

CHINOOK SALMON SPAWNING SURVEYS IN DEEP WATERS OF A LARGE, REGULATED RIVER

GEORGE A. SWAN

Coastal Zone and Estuarine Studies Division, Northwest and Alaska Fisheries Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration, 2725 Montlake Boulevard East, Seattle, Washington 98112, U.S.A.

ABSTRACT

In 1986 research divers surveyed and mapped deep-water spawning redds of fall chinook salmon (*Oncorhynchus tshawytscha*) in selected sites within an impounded segment of the main-stem Columbia River, Washington State, U.S.A. In velocities over 3 m s^{-1} and depths up to 11 m, two divers riding a manoeuvrable sled made cross-current transects communicating observations of substrate materials and deep-water spawning sites. Surface personnel tracked the position of the sled with a laser locating system that logged the information into data storage. Subsequently, the computerized data were translated into overlaying maps depicting location of redds, substrate materials, and depth contours.

Deep-water spawning ($>3 \text{ m}$) occurred at most survey sites in velocities between 0.6 and 0.8 m s^{-1} . The average depth of spawning was 6.5 m , and the maximum was 9.1 m —deeper than the depth redds can normally be detected by aerial observation ($3\text{--}4 \text{ m}$). Deep-water spawning ranged from none to substantial in areas of near identical physical characteristics. A method for estimating abundance and density of deep-water redds, based upon the data collected with this mapping technique, is presented. This study combined with current limited information concerning deep-water spawning suggests that up to 80 per cent of the escapement of fall chinook salmon in this reach may spawn in deep water.

KEY WORDS Fall chinook salmon Deep-water spawning River regulation Diver-sled Laser tracking and location

INTRODUCTION

Main-stem dams provide many benefits relating to irrigation, flood control, navigation, and hydroelectric power in the Columbia River Basin of the northwestern United States. They also inundate and remove from production thousands of kilometres of main-stem spawning habitat used by fall chinook salmon (*Oncorhynchus tshawytscha*) (Fulton, 1968). Development of main-stem and tributary hydroelectric dams has eliminated more than half (from $422\,688$ to $189\,795 \text{ km}^2$) the spawning habitat of anadromous salmonids throughout the Columbia Basin (Becker, 1985).

By 1968, the entire main-stem Columbia River from Bonnaville Dam at river kilometre (rkm) 233.4 (measured from the river's mouth) to the Canadian border was impounded behind a succession of dams except for a 84-km section from the upper end of the McNary Dam reservoir (Lake Wallula) near Richland, Washington, at about rkm 555.2 to Priest Rapids Dam at rkm 638.9. This section of river, known as the Hanford Reach (Figure 1), flows freely, but daily flow rates are regulated at Priest Rapids Dam, primarily for power peaking (Becker *et al.*, 1981). Priest Rapids Dam is dependent on releases from Grand Coulee Dam and other dams upstream. The Hanford Reach is the major spawning area for the most viable race remaining of fall chinook salmon in the mid-Columbia River (Watson, 1970; Chapman *et al.*, 1986). Spawning by this race generally occurs from October to December.

Since 1947, numbers of redds in the Hanford reach were estimated each fall primarily through aerial and limited ground counts. These estimates do not include data on the numbers of redds located in water

too deep to be detected from the air or ground surveys (Watson, 1970, 1976), and hold greatest value as an indicator of year-to-year trends. Redds at depths exceeding about 3 m cannot be seen from the air, ground, or from a boat. Redd detection by these traditional methods is limited by water turbidity, river flow, cloud cover, surface winds, and angle and intensity of sunlight (Chapman *et al.*, 1986).

In recent years, spawning of fall chinook salmon in the Hanford Reach has received considerable attention, especially in relation to powerhouse operations and dredging proposals. However, little was known about deep-water spawning by fall chinook salmon. Extensive deep-water spawning at depths to about 4.5 m in the main-stem Columbia River downstream from Kettle Falls, Washington (rkm 1123.0), was described by Chapman (1943). Meekin (1967) studied main-stem spawning near Brewster, Washington (rkm 853), and found redds at depths to approximately 9 m. Chambers (1955) reported that chinook salmon spawned at depths greater than 7 m in the main-stem Columbia River.

Bauersfeld (1978) observed redds in deep water adjacent to Vernita Bar (located approximately 6.5 km downstream from Priest Rapids Dam at about rkm 632.5 (Figure 1)), but did not attempt to determine the depth distribution. He considered that some redds were dug in water too deep to be seen during his aerial surveys, but he concluded that this was not likely since two of his surveys were conducted during minimum flow (about $1.1 \times 10^3 \text{ m}^3 \text{ s}^{-1}$) and optimum viewing conditions.

Chapman *et al.* (1983) hypothesized that a large but undefined portion of the spawning area at Vernita Bar extended below the depths visible from boat or aircraft. They were unable to accurately estimate redd density in deep water, but did employ observations by scuba divers to define limits of the distribution and depth of spawning. Scuba diving was hampered by the high velocities (usually about $0.9\text{--}2 \text{ m s}^{-1}$) and limited visibility (about 3 m). However, they determined that fall chinook salmon at Vernita Bar spawned in depths as great as 10.7 m.

The Hanford Reach is noted for high velocity currents. Chambers (1955) suggested that in the main-stem Columbia River, velocity played a more important role in redd site selection than depth for chinook salmon utilizing a velocity range of 0.8 to about 1 m s^{-1} and he believed that few spawned in velocities above 0.9 m s^{-1} . Bovee (1978) indicated that fall chinook salmon probably would not spawn at velocities above 1.3 m s^{-1} , with only a 50 per cent probability of spawners using velocities of $\geq 0.7 \text{ m s}^{-1}$. However, Bovee's predictions were based primarily on Smith (1973) who measured velocities at about 12.7 cm above redds in shallow water ($<0.5 \text{ m}$) in Oregon streams.

In fall 1986 research divers surveyed Hanford Reach Spawning. The objective was to survey and map, with particular attention to deeper water, the distribution and relative abundance of fall chinook salmon redds in representative sample areas of the Hanford reach. The effort involved: (1) development of separate overlay maps for each study site depicting (a) depth contours, (b) type and size of rock material on the river bed, and (c) distribution of individual redds and concentrated spawning beds within each study site; and (2) collecting data of surface and near-bottom flow velocities at each study site.

MATERIALS AND METHODS

The experienced diving team (Swan *et al.*, 1986) was assisted in making underwater observations of the river bottom and salmon spawning activity in the high velocity currents found in the Hanford Reach by using a towed, two-diver sled. Descriptions of the sled and its operation are contained in Swan (1987). All divers conformed to NOAA Diving Regulations (Miller, 1979).

