FACTORS AFFECTING THE DISTRIBUTION OF VASCULAR VEGETATION, NON-VEGETATED SUBSTRATE, PERIPHYTON, ASIATIC CLAMS, CRAYFISH AND SCULPIN IN THE HANFORD REACH, COLUMBIA RIVER

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Abstract

The seasonal hydrologic cycle in the free-flowing Hanford Reach of the Columbia River has been modified over the past 60 years by artificially manipulated flows from a series of upriver hydroelectric dams. Superimposed on seasonal fluctuations in river flow, daily fluctuations up to four vertical meters in the river channel were passed through Priest Rapids Dam on a daily basis. In a segment of the Hanford Reach below Priest Rapids Dam, the shoreline distribution of vascular vegetation, non-vegetated substrate, periphyton, clams (*Corbicula fluminea*), crayfish (*Pastifastacs leniusculus*) and sculpin (*Cottus* sp.) were related to the amount of time the shoreline was submerged on an annual basis, and clam, crayfish and sculpin densities were related to habitat features in shoreline areas not dewatered by river fluctuations.

To estimate the amount of time shoreline areas were submerged, spatial map data in geographic information systems were used to depict percentages of time the shoreline was submerged. These percentages of time represented time intervals of shoreline submergence (e.g., submerged 60–65 percent of the time). The distribution study focused on cobble shoreline zones submerged > 50 percent of the time at 26 sites.

Vascular vegetation (X^2=106.84, d.f.=10, $p<0.05$), non-vegetated substrate (X^2=53.60, d.f.=10, $p<0.05$) and periphyton (X^2=93.34, d.f.=10, $p<0.05$) distributions were marked by hydraulic operations. Vascular vegetation occurred in more than half of the observations in shoreline areas experiencing flows greater than 1,970 $m^3 \cdot s^{-1}$ (submerged < 80 percent of the time). Non-vegetated substrate dominated shoreline areas experiencing flows between 1,970–1,353 $m^3 \cdot s^{-1}$ (submerged 80–95 percent of the time), and periphyton were found at shoreline areas submerged by flows greater than

1,353 $m^3 \cdot s^{-1}$ (submerged > 95 percent of the time). These three shoreline zones were also related to clam, crayfish and sculpin use.

Clam distribution was affected by the amount of time the shoreline was submerged (X^2=101.56, d.f.=10, $p<0.05$). Overall, clams were not equally distributed along the three shoreline zones (X^2=154.27, d.f.=2, $p<0.05$). Investigations in the clam size class distribution along the three shoreline zones showed that clams 5–11 mm in shell length were 41 percent of the total clams found in the vascular vegetation zone, but 2 percent and 1 percent of the total clams observed in the non-vegetated substrate and periphyton zones. Clams 11–22 mm in shell length were the most abundant size class in all three shoreline zones. Clams > 22 mm in shell length were most abundant in the periphyton zone. Clams from all three size classes were probably deposited on the vascular vegetation zone during high flows, but it was unlikely clams in the vascular vegetation zone could have survived for extended periods of time in the vascular vegetation zone due to dewatering. Clams in the non-vegetated substrate zone seemed able to persist for greater lengths of time, but they probably experienced reduced growth as a result of repeated short-term dewatering episodes.

Habitat features related to clam densities at depths with persistent periphyton were dominant substrate (PROC GLM, d.f.=7, p=0.0004) and subdominant substrate (PROC GLM, d.f.=7, $p<0.0001$), embeddedness (PROC GLM, d.f.=3, p=0.0185) and current velocity (PROC GLM, d.f.=2, $p<0.0001$). The highest clam densities were found in unembedded cobble substrates (51–200 mm in diameter) with current velocities between 0.1–0.3 $m \cdot s^{-1}$. Clam densities were lowest in boulder/bedrock substrate or sandy or highly embedded substrates with low current velocities.

The amount of time the shoreline was submerged influenced the distribution of crayfish (X^2=23.84, d.f.=8, $p<0.05$). Crayfish use of vascular vegetation, non-vegetated substrate and periphyton zones was not equal (X^2=47.90, d.f.=2, $p<0.05$). No crayfish were found in zones of vascular vegetation. A few were found in some non-vegetated substrates, but crayfish were most abundant in the periphyton zone.

Crayfish densities were influenced by dominant substrate (PROC GLM, d.f.=7, p=0.0009), unconsolidated substrate depth (PROC GLM, d.f.=2, p=0.0056) and shoreline seepage (PROC GLM, d.f.=1, p=0.0008). The highest crayfish densities were observed in cobble substrates (151–250 mm) with interstitial spaces that extended deeper than 10 cm into the substrate and located in places with groundwater seepage. The lowest crayfish densities were found in areas with an unconsolidated substrate depth less than 5 cm. Substrate < 50 mm and > 301 mm also had few crayfish present.

The amount of time the shoreline was submerged did not affect the distribution of sculpin (X^2=8.77, d.f.=8, $p>0.05$). Sculpin seemed to prefer shallow water and moved vertically along shoreline adapting to river elevation changes. However, differences were found between the use of shoreline zones (X^2=7.45, d.f.=2, $p<0.05$). Sculpin were found mostly on submerged non-vegetated substrate and periphyton zones. Only a few sculpin were found on the vascular vegetation zone.

Factors found to affect the densities of sculpin were dominant substrate (PROC GLM, d.f.=7, $p<0.0001$), embeddedness (PROC GLM, d.f.=3, p=0.0075), current velocity (PROC GLM, d.f.=2, p=0.0445) and shoreline seepage (PROC GLM, d.f.=1, p=0.0366). The highest sculpin densities were observed in unembedded substrate

151–300 mm in shoreline seepage areas with current velocities of 0.1–0.3 $m \cdot s^{-1}$. Sculpin were not found in sandy or highly embedded substrate.

Contaminants from the Hanford plutonium production era still remained in the aquifer and entered the river through groundwater seepages. Although contaminants were rapidly diluted by the Columbia River, potential effects from remnant contaminants could affect the aquatic biota where seepages enter the river. While it was known how river elevation changes affected contaminants entering the river, it was not known what effects river fluctuation had on benthic biota, such as clams, crayfish and sculpin—aquatic species most susceptible to contaminant exposure.

It was found that river fluctuations affected the benthic guild in the free-flowing Hanford Reach. The benthic community was most disrupted in areas frequently dewatered. Further studies focused on other benthic species should be conducted or initiated at water depths with persistent periphyton during the low flow time of the year, i.e., September and October. During these months, the periphyton line marked the low-water level.

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1.0 Introduction

The Hanford Reach of the Columbia River was described as the last free flowing stretch of the Columbia River in the United States. Although a downstream dam did not impede the flow in the Hanford Reach, wide variations in river flow existed. The Hanford Reach of the Columbia River experienced artificial flow since the 1940's when Grand Coulee Dam [River Kilometer (RKM) 960.1] became operational. Annual and daily flow fluctuations existed as a result of operations from a series of upstream hydroelectric dams, with Priest Rapids Dam (RKM 639.1) being the nearest upstream dam. The annual flow over Priest Rapids Dam from 1995 to 2002 had an average flow of 3,681 $m^3 \cdot s^{-1}$ and a minimum and maximum flow of 1,093 and 11,750 $m^3 \cdot s^{-1}$, respectively. The highest flows occurred during the spring freshet (May–July) (Columbia River DART 2002). Superimposed on variations of annual flow were daily fluctuations caused by power peaking flows. Daily fluctuations in flow resulted in 3–4 vertical meters of river elevation change in the river channel below Priest Rapids Dam (USACENWD 2002).

Such changes in river elevation have affected many aquatic animals. Becker et al. (1981) reported the stranding and death of aquatic insects (Odonata, Ephemeroptera, Tricoptera, Diptera, and Hemiptera), crayfish and fishes (Centrarchidae, Cottidae, Cyprinidae, Gasterosteidae, and Salmonidae). Juvenile Chinook salmon were the focus of most stranding studies (Becker 1990). Aquatic macroinvertebrates (Tricoptera and Diptera) perished after short periods of air exposure as a result of daily flows patterns released at Priest Rapids Dam (Stark 2001).

Shoreline plant communities were also affected by variable flows. In other lotic systems, Kroger (1973) reported that algal communities became desiccated and perished

after dewatering, and Fickeisen et al. (1980) reported that shoreline submergence affected the riparian (i.e., vascular) plant communities along the Hanford Reach shoreline, thus the shoreline was partitioned into three categorical zones of vascular vegetation, non-vegetated substrate and periphyton (Figure 1).

This thesis research was conducted to determine how shoreline watering and dewatering cycles affected the distribution of vascular vegetation, periphyton, Asiatic clams (*Corbicula fluminea*), signal crayfish (*Pacifastacus leniusculus*) and sculpin (*Cottus* sp.). A second aim of this thesis was to provide information about Asiatic clam, crayfish and sculpin densities at shoreline depths where periphyton persisted. These species were chosen for study because they were abundant throughout the Hanford Reach and representative of the benthic guild. Because past ecological studies in the Hanford Reach have focused primarily on fishes (Becker 1990), little was known about the distribution of these organisms.

The Asiatic clam was introduced from Southeast Asia to North America in the 1920's (McMahon 1983). Its distribution was affected by water temperatures and exposure to air. Mass mortalities were reported in waters with ambient temperatures below 2 °C (McMahon 1983). Junk (1975) reported Asiatic clam populations were eliminated along shoreline zones that experienced dewatering.

Signal crayfish and sculpin were both native to the Columbia River, and both species were strongly associated with shoreline habitat (McPhail and Lindsey 1970; Wydoski and Whitney 1979; Pennak 1989; Simpson and Wallace 1982). However,

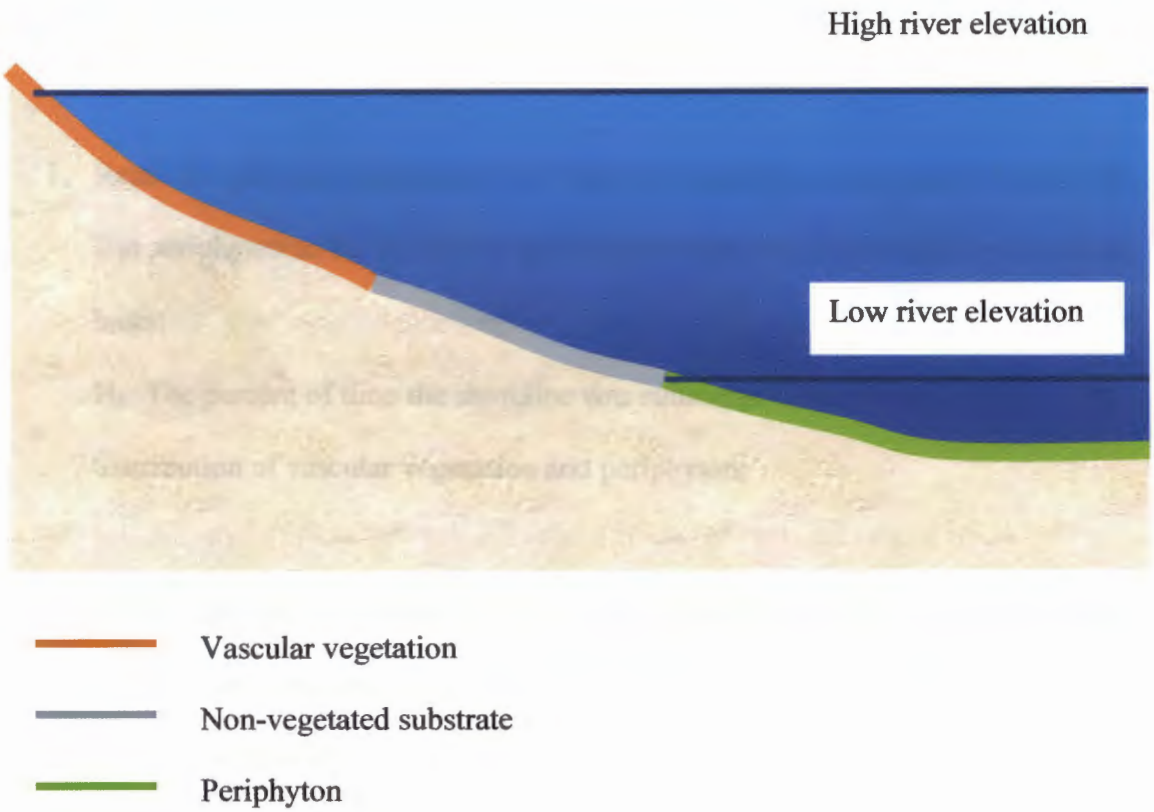

Figure 1. A model of the Hanford Reach shoreline with respect to river submergence, vascular vegetation, non-vegetated substrate and periphyton.

Becker et al. (1981) reported that these organisms were unable to sustain themselves in shoreline areas that experienced dewatering.

Due to the lack of data regarding organisms' distribution and density and physical information on Asiatic clams and crayfish, my thesis objectives and null hypotheses (H_0) were to:

1. Relate the presence and absence of vascular vegetation, non-vegetated substrate and periphyton to the percent of time the shoreline was submerged on an annual basis;

   H_0: The percent of time the shoreline was submerged did not affect the distribution of vascular vegetation and periphyton;

2. Relate the presence of Asiatic clams, crayfish and sculpin to the percent of time the shoreline was submerged on an annual basis;

   H_0: The percent of time the shoreline was submerged did not affect the distribution of Asiatic clams, crayfish and sculpin;

3. Relate the presence of Asiatic clams, crayfish and sculpin to the shoreline zones of vascular vegetation, non-vegetated substrate and periphyton;

   H_0: The shoreline zones of vascular vegetation, non-vegetated substrate and periphyton did not affect the distribution of Asiatic clams, crayfish and sculpin;

4. Relate Asiatic clam size classes to the shoreline zones of vascular vegetation, non-vegetated substrate and periphyton;

5. Relate Asiatic clam densities to the habitat features of dominant substrate, subdominant substrate, unconsolidated substrate depth, embeddedness, aquatic vegetation, current velocity and groundwater seepage;

   H_0: Asiatic clam densities were not explained by the habitat features of dominant substrate, subdominant substrate, unconsolidated substrate depth, embeddedness, aquatic vegetation, current velocity and groundwater seepage;

6. Relate crayfish densities to the habitat features of dominant substrate, subdominant substrate, unconsolidated substrate depth, embeddedness, aquatic vegetation, current velocity and groundwater seepage;

   H_0: Crayfish densities were not explained by the habitat features of dominant substrate, subdominant substrate, unconsolidated substrate depth, embeddedness, aquatic vegetation, current velocity and groundwater seepage;

7. Relate sculpin densities to the habitat features of dominant substrate, subdominant substrate, unconsolidated substrate depth, embeddedness, aquatic vegetation, current velocity and groundwater seepage;

   H_0: Sculpin densities were not explained by the habitat features of dominant substrate, subdominant substrate, unconsolidated substrate depth, embeddedness, aquatic vegetation, current velocity and groundwater seepage;

8. Provide physical information for clams and crayfish. Physical measurements were used to compare clams and crayfish in the Hanford Reach to other populations.

2.0 Materials and Methods

2.1 Study Design

Because both river fluctuations and Hanford Site contaminants that entered the Columbia River had the potential to affect the distribution and demographics of benthic organisms in the Hanford Reach, this study was conducted to separate these two influences. Therefore, river fluctuations were examined as a factor that potentially affected the distribution of shoreline organisms.

Distribution and demographic background information on vascular vegetation, non-vegetated substrate, periphyton, Asiatic clams, crayfish and sculpins were researched in an upstream reference area of the Hanford Reach that was not influenced by Hanford contaminants. To collected distribution data, established bathymetry transects from United States Geologic Survey (USGS) and Grant County Public Utility District (GCPUD) bathymetry datasets were used in conjunction with a river model to create a spatial Geographic Information Systems (GIS) map that showed the amount of time the shoreline was submerged on an annual basis. Bathymetry transects were river cross sections. USGS data bathymetry transects were spaced along the river at distances between 0.5 and 0.8 km. GCPUD were evenly spaced at 0.4 km intervals.

Thirty-eight shoreline transects were available for sampling between Vernita Bar and known Hanford contaminant plumes. Each shoreline transect was broken into 11 sites that represented the amount of time (i.e., < 50%, 50–55%..., 90–95% and > 95 %) the locations were submerged on an annual basis. The geographic locations of these sites were entered into a global positioning system.

Distribution data were collected at 26 of the 38 shoreline transects. Distribution data were not collected at areas where overhead structures interfered with GIS data collection, or where the river model and GIS data were inaccurate, including areas where river structures such as downstream shallow shoals and bars backed up river water to create a higher river elevation than the model predicted.

The field crew used GIS navigation to travel by boat to shoreline transects. At each transect, the sites were located and plot frames were placed on the substrate to record distribution data for vascular vegetation, periphyton, clams, crayfish and sculpin. Due to river conditions, not every shoreline site was sampled for each transect. Sampling only occurred out to a depth of 1.5 m.

Density data were collected by physically counting clams, crayfish and sculpins within plots. Density data were collected where the distribution study was performed and at other shoreline sites with habitats not found in the distribution study. Shoreline habitats in the distribution study were homogeneous, so other habitat features were sought in the study area to better evaluate habitat features that explained clam, crayfish and sculpin density.

Data analyses were performed to test distribution and density hypotheses. Distribution analyses examined the distribution of the three shoreline zones of vascular vegetation, non-vegetated substrate and periphyton for known amounts of time the shoreline was submerged. Clams, crayfish and sculpin distributions were examined by the percentage of time the shoreline was submerged and along the three shoreline zones. The habitat features of substrate type, aquatic vegetation, groundwater seepage and current velocity were investigated for clam, crayfish and sculpin density explanation.

2.2 Study Area

The study area was a 15-km (9.3-mile) stretch of the Columbia River extending from 2.3 km downstream from Priest Rapids Dam (RKM 639.1) to approximately 3 km downstream from Vernita (State Highway 24) Bridge (RKM 622.1) (Figure 2). The section of river was part of the Hanford Reach, the only free-flowing stretch of the Columbia River above Bonneville Dam in the United States (FCRPS 2001). It was characterized by cobble and rock substrate and swift currents (Fickeisen et al. 1980; Dauble and Geist 2000). The study area was located upstream from shutdown nuclear reactor facilities on the near shore. It was believed that these shoreline habitats and corresponding times of shoreline submergence were similar to those downstream habitats but without Hanford Site contaminants present in groundwater seepages.

The average hourly flow from Priest Rapids Dam during the 2002 sampling season was 2,239 $m^3 \cdot s^{-1}$ with a minimum and maximum flow of 1,059 $m^3 \cdot s^{-1}$ and 4,919 $m^3 \cdot s^{-1}$, respectively; the average hourly flow during 2003 sampling season was 1,895 $m^3 \cdot s^{-1}$ with a minimum and maximum flow of 1,085 $m^3 \cdot s^{-1}$ and 4,412 $m^3 \cdot s^{-1}$, respectively (USACENWD 2002; USACENWD 2003). Trends in discharge rates at Priest Rapids Dam showed that flows were typically low on weekends and increasing Monday through Thursday (Figure 3).

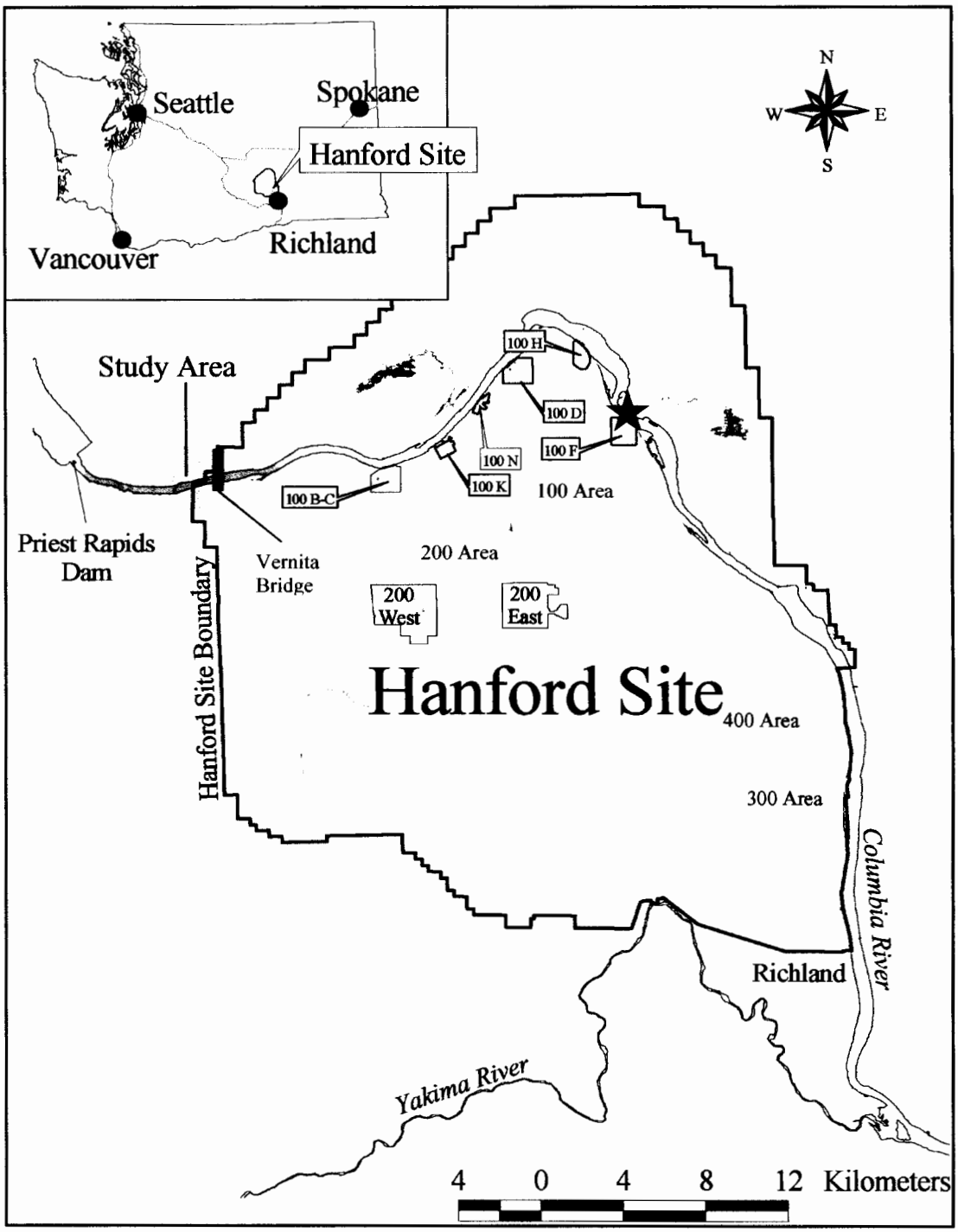

Figure 2. The Hanford Reach of the Columbia River and study area. Nuclear facilities locations were denoted by area numbers.

