu
Upper Daguerra	Below Daguerra	BCRu(2), BCRi
Lower Daguerra	Below Daguerra	BCRu, BCRi
Pyramids	Below Daguerra	BCRu, BCRi, BCG
Hallwood	Below Daguerra	BCRu, BCRi
Lower Hallwood	Below Daguerra	BCP, BCG
Plantz	Below Daguerra	BCRu, BCG
Whirlpool	Below Daguerra	BCP
Side-Channel	Below Daguerra	SCRu, SCP
Sucker Glide	Below Daguerra	FWG
Railroad Bridge	Below Daguerra	FWRu, FWP

sites visually using an inflatable kayak; water visibility was sufficient to sample all areas in our study sites by visual observation above the water surface. We also recorded the percent redd superimposition and periodically recorded water temperature. Flows in the river upstream of Daguerra Dam from the beginning of fall-run spawning (October 1) until data collection for this portion of the river was completed on November 20, 2002 fluctuated between 650-952 cfs. Flows in the river downstream of Daguerra Dam from the beginning of fall-run spawning until data collection for this portion of the river were completed on November 21 fluctuated between 410-657 cfs. The unstable nature of the flows in both portions of the river resulted in some uncertainty that the measured depths and velocities were the same as those present at the time of

[3]Lack of a number in parenthesis indicates one unit for that mesohabitat type in the site.

redd construction. We plan to collect additional HSC for fall-run chinook salmon spawning up and downstream of Daguerra Dam in November-December 2003, with particular effort to be spent on looking for deep redds[4].

We collected HSC data for steelhead/rainbow trout on April 8-10, 2003. We were unable to collect HSC data for steelhead/rainbow trout during the months of February-March due to high water and poor visibility conditions. Upstream of Daguerra Dam, data collection was conducted between the downstream end of the Narrows and the top of U.C. Sierra site, Timbuctoo site, Highway 20 site, and the section of the river downstream of Highway 20 site to just above Island site. Downstream of Daguerra Dam, data collection was conducted in Upper Daguerra, Lower Daguerra, Pyramids, and Hallwood study sites. The steelhead/rainbow trout spawning criteria data collected consisted of habitat suitability data (depth, velocity and substrate), redd widths and lengths, and a count of the number of redds in each distinct spawning area. For redds located outside the study sites, the location of each redd was marked with a GPS unit. The location of redds within the study sites were recorded using a total station. As with the fall-run chinook salmon redds within the study sites, this data will be used for developing HSC and for validating the accuracy of the habitat suitability prediction of the study site 2-D models. We also recorded the percent redd superimposition and periodically recorded water temperature. In most cases, observed redds were in water depths shallow enough to enable measurement by hand. However, 10 redds were observed in deep water on April 9, 2003, between the downstream end of the Narrows and the top of the U.C. Sierra study site. Upstream of Daguerra Dam, flows fluctuated moderately between approximately 1,975-2,100 cfs during the 1-month period prior to the April 8-10, 2003, data collection, with the exception of a 5-day period (March 14-18, 2003) when flows increased up to 4,931 cfs, resulting in some uncertainty that the measured depths and velocities were the same as those present at the time of redd construction. Downstream of Daguerra Dam, flows fluctuated moderately between approximately 1,960-2,200 cfs, with the exception of a 7-day period (March 15-21, 2003) when flows increased up to 5,308 cfs, resulting in some uncertainty that the measured depths and velocities were the same as those present at the time of redd construction. We plan to continue collecting steelhead/rainbow trout spawning HSC data up and downstream of Daguerra Dam in February-April 2004.