The surveying team operated a laser locating system, fathometer, electronic data recorder, mapping and surveying systems, and support equipment including: (1) work boats for depth mapping and transportation of personnel and equipment, an inflatable boat for picking up divers, and a diver-sled towboat; (2) portable Marsh-McBirney (reference to trade names does not imply endorsement by the National Maritime Fisheries Service, NOAA) electromagnetic water current meters (a Model 201 mounted on the towboat and a Model 511 mounted on the diver sled); (3) an Alpha Hydrotracking EDM and Total Laser Surveying System; (4) a Raytheon-119D fathometer for depth sounding; (5) a laser reflecting prism mounted on a streamlined surface float for determining location of redds; (6) portable

radios for survey party communication; and (7) a portable loudspeaker to ward off boaters approaching the survey area.

An initial information gathering process included: (1) a literature search on salmon spawning (particularly, main-stem spawning in deeper water); (2) interviews with individuals who had personal experience and knowledge of salmon spawning in the Hanford Reach; and (3) coordinating the survey with personnel who annually monitor salmon spawning at the Vernita Bar, and who have conducted annual aerial surveys of salmon spawning on the Hanford Reach since 1947.

Our literature search revealed that virtually all spawning information for chinook salmon (prior to the detailed study at Vernita Bar (Chapman *et al.*, 1986) and some surface or aerial observations by other

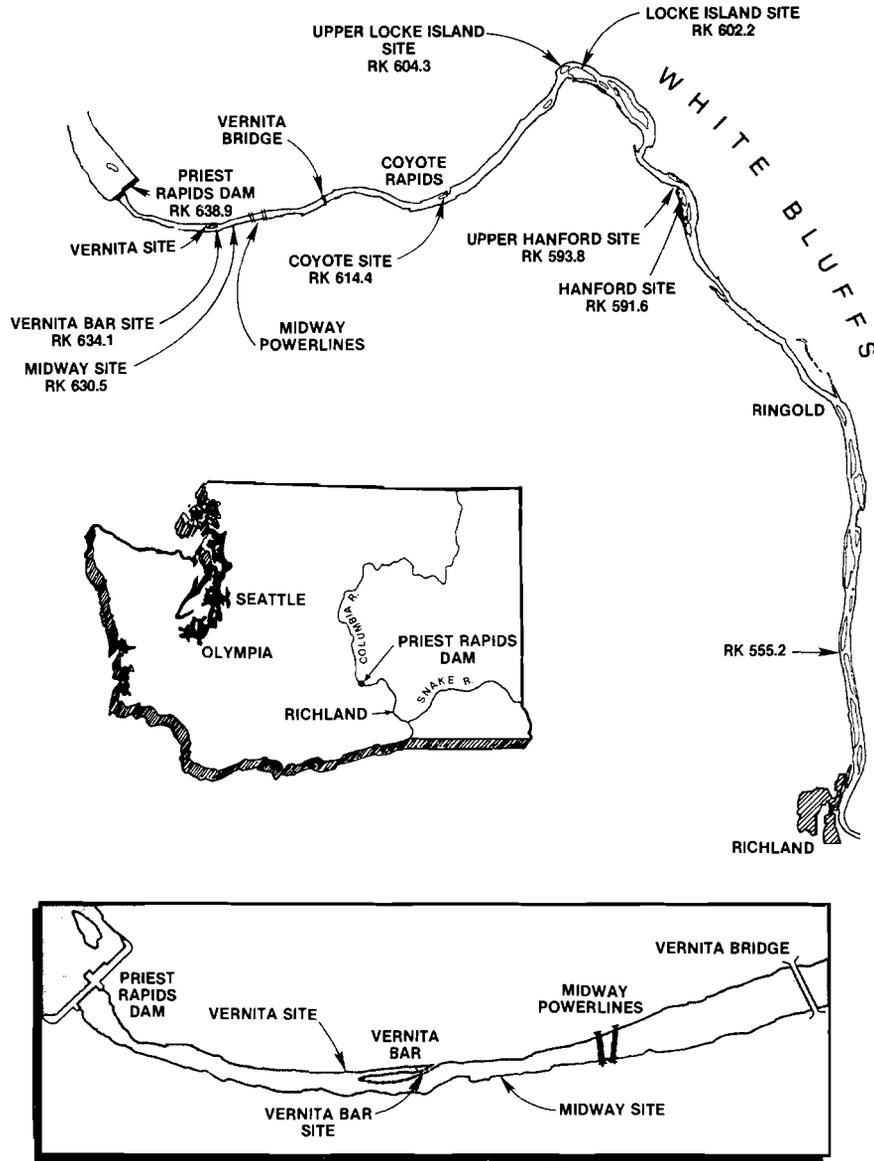


Figure 1. Map of the Hanford Reach of the Columbia River showing the approximate river kilometre and eight study sites for the deep-water survey of fall chinook salmon spawning, 1986

researchers) was based on studies conducted on relatively shallow spawning beds in tributaries. A classic example was Burner (1951). Burner studied the spawning habits of Pacific salmon (*Oncorhynchus* spp.) in tributaries of the Columbia River. His descriptions of the mechanics of redd building, average size and depth of nests, size of gravel used, and stream conditions that modify these characteristics and his illustrations of redds were extremely beneficial in training our divers.

Budget and time constraints, precluded a complete redd count throughout the 84 km of the Hanford Reach. Therefore, based upon the initial information gathering process, we focused our surveys on segments of the river (Figure 1) with deep channels (>3 m—determined from earlier depth profiles for the proposed barge channel) near known sites of concentrated spawning in shallow water. The study sites listed in Table I were designated with names for nearby geographic features. The sites varied from 305 to 610 m in length (parallel to flow) of river channel by the existing width (shore to shore). Each site was marked with a baseline (parallel to river flow) on the most accessible shoreline, and range target stakes were set at 15-m centres for transect lines to provide the boat operator with visual navigation references when making the cross-current transects.

Table I. Survey dates and series for fall chinook salmon spawning sites in the Hanford Reach of the Columbia River, 1986

Survey date	Site	Survey date	Site
15 Oct	Locke Island	04 Nov	Lock Island
16 Oct	Hanford	06 Nov	Upper Hanford
17 Oct	Coyote Rapids	07 Nov	Upper Locke
20 Oct	Vernita	08 Nov	Vernita Bar
21 Oct	Midway	09 Nov	Vernita
22 Oct	Hanford	10 Nov	Midway
23 Oct	Hanford	11 Nov	Coyote Rapids
23 Oct	Locke Island	12 Nov	Hanford
26 Oct	Coyote Rapids	12 Nov	Upper Hanford
27 Oct	Hanford	13 Nov	Locke Island
28 Oct	Locke Island	13 Nov	Upper Locke
29 Oct	Coyote Rapids	14 Nov	Vernita
30 Oct	Midway	16 Nov	Vernita Bar
03 Nov	Vernita	17 Nov	Midway
		18 Nov	Upper Hanford
		19 Nov	Upper Locke
		20 Nov	Midway
		21 Nov	Vernita Bar

Each site selected was surveyed. The 2.54 cm = 15.24 m scale, 0.3-m interval contour bottom-mapping began with cross-sections profiled every 15 m from the high water mark (vegetation line) bank to bank. The cross-section interval was later revised to 46-m centres, with the exception of the Upper Locke Site (established at 15-m intervals because of the site's relatively short length). After the sites were mapped for bathymetry, the river bottom contour maps were used as the base for the bottom materials and redd location mapping.