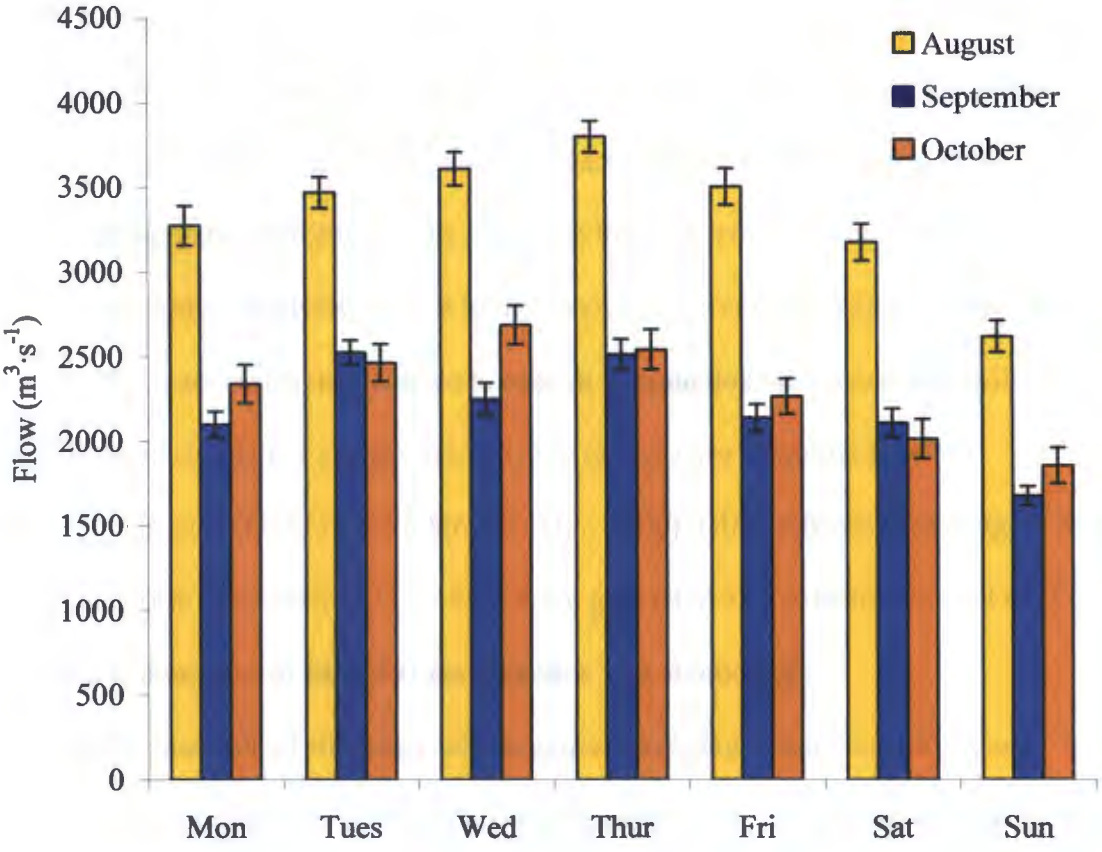

Figure 3. Average hourly total outflow by day (with standard errors) released at Priest Rapids Dam (Grant County Public Utility District) for August through October 2002.

2.3 Percentage of time the shoreline was submerged

To provide a quantitative assessment of shoreline areas influenced by fluctuations in flow rates, a spatial analysis was conducted using surface elevation data, bathymetry data, and average seasonal river flow data. Hourly discharge rates from Priest Rapids Dam (1994–2001) were used to determine the percent of time shorelines were submerged on an annual basis (Table 1). Only full-year datasets were combined to represent shoreline submergence percentages the shoreline biota experienced annually.

For the spatial analysis, United States Geologic Survey and Grant County Public Utility District bathymetry transects were used in conjunction with a one-dimensional modular aquatic simulation system (MASS1) to model river elevation levels at bathymetry transects (Figure 4) (Richmond et al., 2000). GIS positions (Washington State Plane 4602, North American Datum 1983) were generated along the transects at sites of established percentages of time that the shoreline was submerged.

Eleven intervals of shoreline submergence percentages were used from ten established percentages of time the shoreline was submerged. The ten percentages of time used to describe shoreline submergence were: 1) 50 percent, 2) 55 percent, 3) 60 percent, 4) 65 percent, 5) 70 percent, 6) 75 percent, 7) 80 percent, 8) 85 percent, 9) 90 percent, and 10) 95 percent (Table 1). These ten percentages were used to establish the eleven time intervals of shoreline submergence: 1) submerged < 50 percent of the time, 2) submerged 50–55 percent of the time, 3) submerged 55–60 percent of the time, 4) submerged 60–65 percent of the time, 5) submerged 65–70 percent of the time,

Table 1. The percentage of time the shoreline was submerged and corresponding flows used to compose the eleven intervals of shoreline submergence for 2002.

Percentage of time shoreline submerged	$ft^3 \cdot s^{-1}$	$m^3 \cdot s^{-1}$
50.00	122,400	3,463
55.00	114,400	3,238
60.00	105,400	2,983
65.00	96,100	2,720
70.00	85,700	2,425
75.00	75,600	2,139
80.00	69,600	1,970
85.00	64,900	1,837
90.00	57,600	1,630
95.00	47,800	1,353

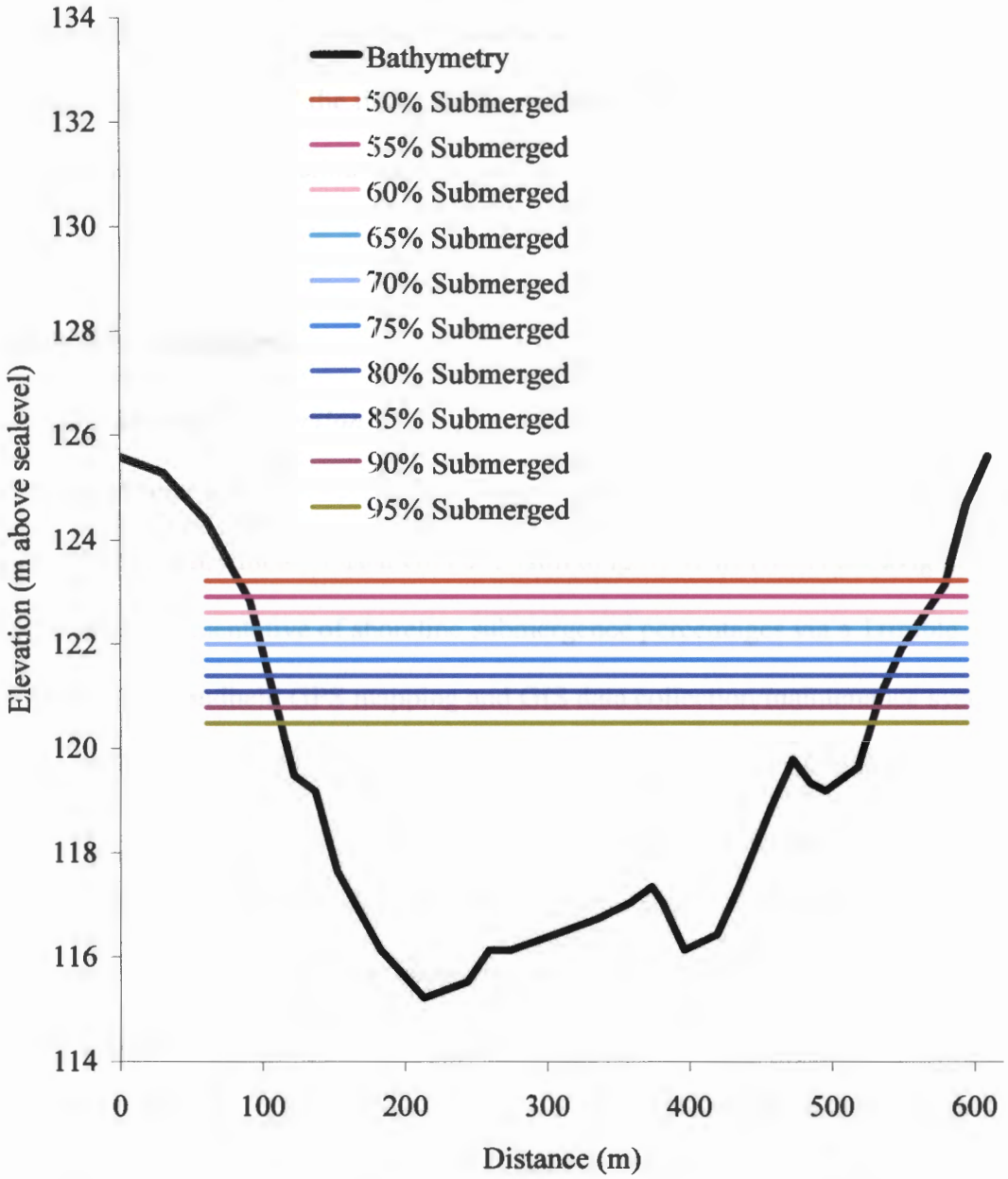

Figure 4. A depiction of Columbia River bathymetry cross-section RKM 360.9 with MASS1 flow levels ran to equilibrium. GPS positions (i.e., shoreline submergence percentages) were calculated where the flow level intersected the bathymetry transect.

6) submerged 70–75 percent of the time, 7) submerged 75–80 percent of the time, 8) submerged 80–85 percent of the time, 9) submerged 85–90 percent of the time, 10) submerged 90–95 percent of the time, and 11) submerged >95 percent of the time. These percentages of time the shoreline was submerged were representative of annual submergence patterns.

2.4 Field data collection

2.4.1 Distribution data collection

Two similar methods were used to acquire distribution data along shoreline transects. The primary method used Global Positioning Systems (GPS) to navigate to shoreline sites representative of shoreline submergence percentages via a Trimble GeoExplorer® 3 handheld GPS mapping and GIS data collection/maintenance system. After a sample site was located, a sample plot frame was placed on the substrate for data collection. A second method was used when satellite configuration did not allow precise positions to be determined. In that case, an averaged position of the site submerged 50 percent of the time was found and coupled with the bearing of the shoreline transect to place sample plots equidistant along the transect.

Distribution data were collected on 26 shoreline transects (14 left bank and 12 right bank) from August 30–September 29, 2002 (Figure 5). Left and right bank orientation was assigned facing downstream. At each sampled plot along a shoreline transect, regardless of method, a GIS point feature was collected by averaging 100 positions at a collection rate of one position per second and at an antenna height of 1.5 m to obtain horizontal and vertical precisions less than 3 meters. Pathfinder Office 2.80 was used to differentially correct data points and export data as shapefiles. The exported data

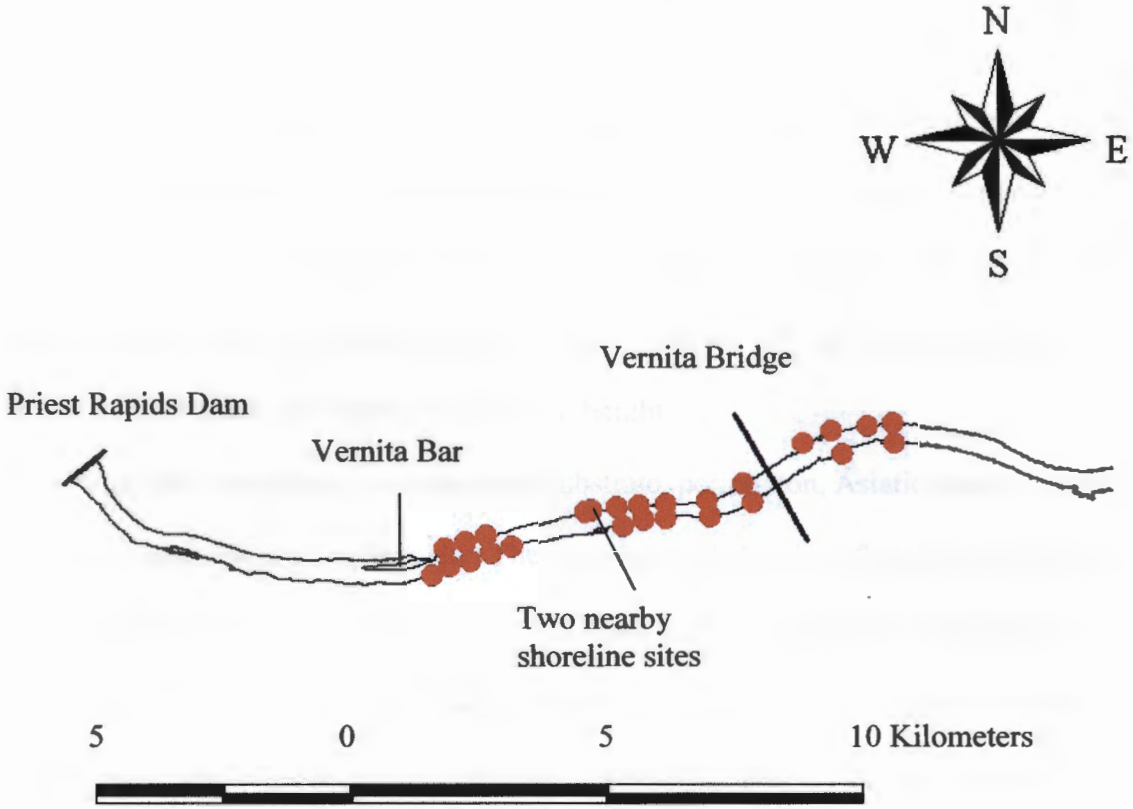

Figure 5. The 26 shoreline transects where distribution data were collected in 2002.

were viewed on ArcView 3.2 to spatially overlay sampled positions with the GIS coverage for shoreline submergence time intervals.

Plot placement occurred at submerged and non-submerged shoreline sites. Sampling the submerged sites required snorkeling (performed with a combination of 6 mm wet suits, O.S. Systems® Drysuits, masks, snorkels, and lead belts). Large amounts of weight were needed to maintain position due to current velocity. Snorkeling data collection did not occur at depths below chest height.

Vascular vegetation, non-vegetated substrate, periphyton, Asiatic clams, crayfish and sculpin were recorded at each site. The presence and absence of vascular vegetation and periphyton were assigned for 1 m x 1 m survey plots. Non-vegetated substrate was assigned when vascular vegetation and periphyton were both absent (Figure 6, Figure 7). For the assignment of Asiatic clam presence and absence, two 0.1-m^2 subplots (31.62 cm x 31.62 cm) were randomly placed with in the 1-m^2 plot (Figure 8). Clams were found by removing all non-compacted substrate from the plot and searching through the compacted layer of substrate. If at least one living clam was present in either of the 0.1-m^2 subplots, clam presence was assigned to the observation. If clams were not detected within either of the subplots, clam absence was assigned. Crayfish and sculpin presence and absence were separately assigned for only submerged 1-m^2 plots; crayfish and sculpin presence and absence were not assigned to plots above the river surface elevation.

Figure 6. Vascular vegetation and non-vegetated substrate band observed on the Hanford Reach shoreline.

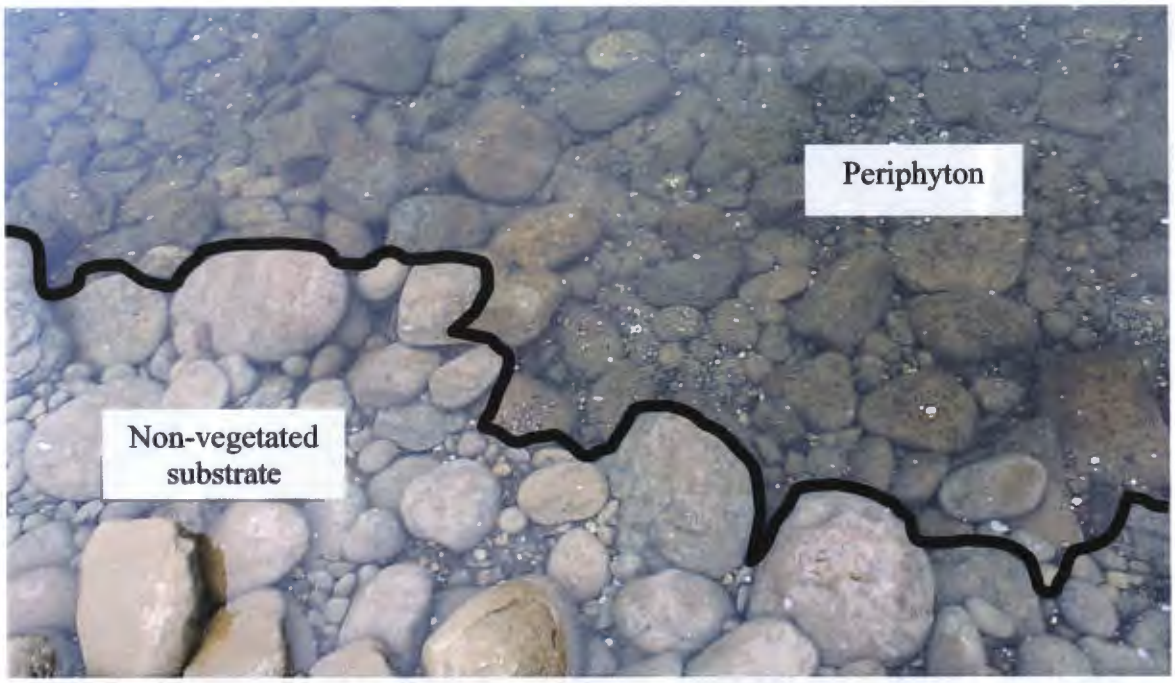

Figure 7. The periphyton line observed on rocky substrate in the Hanford Reach.

Figure 8. Sample plots used for Asiatic clam, crayfish and sculpin density counts.

2.4.2 Density data collection

Density counts for clams, crayfish and sculpin were focused at depths where periphyton persisted. Persistent periphyton was used to identify shoreline substrates that did not experience daily dewatering. Density data at persistent periphyton depths were collected at 21 shoreline sites from August 30, 2002 to October 27, 2002, and from September 2, 2003 to September 22, 2003 (n=97 for Asiatic clams; n=98 for crayfish and sculpin) (Figure 9). Physical counts were used to determine Asiatic clam densities. Two 0.1-m^2 subplots randomly placed within a 1-m^2 plot were used to determine the clam density for each observation. For each of 0.1-m^2 subplots within the 1-m^2 subplot, substrate was removed and all clams greater than 5 mm in shell length were placed into mesh collection bags. For each observation, the two subplots were used to calculate the clam density with the equation: (subplot1 + subplot2) multiplied by 5. Crayfish and sculpin densities were determined by visual counts within the 1-m^2 plots. Crayfish and sculpin were removed from the plot following observation to avoid inflated counts. A methodology based on physical counts was selected to determine clam, crayfish and sculpin densities because cobble substrate prevented the use of dredges and traps were shown to be ineffective (Tiller 2002).

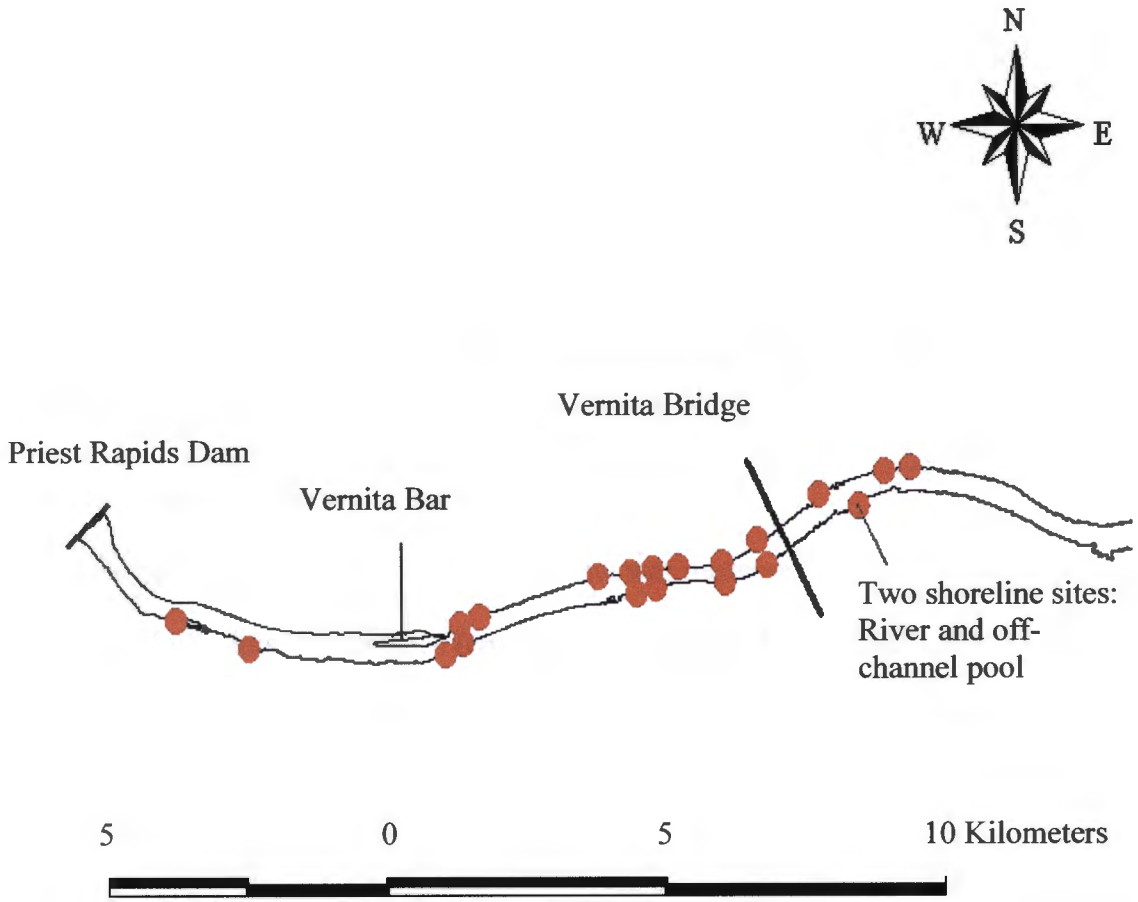

Figure 9. The 21 shoreline sites where density data of Asiatic clams, crayfish and sculpin were collected at depths that possessed persistent periphtyon during 2002–2003.

2.4.3 Habitat factors affecting densities

The following habitat variables were recorded to determine if these factors affected species' densities: substrate, unconsolidated substrate depth, embeddedness, aquatic vegetation, groundwater seepage and current velocity. Substrate variables were recorded using a 50 mm interval substrate scale based on the intermediate axis of substrate particles (Table 2). The substrate scale was used to classify dominant and subdominant substrate, with dominant being the most prevalent substrate and subdominant being the second most prevalent substrate.