For HSC data collection, all of the active redds (those not covered with periphyton growth) which could be distinguished were measured. Data were collected from an area adjacent to the redd which was judged to have a similar depth and velocity as was present at the redd location prior to redd construction. This location was generally about 2 to 4 feet upstream of the pit of the redd; however it was sometimes necessary to make measurements at a 45 degree angle upstream, to the side, or behind the pit. The data were almost always collected within 6 feet of the pit of the redd. Depth was recorded to the nearest 0.1 foot (ft) and average water column velocity was recorded to the nearest 0.01 ft/second. Substrate was visually assessed for the dominant particle

[4] We have recently purchased a new light-weight boat which should enable us to sample deep areas for redds even at low flows.

size range (i.e., range of 1-2 inches) at three locations: 1) in front of the pit; 2) on the sides of the pit; and 3) in the tailspill. Substrate embeddedness data were not collected because the substrate adjacent to all of the redds sampled was predominantly unembedded. The substrate coding system used is shown in Table 3.

Table 3
Substrate Descriptors and Codes

Code	Type	Particle Size (inches)
0.1	Sand/Silt	< 0.1
1	Small Gravel	0.1 - 1
1.2	Medium Gravel	1 - 2
1.3	Medium/Large Gravel	1 - 3
2.4	Gravel/Cobble	2 - 4
3.5	Small Cobble	3 - 5
4.6	Medium Cobble	4 - 6
6.8	Large Cobble	6 - 8
8	Large Cobble	8 - 10
9	Boulder/Bedrock	> 12
10	Large Cobble	10-12

Location of steelhead/rainbow trout redds in deep water was accomplished by boat using underwater video. When searching for redds in deep water using underwater video, a series of parallel runs with the boat upstream within a mesohabitat unit was performed. After locating a redd in deep water, substrate size was measured using underwater video directly over the redds. Depth and water velocity was measured over the redds using the Aquatic Doppler Current Profiler (ADCP). The location of all redds (both in shallow and deep water) was recorded with a GPS unit, so that we could ensure that redds were not measured twice.

Results

We collected HSC for 252 fall-run chinook salmon redds upstream of Daguerra Dam (U.C. Sierra = 70, Timbuctoo = 112, Highway 20 = 33, Hammond = 37) and for 171 fall-run chinook salmon redds downstream of Daguerra Dam (Upper Daguerra = 27, Lower Daguerra = 59, Pyramids = 40, Plantz = 45).

HSC data were collected for 45 steelhead/rainbow trout redds upstream of Daguerra Dam (Timbuctoo = 19, Highway 20 = 7, all other locations surveyed = 19). Downstream of Daguerra Dam HSC data were collected for five redds that were found in and in the vicinity of Upper Daguerra, Lower Daguerra, and Hallwood. Due to the difficulty in distinguishing between steelhead trout and endemic rainbow trout, it was impossible to verify whether the redds were constructed by steelhead trout. Based on data collected by CDFG on fall-run chinook salmon and steelhead redds in the Lower American River, we have developed the following criteria to distinguish steelhead/rainbow trout redds from chinook salmon redds: steelhead/rainbow trout redds have a length less than 5.1 feet and a width less than 4.5 feet, while chinook salmon redds have a length greater than 5.1 feet or a width greater than 4.5 feet. These criteria correctly classified 96 percent of 129 chinook salmon redds and 53 percent of 28 steelhead redds from the Lower American River. Since our goal is to avoid classifying chinook salmon redds as steelhead redds, we feel that the above criteria are sufficiently accurate for purposes of collecting steelhead/rainbow trout spawning criteria, particularly since there appear to be relatively few late-fall-run chinook salmon in the Yuba River.

Juvenile Rearing

HSC are used within both PHABSIM and 2-D habitat modeling to translate hydraulic and structural elements of rivers into indices of habitat quality (Bovee 1994). The collection of chinook salmon and steelhead/rainbow trout fry and juveniles Young of Year (YOY) rearing HSC data began during FY 2003 with surveys conducted on September 8-11, 2003. Snorkeling surveys were conducted along the banks, while SCUBA was employed to survey the deep water portion of the habitat units.