Surveys began at the upstream end of a study site. About a 1-m minimum depth was required for operation of the boat and sled. Each study site was surveyed by towing the diver-sled on cross-current transects from shore to shore along the 46-m cross-section intervals used to map depth profiles. Each site was to be surveyed at least three times between mid-October and late November to acquire early-, mid-, and late-spawning seasonal data. Table I lists the survey dates for each site.

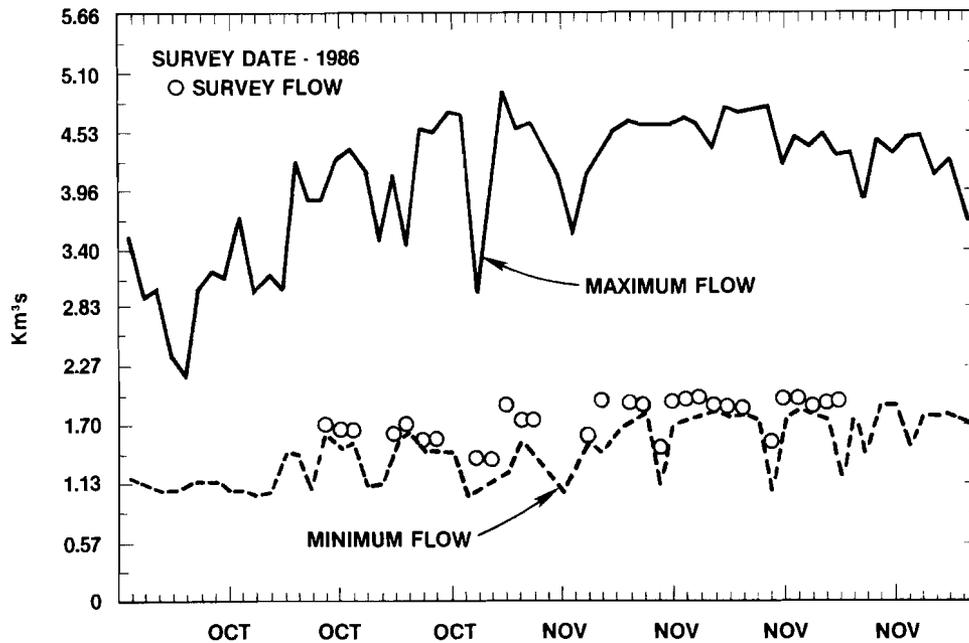


Figure 2. River flow ($\text{km}^3 \text{s}^{-1}$) at Priest Rapids Dam during the deep-water survey of fall chinook salmon spawning in the Hanford Reach of the Columbia River during October and November, 1986

Prior to the spawning surveys, divers conducted surveys at each site to document the river bottom composition according to the following criteria:

Type	Approximate particle size
Sand	Loose particles to 50.8 mm
Gravel	50.9 to 101.6 mm
Rubble	101.7 to 203.2 mm
Rock	203.3 to 304.8 mm
Boulders	Greater than 304.8 mm
Bed rock	Solid rock bottom

Throughout the spawning survey, river flows discharged from Priest Rapids Dam were regulated to a maximum of about $2 \times 10^3 \text{ m}^3 \text{ s}^{-1}$ during the daytime (0800–1600 hours) when all surveys were conducted. We surveyed at near-minimum flows (Figure 2), at sechi-disc transparencies of 1.7–3.9 m, and temperatures of 9–16°C (Table II). discharge from the dam affected elevation of the river surface (fluctuating as much as 3 m over 24 hours) in the upper end of the Hanford Reach. This effect gradually diminished downstream to about the middle of the reach, where the river surface was nearly equal to the forebay level at McNary Dam near Umatilla, Oregon (Carlson, personal communication).

After mapping of the redds was completed, elevation (el.) of the redds, compared to the high water (vegetation line) elevation at each study site, provided a common baseline to calculate depths of redds.

SPAWNING SURVEYS

The actual spawning survey for redd mapping began on 15 October at the Locke Island Site (rkm 602.2) (Table I). River temperature was 15.6°C, and underwater visibility ranged from 1.95 to 3.7 m (Table II). The second series of surveys began with the Hanford Site on 22 October. Considerable numbers of adult

salmon were observed in the study sites, but no true redds were discovered by the end of this series (26 October). However, areas that the divers termed 'test holes' were located in areas of lower velocity where fish apparently had been moving the gravel, making circular depressions about 15 cm deep and approximately 30–45 cm in diameter—so noted by the bright and clean condition (free of algae) of the area disturbed by the fish.

Welsh (1983), described 'false redds' as initial egg pockets that had been abandoned by the female before egg deposition (similar to the 'test holes'). However, the typical size, shape, and configuration of salmonid redds were not present. Welsh believes the 'test holes' represent a 'tune-up exercise' or practice for spawning prompted by the fish's increasing maturation, and he has observed this phenomenon on the bottom of pools in substrate that was unsuitable for spawning. Chapman (personal communication) suggests that the fish begin redds in areas of apparent suitable velocity and substrate and if the initial digging shows that the substrate at depth is unsuitable, the fish moves on; but if conditions are suitable, redd construction continues.

One more complete resurvey of the five sites between 27 October and 3 November revealed more 'test holes' and a small number of redds. Spawning in the shallow waters throughout the Hanford Reach began about 22 October (Dell, personal communication).

On 1 November, when water surface and sunlight conditions were exceptionally favourable an aerial survey pointed out large numbers of redds in shallow water that appeared to extend into deeper water in many areas, especially in the vicinity of Vernita Bar and upstream from the Locke Island and Hanford sites. Large numbers of redds observed from the air appeared to be concentrated upstream or downstream from the boundaries of our three unproductive survey sites. Three new survey sites were added to the redd mapping program—Upper Hanford (rkm 593·8), Upper Locke Island (rkm 604·3), and Vernita Bar (rkm 643·2) (Figure 1). When these sites were surveyed a few days later with the diver-sled, there was indeed spawning activity in deep water (>3m).