The depth of the unconsolidated substrate was measured. For the two randomly placed 0.1-m^2 subplots, the distance (cm) from the bottom of the 0.1-m^2 subplot to the compacted substrate (i.e., where rock interstitial spaces were filled with fine substrate) was measured with a ruler. The average of the two measurements was used to represent the unconsolidated substrate depth for each observation (i.e., each 1-m^2 plot). For uneven substrate, the middle height measure was recorded for each subplot. From the averaged unconsolidated substrate depth measurements, substrate depth was assigned into three categories (Table 3).

Visual scales of embeddedness, which was the amount of fine substrate (e.g., sand, silt, clay) compacting rocky substrates, and aquatic vegetation cover were used to classify these variables (Table 4, Table 5). These habitat categories were previously used to describe habitat in the Hanford Reach, Columbia River (Nugent et al. 2001).

Table 2. Substrate scale used to classify dominant and subdominant substrate in the Hanford Reach shoreline.

Category	Average particle diameter size (mm)
1	0–50
2	51–100
3	101–150
4	151–200
5	201–250
6	251–300
7	301–350
8	>350

Table 3. Unconsolidated substrate codes used to classify the depth of loose, unembedded substrate in the Hanford Reach shoreline.

Code	Substrate depth (cm)
1	0–5
2	5–10
3	>10

Table 4. Substrate embeddedness codes used to describe embeddedness along the Hanford Reach shoreline[(Platts et al. 1983) reported in Nugent et al. 2001].

Code	% Fines	Description
1	0–25	Openings between dominant sized particles are 1/3 to 1/2 the size of the particles. Few fines in between. Edges are clearly discernable.
2	25–50	Openings are apparent but < 1/4 the size of the particles. Edges are discernable but up to half obscured.
3	50–75	Openings are completely filled but half of edges are still discernable.
4	75–100	All openings are obscured. Only one or two edges discernable and size cannot be determined without removal.

Table 5. Aquatic vegetation codes used to describe macrophytes along the Hanford Reach shoreline (Nugent et al. 2001).

Code	Description
1	No vegetation present.
2	Sparse vegetation, substrate is completely evident.
3	Medium vegetation, substrate is only partially obscured.
4	Dense vegetation, substrate is nearly or completely obscured by the vegetation.

The presence of groundwater seepage was identified by visual observation or by bottom specific conductance readings greater than 165 μS/cm. All plots along a specific transect bank were classified as influenced by groundwater seepage if groundwater seepage was present anywhere along the transect bank because groundwater seepages move up and down the river bank as a result of variable flows (Arntzen 2001). The typical specific conductance range of near-shore river water was reported to range from 130 to 150 $\mu S \cdot cm^{-1}$ (Peterson and Connelly 2001).

Conductivity (μS/cm) was recorded with a Yellowsprings Scientific Instrument (YSI) 85 handheld water quality instrument at the compacted substrate layer for all plots. The YSI 85 was calibrated with 1,000 $\mu mhos \cdot cm^{-1}$ conductivity standard from Fisher Scientific. The conductivity measurement micromhos was renamed to microsiemens—the measurements were equal.

A standardized current velocity measurement was used to describe water velocities along the sampled shorelines. Due to the variable discharge at Priest Rapids Dam, a standardized current velocity was recorded for each sampled transect at a depth 0.5 meters deeper than the periphyton line. Current velocity was recorded 5 cm above the substrate with a Flowmate flowmeter during low flow conditions. These standardized current velocities were assigned into three categories (Table 6).

2.4.4 Physical measurements for Asiatic clams

Shell height, shell length, and wet weight were recorded for Asiatic clams. Shell height was measured from the greatest umbo-ventral dimension across the shell to the nearest 0.1 mm with Vernier calipers (Figure 10). Clam wet weight was recorded to the

Table 6. Standardized current velocity codes used to describe current velocities representative of sample sites on the Hanford Reach shoreline.

Code	Standardized Current velocity ($m \cdot s^{-1}$)
1	0–0.1
2	0.1–0.3
3	>0.3

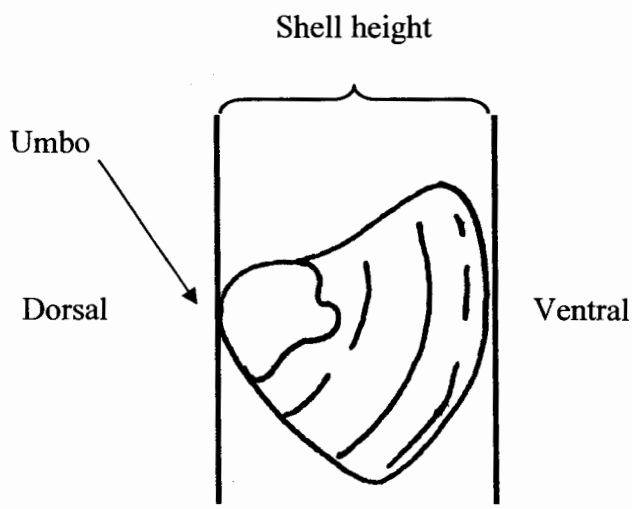

Figure 10. Shell height measurement recorded on Asiatic clams in the Hanford Reach, Columbia River.

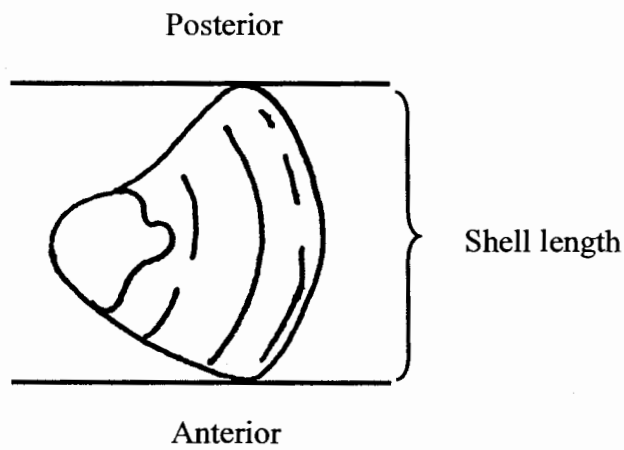

Figure 11. Shell length measurement recorded on Asiatic clams in the Hanford Reach, Columbia River.

nearest 0.1 g with an Ohaus Navigator™ digital balance. The internal calibration feature was used to calibrate the balance. Clam shell height and clam wet weight were recorded for a maximum of 50 randomly selected clams per observation. Only a portion of the sampled clams had wet weight recorded for length-weight regressions.

For each observation, a maximum of 50 randomly selected clams were measured. If more than 10 clams were present within the first 0.1-m^2 subplot, only clams from the first subplot had shell height and wet weight recorded. If fewer than 10 clams were present within the first 0.1-m^2 subplot, clams from the second subplot were measured until either all clams were measured or until 50 clams were measured.

An additional sampling event occurred on August 5, 2003, to obtain a shell length-shell height linear transformation equation. Two hundred Asiatic clams were collected to record shell length (Figure 11) and shell height to the nearest 0.1 mm to create a linear transformation equation. Microsoft Excel was used to perform linear regressions on the data, and the resulting linear equation (shell length = 1.0232(shell height) + 0.8202, $R^2 = 0.935$) was used to transform all 2002 shell height measurements to shell length for size class establishment.

2.4.5 Physical measurements for crayfish

The first four crayfish observed in each 1-m^2 plot frame were collected to record carapace length, weight, and sex. Carapace length was measured from the posterior portion of the eye socket to the posterior median edge of the cephalothorax to the nearest 0.1 mm with Vernier calipers. (Figure 12). Weight was recorded to the nearest 0.1 g with an Ohaus Navigator™ digital balance. Sex was recorded as male or female. For

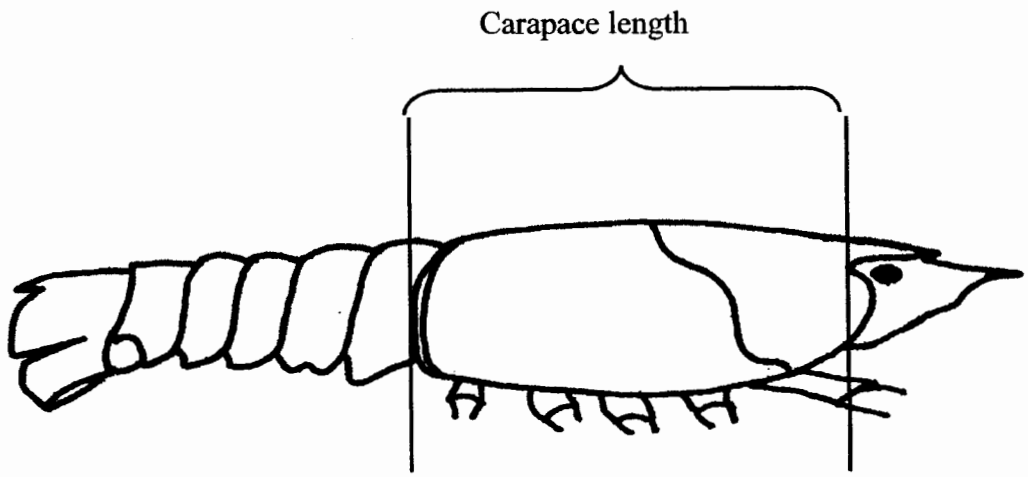

Figure 12. Carapace length measurement recorded on crayfish collected in the Hanford Reach, Columbia River.

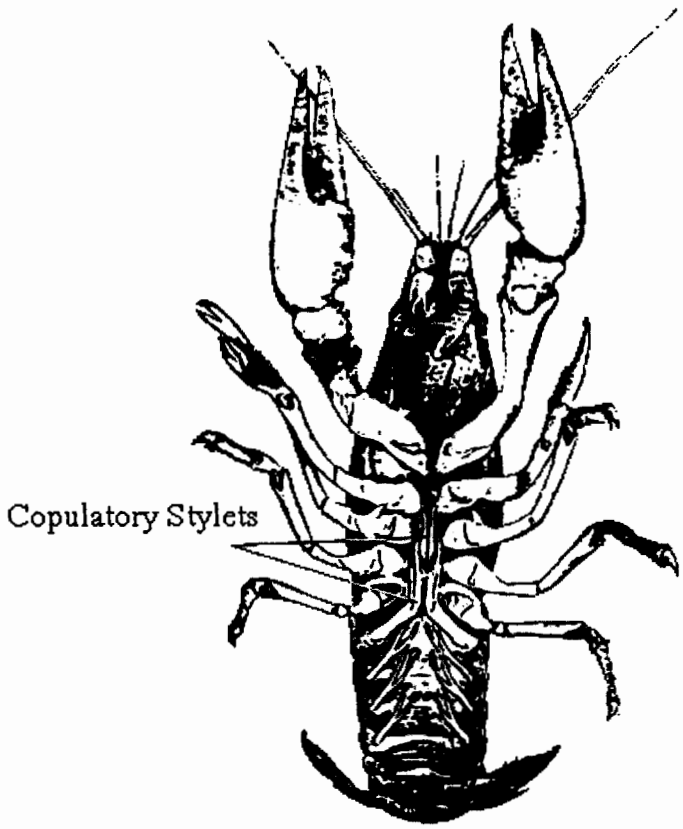

Figure 13. Copulatory stylets used to determine crayfish sex. Males possessed these modified pleopods. The picture was modified from Grunderson (2002).

specimens to young to sex, a juvenile status was assigned. The presence of copulatory stylets was used to determine sex (Figure 13). Male crayfish possessed the modified pleopods to transfer the spermatophore to female crayfish. These modified pleopods are vestigial in female crayfish (Holdrich 2002).

2.5 Data analysis

2.5.1 Factors affecting the distribution of vascular vegetation, non-vegetated substrate, periphyton, Asiatic clams, crayfish, and sculpin

Distributions of vascular vegetation, non-vegetated substrate, periphyton, Asiatic clams, crayfish and sculpin were presented by frequency of occurrence for the percentages of time the shoreline was submerged on an annual basis. Frequencies of occurrence were used to show trends for the subjects of vascular vegetation, non-vegetated substrate, periphyton, Asiatic clams, crayfish and sculpin between the percentages of time the shoreline was submerged. For Asiatic clams, crayfish and sculpin, the shoreline zones of vascular vegetation, non-vegetated substrate and periphyton were also used to show frequencies of occurrence.

The null hypotheses tested were that amount of time the shoreline was submerged had no effect on the distribution of vascular vegetation, periphyton, Asiatic clams, crayfish and sculpin and that probabilities of Asiatic clam, crayfish and sculpin presence for the shoreline zones of vascular vegetation, non-vegetated substrate and periphyton were equal.

Chi-Square analyses were performed on the raw data, not frequencies of occurrence. Chi-Square Tests of Homogeneity were conducted using Microsoft Excel

(α=0.05) (Johnson and Bhattacharyya 2001). A total of 218 observations were used to test distributions of vascular vegetation, non-vegetated substrate, periphyton, Asiatic clams between the 11 time intervals of shoreline submergence. Of these 218 observations, only 108 were submerged during data collection. Therefore, only those 108 observations were available to assess the distribution of crayfish and sculpin. A total of 216 observations were used to test the distribution of Asiatic clams and 106 observations were used to test the distribution of crayfish and sculpin between shoreline zones of vascular vegetation, non-vegetated substrate and periphyton. Two observations were omitted because they possessed both vascular vegetation and periphyton.

Chi-Square expected values were calculated for each group. Expected values were based on the total number of observations in each group. Expected values were calculated by multiplying row (percentage of time the shoreline was submerged or shoreline zone) and column totals (present or absent) then dividing by the total number of samples. Pairwise comparisons (α=0.05) for distributions between groups were performed when X^2 Test of Homogeneity were significant (Marascuilo and McSweeney 1977).

To identify Asiatic clam size classes, all 2002 data were used to create a histogram. The distribution of the identified clam size classes were presented by the percent occurrence and standard error for clams found in the shoreline zones of vascular vegetation, non-vegetated substrate and periphyton.

2.5.2 Densities of Asiatic clams, crayfish, and sculpin

To assess whether habitat factors explained the densities of Asiatic clams, signal crayfish, and sculpin, SAS® System Software, Version 8, was used to perform the SAS general linear model procedure (PROC GLM). The general linear model was constructed

to relate one or more continuous dependent variables with one or more independent variables. For the analyses, the independent variables of dominant substrate, subdominant substrate, unconsolidated substrate depth, embeddedness, aquatic vegetation, groundwater seepage and current velocity were identified as classification variables. The analyses tested if the models, which were composed of all seven habitat variables, were significant ($\alpha=0.05$) in explaining density. It analyzed all pairwise differences. Sum of squares with corresponding F-values and p-values were also generated for each variable in the model, so those factors significantly ($p<0.05$) explaining organism densities were identified (SAS OnlineDoc 2000).

3.0 Results

The distributions of vascular vegetation, non-vegetated substrate, periphyton, clams and crayfish were affected by the amount of time the shoreline was submerged (3.1.1–3.1.5). Sculpin distribution was not affected by the amount of time the shoreline was submerged (3.1.6). Due to hydraulic operations, the shoreline was marked by the three zones of vascular vegetation, non-vegetated substrate and periphyton. Clam, crayfish and sculpin use of these areas differed. Clams and crayfish were prevalent in substrate with periphyton (3.2.1–3.2.2), while sculpin moved between shoreline areas of non-vegetated substrate and periphyton (3.2.3).

Clam densities were significantly related to dominant substrate, subdominant substrate, embeddedness and current velocity. Unconsolidated substrate depth, aquatic vegetation cover and groundwater seepage were factors that did not significantly related to clam densities. Clam densities were greatest in dominant substrate 51–200 mm in diameter. Densities declined as embeddedness decreased. Densities were highest in current velocities between 0.1–0.3 $m \cdot s^{-1}$ (3.4.1).

Crayfish densities were significantly related to dominant substrate, unconsolidated substrate depth and groundwater seepage. Crayfish densities were highest in substrate 151–250 mm. As substrate size decreased and increased from 151–250 mm, densities declined. Densities increased as the depth of unconsolidated substrate increased. In similar habitats, densities were greater in areas with groundwater seepage present (3.4.2).

Sculpin densities were significantly related to dominant substrate, embeddedness, current velocity and groundwater seepage. Densities were greatest in substrate 251–300

mm. As substrate size decreased and increased, densities declined. Densities declined as embeddedness increased. Densities were lower in currents less than 0.1 $m \cdot s^{-1}$. Densities were greater in areas with groundwater seepage (3.4.3).

3.1 The effects of shoreline submergence on the distribution of vascular vegetation, non-vegetated substrate, periphyton, Asiatic clams, crayfish and sculpin

3.1.1 Vascular vegetation

Vascular vegetation was affected by the amount of time the shore was submerged. The vascular vegetation distribution based on frequency of occurrence indicated that vascular vegetation occurrence decreased as the shoreline was submerged for greater amounts of time (Figure 14). The Chi-Square test for vascular vegetation distribution was significant (X^2=106.84, d.f.=10, $p<0.05$), thus the null hypothesis that vascular vegetation was not affected by the amount of time of shoreline was submerged was rejected (Table 7). Pairwise comparisons for vascular vegetation distributions showed that vegetation occurred significantly more often at shoreline areas submerged less than 80 percent of the time than shoreline areas submerged greater than 80 percent of the time on an annual basis (Table 8, Figure 14).

In Table 8, vascular vegetation distributions not significantly different from each other were identified with the same letter. The occurrence of vascular vegetation significantly decreased from shoreline areas submerged 75–80 to 80–85 percent of the time. At shoreline areas submerged more than 80 percent of the time, vascular vegetation was present for less than half of the observations.

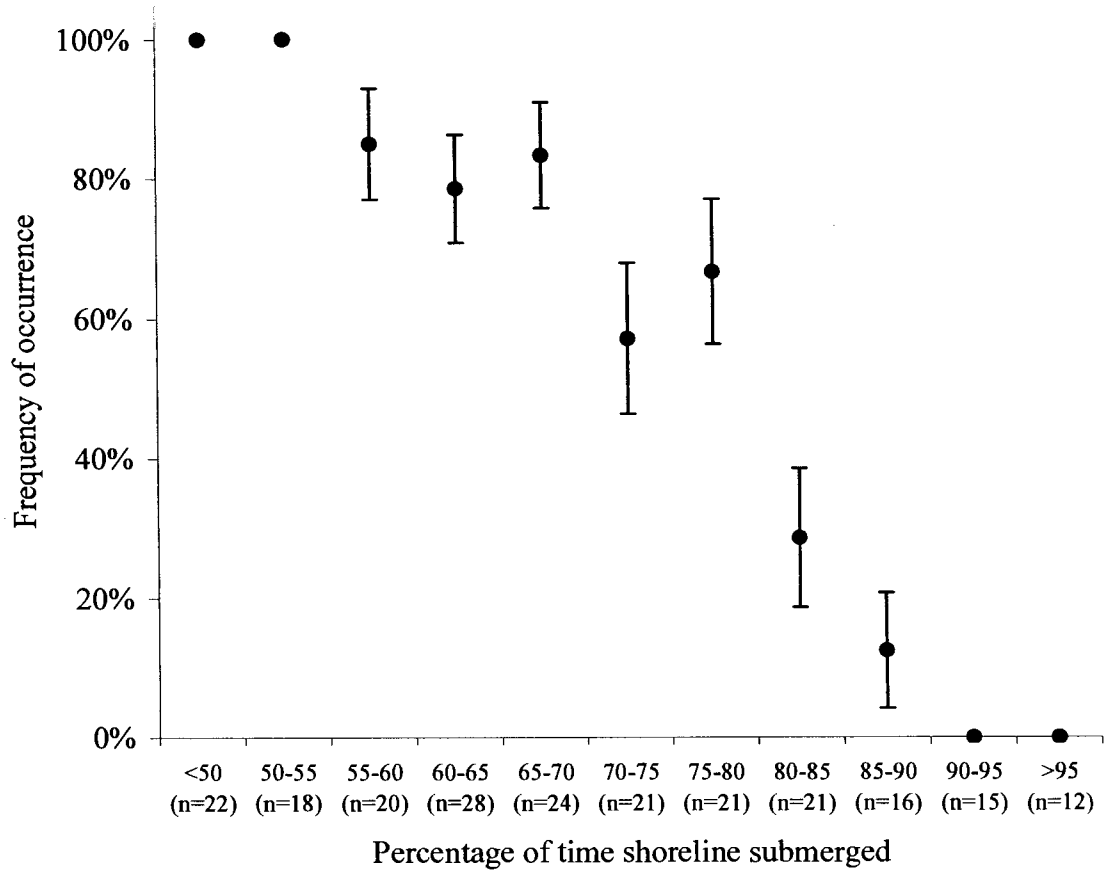

Figure 14. The frequencies of vascular vegetation occurrence ± 1 S.E. for percentages of time the shoreline was submerged. For shoreline areas submerged <50, 50–55, 90–95 and >95 percent of the time, the S.E. was less than the distance of the points.

Table 7. Chi-Square analysis results for the distribution of vascular vegetation for percentage of time the shoreline was submerged.

		Present		Absent		(Observed-Expected)^2/ Expected	
% of time	n	Observed	Expected	Observed	Expected	Present	Absent
<50	22	22	13.42	0	8.58	5.48	8.58
50-55	18	18	10.98	0	7.02	4.49	7.02
55-60	20	17	12.20	3	7.80	1.89	2.95
60-65	28	22	17.08	6	10.92	1.42	2.21
65-70	24	20	14.64	4	9.36	1.96	3.07
70-75	21	12	12.81	9	8.19	0.05	0.08
75-80	21	14	12.81	7	8.19	0.11	0.17
80-85	21	6	12.81	15	8.19	3.62	5.67
85-90	16	2	9.76	14	6.24	6.17	9.66
90-95	15	0	9.15	15	5.85	9.15	14.32
>95	12	0	7.32	12	4.68	7.32	11.46
Total	218	133		85			$X^2 = 106.84$

d.f. of $X^2 = (11-1)(2-1) = 10$

$p<0.05$

Table 8. Vascular vegetation pairwise comparisons of frequencies of occurrence for percentages of time the shoreline was submerged. Time intervals with the same letter are not significantly different.