We also collected depth, velocity, adjacent velocity[5] and cover data on locations which were not occupied by juvenile chinook salmon and steelhead/rainbow trout (unoccupied locations). This was done so that we could apply a method presented in Rubin et. al. (1991) to explicitly take into account habitat availability in developing HSC criteria, without using preference ratios (use divided by availability). Traditionally, criteria are created from observations of fish use by fitting a nonlinear function to the frequency of habitat use for each variable (depth, velocity, cover,

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[5] The adjacent velocity was measured within 2 feet on either side of the location where the velocity was the highest. Two feet was selected based on a mechanism of turbulent mixing transporting invertebrate drift from fast-water areas to adjacent slow-water areas where fry and juvenile salmon and steelhead/rainbow trout reside, taking into account that the size of turbulent eddies is approximately one-half of the mean river depth (Terry Waddle, USGS, personal communication), and assuming that the mean depth of the Yuba River is around 4 feet (i.e., 4 feet x ½ = 2 feet). This measurement was taken to provide the option of using an alternative habitat model which considers adjacent velocities in assessing habitat quality. Adjacent velocity can be an important habitat variable as fish, particularly fry and juveniles, frequently reside in slow-water habitats adjacent to faster water where invertebrate drift is conveyed. Both the residence and adjacent velocity variables are important for fish to minimize the energy expenditure/food intake ratio and maintain growth.

adjacent velocity). One concern with this technique is what effect the availability of habitat has on the observed frequency of habitat use. For example, if cover is relatively rare in a stream, fish will be found primarily not using cover simply because of the rarity of cover, rather than because they are selecting areas without cover. Rubin et.al. (1991) proposed a modification of the above technique where depth, velocity, cover and adjacent velocity data are collected both in locations where fish are present and in locations where fish are absent. Criteria are then developed by using a nonlinear regression procedure (suited to data with a Poisson distribution) with number of fish as the dependent variable and depth, velocity, cover and adjacent velocity as the independent variables, and all of the data (in both occupied and unoccupied locations) are used in the regression. An alternative approach is to use a logistic regression procedure, with the only difference being that the dependent variable is the presence or absence of fish.

Before going out into the field, a data book was prepared with one line for each unoccupied location where depth, velocity, cover and adjacent velocity would be measured. Each line had a distance from the bank, with a range of 0.5 to 10 feet by 0.5 foot increments, with the values produced by a random number generator. In areas where we were able to sample up to 20 feet from the bank, we doubled the above distances.

When conducting snorkeling surveys adjacent to the bank, one person snorkeled upstream along the bank and placed a weighted, numbered tag at each location where YOY chinook salmon or steelhead/rainbow trout were observed. The snorkeler recorded the tag number, the species, the cover code[6] and the number of individuals observed in each 10-20 mm size class on a Poly Vinyl Chloride (PVC) wrist cuff. Water temperature, the average and maximum distance from the water's edge that was sampled, cover availability in the area sampled (percentage of the area with different cover types) and the length of bank sampled (measured with a 300-foot tape) was also recorded.

A 300-foot tape was put out with one end tied at the location where the snorkeler finished and the other end loose with a small buoy attached. Three people went up the tape, one with a stadia rod and data book and the other two with a wading rod and velocity meter. At every 20-foot interval along the tape, the person with the stadia rod measured out the distance from the bank given in the data book. If there was a tag within 3 feet of the location, "tag within 3" was recorded on that line in the data book and the people proceeded to the next 20-foot mark on the tape, using the distance from the bank on the next line. If the location was beyond the sampling distance, based on the information recorded by the snorkeler, "beyond sampling distance" was recorded on that

[6] If there was no cover elements (as defined in Table 4) within 1 foot horizontally of the fish location, the cover code was 0 (no cover).

Table 4
Cover Coding System

Cover Category	Cover Code[7]
no cover	0
cobble (3-12" diameter)	1
boulder (> 1' diameter)	2
fine woody vegetation (< 1" diameter)	3
branches	4
log (> 1' diameter)	5
overhead cover (> 2' from substrate)	7
undercut bank	8
aquatic vegetation	9
rip-rap	10

line and the recorder went to the next line at that same location, repeating until reaching a line with a distance from the bank within the sampling distance. If there was no tag within 3 feet of that location, one of the people with the wading rod measured the depth, velocity, adjacent velocity and cover at that location. Depth was recorded to the nearest 0.1 ft and average water column velocity and adjacent velocity were recorded to the nearest 0.01 ft/s. Another individual retrieved the tags, measured the depth and mean water column velocity at the tag location, measured the adjacent velocity for the location, and recorded the data for each tag number. Data taken by the snorkeler and the measurer were correlated at each tag location.