Bathymetric mapping and setting baselines for the three new sites were completed between 4 and 9 November. At least one more survey was conducted in each of the five original sites to verify lack of spawning activity. Further surveys were discontinued at the Hanford, Locke Island, and Coyote Rapids sites.

Spawning activity had increased and large concentrations of overlapping redds were observed, making it virtually impossible, on some transects to enumerate individual redds. Therefore, areas of concentrated spawning were portrayed on the initial redd maps by regularly spacing the symbol 'o' for redds, at 3-m intervals at the scale of 2·54 cm = 15·24 m. Dell (personal communication) verified this spacing agrees with the average size and conformation of fall chinook salmon redds at Vernita Bar (about 5·6 m long [parallel to flow] × 3 m wide).

By 16 November, spawning in the Hanford Reach appeared to peak. Water temperature had dropped from 15·6°C to about 10°C since the beginning of the surveys (Table II). The water remained clear. Light penetration from the surface ranged from 2·5 to 3·9 m (Table II) with an average of about 3 m of underwater visibility between 3 and 21 November (period of peak redd count days in the study sites). The surveys continued through 21 November at the five productive survey sites.

SURVEY SITE CHARACTERISTICS

The physical characteristics and the distribution and relative abundance of the observed spawning activity for the Midway Site (Figure 3) are described as representative of the type of information recorded for each of the eight study sites.

Midway Site—rkm 630·5

Km below Priest Rapids Dam: 8·4

Dimensions:

About 594 m long × 366 m wide (about 217 393 m² or 19·8 ha).

Maximum depth:

9·1 m, based on the vegetation line at 122 m el.

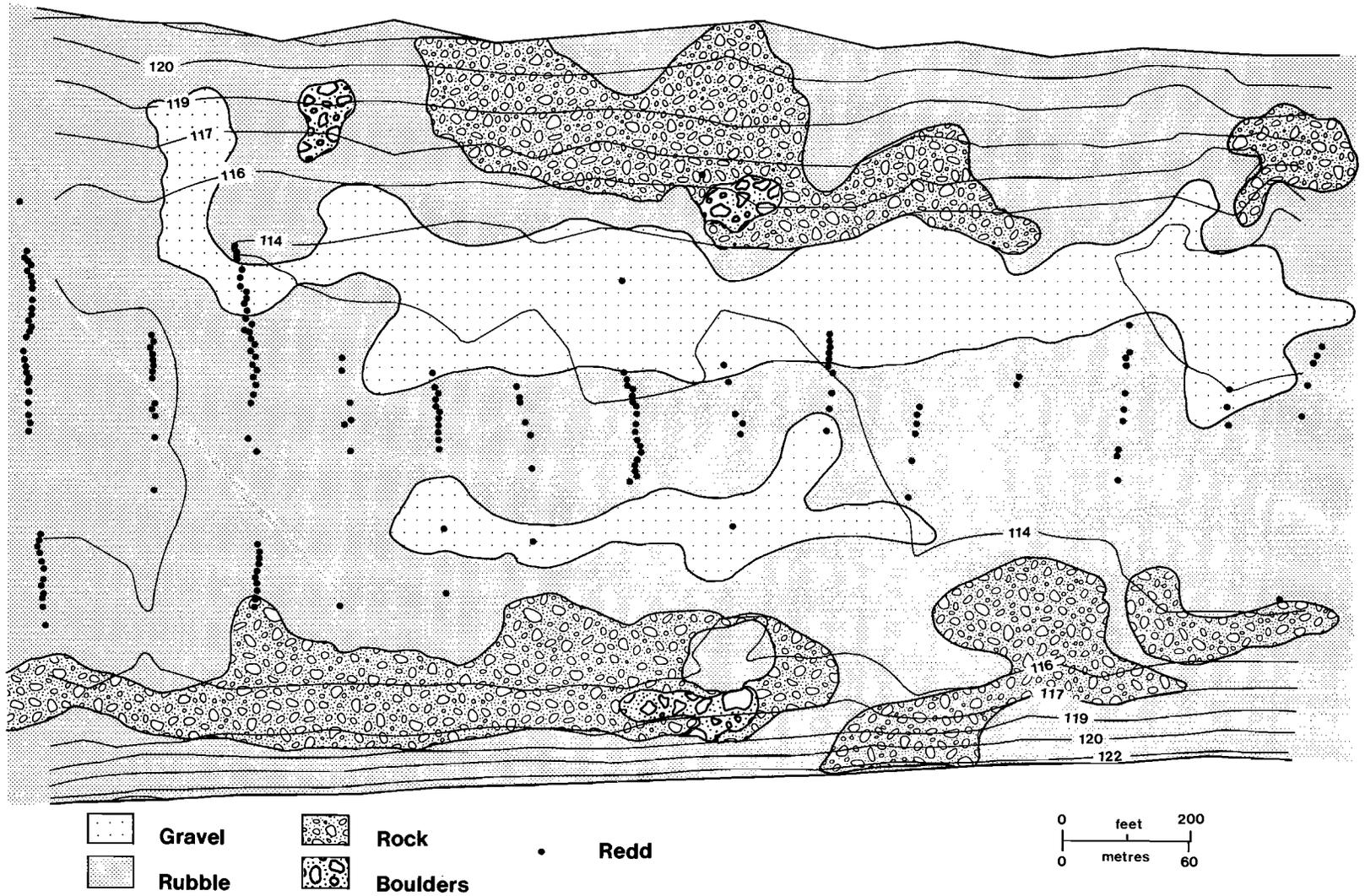


Figure 3. Substrate map of the Midway Study Site (rkm 630.5) showing bottom materials, depth contours (m), and the location of deep-water redds observed from the diver-sled (reproduction of a map from Swan *et al.* [1981])

Table II. Average daily water temperature, light penetration (secchi disk), and average daily discharge observations at Priest Rapids Dam, Columbia River, October and November 1986