Alpha	0.05
Degrees of freedom	10

% of time	<50	50–55	55–60	60–65	65–70	70–75	75–80	80–85	85–90	90–95	>95
Presence proportion	1.00	1.00	0.85	0.79	0.83	0.57	0.67	0.29	0.13	0.00	0.00
	A	A	A	A	A	A	A				
				B		B	B	B			
						C	C	C	C		
								D	D	D	D

3.1.2 Non-vegetated substrate

The distribution of non-vegetated substrate was affected by amount of time the shoreline was submerged. From shoreline areas submerged less than 55 percent of the time to shoreline areas submerged 80–85 percent of the time, non-vegetated substrate frequencies of occurrence increased, however the occurrence of non-vegetated substrate declined for shoreline areas submerged more than 80 percent of the time (Figure 15). Chi-Square analysis was significant for the distribution of non-vegetated substrate ($X^2>53.60$, d.f.=10, $p<0.05$), thus the hypothesis that amount of time the shoreline was submerged did not affect the distribution of non-vegetated substrate was rejected (Table 9). Non-vegetated substrate pairwise comparisons showed occurrence was significant different between shoreline areas submerged greater than 70 percent of the time and shoreline areas submerged less than 70 percent of the time. Non-vegetated substrate occurred more often in substrate submerged greater than 70 percent of the time on an annual basis (Table 10).

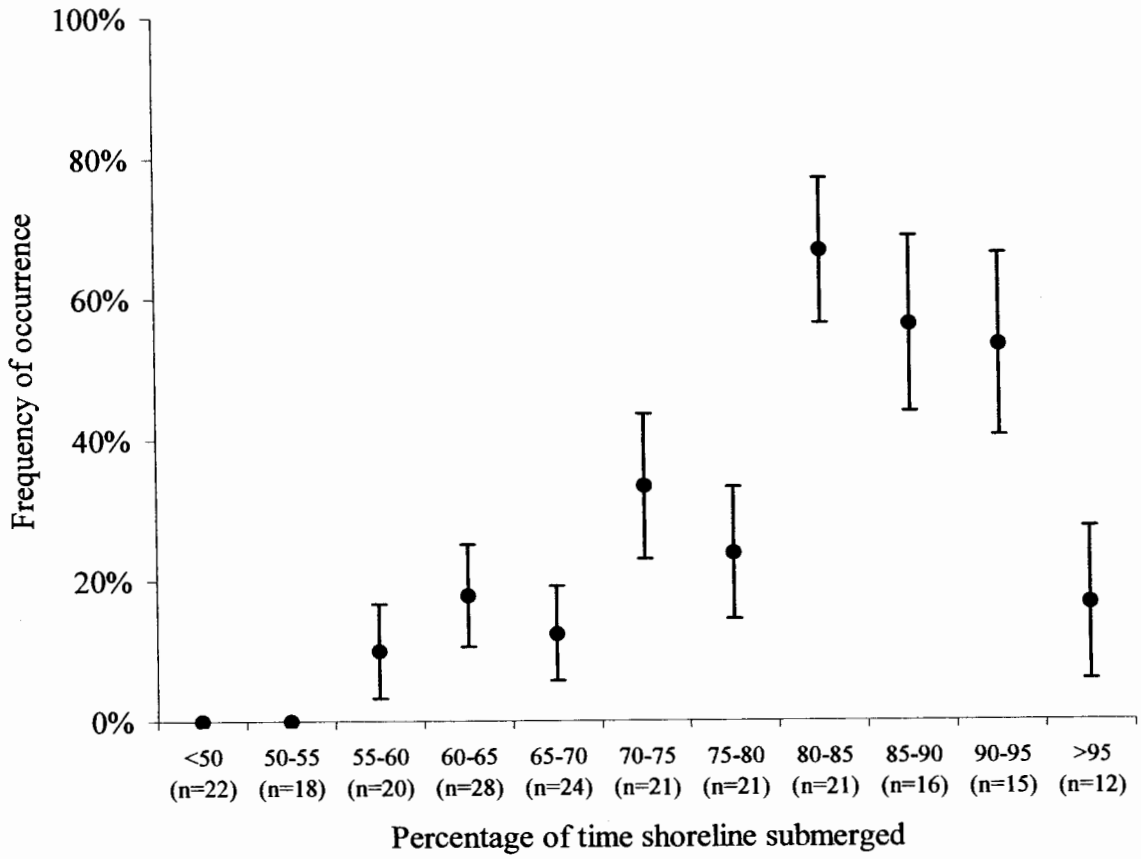

Figure 15. The frequencies of non-vegetated substrate occurrence ± 1 S.E for the percentages of time the shoreline was submerged. For shoreline areas submerged <50 and 50–55 percent of the time, the S.E. was less than the distance of the points.

Table 9. Chi-Square analysis results for the distribution of non-vegetated substrate for percentage of time the shoreline was submerged.

		Present		Absent		(Observed-Expected)^2/ Expected	
% of time	n	Observed	Expected	Observed	Expected	Present	Absent
<50	22	0	5.55	22	16.45	5.55	1.87
50–55	18	0	4.54	18	13.46	4.54	1.53
55–60	20	2	5.05	18	14.95	1.84	0.62
60–65	28	5	7.06	23	20.94	0.60	0.20
65–70	24	3	6.06	21	17.95	1.54	0.52
70–75	21	7	5.30	14	15.70	0.55	0.18
75–80	21	5	5.30	16	15.70	0.02	0.01
80–85	21	14	5.30	7	15.70	14.29	4.82
85–90	16	9	4.04	7	11.96	6.10	2.06
90–95	15	8	3.78	7	11.22	4.70	1.58
>95	12	2	3.03	10	8.97	0.35	0.12
Total	218	55		163			$X^2 = 53.60$
							d.f. of $X^2 = (11-1)(2-1) = 10$
							$p<0.05$

Table 10. Non-vegetated substrate pairwise comparisons of frequencies of occurrence for percentages of time the shoreline was submerged. Time intervals with the same letter are not significantly different.

Alpha	0.05
Degrees of freedom	10

% of time	<50	50–55	55–60	60–65	65–70	70–75	75–80	80–85	85–90	90–95	>95
Presence proportion	0.00	0.00	0.100	0.18	0.13	0.33	0.24	0.67	0.56	0.53	0.17
	A	A	A	A	A	A	A			A	A
			B	B	B	B	B		B	B	B
						C	C	C	C	C	C

3.1.3 Periphyton

Shoreline dewatering significantly affected the distribution of periphyton. Its occurrence increased as the shoreline was submerged for greater amounts of time (Figure 16). Periphyton frequencies of occurrence were less than 10 percent for shoreline areas submerged less than 85 percent of the time an a yearly basis, but periphyton occurrence greatly increased when the shoreline was submerged more than 85 percent of the time. Chi-Square analysis results were significant ($X^2>93.34$, d.f.=10, $p<0.05$), thus the null hypothesis that amount of time that the shoreline was submerged did not affect the distribution of periphyton was rejected (Table 11). Pairwise comparisons for periphyton frequencies of occurrence showed that periphyton occurrence in shoreline areas submerged less than 85 percent of the time were significantly lower than shoreline areas submerged greater than 85 percent of the time (Table 12). Shoreline areas submerged 85–90, 90–95 and > 95 percent of the time were not statistically significant from each other, but as observed in Figure 16, periphyton frequencies of occurrence only exceeded 50 percent for observations at shoreline areas submerged more than 95 percent of the time on a yearly basis.

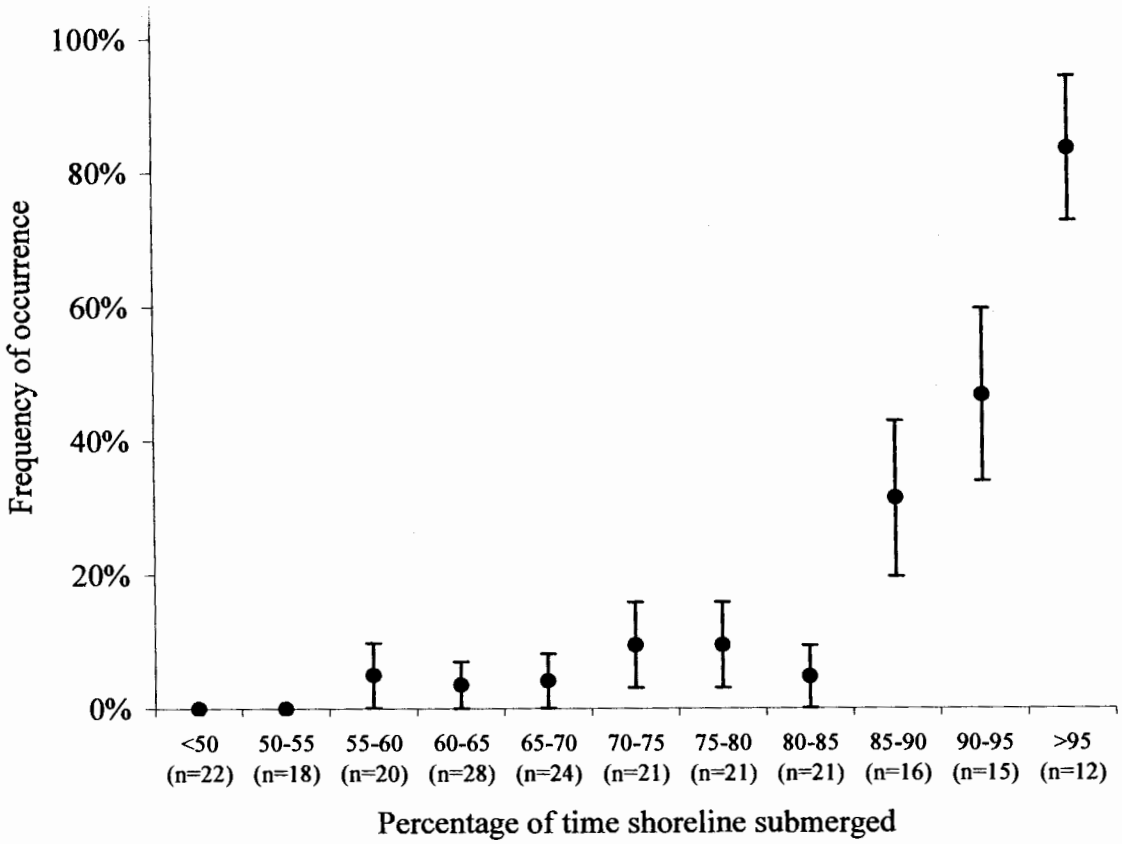

Figure 16. The frequencies of periphyton occurrence ± 1 S.E. for the percentages of time the shoreline was submerged. For shoreline areas submerged <50 and 50–55 percent of the time, the S.E. was less than the distance of the points.

Table 11. Chi-Square analysis results for the distribution of periphyton for percentage of time the shoreline was submerged.

		Present		Absent		(Observed-Expected)^2/ Expected	
% of time	n	Observed	Expected	Observed	Expected	Present	Absent
<50	22	0	3.03	22	18.97	3.03	0.39
50–55	18	0	2.48	18	15.52	2.48	0.5
55–60	20	1	2.75	19	17.25	1.12	0.18
60–65	28	1	3.85	27	24.15	2.11	0.14
65–70	24	1	3.30	23	20.70	1.61	0.17
70–75	21	2	2.89	19	18.11	0.27	0.04
75–80	21	2	2.89	19	18.11	0.27	0.04
80–85	21	1	2.89	20	18.11	1.24	0.18
85–90	16	5	2.20	11	13.80	3.56	0.91
90–95	15	7	2.06	8	12.94	11.8	3.4
>95	12	10	1.65	2	10.35	42.21	17.7
Total	218	30		188			$X^2 = 93.34$
							d.f. of $X^2 = (11-1)(2-1) = 10$
							$p<0.05$

Table 12. Periphyton pairwise comparisons of frequencies of occurrence for percentages of time the shoreline was submerged. Time intervals with the same letter are not significantly different.

Alpha	0.05
Degrees of freedom	10

% of time	<50	50–55	55–60	60–65	65–70	70–75	75–80	80–85	85–90	90–95	>95
Presence proportion	0.00	0.00	0.05	0.04	0.04	0.10	0.10	0.05	0.31	0.47	0.83
	A	A	A	A	A	A	A	A	A	A	
									B	B	B

3.1.4 Asiatic clams

The distribution of Asiatic clams was affected by the amount of time the shoreline was submerged. Overall, Asiatic clam occurrence increased as the shoreline was submerged for greater amounts of time (Figure 17). At shoreline areas submerged more than 90 percent of the time, Asiatic clams were prevalent. Chi-Square tests were significant ($X^2>101.56$, d.f.=10, $p<0.05$), thus the null hypothesis that the amount of time the shoreline was submerged did not affect the distribution of Asiatic clams was rejected (Table 13). Pairwise comparisons showed that Asiatic clam frequencies of occurrence for shoreline areas submerged less than 70 percent and 75–80 percent of the time were not significantly different from each other. Clam occurrences for shoreline areas submerged 70–75 and greater than 80 percent of the time were also not significantly different from each other (Table 14).

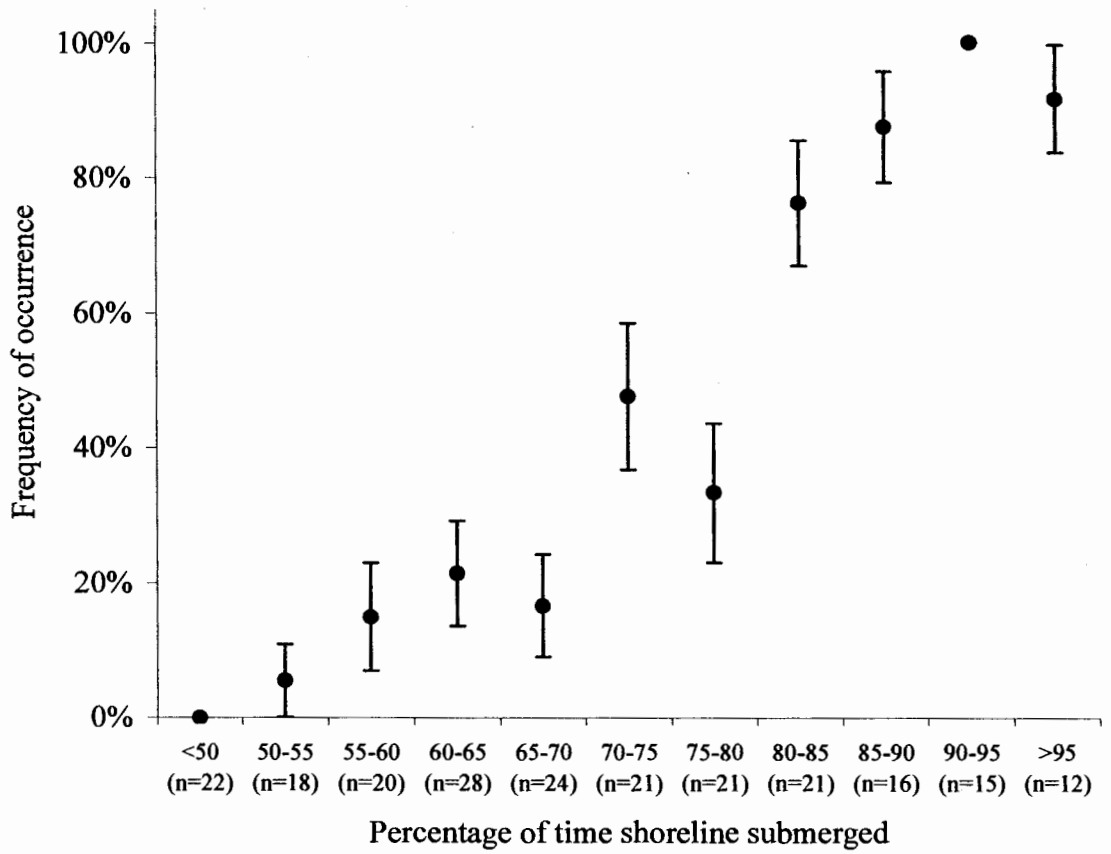

Figure 17. The frequencies of Asiatic clam occurrence ± 1 S.E. for the percentages of time the shoreline was submerged. For shoreline areas submerged <50 and 90–95 percent of the time, the S.E. was less than the distance of the points.

Table 13. Chi-Square analysis results for the distribution of Asiatic clams for percentage of time the shoreline was submerged.

		Present		Absent		(Observed-Expected)^2/ Expected	
% of time	n	Observed	Expected	Observed	Expected	Present	Absent
<50	22	0	8.78	22	13.22	8.78	5.83
50–55	18	1	7.18	17	10.82	5.32	3.53
55–60	20	3	7.98	17	12.02	3.11	2.06
60–65	28	6	11.17	22	16.83	2.40	1.59
65–70	24	4	9.58	20	14.42	3.25	2.16
70–75	21	10	8.38	11	12.62	0.31	0.21
75–80	21	7	8.38	14	12.62	0.23	0.15
80–85	21	16	8.38	5	12.62	6.93	4.60
85–90	16	14	8.38	2	9.61	9.08	6.03
90–95	15	15	5.97	0	9.01	13.57	9.01
>95	12	11	4.79	1	7.21	8.06	5.35
Total	218	87		131			$X^2 = 101.56$
							d.f. of $X^2 = (11-1)(2-1) = 10$
							$p<0.05$

Table 14. Asiatic clam pairwise comparisons of frequencies of occurrence for percentages of time the shoreline was submerged. Time intervals with the same letter are not significantly different.

Alpha	0.05
Degrees of freedom	10

% of time	<50	50–55	55–60	60–65	65–70	70–75	75–80	80–85	85–90	90–95	>95
Presence proportion	0.00	0.06	0.15	0.21	0.17	0.48	0.33	0.76	0.88	1.00	0.92
	A	A	A	A	A		A				
			B	B	B	B	B				
						C	C	C	C		
						D		D	D	D	D

3.1.5 Crayfish

The crayfish distribution was affected by the amount of shoreline dewatering. Crayfish were not observed in shoreline areas submerged less than 65 percent of the time. Crayfish were found in shoreline areas submerged 65–85 percent of the time. Crayfish frequencies of occurrence were greater in shoreline areas submerged more than 85 percent of the time (Figure 18). Chi-Square tests results were significant ($X^2>23.84$, d.f.=8, $p<0.05$), thus the null hypothesis that the distribution of crayfish was not affected by the amount of time the shoreline was submerged was rejected (Table 15). Crayfish pairwise comparisons for the percentages of time the shoreline was submerged showed variability in crayfish distribution, thus crayfish occurrences for shoreline areas submerged more than 65 percent of the time were not significant from each other (Table 16).

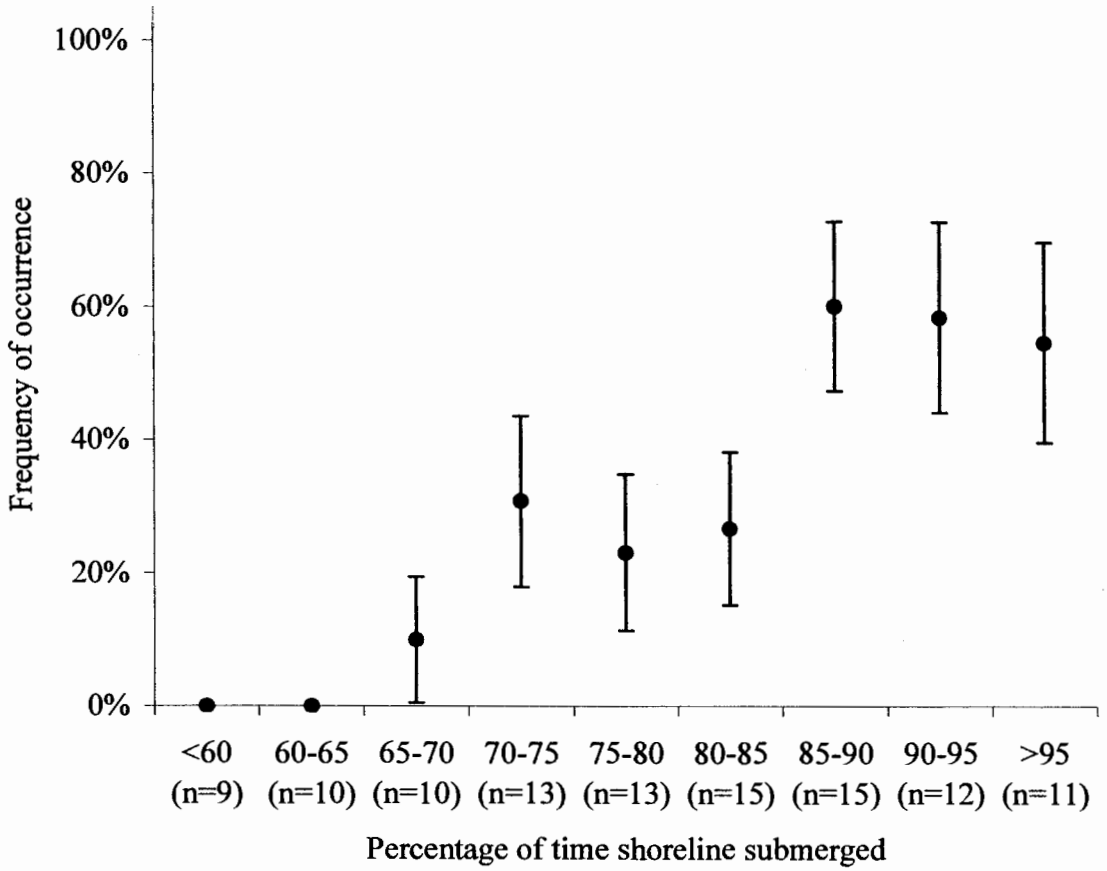

Figure 18. The frequencies of crayfish occurrence ± 1 S.E. for the percentages of time the shoreline was submerged. For shoreline areas submerged <60 and 60–65 percent of the time, the S.E. was less than the distance of the points.

Table 15. Chi-Square analysis results for the distribution of crayfish for percentage of time the shoreline was submerged.

		Present		Absent		(Observed-Expected)^2/ Expected	
% of time	n	Observed	Expected	Observed	Expected	Present	Absent
<60	9	0	2.83	9	6.17	2.83	1.30
60–65	10	0	3.15	10	6.85	3.15	1.45
65–70	10	1	3.15	9	6.85	1.47	0.67
70–75	13	4	4.09	9	8.91	0.00	0.00
75–80	13	3	4.09	10	8.91	0.29	0.13
80–85	15	4	4.72	11	10.28	0.11	0.05
85–90	15	9	4.72	6	10.28	3.88	1.78
90–95	12	7	3.78	5	8.22	2.75	1.26
>95	11	6	3.46	5	7.54	1.86	0.85
Total	108	34		74			$X^2 = 23.84$
							d.f. of $X^2 = (9-1)(2-1) = 8$
							$p<0.05$

Table 16. Crayfish pairwise comparisons of frequencies of occurrence for percentages of time the shoreline was submerged. Time intervals with the same letter are not significantly different.