Scuba surveys of deep water mesohabitat areas were conducted by first anchoring a rope longitudinally upstream through the area to be surveyed to facilitate upstream movement by the divers and increase diver safety. Two divers entered the water at the downstream end of the rope and proceeded along the rope upstream using climbing ascenders. One diver concentrated on surveying the water below and to the side, while the other diver concentrated on surveying the water above and to the side. When a juvenile salmon or steelhead/rainbow trout was observed, a weighted buoy was placed by the divers at the location of the observation. The cover code and

[7] In addition to these cover codes, we have been using the composite cover codes 3/7, 4/7, 5/7 and 9/7; for example, 4/7 would be branches plus overhead cover.

the number of individuals observed in each 10-20 mm size class was then recorded on a PVC wrist cuff. Water temperature, cover availability in the area sampled (percentage of the area with different cover types) and the length of river sampled (measured with the electronic distance meter) were also recorded.

After the dive was completed, the ADCP was turned on (to record unoccupied depth and velocity data) as we started to pull in the rope after the dive. The boat followed the course of the dive as the rope was pulled back into the boat. If there were any observations during the dive, the ADCP was stopped 3 feet before the location of the observation and started again 3 feet after the location of the observation. For each occupied location, individuals in the boat retrieved each buoy and measured the water velocity and depth over that location with the ADCP, making at least 12 observations. For each set of data collected using the ADCP for a juvenile fish observation, the average depth and velocity are considered the depth and velocity, while the maximum velocity is considered the adjacent velocity. The ADCP was turned off at the location where the dive ended.

A random number generator was used to select ADCP measurements of depth and velocity for unoccupied locations. The number of unoccupied cells selected for each site was the lesser of either 10 percent of the total distance (feet) sampled or 30 percent of the total number of ADCP points. For the SCUBA data, cover was assigned to all of the observations in proportion to which they were observed during the dive. The adjacent velocity for each unoccupied location was the largest of the three following values: the velocity at the location immediately prior to the unoccupied location, the velocity at the unoccupied location, and the velocity at the location immediately after the unoccupied location.

All YOY chinook salmon observed have been classified by race according to a table provided by CDFG correlating race with life stage periodicity and total length. Data were also compiled on the length of each mesohabitat and cover type sampled to try to have equal effort in each mesohabitat and cover type and that each location was only sampled once at the same flow (to avoid problems with pseudo-replication).

Results

We collected a total of 30 measurements of cover, depth, velocity and adjacent velocity where juvenile steelhead/rainbow trout and chinook salmon were observed. All 30 observations were of juvenile steelhead/rainbow trout, with no juvenile chinook salmon observed. All 30 of these observations were made near the river banks while snorkeling, and all observations were made upstream of Daguerra Dam. There were 29 observations of 40-60 mm fish, 5 observations of 60-80 mm fish and 1 observation of fish greater than 80 mm[8]. We made 209 measurements for

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[8] These numbers total more than 30 because most of the observations included YOY of several size classes and only one measurement was made per group of closely associated

unoccupied locations (178 in shallow areas and 31 in deep areas). Depth, velocity and adjacent velocity were measured at all 209 locations, and cover was recorded at all of the shallow locations.

A total of 12 mesohabitat units (7 upstream of Daguerra Dam and 5 downstream of Daguerra Dam) were surveyed in September 2003. Two of these mesohabitat units were surveyed using SCUBA, with 11 surveyed by snorkeling. A total of 2,915 feet of near-bank habitat and 1,050 feet of deep water habitat were sampled. Table 5 summarizes the number of feet of different mesohabitat types sampled to date and Table 6 summarizes the number of feet of different cover types sampled to date.