Date	Temp. (°C)	October	Discharge $\text{m}^3 \text{s}^{-1}$ (1000)	Temp. (°C)	November	Discharge $\text{m}^3 \text{s}^{-1}$ (1000)
		Light penetration (m)			Light penetration (m)	
1	15.5	1.68	2.49	14.4	2.35	1.47
2	15.6	2.47	1.81	13.9	2.68	1.50
3	15.6	2.99	1.84	13.9	3.20	1.59
4	15.6	2.83	1.36	13.9	3.29	1.93
5	16.1	2.74	1.22	13.9	3.23	1.87
6	16.7	2.93	2.12	13.3	2.59	1.90
7	16.1	3.08	1.53	13.3	2.90	1.87
8	16.1	2.35	1.44	12.8	2.96	1.47
9	16.1	2.96	1.90	12.2	2.47	1.90
10	16.1	3.08	1.64	11.7	2.71	1.93
11	15.6	2.41	2.32	12.2	2.71	1.95
12	15.6	2.04	2.35	11.7	3.11	1.87
13	15.6	3.08	2.72	11.1	3.29	1.87
14	15.6	2.47	2.04	11.1	2.96	1.84
15	15.6	2.32	1.70	11.1	3.11	1.98
16	16.1	2.23	1.67	10.6	3.35	1.53
17	16.1	2.53	1.64	10.0	3.11	1.95
18	16.1	2.53	1.64	10.0	3.11	1.95
19	16.1	3.08	1.19	10.6	3.17	1.87
20	15.6	2.56	1.61	10.6	3.11	1.90
21	15.0	2.29	1.70	10.6	3.87	1.93
22	15.6	3.08	1.53	10.6	3.02	1.98
23	15.6	3.05	1.59	10.6	2.47	1.76
24	15.6	3.72	1.56	10.6	2.35	1.98
25	15.6	3.54	1.39	10.6	3.23	1.95
26	15.6	3.29	1.36	10.0	2.96	1.90
27	15.6	1.95	1.36	10.0	2.99	2.01
28	15.6	3.32	1.90	10.0	2.41	1.93
29	15.0	2.62	1.73	9.4	2.29	1.93
30	14.4	2.62	1.73	9.4	2.29	1.93
31	14.4	2.50	1.90			

The Midway Site was located about halfway between Priest Rapids Dam and the Vernita Bridge (Figure 1). This study site offered an excellent example of deep-water spawning in a large, regulated river. Prior to this survey, visual surface characteristics and aerial observations of the shorelines gave no indication of spawning activity, although Chapman (personal communication) and Watson (personal communication) had suspected deep-water spawning occurred from Vernita Bar downstream for an unknown distance. The river bottom sloped sharply from the vegetation line on both shorelines to a depth of about 6 m. As shown by the contour line spacing (0.3 m) in Figure 3, the middle half of the river bed was basically flat, reaching a maximum depth of just over 9 m. Bottom materials in this study site were primarily rubble, with large areas of rock near each shoreline and a strip of gravel about 61 m wide oriented parallel to and just north of the centreline of the river. The substrate composition appeared to result from erosion of materials from Vernita Bar, about 0.8 km upstream. Velocities measured while performing transects ranged from 0.9 to 2.4 m s^{-1} near the surface and 0.8 to 1.6 m s^{-1} near the bottom.

This site was surveyed on 21 and 30 October and 10, 17, and 20 November 1986 with 14 transect lines at 46-m intervals. Dimensions of the concentrated spawning area were approximately 595 m \times 76 m (45 290 m^2 or 4.5 ha), about 22 per cent of the study area. It was located in the large area of rubble almost

Table III. Redd counts, peak (Survey day with highest count), and total (non-cumulative count of redds for the season) observed at each study site during deep-water spawning surveys in the Hanford Reach of the Columbia River, 1986

Survey site	River kilometre	Maximum redd depth (m)	Peak date	Peak redd count	Total redd count
Hanford	591.6	—	—	0	0
Upper Hanford	593.8	3.05	12 Nov	66	98
Locke Island	602.2	4.57	28 Oct	5	5
Upper Locke Is.	604.3	7.62	19 Nov	180	267
Coyote Rapids	614.4	—	—	0	0
Midway	630.5	9.14	17 Nov	182	384
Vernita Bar	632.2	7.01	16 Nov	141	163
Vernita	634.1	6.71	9 Nov	88	217

centred in the site. Redds in this site were observed in water depths of up to 9.1 m deep, but virtually all were at depths of 6.1 to 7.6 m. Here, the divers observed on 17 November the most live salmon seen at any site. A total of 182 redds were counted. The highest total redd count for any of our study sites was recorded at Midway Site—384 deep-water redds, despite the absence of surface indications of spawning (Table III).

RESULTS AND DISCUSSION

Observations of maximum spawning depths, peak redd count dates (survey day with highest redd count), peak redd counts, and the total number of redds counted (not cumulative) for each site for the survey season are summarized in Table III. Total redd counts for each study site were determined by overlaying maps for each survey day and counting total redds. Table IV shows the estimated per cent utilization of the substrate area in each survey site and the general appearance for spawning suitability when viewed from the surface.

Fish spawned in five of the eight study sites and there was virtually no spawning in the remaining three sites (only five redds were found in the Locke Island Site). However, the requirements for salmon spawning, in shallow water (i.e. suitable current velocity and substrate), appeared to be present in all sites

Table IV. Per cent utilization by fall chinook salmon of total substrate area within spawning survey study sites in the Hanford Reach, Columbia River, compared to appearance for spawning suitability when viewed from the surface

Site	Area of river bottom (m ²)	Substrate appearance	Percent utilized for spawning
Hanford	297 280	Suitable	0
Upper Hanford	117 054	Suitable	36
Locke Island	292 635	Suitable	<1
Upper Locke Island	87 791	Suitable	33
Coyote Rapids	234 108	Questionable	0
Midway	217 393	Unsuitable	22
Vernita Bar	108 693	Suitable	25
Vernita	292 635	Suitable	13

Table V. Summation of habitat characteristics and spawning activity observed at each study site during deep-water spawning surveys in the Hanford Reach of the Columbia River, 1986

Survey site	Predominate substrate type*	Maximum redd depth (m)	Mean near bottom velocity (ms ⁻¹)	Total redds (estimated)	Redds hectare ⁻¹ in concentrated spawning area [†] (estimated)	Utilization (per cent)
Hanford	Rock and rubble	—	1.83 (1.81) [‡]	—	—	—
Upper Hanford	Rock and rubble	3.05	2.29	540	133	34
Locke Island	Rock and gravel	4.57	2.23	—	—	—
Upper Locke Is.	Rock and rubble	7.62	2.11	654	231	32
Coyote Rapids	Rock and rubble	—	1.35	—	—	—
Midway	Rock and rubble	9.14	1.18	1691	380	22
Vernita Bar	Rubble	7.01	1.83	1301	460	26
Vernita	Rock and rubble	6.71	1.18 (0.64) [‡]	800	220	13
Grand average	Rock and rubble	6.35 (6.71) [§]	1.75 (1.23) [¶]		280	22
Total estimated redds				4986		

*Substrate material size: gravel = 50.8 to 101.6 mm; rubble = 101.6 to 203.2 mm; rock = 203.2 to 304.8 mm.

[†]One acre = 4047 m²; one hectare = 2.471 acres.

[‡]Average near bottom velocity measured with the towboat and diver-sled held stationary in the current (no spawning was observed at the Hanford site).