Alpha	0.05
Degrees of freedom	8

% of time	<60	60–65	65–70	70–75	75–80	80–85	85–90	90–95	95 <
Presence proportion	0.00	0.00	0.10	0.31	0.23	0.27	0.60	0.58	0.55
	A	A	A	A	A	A		A	A
			B	B	B	B	B	B	B

3.1.6 Sculpin

Sculpin were distributed throughout most of the shoreline, but sculpin frequencies of occurrence were greatest in shoreline areas submerged more than 85 percent of the time (Figure 19). Chi-Square test results for the distribution of sculpin were not significant (X^2=8.77, d.f.=8, 0.50>p>0.10) (Table 17). Because amount of time the shoreline was submerged did not affect the distribution of sculpin, no pairwise comparisons were performed.

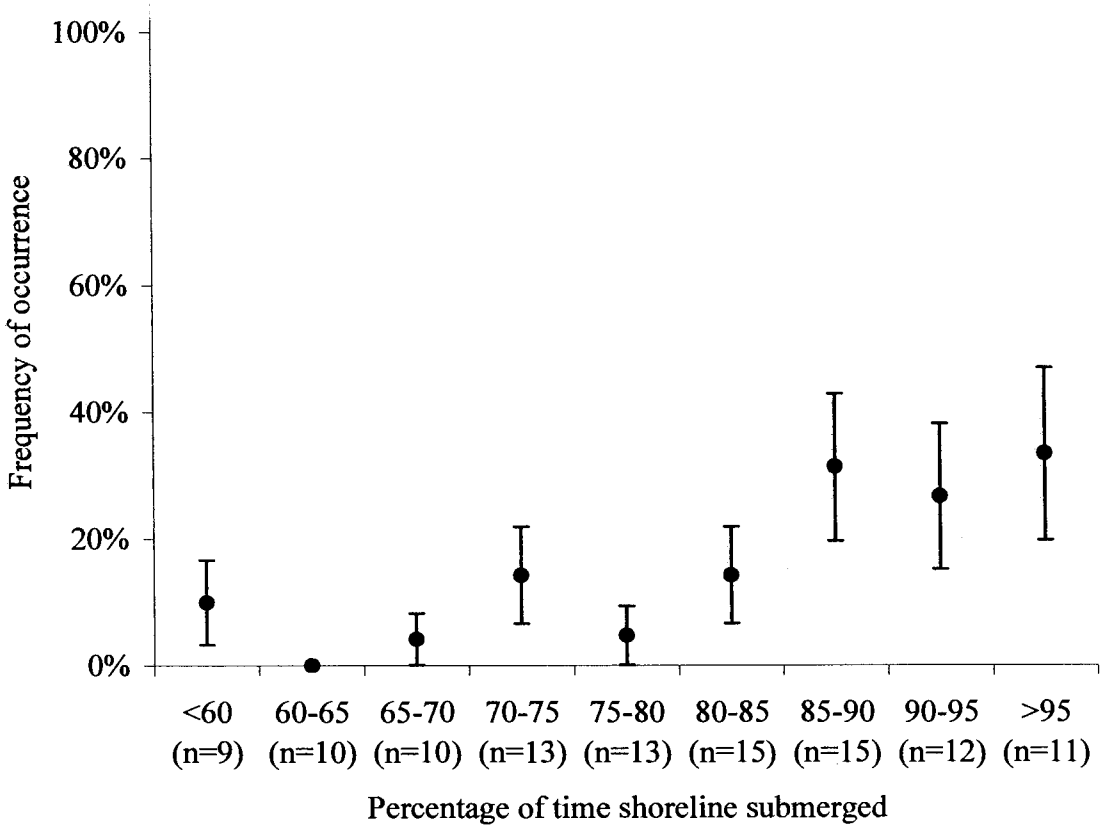

Figure 19. The frequencies of sculpin occurrence for ± 1 S.E. for the percentages of time the shoreline was submerged. For shoreline areas submerged 60–65 percent of the time, the S.E. was less than the distance of the point.

Table 17. Chi-Square analysis results for the distribution of sculpin for percentage of time the shoreline was submerged.

		Present		Absent		(Observed-Expected)^2/ Expected	
% of time	n	Observed	Expected	Observed	Expected	Present	Absent
<60	9	2	1.92	7	7.08	0.00	0.00
60–65	10	0	2.13	10	7.87	2.13	0.58
65–70	10	1	2.13	9	7.87	0.60	0.16
70–75	13	3	2.77	10	10.23	0.02	0.01
75–80	13	1	2.77	12	10.23	1.13	0.31
80–85	15	3	3.19	12	11.81	0.01	0.00
85–90	15	5	3.19	10	11.81	1.02	0.28
90–95	12	4	2.56	8	9.44	0.82	0.22
>95	11	4	2.34	7	8.66	1.17	0.32
Total	108	23		85			$X^2 = 8.77$

d.f. of $X^2 = (9-1)(2-1) = 8$

$0.50>p>0.10$

3.2 Asiatic clams, crayfish and sculpin distributions between the shoreline zones of vascular vegetation, non-vegetated substrate and periphyton

3.2.1 Asiatic clams

The distribution of Asiatic clams varied across the shoreline zones. Of the observations collected in shoreline zones with vascular vegetation, fewer than 10 percent of the plots contained live clams. Clams occurred more frequently in shoreline zones with non-vegetated substrate and periphyton. Samples in the persistent periphyton zone had clams present in all observations (Figure 20). The Chi-Square test was significant (X^2=154.27, d.f.=2, $p<0.05$), thus the null hypothesis that the distribution of clams between the shoreline zones were equal was rejected (Table 18). Pairwise comparisons showed that significant differences in clam distribution existed between all three zones (Table 19). Clam presence was significantly greater for non-vegetated substrate than for vascular vegetation and clam presence for persistent periphyton was significantly greater than non-vegetated substrate.

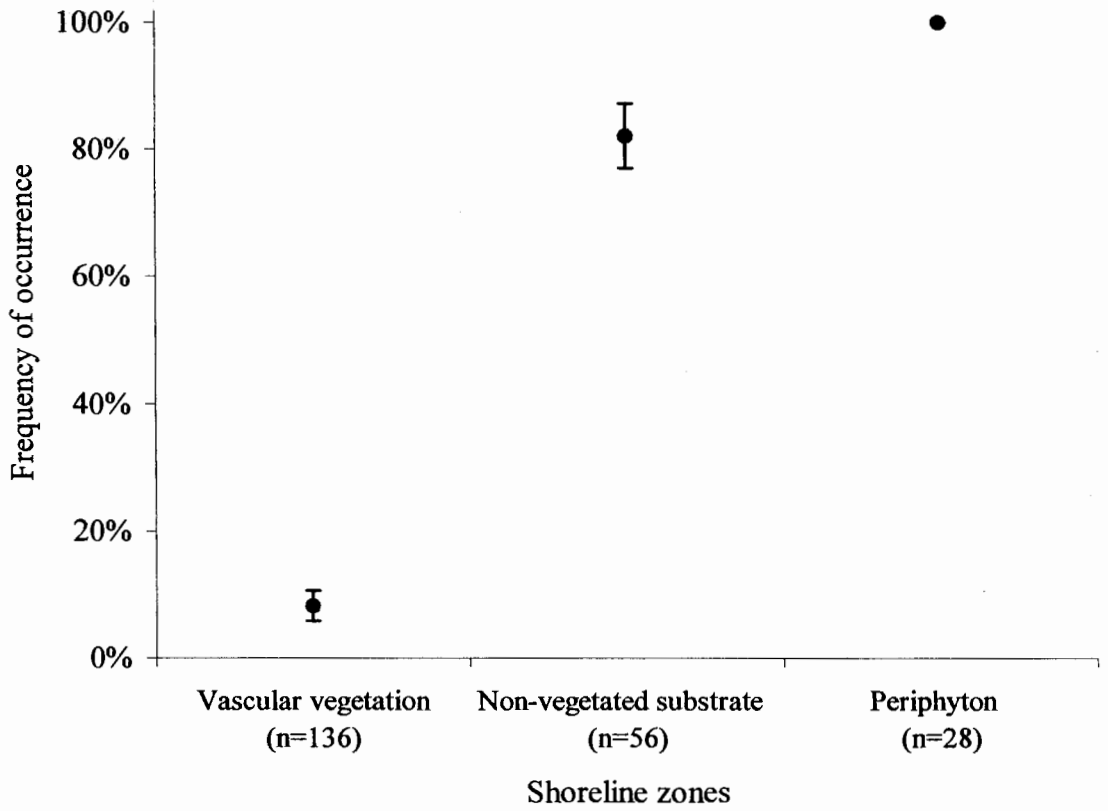

Figure 20. The frequencies of Asiatic clam occurrence ± 1 S.E. for the shoreline zones of vascular vegetation, non-vegetated substrate and periphyton. For periphyton, the S.E. was less than the distance of the point.

Table 18. Chi-Square analysis results for the distribution of Asiatic clams for the shoreline zones of vascular vegetation, non-vegetated substrate and periphyton.

		Present		Absent		$(Observed-Expected)^2/$ Expected	
	n	Observed	Expected	Observed	Expected	Present	Absent
Vascular vegetation	132	11	43.58	121	88.42	24.36	12.01
Non-vegetated substrate	56	46	18.49	10	37.51	40.93	20.18
Periphyton	28	28	9.25	0	18.75	38.05	18.75
Total	216	82		131			$X^2 = 154.27$
							d.f. of $X^2 = (3-1)(2-1) = 2$
							$p<0.05$

Table 19. Asiatic clam pairwise comparisons of frequencies of occurrence for shoreline zones. Shoreline zones with the same letter are not significantly different.

Alpha	0.05
Degrees of freedom	2

Shoreline zone	Vascular vegetation	Non-vegetated substrate	Periphyton
Presence proportion	0.08	0.82	1.00
	A	B	C

3.2.2 Crayfish

The distribution of crayfish varied between the three shoreline zones. Crayfish were not observed in submerged vascular vegetation, but one-third of the observations for non-vegetated substrate had crayfish present. Crayfish were present in 81 percent of observations in the periphyton zone (Figure 21). Chi-Square test results were significant (X^2=47.90, d.f.=2, $p<0.05$) for the distributions of crayfish between the three shoreline zones (Table 20). Pairwise comparisons showed that crayfish distributions were significantly different for the three shoreline zones (Table 21). Crayfish presence significantly increased from vascular vegetation to non-vegetated substrate and from non-vegetated substrate to periphyton.

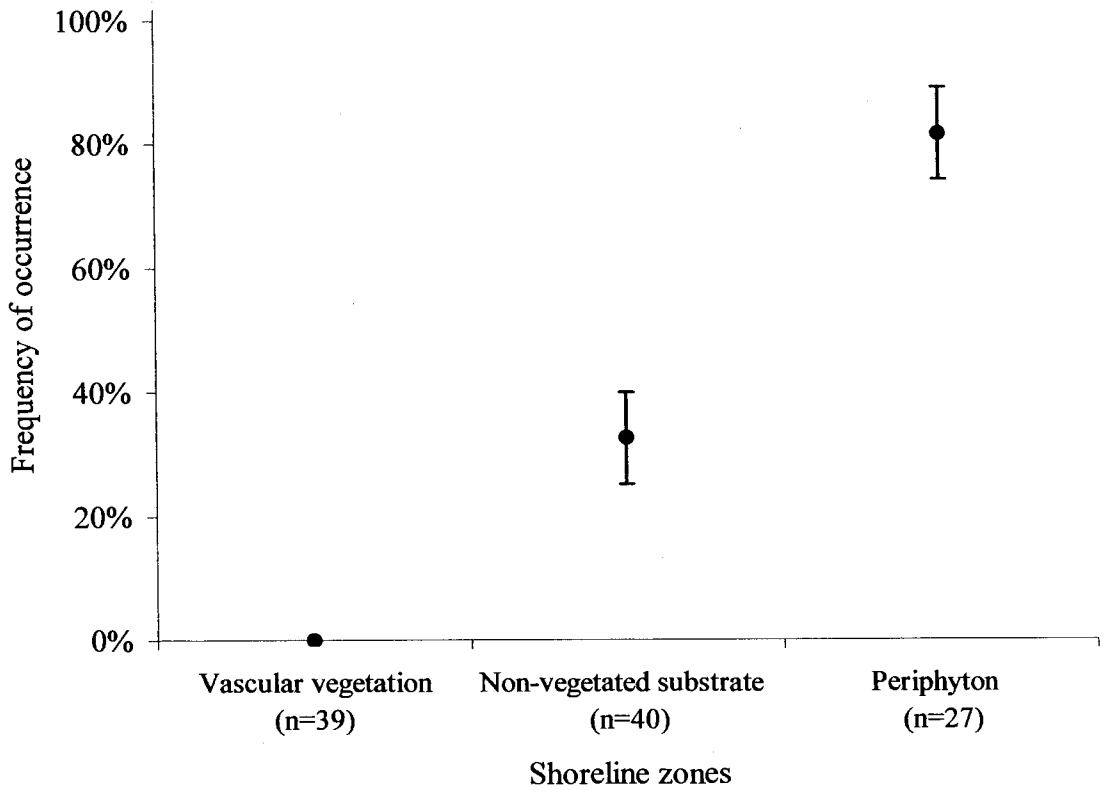

Figure 21. The frequencies of crayfish occurrence ± 1 S.E. for the shoreline zones of vascular vegetation, non-vegetated substrate and periphyton. For vascular vegetation, the S.E. was less than the distance of the point.

Table 20. Chi-Square analysis results for the distribution of crayfish for the shoreline zones of vascular vegetation, non-vegetated substrate and periphyton.

		Present		Absent		(Observed-Expected)^2/ Expected	
	n	Observed	Expected	Observed	Expected	Present	Absent
Vascular vegetation	39	0	12.88	39	26.12	12.88	6.35
Non-vegetated substrate	40	13	13.21	27	26.79	0.00	0.00
Periphyton	27	22	8.92	5	18.08	19.21	9.47
Total	106	32		71			$X^2 = 47.90$
							d.f. of $X^2 = (3-1)(2-1) = 2$
							$p<0.05$

Table 21. Crayfish pairwise comparisons of frequencies of occurrence for shoreline zones. Shoreline zones with the same letter are not significantly different.

Alpha	0.05
Degrees of freedom	2

Shoreline zone	Vascular vegetation	Non-vegetated substrate	Periphyton
Presence proportion	0.00	0.33	0.81
	A	B	C

3.2.3 Sculpin

The distribution of sculpin differed for all three shoreline zones. Submerged vascular vegetation had sculpin in eight percent of the observations. Sculpin occurred in periphyton zone more often than non-vegetated substrate zone. One-third of the observations found at least one sculpin in periphyton zone. Sculpin were found in 28 percent of the observations for non-vegetated substrate (Figure 22). Chi-Square test results were significant (X^2=7.45, d.f.=2, $p<0.05$), so the null hypothesis that the distribution of sculpin was equal for the three shoreline zones was rejected (Table 22). Pairwise comparisons showed that the distributions between vascular vegetation and periphyton were significantly different; however, distributions between vascular vegetation and non-vegetated substrate and distributions between non-vegetated substrate and periphyton were not significantly different (Table 23).

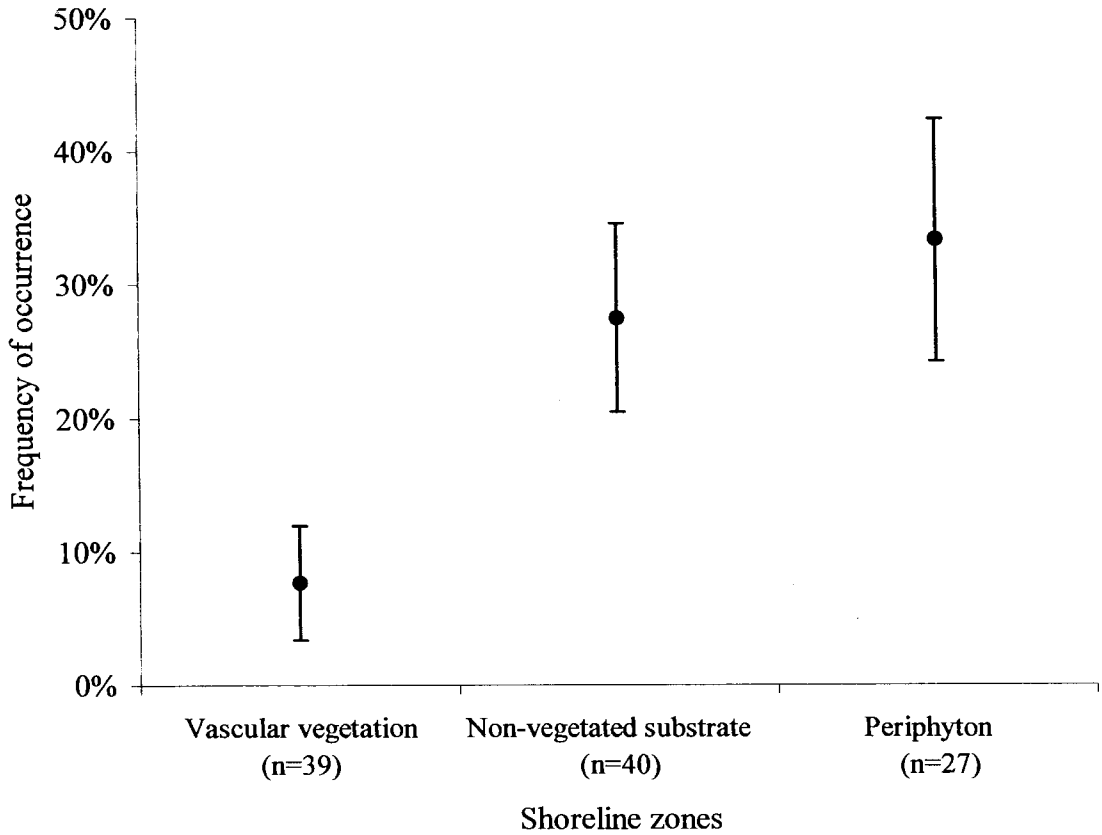

Figure 22. The frequencies of sculpin occurrence ± 1 S.E. for the shoreline zones of vascular vegetation, non-vegetated substrate and periphyton.

Table 22. Chi-Square analysis results for the distribution of sculpin for the shoreline zones of vascular vegetation, non-vegetated substrate and periphyton.

		Present		Absent		(Observed-Expected)^2/ Expected	
	n	Observed	Expected	Observed	Expected	Present	Absent
Vascular vegetation	39	3	8.46	36	30.54	3.53	0.98
Non-vegetated substrate	40	11	8.68	29	31.32	0.62	0.17
Periphyton	27	9	5.86	18	21.14	1.68	0.47
Total	106	23		83			$X^2 = 7.45$
							d.f. of $X^2 = (3-1)(2-1) = 2$
							$p<0.05$

Table 23. Sculpin pairwise comparisons of frequencies of occurrence for shoreline zones. Shoreline zones with the same letter are not significantly different.

Alpha	0.05
Degrees of freedom	2

Shoreline zone	Vascular vegetation	Non-vegetated substrate	Periphyton
Presence proportion	0.08	0.28	0.33
	A	A	
		B	B

3.3 Asiatic clam size class distribution across shoreline zones

3.3.1 Asiatic clam cohort analysis

To determine Asiatic clam size classes from yearly recruitment, shell lengths to the nearest 0.1 mm were used. A shell length histogram composed of 3,090 clam measurements indicated that three size classes were present: 1) 5–11 mm, 2) 11–22 mm, and 3) greater than 22 mm in shell length. These size classes were used for distribution analyses (Figure 23). These three cohorts were readily observed in the field (Figure 24).

3.3.2 Asiatic clam size class distribution by shoreline zone

Differences for Asiatic clam size classes between the three shoreline zones were observed. Forty-one percent of the clams found in the vascular vegetation zone were clams 5–11 mm in shell length. Clams 5–11 mm in shell length only composed two and one percent of the clams found in the shoreline zones of non-vegetated substrate and periphyton. Clams 11–22 mm in shell length were the largest proportion of clams found in all three shoreline zones. The highest percent occurrence of clams 11–22 mm in shell length was found in the non-vegetated substrate zone where 88 percent of the clams were between 11–22 mm in shell length. Clams greater than 22 mm in shell length were most abundant in the periphyton zone, but two of these larger clams were found in the vascular vegetation zone (Figure 25).

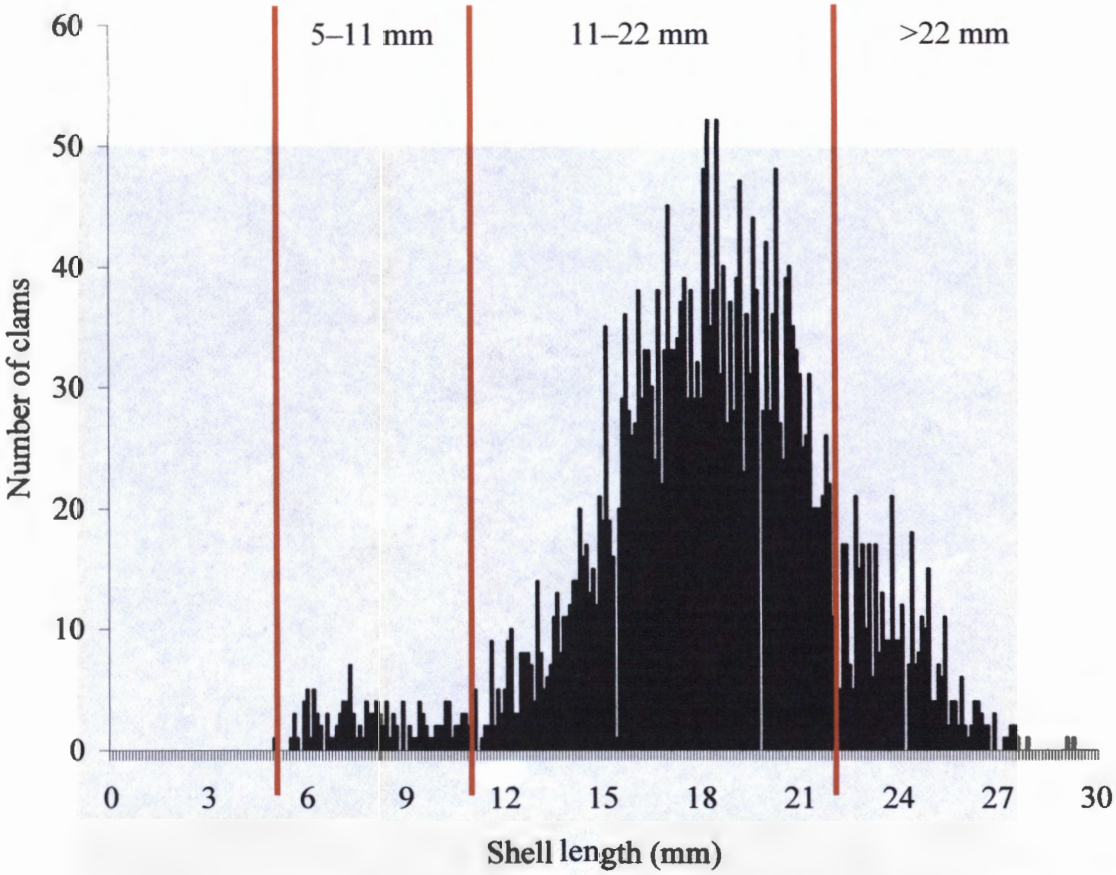

Figure 23. Asiatic clam shell length from 2002 collections (n=3090). Shell lengths were transformed from shell height measurements with the equation (Shell length = 1.0232(shell height) + 0.8202).