We have developed two different groups of cover codes based on snorkel surveys we conducted on the Sacramento River: Cover Group 1 (cover codes 4 and 7 and composite [instream+overhead] cover), and Cover Group 0 (all other cover codes). We sampled 2,648 feet of Cover Group 0 and 267 feet of Cover Group 1 in near-bank habitat (snorkeling), and sampled only Cover Group 0 in mid-channel habitat (SCUBA). The collection of chinook salmon and steelhead/rainbow trout fry and juveniles (YOY) rearing HSC data will continue in FY 2004 with data collection planned every 2 months through the year.

Table 5
Distances (feet) Sampled for Juvenile Salmonid HSC Data - Mesohabitat Types

Mesohabitat Type	Near-bank habitat distance sampled	Mid-channel habitat distance sampled
Bar Complex Glide	600	0
Bar Complex Pool	515	1050
Bar Complex Riffle	300	0
Bar Complex Run	600	0
Flatwater Glide	300	0
Flatwater Pool	0	0
Flatwater Riffle	0	0
Flatwater Run	0	0
Side-Channel Glide	300	0
Side-Channel Pool	150	0
Side-Channel Riffle	0	0
Side-Channel Run	150	0

individuals.

Table 6
Distances (feet) Sampled for Juvenile Salmonid HSC Data - Cover Types

Cover Type	Near-bank habitat distance sampled	Mid-channel habitat distance sampled
None	630	178
Cobble	1682	100
Boulder	282	278
Fine Woody	149	0
Branches	119	0
Log	3	0
Overhead	34	0
Undercut	0	0
Aquatic Vegetation	18	495
Rip Rap	0	0
Overhead + instream	219	0

Hydraulic Model Construction and Calibration

Spawning

Hydraulic and structural data collection continued in FY 2003. The data collected at the inflow and outflow transects include: 1) WSEL, measured to the nearest 0.01 foot at a minimum of three significantly different stream discharges using standard surveying techniques (differential leveling); 2) wetted streambed elevations determined by subtracting the measured depth from the surveyed WSEL at a measured flow; 3) dry ground elevations to points above bankfull discharge surveyed to the nearest 0.1 foot; 4) mean water column velocities measured at a mid-to-high-range flow at the points where bed elevations were taken; and 5) substrate and cover classification at these same locations (Tables 1 and 2) and also where dry ground elevations were surveyed. Data collected between the transects include: 1) bed elevation; 2) northing and easting (horizontal location); 3) cover; and 4) substrate. These parameters are collected at enough points to characterize the bed topography, substrate and cover of the site.

We have used two techniques to collect the data between the top and bottom transects: 1) for areas that were dry or shallow (less than 3 feet), bed elevation and horizontal location of individual points are obtained with a total station, while the cover and substrate are visually assessed at each point; and 2) in portions of the site with depths greater than 3 feet, the ADCP is used in concert with the total station to obtain bed elevation and horizontal location. Specifically, the ADCP is run across the channel at 50 to 150-foot intervals, with the initial and final horizontal location of each run measured by the total station. The WSEL of each ADCP run is measured with the level before starting the run. The WSEL of each run is then used together with the depths from the ADCP to determine the bed elevation of each point along the run. Velocities at each point measured by the ADCP will be used to validate the 2-D model. To validate the velocities predicted by the 2-D model for shallow areas within a site, depth, velocities, substrate and cover measurements will be collected along the right and left banks within each site by wading with a wading rod equipped with a Marsh-McBirney[R] model 2000 or a Price AA velocity meter. The horizontal locations and bed elevations will be determined by taking a total station shot on a prism held at each point where depth and velocity were measured. A minimum of 25 representative points will be measured along the length of each side of the river per site.

Water surface elevations have been measured at low, medium, and high flows for all 10 study sites. Discharge measurements for the above WSEL have been made on all sites except Hallwood and Plantz[9]. Velocity sets have been collected for the transects at all ten study sites. Depth and velocity measurements were made using a boat-mounted ADCP and by wading with a wading rod equipped with a Marsh-McBirney[R] model 2000 or a Price AA velocity meter.