[§]Average maximum depth of spawning for five sites with appreciable spawning.

[¶]Grand average of ([‡]).

(Table V). At all five study sites where spawning occurred, spawning was concentrated (Figure 3 and Table IV). In the spawning areas, deep-water redds commonly overlapped during the latter portion of the spawning season. We did not attempt to determine the degree of superimposition.

Abundance and density of redds

An attempt was made to estimate the abundance and density of redds in each study site using the Welsh method (1983). He proposed that if divers could delineate the outer boundaries of the spawning area, and then establish the average redd size, the maximum possible number of redds could be crudely estimated by dividing the spawning area by the average area of a redd. Our redd mapping technique accurately delineated the outer boundaries of the spawning areas in our study sites. We made no measurements of redd size. However, Chapman *et al.* (1983) measured 262 redds at Vernita Bar and found the average size to be 17 m², including tailspill. Their study found that the size of fall chinook salmon redds in different elevation zones did not vary greatly, whether continually covered by water (deeper spawning) or intermittently exposed above the wetted channel by lower flows (shallow spawning). Therefore, based on Chapman's data for an average redd size and our measurements of the concentrated spawning area within each study site, we used Welsh's method for calculating abundance of redds and arrived at rough estimates of redd abundance and density in the five study sites where spawning occurred (Table VI) (Welsh, 1983). Welsh's method of estimating abundance of redds appears to provide a reasonable estimate (an overall average of 587 redds per ha), but assumes that the spawning area is completely covered with redds with no allowance for spaces between redds.

In an effort to achieve a more accurate estimate of abundance and densities of deep-water redds based on our methodology for data collection, we developed an alternative to Welsh's method. We estimated

Table VI. Estimated redd abundance and density within concentrated areas of spawning (study sites) where spawning was detected during the deep-water spawning survey in the Hanford Reach, Columbia River, 1986 (based on Welsh's method, 1983)

Survey site	Area (m ²)	Hectares*	Total redds [†] (estimated)	Redds hectare ⁻¹ in concentrated spawning area (estimated)
Upper Hanford	41 805	4.2	2 459	585
Upper Locke Is.	29 263	3.0	1 721	574
Midway	45 290	4.5	2 664	592
Vernita Bar	27 173	2.7	1 598	592
Vernita	37 160	3.7	2 186	591
Grand total	180 691	18.1	10 628	Grand average 587

*One acre = 4047 m²; one hectare = 2.471 acres.

[†] Calculated by dividing the area of concentrated spawning by 17 m², the average size of redds measured at Vernita Bar (Chapman *et al.*, 1983).

average redds per transect (*ART*) in each study site by dividing the total number of redds for all transects at each site (*TR*) by the number of transects (*NT*).

$$ART = \frac{TR}{NT}$$

We then estimated total redds for each site (*TRS*) by dividing the length of the site (*LS*) by the width of the transects (*WT*) and multiplying this value by (*ART*).

$$TRS = \frac{LS}{WT} \times (ART)$$

Redds per hectare at each site (*RHS*) was estimated by dividing (*TRS*) by the total hectares within each site (*HS*).

$$RHS = \frac{TRS}{HS}$$

- TR* = Total redds for all transects for each site,
NT = Number of transects,
ART = Average redds per transect for each site,
LS = Length of site in metres,
WT = Width of transects = 4.57 m (the average field of view of divers),
TRS = Total redds per site,
RHS = Redds per hectare,
HS = Hectares per site.

Our extrapolations for redd densities contained in the concentrated area of spawning observed at each study site (where spawning occurred) resulted in an overall average of 280 redds per ha (Table VII). We then estimated average redd density for the total area within the same five sites as 65 redds per ha (Table

Table VII. Estimated density of redds for the area of concentrated spawning within each study site surveyed for deep-water spawning in the Hanford Reach, Columbia River, 1986

Survey site	Peak redd count date	Transect lines (NT)	Redd count (TR) (site)	Redds per transect (ART)	Length of spawning area* (LS) (m)	Total redds [†] estimated (TRS)	Concentrated spawning area (HS) (hectares)	Redds hectare ⁻¹ in concentrated spawning area (estimated)
Hanford	no spawning	14	—	—	—	—	—	—
Upper Hanford	12 Nov	7	66	9	274.32	540	4.05	133
Locke Island	no spawning	14	5 [‡]	—	—	—	—	—
Upper Locke Is.	19 Nov	13 [§]	180	14	213.36	654	2.83	231
Coyote Rapids	no spawning	14	—	—	—	—	—	—
Midway	17 Nov	14	182	13	594.36	1691	4.45	380
Vernita Bar	16 Nov	14	140	10	594.36	1301	2.83	460
Vernita	9 Nov	14	88	6	609.06	800	3.64	220
Grand total			656	10	2286	4986	17.80	Grand average 280

*Length of a study site was oriented parallel to the direction of main river flow.

[†] Estimated redds were calculated by dividing the length of the survey site by 4.57 m (estimated field of visual observation of divers) and multiplying that quotient by the average number of redds per transect line.

[‡] Site was abandoned for lack of significant spawning; therefore, these data were not used in the calculations.

[§] Transect numbers 13 and 14 for this site revealed no redds; therefore, only 13 transects were used for this estimate of redds within the boundaries of concentrated spawning.

Table VIII. Spawning utilization of total area (in hectares) of study sites where spawning by upriver bright fall chinook salmon was detected during the deep-water spawning survey in the Hanford Reach, Columbia River, 1986

Concentrated survey site	Total area (hectares)	Spawning area (hectares)	Utilization (per cent)	Redds hectare ⁻¹ for entire study site (estimated)
Upper Hanford	11.74	4.05	34	54
Upper Locke	8.90	2.83	32	88
Midway	19.83	4.45	22	85
Vernita Bay	10.93	2.83	26	119
Vernita	29.14	3.64	13	29
Total	80.54	17.80	Mean 22	65

VIII). In addition, we compared the total area of the individual sites to the total overall area of the study sites, and arrived at an estimate that suggests that only 22 per cent of the river bottom, within the five study sites where spawning occurred, was utilized for spawning (Table VIII). These estimates, based on our deep-water observations performed on transect intervals, assume that the distribution of redds within the boundaries of the individual site is represented by the average redds per transect.

Velocity measurements were not included in the original objectives and were intended only to provide a rough comparison of habitat characteristics between study sites. However, these estimates do provide relative baseline data for deep-water spawning habitat and appear to agree with the findings of Chapman *et al.* (1983) that fall chinook salmon spawned at velocities of well over 1 m s⁻¹, with velocities of about 0.7 m s⁻¹ during daily minimum flows. We found near bottom velocities of between 0.6 m s⁻¹ and 1.9 m s⁻¹.