Figure 24. Asiatic clam size classes observed in the Hanford Reach, Columbia River.

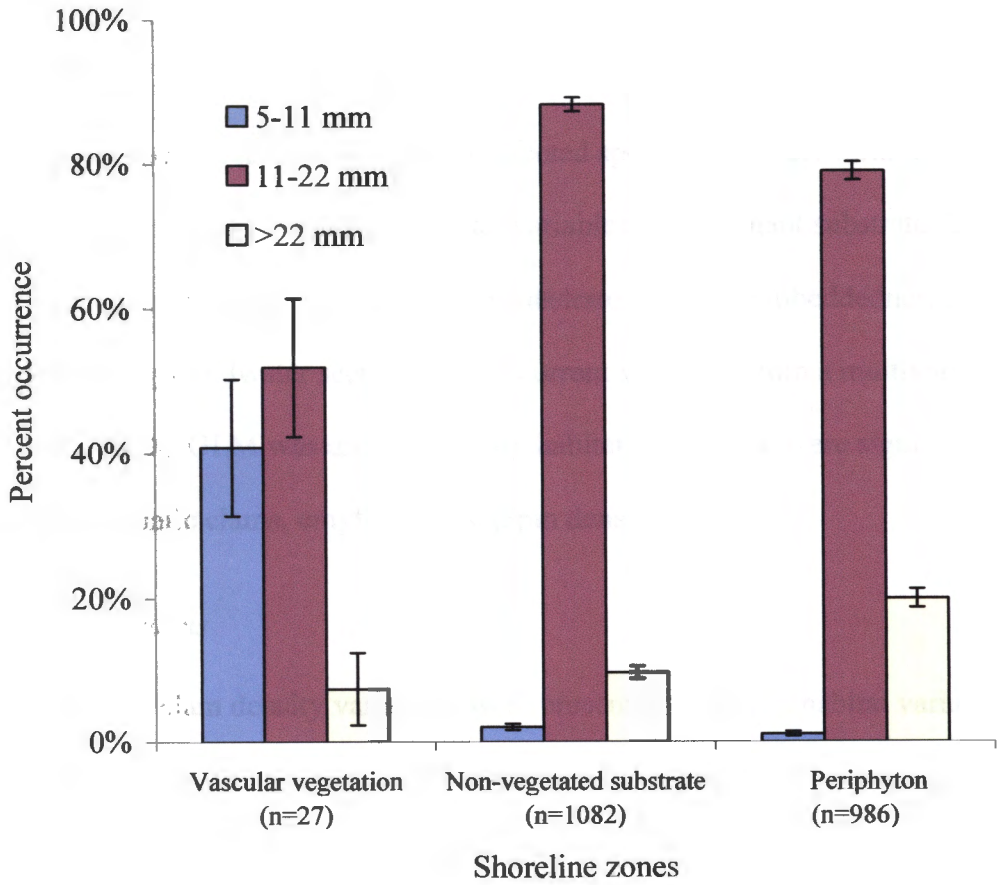

Figure 25. Asiatic clam size class percent occurrences ± 1 S.E. for the shoreline zones of vascular vegetation, non-vegetated substrate and periphyton.

3.4 Habitat factors affecting the densities of Asiatic clams, crayfish and sculpin

To determine habitat factors that affected species densities, variations were presented for the seven categorical habitat variables: 1) dominant substrate, 2) subdominant substrate, 3) unconsolidated substrate depth, 4) embeddedness, 5) aquatic vegetation, 6) groundwater seepage and 7) current velocity. From a multivariate approach, PROC GLM was used to identify habitat factors that were significant in explaining Asiatic clams, crayfish and sculpin densities.

3.4.1 Asiatic clams

Asiatic clam density variations were presented for seven habitat variables. For dominant substrate, clam densities were the highest, yet uniform, in substrate size classes 51–100, 101–150 and 151–200 mm—all had average clam densities between 498–508 clam·m^{-2}. Substrates 201–250, 251–300, and greater than 301 mm had average densities that declined from 341 to 50 clams·m^{-2}. Substrate less than 50 mm in diameter averaged 209 clams·m^{-2} (Figure 26).

All subdominant substrates groups, except substrates 251–300 and 301–350 mm, had average densities between 227 and 410 clams·m^{-2}. Substrates groups 251–300 and 301–350 mm each were represented with one observation each with densities of 1,835 and 825 clams·m^{-2}, respectively (Figure 27).

Clam densities were lowest in unconsolidated substrate depths less than 5 cm, where an average of 135 clams·m^{-2} were observed. For unconsolidated substrate depths

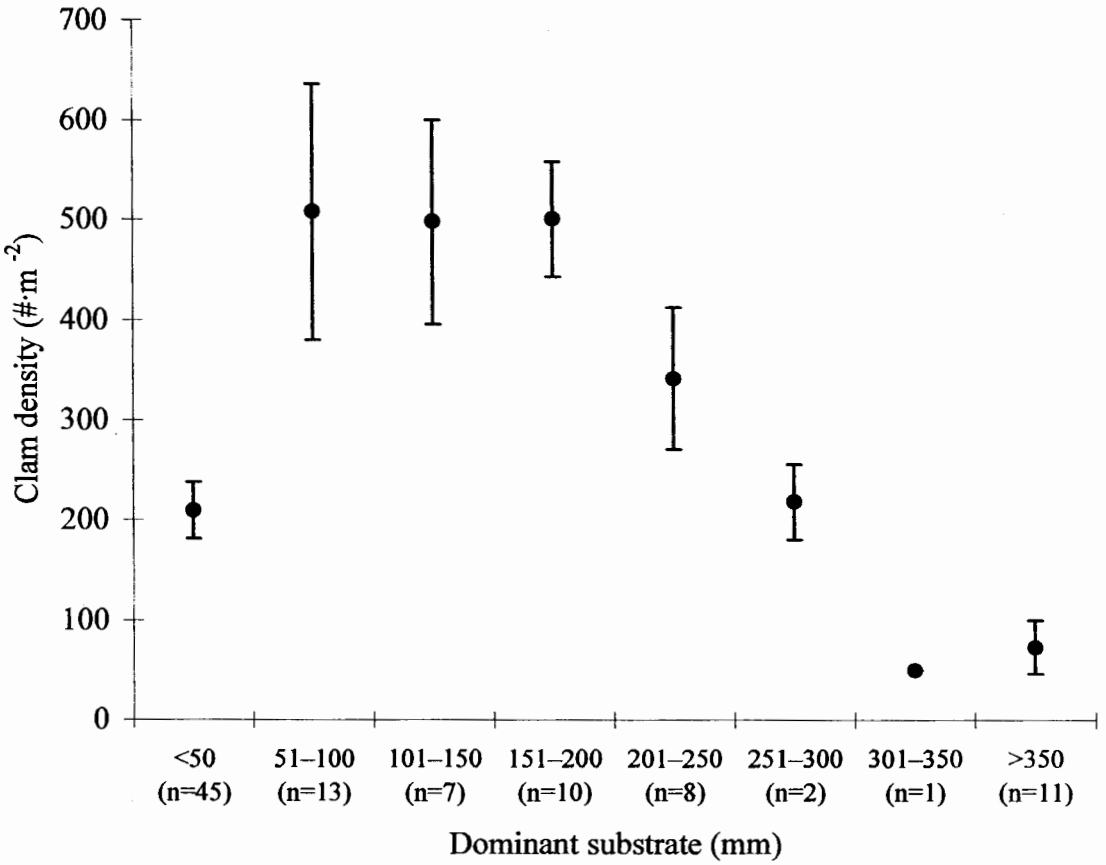

Figure 26. Average Asiatic clam densities ± 1 S.E. for dominant substrate. For substrate 301–350 mm, the S.E. was less than the distance of the point.

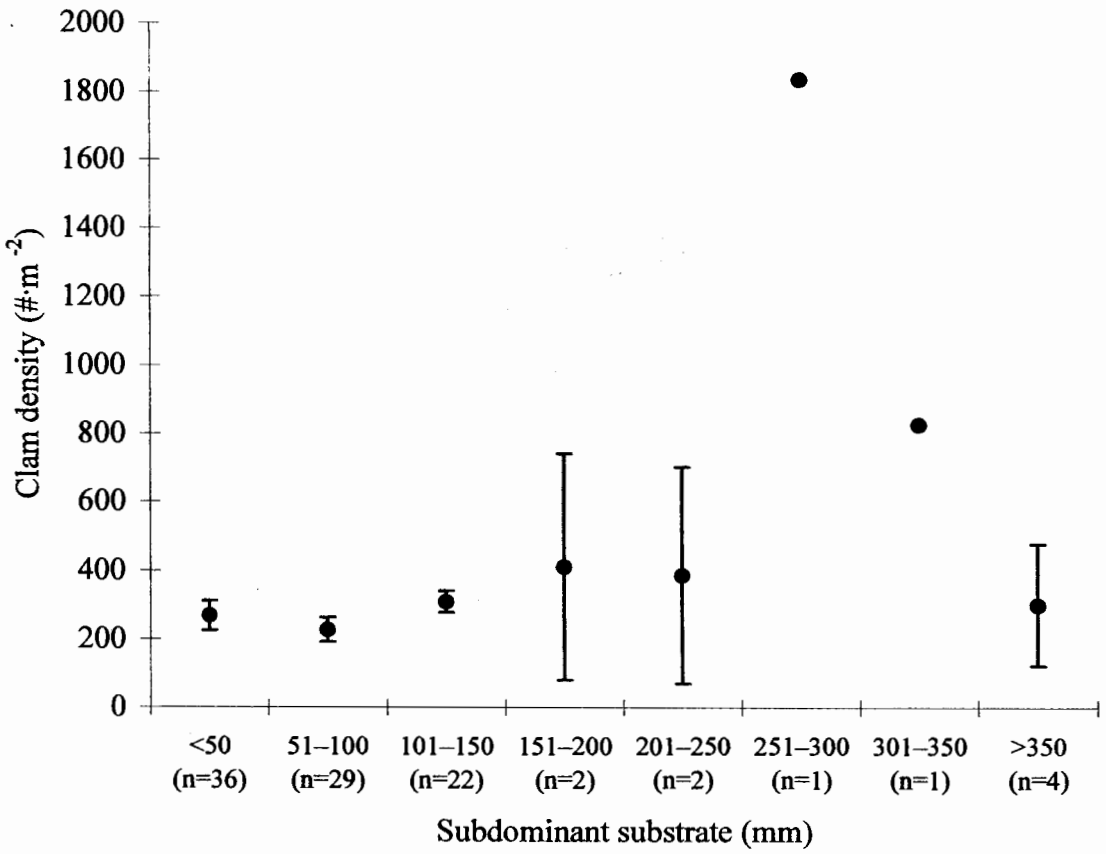

Figure 27. Average Asiatic clam densities ± 1 S.E. for subdominant substrate. For substrate 251–300 and 301–350 mm, the S.E. was less than the distance of the point.

depths 5–10 and greater than 10 cm, clam densities were 378 and 448 clams·m^{-2} (Figure 28).

Asiatic clam densities decreased as substrate became more than 50 percent embedded. Average clam densities in substrate 0–25 and 25–50 percent embedded were 383 and 416 clams·m^{-2}, but for substrate 50–75 and 75–100 percent embedded densities were 268 and 76 clam·m^{-2}, respectively (Figure 29).

When aquatic vegetation became present and its abundance increased, clam densities decreased. In the absence of aquatic vegetation, clam densities exceeded 300 clams·m^{-2}. As vegetation became present (i.e., sparse), densities dropped on the average, but large variation was also present. Where aquatic vegetation patches occurred, densities were less than 25 clams·m^{-2} (Figure 30).

No differences were observable for Asiatic clam densities between shorelines with and without groundwater seepage. Both shorelines had densities around 300 clams·m^{-2} (Figure 31).

Densities did vary between the three categories of current velocity. Current velocities less than 0.1 m·s^{-1} had the lowest densities with an average of 142 clams·m^{-2}. Current velocities greater than 0.3 m·s^{-1} had an average density of 427 clams·m^{-2}, but current velocities between 0.1–0.3 m·s^{-1} had the highest clam density with over 710 clams·m^{-2} (Figure 32).

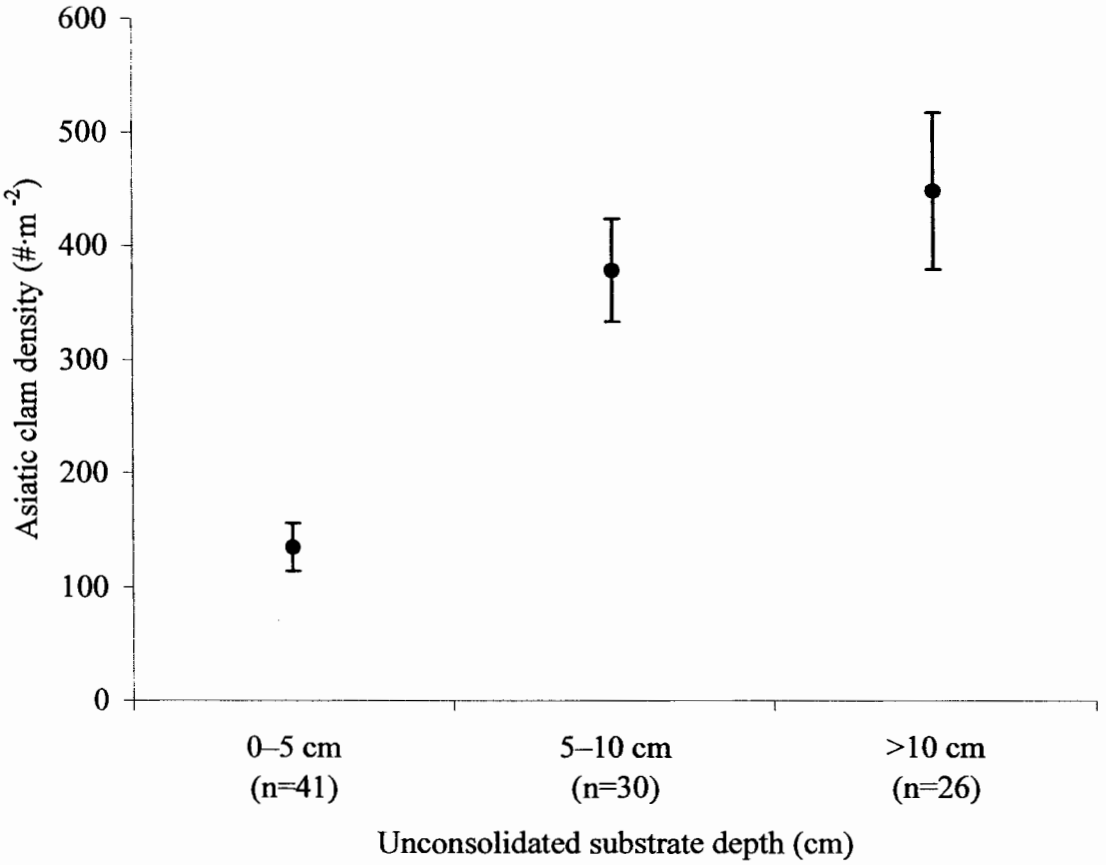

Figure 28. Average Asiatic clam densities ± 1 S.E. for unconsolidated substrate depth.

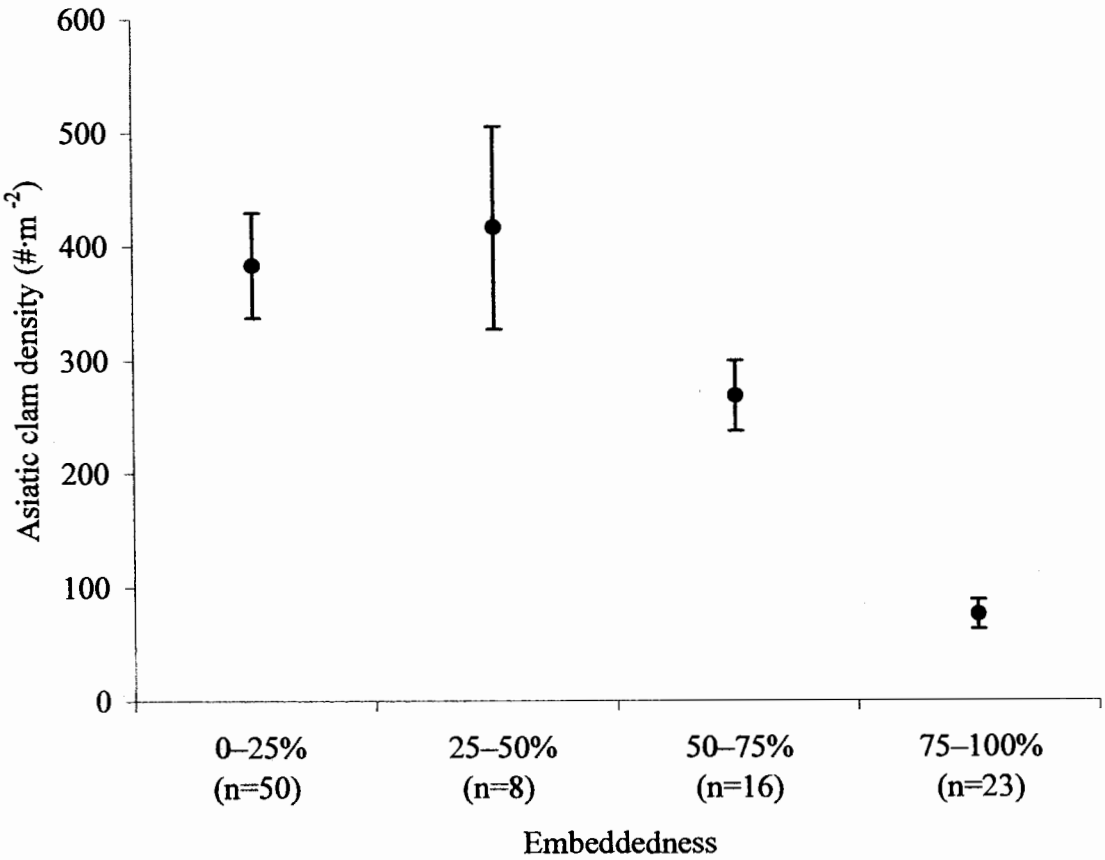

Figure 29. Average Asiatic clam densities ± 1 S.E. for embeddedness.

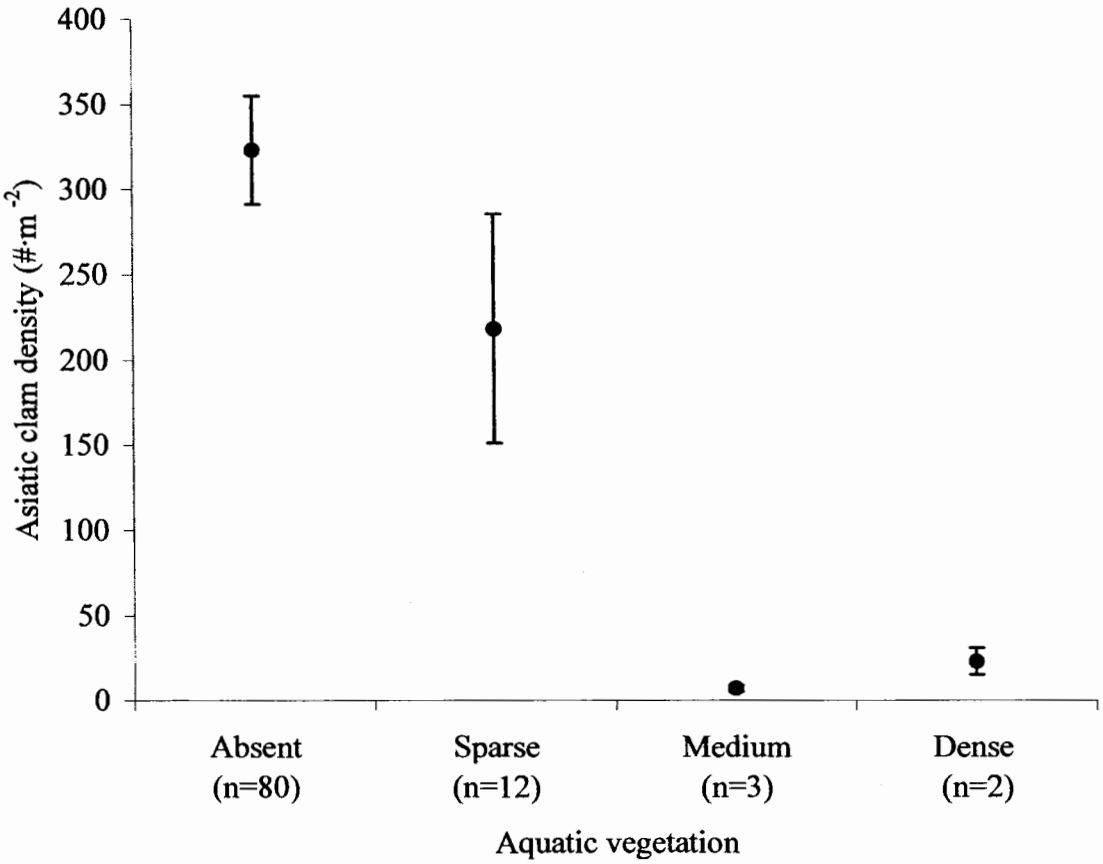

Figure 30. Average Asiatic clam densities ± 1 S.E. for aquatic vegetation. For medium vegetation density, the S.E. was less than the distance of the point.