A tape or an electronic distance meter were used to measure stations along the transects. Substrate and cover along the transects were determined visually. Dry bed elevations along the transects have been collected for all 10 study sites. Substrate and cover data along the transects have been collected for all 10 study sites. Vertical benchmarks have been tied together for all 10 study sites.

We have collected the data between the top and bottom transects by obtaining the bed elevation and horizontal location of individual points with a total station, while the cover and substrate are visually assessed at each point. Through the end of FY 2003, bed topography data were collected for all 10 study sites, with the exception of a small portion of Timbuctoo study site. Bed elevations, substrate and cover data for portions of the sites over 3 feet in depth have been collected using the ADCP and total station for all 10 study sites. All of the area of the sites was shallow enough that the underwater video has not been needed to collect substrate and cover data; instead the substrate and cover data were directly visually determined. Shallow validation velocity data collection for the 10 study sites were completed during FY 2003. We anticipate completing the hydraulic and structural data collection for all 10 spawning study sites in early FY 2004. We also anticipate establishing the remaining eight new study sites for juvenile rearing and completing the hydraulic and structural data collection for these sites by the end of FY 2004.

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[9] We will be using the Marysville gage (USGS No. 11421000) flow for the discharge for these two sites.

APPLICATION OF NEW TECHNOLOGIES

We published a paper (Appendix A) in the November 2003 issue of the North American Journal of Fisheries Management presenting the methods used in our 1997-2001 CVPIA-funded studies on the lower American River and the Sacramento River. The paper presents the results of our use of new technologies and the time savings associated with these technologies.

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APPENDIX A

GARD AND BALLARD 2003

North American Journal of Fisheries Management 23:1114–1125, 2003
American Fisheries Society 2003

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.

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.

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Received September 9, 2002; accepted January 17, 2003

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 (MicroSeaCam 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

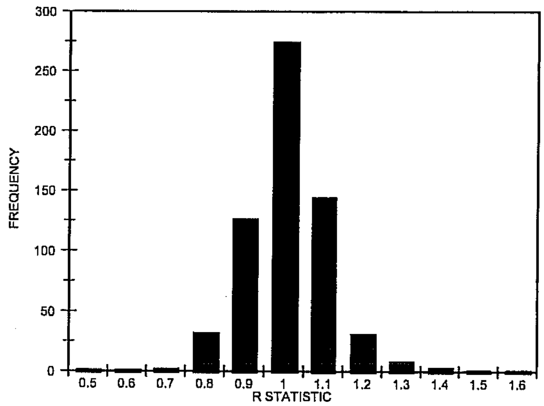

FIGURE 1.—Frequency distribution of R (velocity quality control statistic) for data collected in 1995 on the lower American River with a Price AA velocity meter; $R = \mathrm{Vel}_i/(\mathrm{Vel}_{i-1} + \mathrm{Vel}_{i+1})/2$ at station i, where $i - 1$ refers to the station immediately before station 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:

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

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

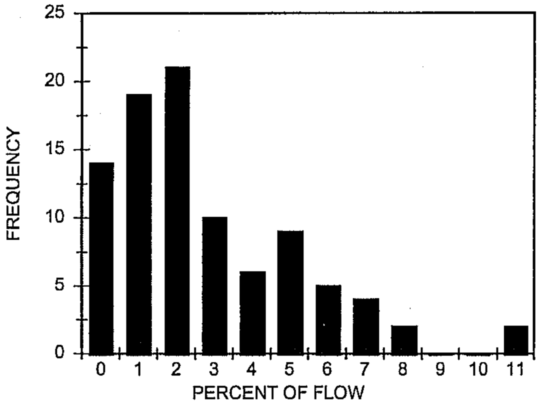

FIGURE 2.—Frequency distribution of errors in acoustic Doppler current profiler (ADCP) flow measurements. The x-axis is the percentage difference between the flow measured with the ADCP and the actual flow, based on gauge records. The average error was 2.7% (n = 93).