Importance of deep-water spawning

The magnitude of suspected deep-water spawning by fall chinook salmon in the Hanford Reach can be demonstrated by calculating the portion of the steadily increasing escapement that apparently spawns in water too deep for aerial redd counting. The escapement of fall chinook salmon to the Hanford Reach (Table IX) equals the McNary Dam adult count less the sum of the adult counts at Ice Harbor Dam (Snake River), Priest Rapids Dam, Priest Rapids Hatchery, fish taken in the Priest Rapids volunteer trap (Chapman *et al.*, 1983), and the sport fishing catch (Dammers, personal communication). Throughout the 1978–1983 period, escapement of fall chinook salmon to the Hanford Reach averaged nearly 23 000. In 1984, the escapement increased to about 47 000 fish (Chapman *et al.*, 1986).

The escapement of fall chinook salmon to the Hanford Reach set a record high of over 76 000 adults in 1986 (Table IX) and it increased again in 1987, exceeding 96 000 (Dell, personal communication). Based on adult returns to the hatchery downstream from Priest Rapids Dam and carcass recoveries throughout the Hanford Reach, the sex ratio was about 50 per cent females for both years. Theoretically, if each female fall chinook salmon contributed one redd, a potential existed for the construction of about 38 000

Table IX. Estimate of adult fall chinook salmon escapement to the Hanford Reach, Columbia River, 1986

McNary Dam adult count	113 175
Priest Rapids Dam adult count	19 015
Ice Harbor Dam adult count	3 152
Priest Rapids Dam Hatchery/Spawning facility	11 114
Sport fishing catch	3 462
Estimated Hanford Reach escapement	76 432

redds in 1986 and 48 000 in 1987. Aerial counts for the entire Hanford Reach by Watson in 1986 and 1987, revealed 8291 and 8616 redds, respectively (Watson, personal communication). Therefore, assuming each female spawned, the redds in deep spawning areas (undetected by aerial observation) in the Hanford Reach could have totalled 30 000 in 1986 and 40 000 in 1987. If this is valid, possibly 80 per cent of the spawning by fall chinook salmon in the Hanford Reach may occur in water too deep for detection by aerial observation.

Large discrepancies have occurred in upstream passage counts for adult salmon at main-stem Columbia River dams. These discrepancies may, in part, be due to other main-stem spawning in the relatively higher velocities of tailwaters downstream from dams, shallow runs, and at confluences with tributaries. In 1987, aerial observations over the mid-Columbia River produced substantial increases in redd counts for areas where little, if any, spawning had been occurring in recent years. Fall chinook salmon are known to have spawned in large numbers in the tailwaters of Wells Dam (rkm 829.4) and redds were observed in the mouth of the Entiat River (rkm 778.4) (Hays, personal communication). Watson (personal communication) also noted a substantial increase in spawning in the tailwaters below Wanapum Dam (rkm 668.5).

Assuming the majority of fall chinook salmon escapement to the Hanford Reach is spawning in deeper water, it is uncertain whether the survival of fry from redds in deep water is any different from redds in shallow water. The higher flows discharged daily from Priest Rapids Dam between 1900 and 0800 hours may affect redds in deep water because higher velocities may move substrate materials. Conceivably, this movement could either add to the gravel covering egg pockets or tend to cause exposure through erosion. The latter seems unlikely due to the tendency for particles to settle into the depression located just upstream from the tailspill of a redd until the substrate is again leveled. In spawning habitat with appreciable proportions of fine substrate materials (small enough to sift into egg pockets), the result could be detrimental to eggs and fry.

Deep-water versus shallow-water spawning

In comparing data from our estimates for deep-water spawning in the study sites with that of Chapman *et al.* (1986) for shallow-water spawning at Vernita Bar, we found that concentrated spawning in the deep-water study sites occurred at a greater density (280 redds ha⁻¹) than in shallow water on Vernita Bar (198 redds ha⁻¹). Chapman *et al.* (1986) verified that redd densities in the deeper zones exceeded densities in the shallower zones, even though mean daily flows for over 16 consecutive hours per day would have permitted spawning at higher elevations (shallower water). They concluded that fall chinook salmon tend to spawn in lower elevation zones (deeper water) on the bar until spawner density forces higher-elevation spawning. Our observations in the areas of spawning concentrations indicated that the substrate is probably loose because of annual spawning activity, possibly allowing better percolation and deposition of pheromones (from residual traces of egg casings and carcass deterioration) deposited in the substrate (Dell, personal communication) which could encourage utilization of these areas until spawning densities and competition force the fish to utilize other areas. Therefore, if our density estimates are valid for deep-water spawning, the higher spawning densities for deep water may indicate a greater propensity for superimposition or overlapping of redds, which raises the question of the resultant viability of, and survivability of fry, from deep-water sites.

Chapman *et al.* (1983) suspected topography or morphology of the river bottom may be a major factor in the utilization of deep-water spawning habitat due to resultant downstream effect of flows or velocities created by upstream bottom morphology. They also determined that the redds and size of spawning substrate materials were much larger and velocities were higher at Vernita Bar than found by researchers studying salmon spawning in tributaries or smaller streams at other locations. They suggested that these observations might be related to the relatively large size of upriver bright fall chinook salmon. Based on our limited observations throughout the Hanford Reach, we concur. We observed spawning predominantly in substrate material sizes of rubble or rock (Table V) and suspect the higher velocities probably assist fall chinook salmon in moving these relatively large substrate materials. C. D. Becker (personal communication) suggested that large rubble may be essential to the stability of gravel areas in

the Hanford Reach, as shifting particles of small size could destroy embryos incubating in the gravel over winter. Spawning areas that appear satisfactory may, in fact, be unsuitable because of gravel mobility. At the lower flows near $1 \times 10^3 \text{ m}^3 \text{ s}^{-1}$ during our surveys, substrate particles up to rubble size were occasionally observed to move. However, the effect of increasing discharge (up to $4.9 \times 10^3 \text{ m}^3 \text{ s}^{-1}$) from 1700 to 0800 hours is unknown. Bottom profiles at the U.S. Geological Survey's gauging station upstream from Vernita Bar have not changed appreciably over time, and D. W. Chapman (personal communication) suggests that most substrate that moves has first been moved by female chinook salmon and now must be much lower than bed mobility during the pre-regulation period.