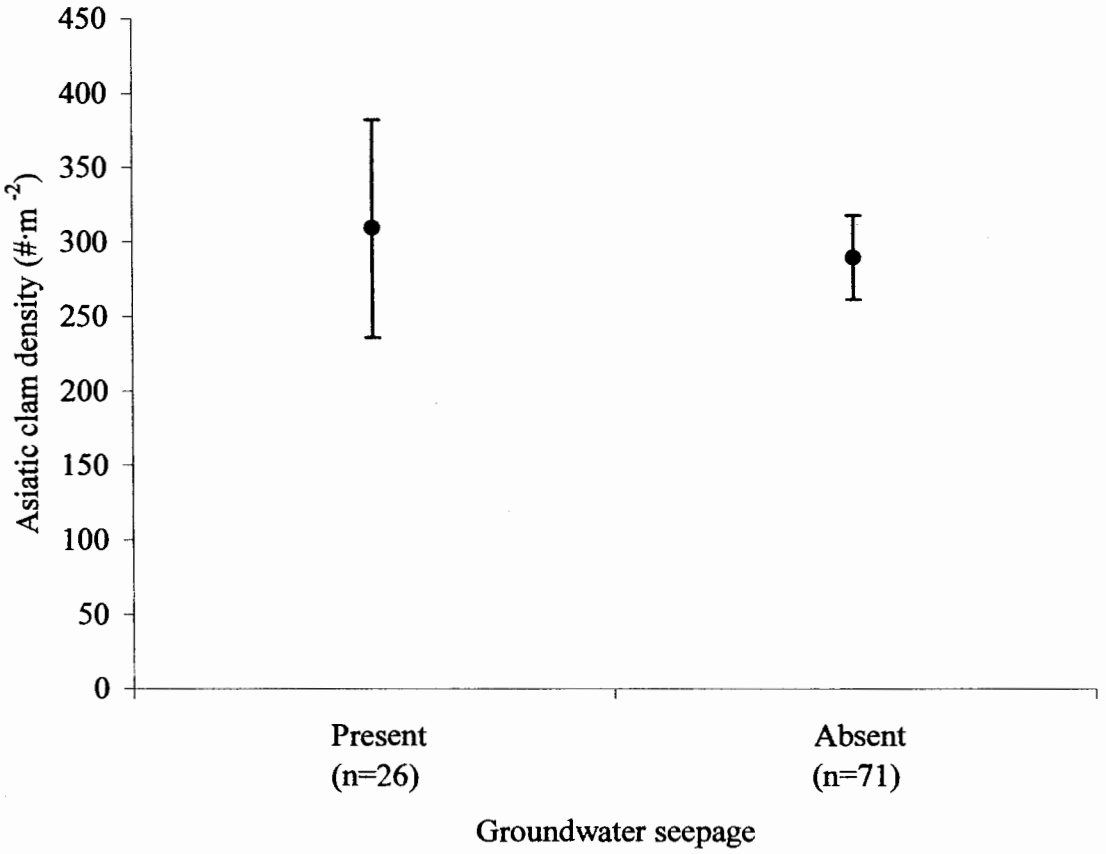

Figure 31. Average Asiatic clam densities ± 1 S.E. for groundwater seepage.

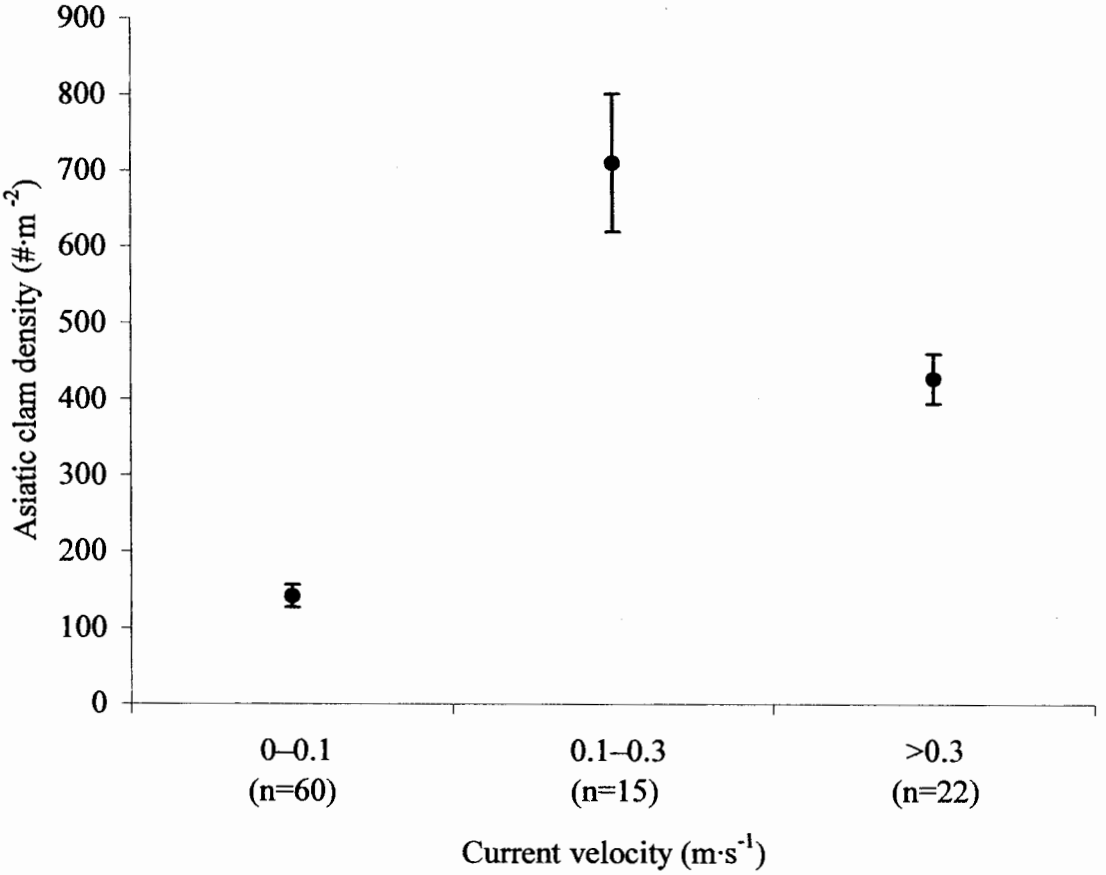

Figure 32. Average Asiatic clam densities ± 1 S.E. for current velocity.

The SAS PROC GLM result for the model composed of the 7 categorical habitat variables was significant ($p<0.0001$) in explaining 88 percent ($R^2=0.88$) of the variation observed in Asiatic clam densities (Table 24). Current velocity ($p<0.0001$), subdominant substrate ($p<0.0001$), dominant substrate ($p=0.0004$) and embeddedness ($p=0.0185$) were significant factors in explaining the densities of Asiatic clams (Table 25). Due to a large F-value coupled with only two degrees of freedom, current velocity was the most significant factor affecting clam densities. Unconsolidated substrate depth, aquatic vegetation and groundwater seepage were not significant factors explaining Asiatic clam densities.

Table 24. The SAS PROC GLM results for Asiatic clam density for the recorded habitat variables in the Hanford Reach, Columbia River.

Source	d.f.	Sum of squares	Mean square	F value	Pr > F
Model	25	6607927	264317	21.53	<0.0001
Error	71	871724	12277.8		
Corrected Total	96	7479651			

Table 25. The SAS PROC GLM results for habitat variable significance in relation to Asiatic clam density. Significant difference denoted by bold type.

Source	d.f.	Type III sum of squares	Mean square	F value	Pr > F
Dominant substrate	7	376886	53840.8	4.39	**0.0004**
Subdominant substrate	7	1227671	175382	14.28	**<0.0001**
Unconsolidated substrate depth	2	32270.7	16135.3	1.31	0.2751
Embeddedness	3	130989	43663.1	3.56	**0.0185**
Aquatic vegetation	3	42222.9	14074.3	1.15	0.3364
Current velocity	2	1066017	533009	43.41	**<0.0001**
Groundwater seepage	1	1111.92	1111.92	0.09	0.7643

3.4.2 Crayfish

Crayfish density variations were presented for the habitat variables of dominant substrate, subdominant substrate, unconsolidated substrate depth, embeddedness, aquatic vegetation, groundwater seepage and current velocity. Dominant substrates between 151–250 mm had the highest crayfish densities with about 11 crayfish·m^{-2}. Nearly 8 crayfish·m^{-2} were found in substrate 251–300 mm. Substrates smaller than 100 mm and larger than 300 mm had crayfish densities less than 4 crayfish·m^{-2}. Crayfish densities in substrate less than 50 mm were 0.4 crayfish·m^{-2} (Figure 33).

Crayfish densities in subdominant substrate were variable. For subdominant substrate less than 250 mm, average crayfish densities were between 2 and 3.4·crayfish·m^{-2} with greater densities within that substrate range occurring in substrate 0–50 and 51–100 mm in diameter. Substrate ranges 251–300 and 301–350 mm had one observation each with densities of 7 and 10 crayfish·m^{-2} (Figure 34).

Crayfish densities increased with unconsolidated substrate depth. Crayfish were rarely observed in unconsolidated substrate depths less than 5 cm—the average density was 0.02 crayfish·m^{-2}. In unconsolidated substrate 5–10 cm in depth, an average density of 2.06 crayfish·m^{-2} was found. Unconsolidated substrate greater than 10 cm in depth had an average density of 9.31 crayfish·m^{-2} (Figure 35).

Crayfish densities declined in substrate embedded more than 50 percent. Substrate 0–25 and 25–50 percent embedded had an average density of 4.96 and 5.67 crayfish·m^{-2}. Substrates 50–75 percent embedded had 0.5 crayfish·m^{-2}, and no crayfish were observed in substrate more than 75 percent embedded (Figure 36).

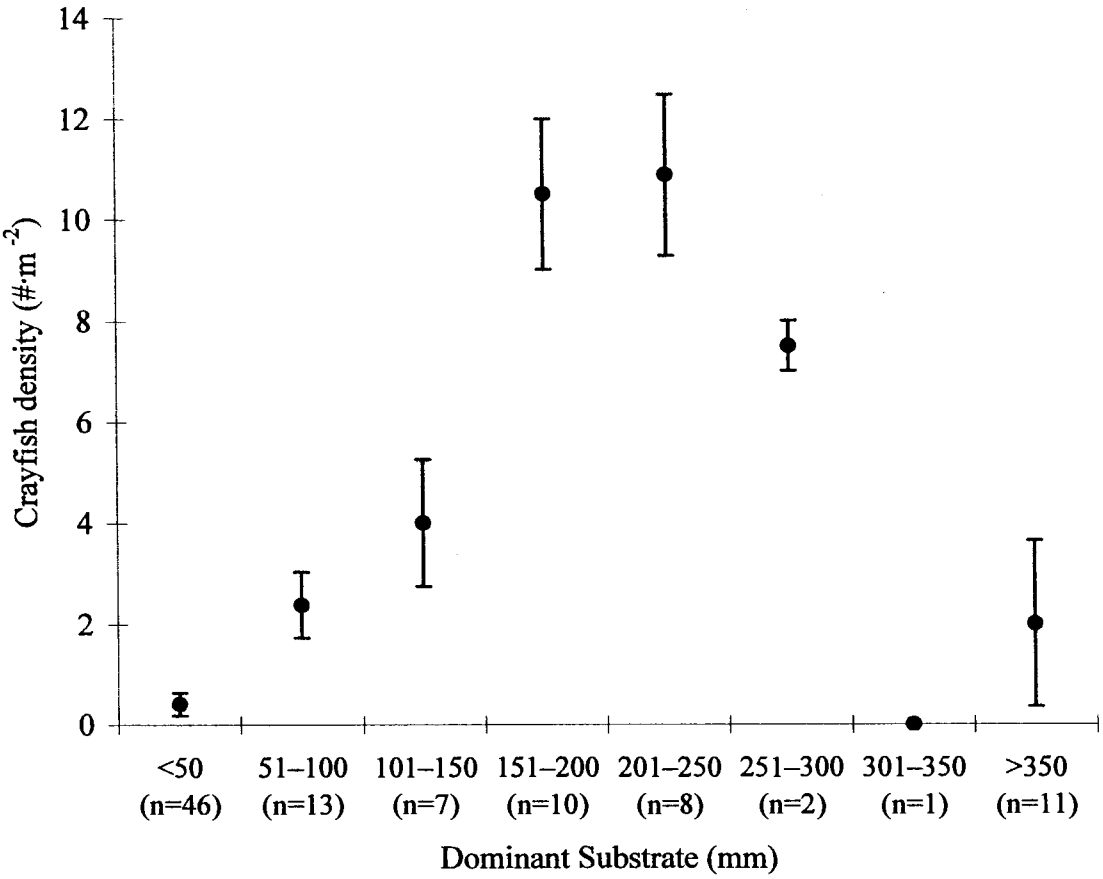

Figure 33. Average crayfish densities ± 1 S.E. for dominant substrate. For substrate 301–350 mm, the S.E. was less than the distance of the point.

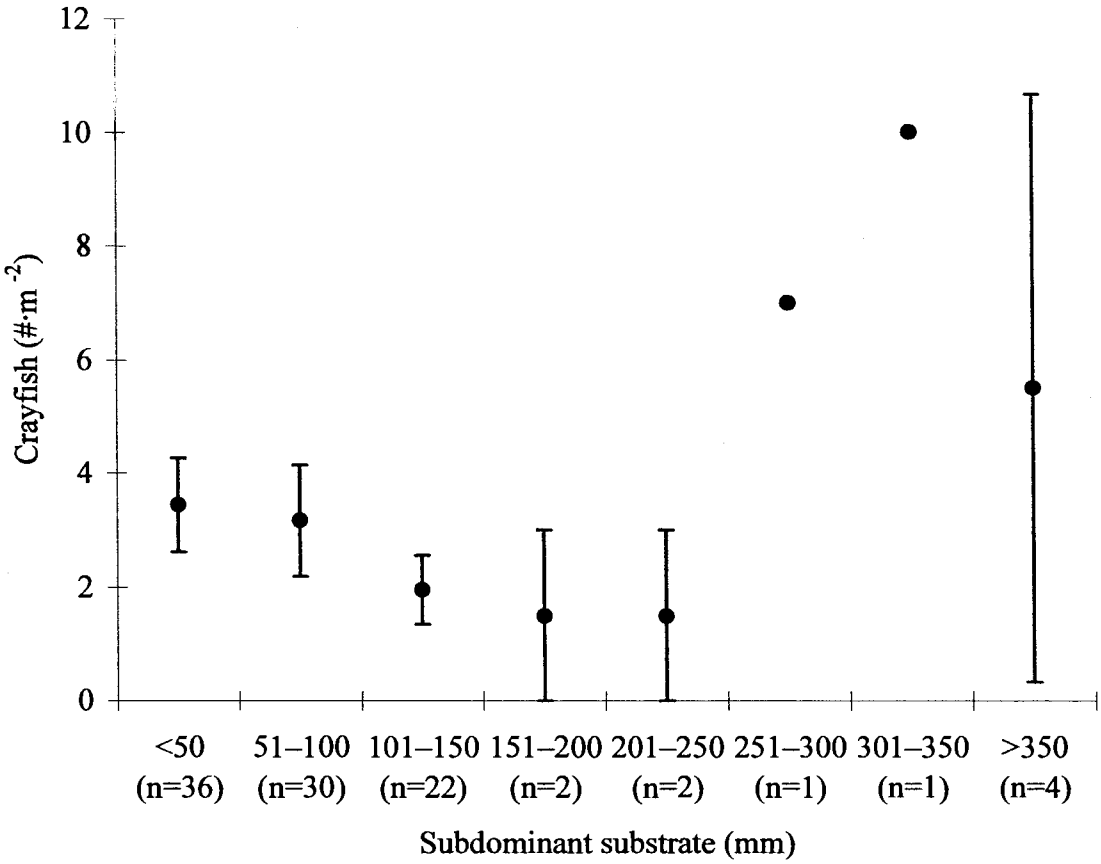

Figure 34. Average crayfish densities ± 1 S.E. for subdominant substrate. For substrate 251–300 and 301–350 mm, the S.E. was less than the distance of the point.

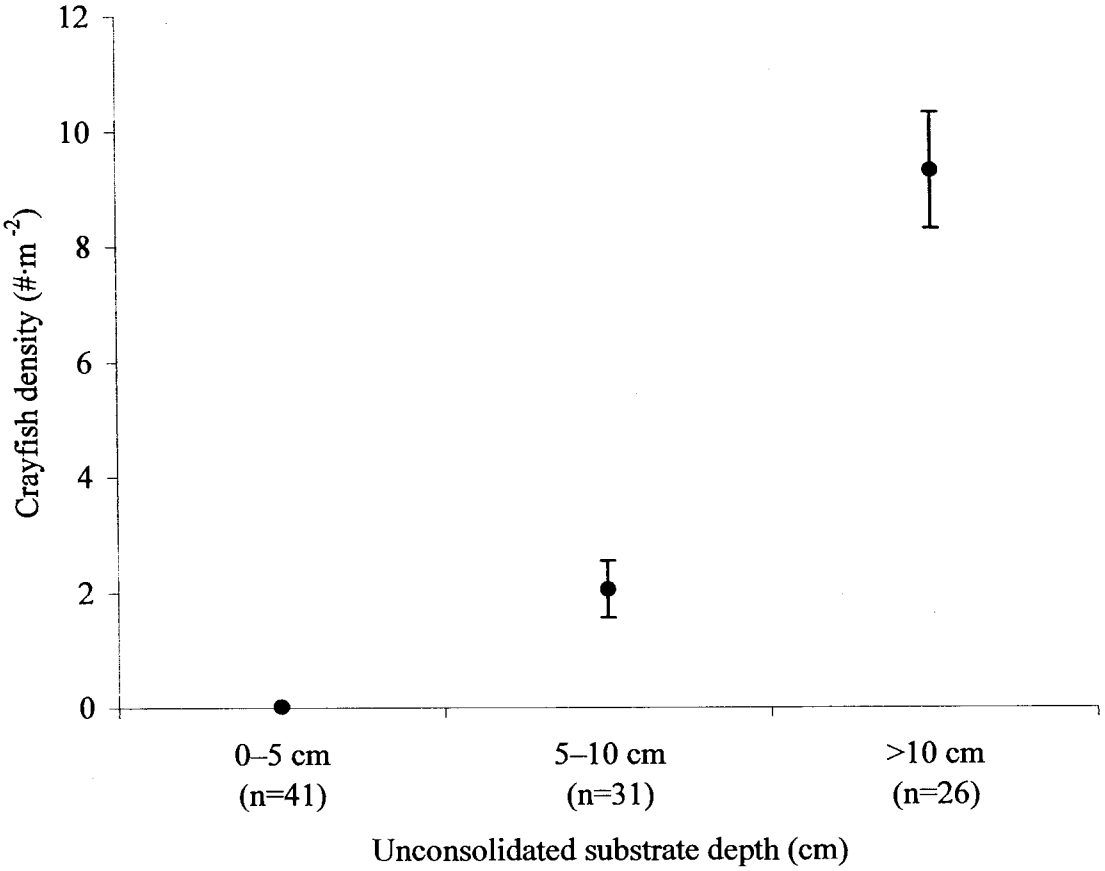

Figure 35. Average crayfish densities ± 1 S.E. for unconsolidated substrate depth. For unconsolidated substrate 0–5 cm in depth, the S.E. was less than the distance of the point.

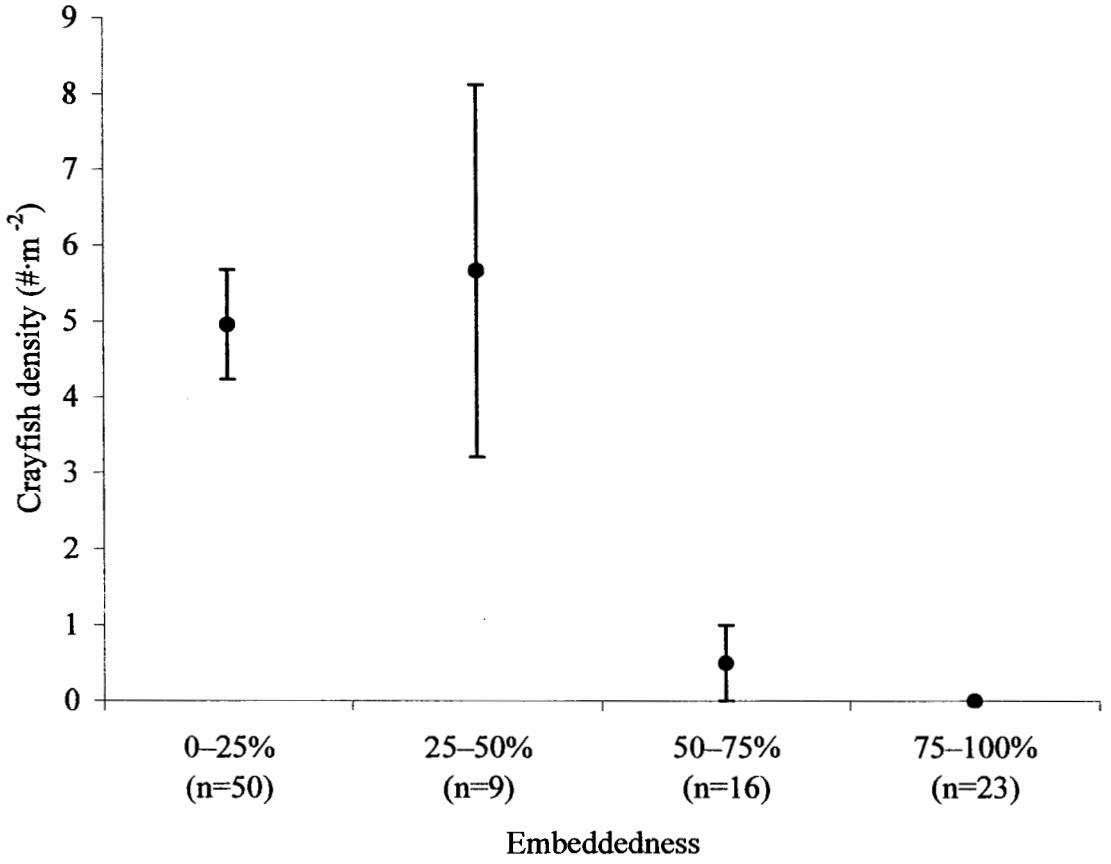

Figure 36. Average crayfish densities ± 1 S.E. for embeddedness. For substrate embedded 75–100 percent, the S.E. was less than the distance of the point.

The highest crayfish densities were observed in the absence of aquatic vegetation. No crayfish were observed in medium and dense aquatic vegetation. In sparse vegetation, 0.75 crayfish·m^{-2} were observed. Crayfish densities averaged 3.68 crayfish·m^{-2} in areas without aquatic vegetation (Figure 37).

Shoreline areas with groundwater seepage had a higher average density than shoreline areas without groundwater seepage. Densities in shoreline areas with seepages averaged 4.19 crayfish·m^{-2} while areas without seepages averaged 2.75 crayfish·m^{-2} (Figure 38).

For the three current velocity categories of 0–0.1, 0.1–0.3, and greater than 0.3 m·s^{-1}, crayfish densities were highest in current velocities between 0.1–0.3 m·s^{-1} with 7.75 crayfish·m^{-2}. Crayfish densities in current velocities greater than 0.3 m·s^{-1} were half (3.68 crayfish·m^{-2}) that found in current velocities between 0.1–0.3 m·s^{-1}. An average density of 1.7 crayfish·m^{-2} were observed in current velocities less than 0.1 m·s^{-1} (Figure 39).