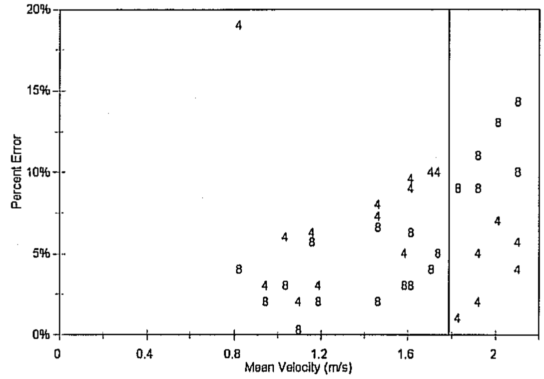

FIGURE 3.—Error relative to gauge flows for discharge measurements made on 19 Sacramento River physical habitat simulation (PHABSIM) Chinook salmon spawning transects with ADCP modes 4 (points labeled 4) and 8 (points labeled 8). The x-axis is the mean of all of the velocity measurements made on each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

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/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-

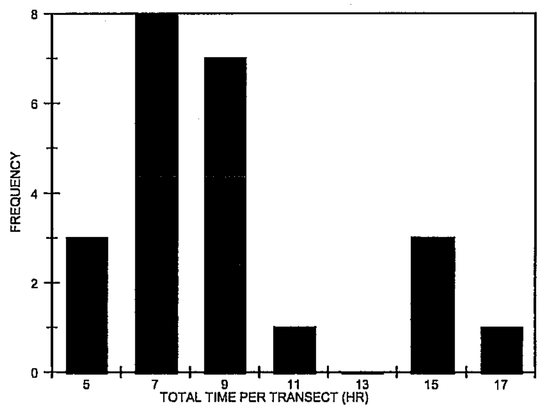

FIGURE 4.—Frequency distribution of total time per PHABSIM transect for lower American River and Sacramento River Chinook salmon spawning sites and for Sacramento River Chinook salmon rearing sites. The x-axis is the midpoint of the interval of the total time per transect. The average time was 9 h (n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

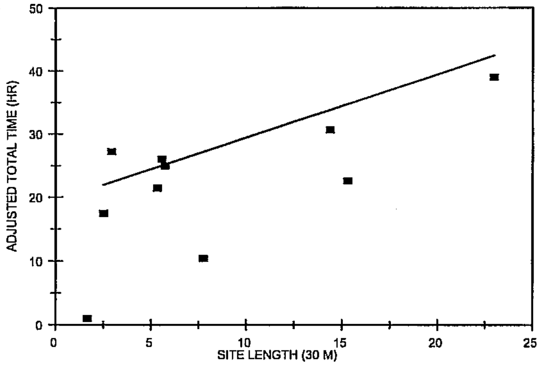

FIGURE 5.—Estimated relationship between adjusted total time and site length; adjusted total time = 19.5 h + site length (30 m; r = 0.53, P = 0.017, n = 10).

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 × 3.4 × 7 people) with scuba techniques, versus 3.9 person-hours per transect (1.3 h × 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 × 11 people per two transects) with the previous technology, versus 4.2 person-hours per transect (1.4 h × 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 × 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 × 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 × [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