These implications raise questions regarding the carrying capacity or ultimate utilization potential for the main-stem spawning habitat by the wild fall chinook salmon spawning in the Hanford Reach. In recent years, supplemental juvenile fall chinook salmon transported from hatcheries have been released directly into the Hanford Reach. Additional releases from the hatchery at Priest Rapids Dam and upstream hatcheries and rearing facilities also complement the natural production of wild fall chinook salmon and there may be a blending of spawning by late summer-run chinook salmon with that of fall chinook salmon. Apparently, many of the supplemental fish are returning to spawn there. If deep-water redds are viable, the deep water spawning potential for the Hanford Reach may be largely unrealized. It is suspected that increased density of spawners could very well force utilization of other unused segments of the Hanford Reach that exhibit suitable habitat. In 1987, Watson (personal communication) recorded a renewed increase in redds occurring near Ringold (about rkm 571), near the lower end of the Hanford Reach, that could be related to the increased escapement.

Further research is needed to fully understand the effects of deep-water spawning by fall chinook salmon on the total productivity of the Hanford Reach. Answers to these and other related questions could aid fisheries managers in protecting and managing this important population of salmon in the unique spawning habitat of the Hanford Reach and other main-stem segments of this large regulated river. The sled methodology for data gathering is sound and can provide much useful information on redd abundance and spawning habit as leading to improved evaluations of year-to-year changes and environmental perturbations.

ACKNOWLEDGEMENTS

This study was a result of cooperative research by the National Marine Fisheries Service and Horton Dennis and Associates, Kirkland, Washington, and it was sponsored in part by the U.S. Army Corps of Engineers. The author thanks all the participants for their assistance and contributions: Especially NMFS divers—W. F. Cobb (for his thoroughness in fabricating and outfitting the diver-sled and serving as Divemaster), E. M. Dawley, R. D. Ledgerwood, and W. T. Norman; NMFS diver support—R. D. Umphres, G. R. Marques, and D. G. Woodcock; HDA surveyors—D. T. Hartman (Supervisor), M. Root (crew leader). In addition, I thank the many individuals who provided their helpful suggestions during the preparation of this manuscript, particularly, C. D. Becker, D. W. Chapman, D. M. Damkaer, D. Dauble, M. B. Dell, W. J. Ebel, A. E. Giorgi, S. G. Hays, N. Iadanza, G. E. Monan, J. R. Mullan, W. Nelson, D. Park, E. Slatick, D. G. Watson, and L. Wasserman.

REFERENCES

- Bauersfeld, K. 1978. 'The effect of daily flow fluctuations on spawning fall chinook in the Columbia River', *Washington Department of Fisheries Technical Report*, **38**, 1-32.
- Becker, C. D. 1985. *Anadromous salmonids of the Hanford Reach, Columbia River: 1984 status*, PNL-5371, Battelle Pacific Northwest Laboratory, Richland, Washington, U.S.A., 73 pp.
- Becker, C. D., Fickeisen, D. H. and Montgomery, J. C. 1981. *Assessment of impacts from water level fluctuations on fish in the Hanford Reach, Columbia River*, PNL-3813, Battelle Pacific Northwest Laboratory, Richland, Washington, U.S.A., 53 pp.
- Bovee, K. D. 1978. 'Probability-of-use criteria for the family salmonidae', *Instream Flow Group Information Paper*, **4**, U.S. Fish and Wildlife Service, Fort Collins, Colorado, U.S.A., 81 pp.
- Burner, C. J. 1951. 'Characteristics of spawning and nests of Columbia River salmon', *Fishery Bull. Fish Wildl. Serv. U.S.*, **61**, 97-110.

- Chambers, J. S. 1955. 'Research relating to study of spawning grounds in natural areas', in *Washington Department of Fisheries, Report to U.S. Army Corps of Engineers*, 88-94.
- Chapman, W. M. 1943. 'The spawning of chinook salmon in the main Columbia River', *Copeia*, 3, 168-170.
- Chapman, D. W., Weitkamp, D. E., Welsh, T. L. and Schadt, T. H. 1983. 'Effects of minimum flow regimes on fall chinook spawning at Vernita Bar, 1978-82', *Report to Grant County Public Utility District, Ephrata, Washington, U.S.A.*, 123 pp.
- Chapman, D. W., Weitkamp, D. E., Welsh, T. L., Dell, M. B. and Schadt, T. H. 1986. 'Effects of river flow on the distribution of chinook salmon redds', *Trans. Am. Fish. Soc.*, 115, 537-547.
- Fulton, L. A. 1968. 'Spawning areas and abundance of chinook salmon *Oncorhynchus tshawytscha* in the Columbia River Basin—past and present', *Fishery Bull. Fish. Wildl. Serv. Special Scientific Report*, 26 pp.
- Meekin, T. K. 1967. 'Observations of exposed fall chinook redds below Chief Joseph Dam during periods of low flow', *Washington State Department of Fisheries, Report to Douglas County Public Utility District, Ephrata, Washington, U.S.A.*, 25 pp.
- Miller, J. W., (Ed.) 1979. *NOAA Diving Manual. 2nd Edition*, U.S. Department of Commerce, U.S. Government Printing Office, 657 pp.
- Smith, A. K. 1973. 'Development and application of spawning velocity and depth criteria for Oregon salmonids', *Trans. Am. Fish. Soc.*, 102, 312-316.
- Swan, G. A. 1987. 'Use of a diver's sled and laser location system for salmon spawning surveys', in Lang, M. A. (Ed), *Proceedings of the Coldwater Diving for Science Symposium, 1987*. American Academy of Underwater Sciences, Costa Mesa, California, U.S.A., 265-277.
- Swan, G. A., Withrow, T. G. and Park, D. L. 1986. 'Survey of fish protective facilities at water withdrawal sites on the Snake and Columbia Rivers', *NOAA Technical Report, National Marine Fisheries Service*, 39, 34 pp.
- Swan, George, A., Dawley, E. M., Ledgerwood, R. D., Norman, W. T., Cobb, W. F. and Hartman, D. T. 1988. 'Distribution and relative abundance of deep-water redds for spawning fall chinook salmon at selected study sites in the Hanford Reach of the Columbia River', *Final Report to the U.S. Army Corps of Engineers, Contract E86-87-3092*, 42 pp.
- Watson, D. G. 1970. *Fall chinook salmon spawning in the Columbia River near Hanford 1947-1969*, BNWL-1515, Battelle Pacific Northwest Laboratory, Richland, Washington, U.S.A., 40 pp.
- Watson, D. G. 1976. *Temporal and spatial fall chinook salmon redd distribution near Hanford, 1967-1976*, BNWL-2163, Battelle Pacific Northwest Laboratory, Richland, Washington, U.S.A., 6 pp.
- Welsh, T. L. 1983. 'Redd counting', in Platts, W. S., Megahan, W. F. and Minshall, G. W. (Eds), *Methods for Evaluating Stream, Riparian, and Biotic Conditions*, Gen. Tech. Rep INT-138, Intermountain Forest and Range Experiment Station, U.S. Dept. Agric., Forest Service, Ogden, Utah, U.S.A. 49 pp.