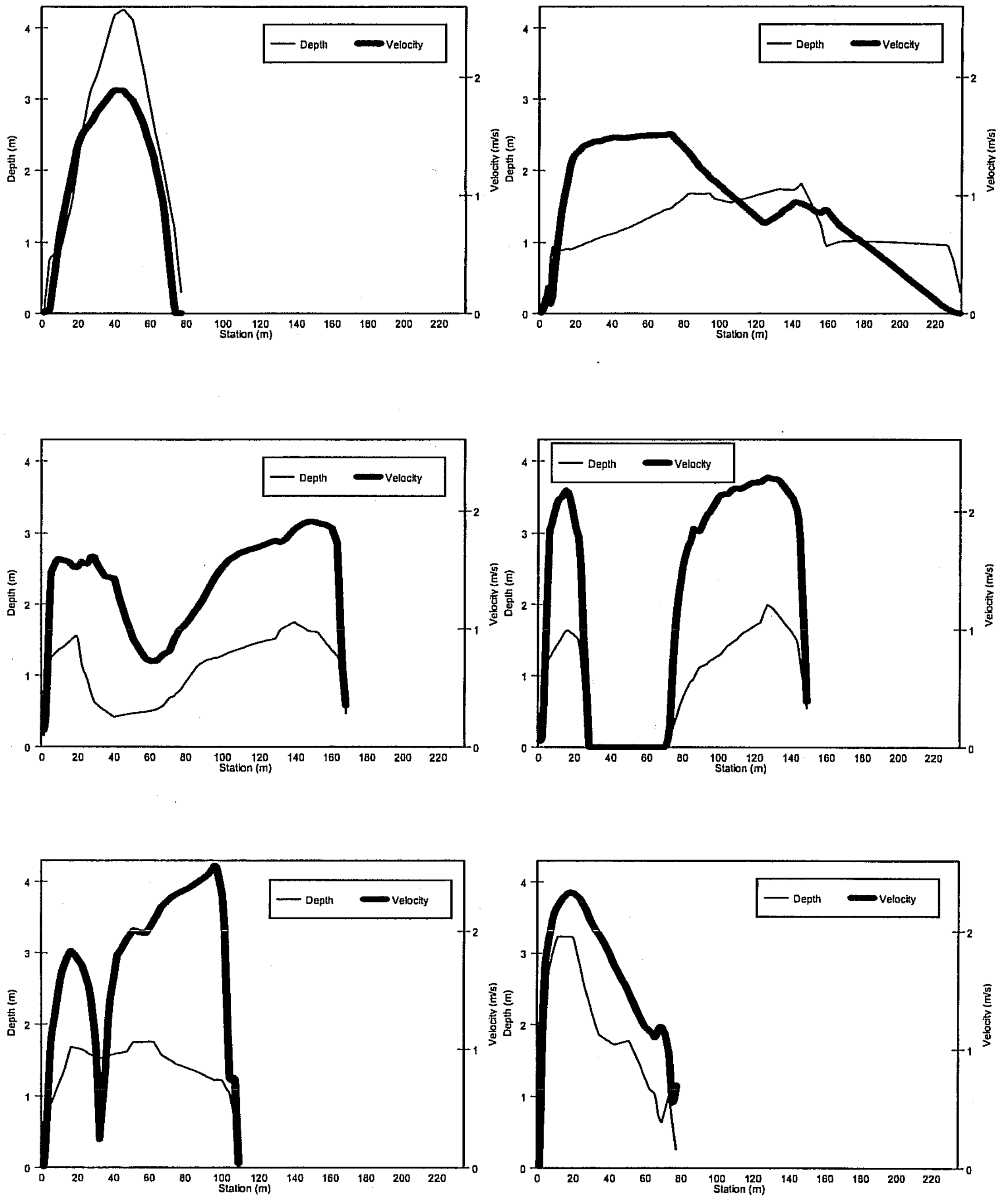

FIGURE 6.—Depth and velocity profiles, at a flow of 295.8 m^3/s, of transects that would have been needed to represent the habitat (in terms of the variation in depth and velocity profiles) for one of the longer two-dimensional (2-D) juvenile habitat modeling sites in the Sacramento River. Data were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

Acknowledgments

We thank J. Thomas, W. Amy, B. Cordone, J. Kelly, J. Kent, R. Williams, E. Sauls, J. Big Eagle, J. Ly, S. Boring, and K. Brown for assistance with the studies discussed in this paper. We also thank B. Mendenhall and S. Pike of the California Department of Water Resources for access to the data from their 1987 Sacramento River instream flow study, and K. Brown of the U.S. Fish and Wildlife Service office in Red Bluff, California, for access to the scuba dive-planing data. The studies were funded by the Central Valley Project Improvement Act Title XXXIV of P.L. 102-575.

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