The SAS PROC GLM result for the model composed of the 7 categorical habitat variables was significant ($p<0.0001$) in explaining a large portion of the variation ($R^2=0.79$) observed in crayfish densities (Table 26). Groundwater seepage ($p=0.0008$), dominant substrate ($p=0.0009$) and unconsolidated substrate depth ($p=0.0056$) were significant in explaining crayfish densities. Subdominant substrate, embeddedness, aquatic vegetation, and current velocity were not significant in explaining crayfish densities (Table 27).

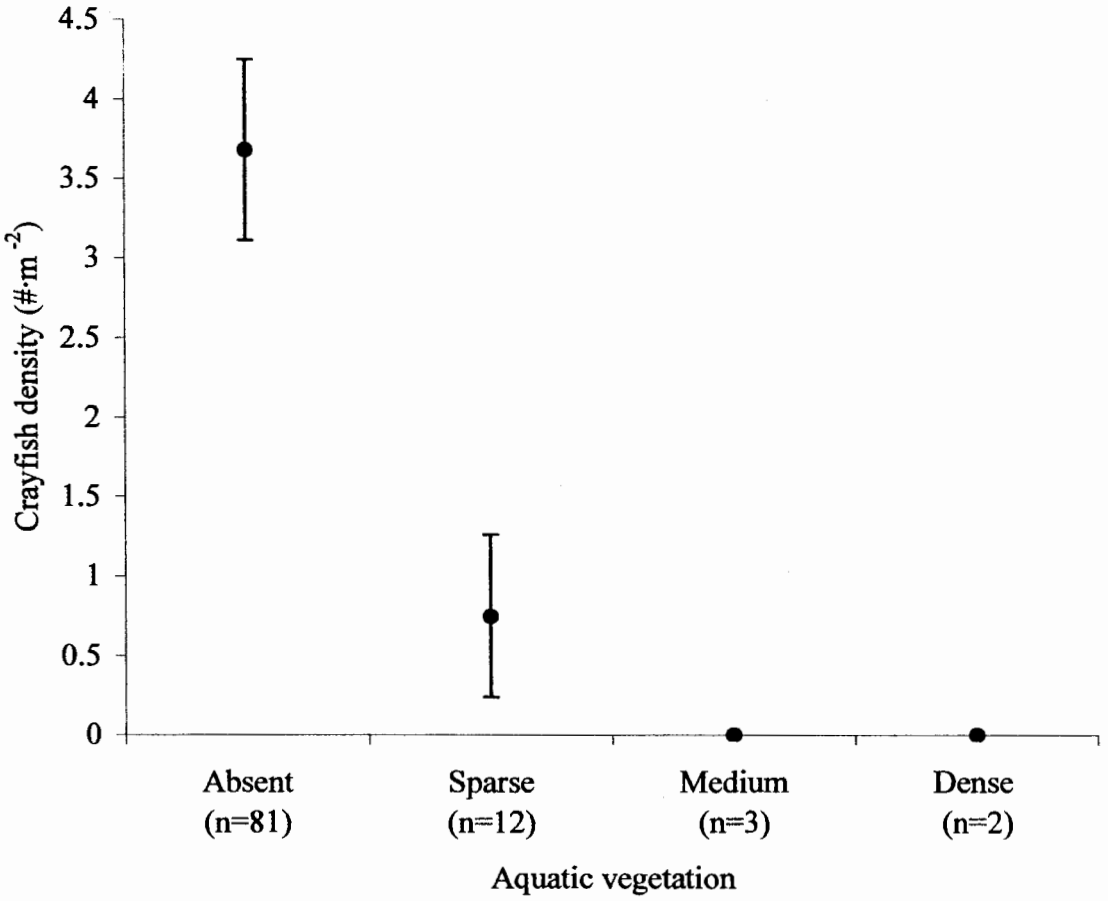

Figure 37. Average crayfish densities ± 1 S.E. for aquatic vegetation. For medium and dense aquatic vegetation, the S.E. was less than the distance of the point.

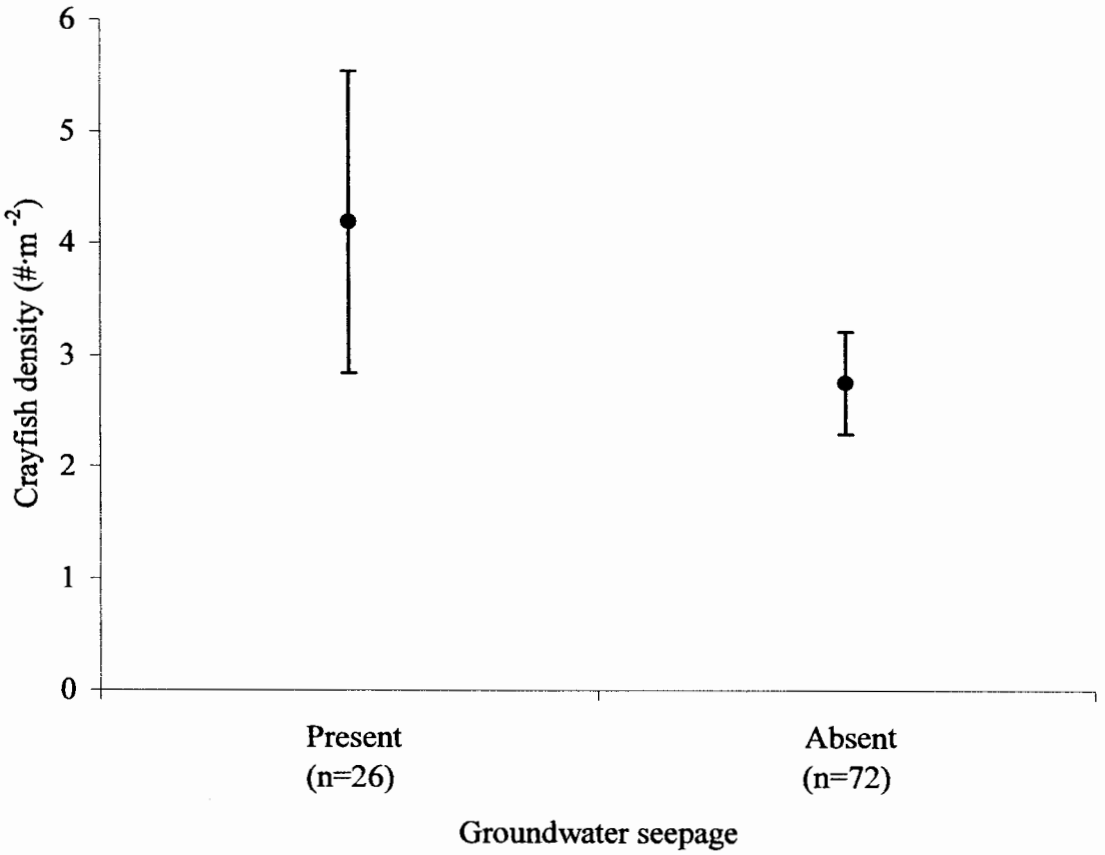

Figure 38. Average crayfish densities ± 1 S.E. for groundwater seepage.

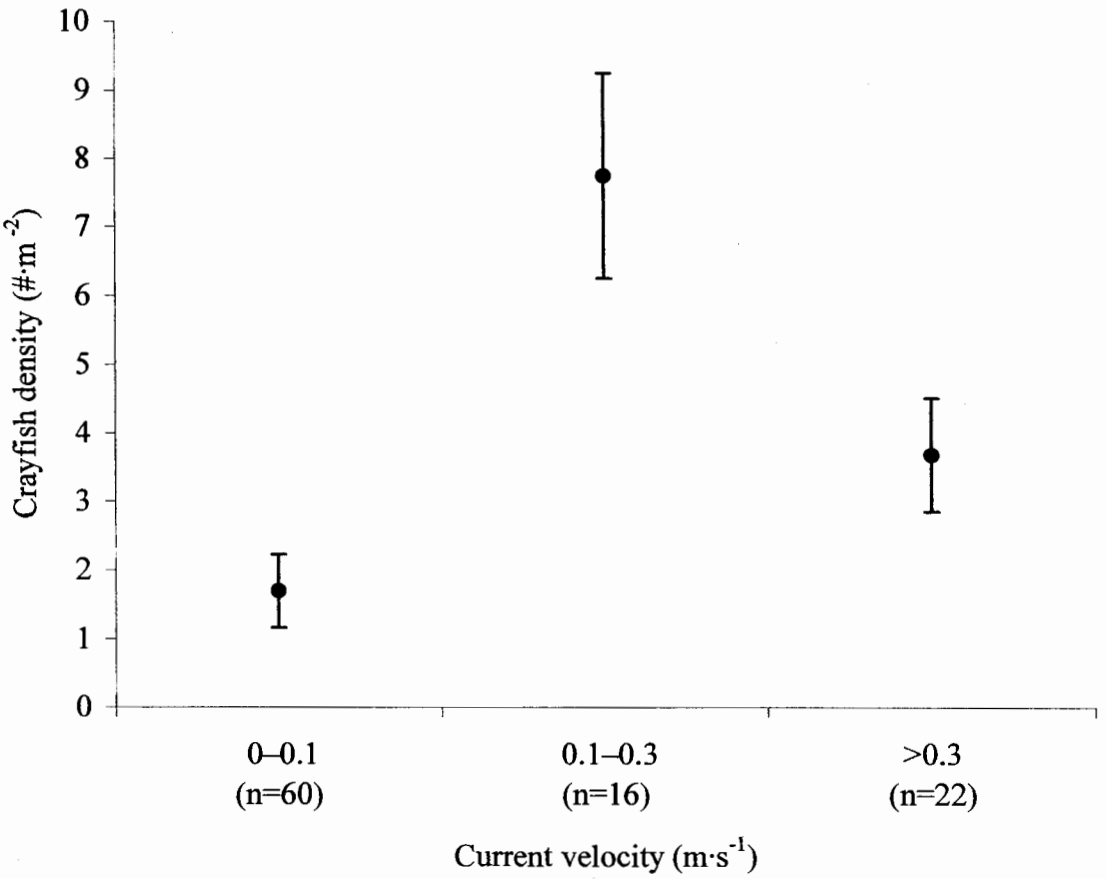

Figure 39. Average crayfish densities ± 1 S.E. for current velocity.

Table 26. The SAS PROC GLM results for crayfish density for the recorded habitat variables in the Hanford Reach, Columbia River.

Source	d.f.	Sum of squares	Mean square	F value	Pr > F
Model	25	1845.07	73.8028	11.25	<0.0001
Error	72	472.206	6.55842		
Corrected Total	97	2317.28			

Table 27. The SAS PROC GLM results for habitat variable significance in relation to crayfish density. Significant difference denoted by bold type.

Source	d.f.	Type III sum of squares	Mean square	F value	Pr > F
Dominant substrate	7	184.931	26.4188	4.03	**0.0009**
Subdominant substrate	7	31.2539	4.46485	0.68	0.6877
Unconsolidated substrate depth	2	73.1596	36.5798	5.58	**0.0056**
Embeddedness	3	3.92759	1.3092	0.2	0.8963
Aquatic vegetation	3	29.4014	9.80047	1.49	0.2234
Current velocity	2	23.417	11.7085	1.79	0.1751
Groundwater seepage	1	79.5458	79.5458	12.13	**0.0008**

3.4.3 Sculpin

Sculpin density variations were presented for the habitat variables of dominant substrate, subdominant substrate, unconsolidated substrate depth, embeddedness, aquatic vegetation, groundwater seepage and current velocity. Sculpin densities increased nearly 30 fold from substrates less than 50 mm to substrate 251–300 mm. In substrates less than 50 mm, sculpin density was 0.1 sculpin·m^{-2} whereas in substrates 251–300 mm sculpin density was 2.5 sculpin·m^{-2}. No sculpin were observed in substrates greater than 301 mm (Figure 40).

Sculpin densities in subdominant substrate were highly variable. Substrate less than 50, 51–100 and 101–150 mm had densities between 0.3–0.6 sculpin·m^{-2}. Low sample sizes were present in substrate greater than 150 mm, and mean densities were either zero or 1 sculpin·m^{-2} (Figure 41).

As unconsolidated substrate depth increased, the average densities of sculpin increased. For substrate depths less than 5 cm, about 1 sculpin was observed every 40 m^2 whereas unconsolidated substrate with depths greater than 10 cm had sculpin densities of 1.12 sculpin·m^{-2} (Figure 42).

As substrate embeddedness increased, sculpin densities decreased. Substrate less than 25 percent embedded had sculpin densities of 0.72 sculpins·m^{-2}, but no sculpin were observed in substrates more than 75 percent embedded (Figure 43).

If aquatic vegetation was present, regardless if aquatic vegetation was present as only a few plants or as a dense patch, no sculpin were observed. Only observations without aquatic vegetation had sculpin observed, and sculpin densities were 0.53 sculpin·m^{-2} (Figure 44).

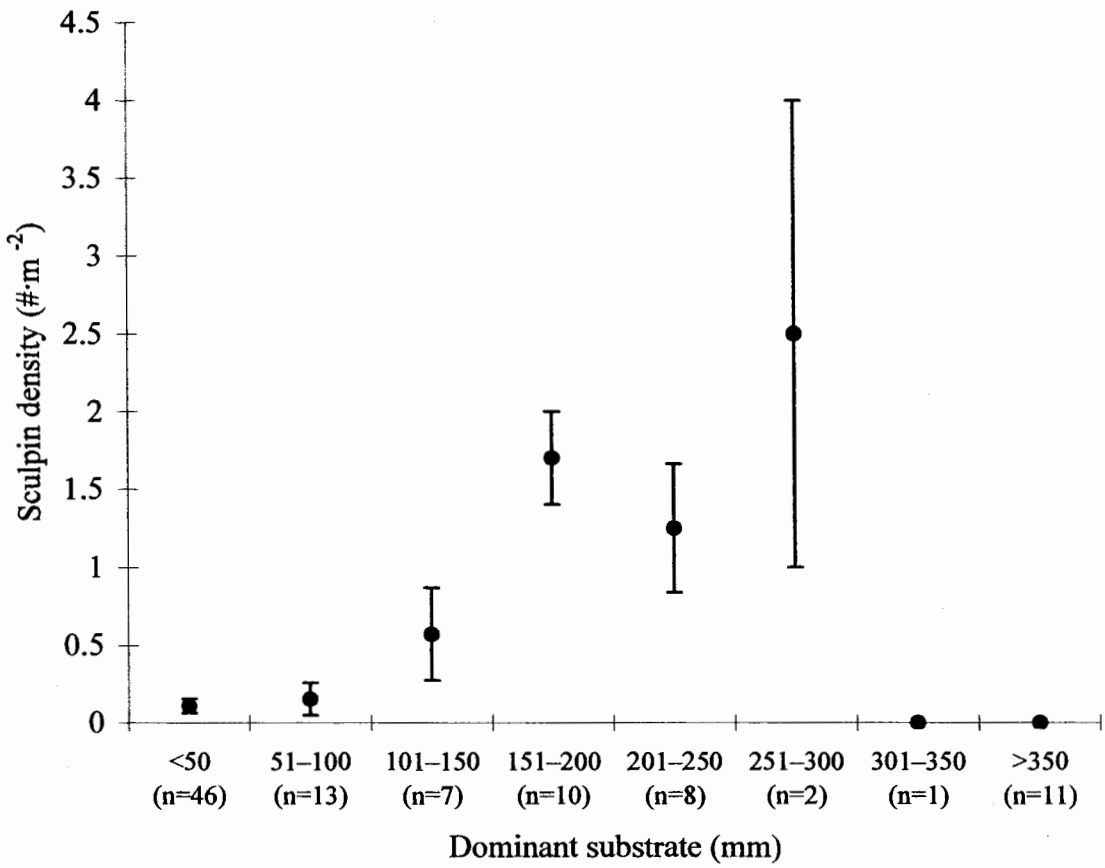

Figure 40. Average sculpin densities ± 1 S.E. for dominant substrate. For substrates 301–350 and >350 mm, the S.E. was less than the distance of the points.

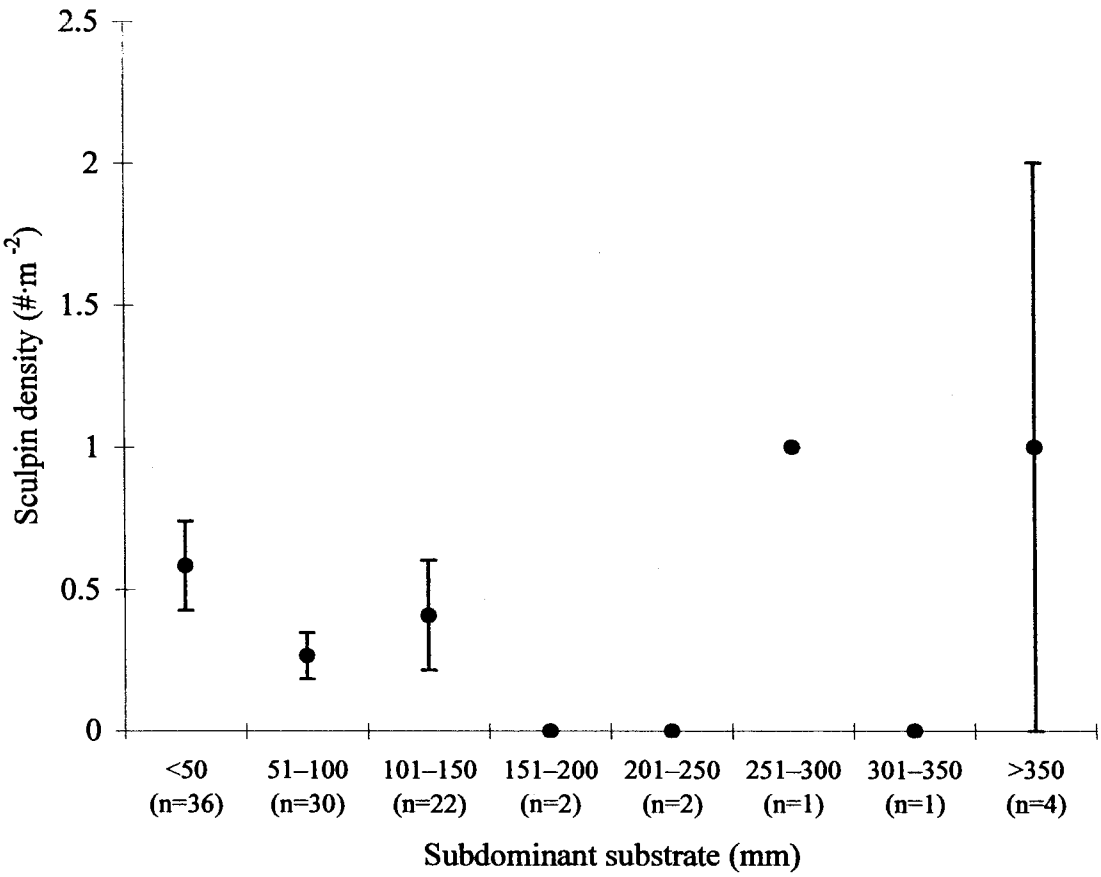

Figure 41. Average sculpin densities ± 1 S.E. for subdominant substrate. For substrates 151-200, 201–250, 251–300 and 301–350 mm, the S.E. was less than the distance of the point.

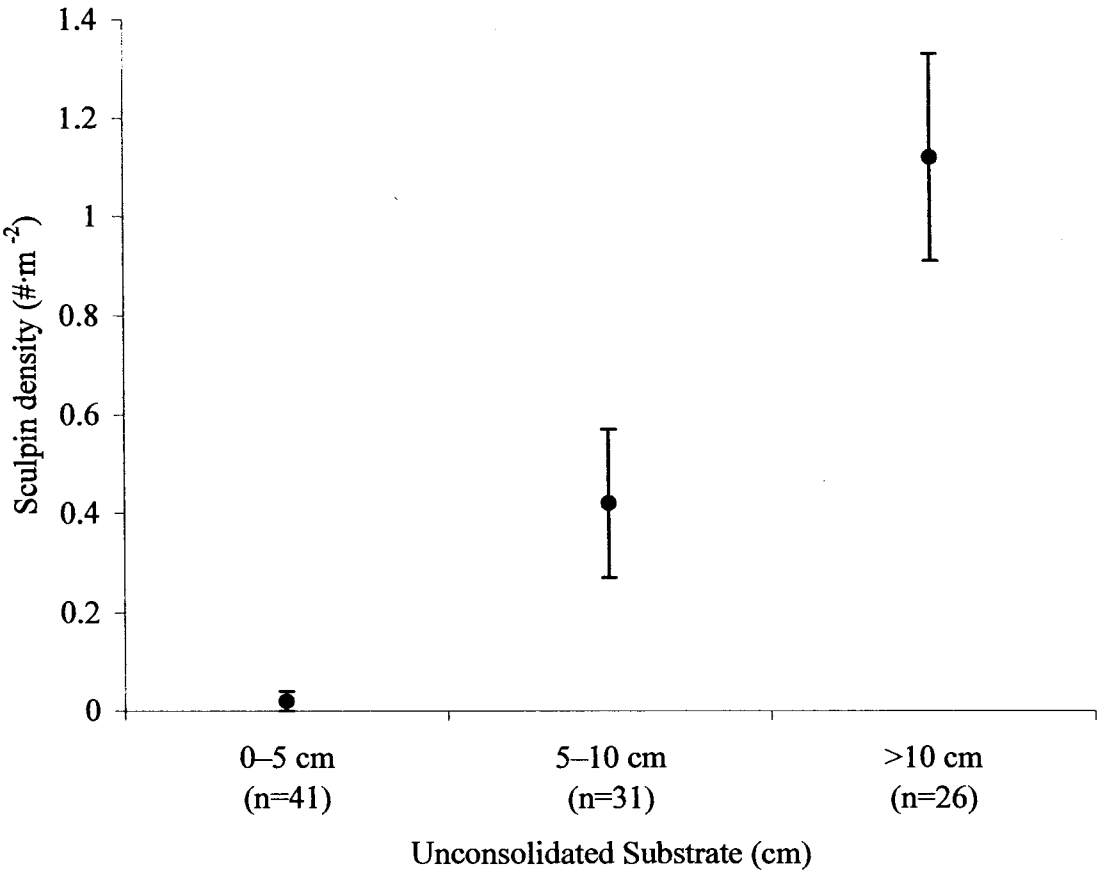

Figure 42. Average sculpin densities ± 1 S.E. for unconsolidated substrate depth. For unconsolidated substrate 0–5 cm in depth, the S.E. was less than the distance of the point.

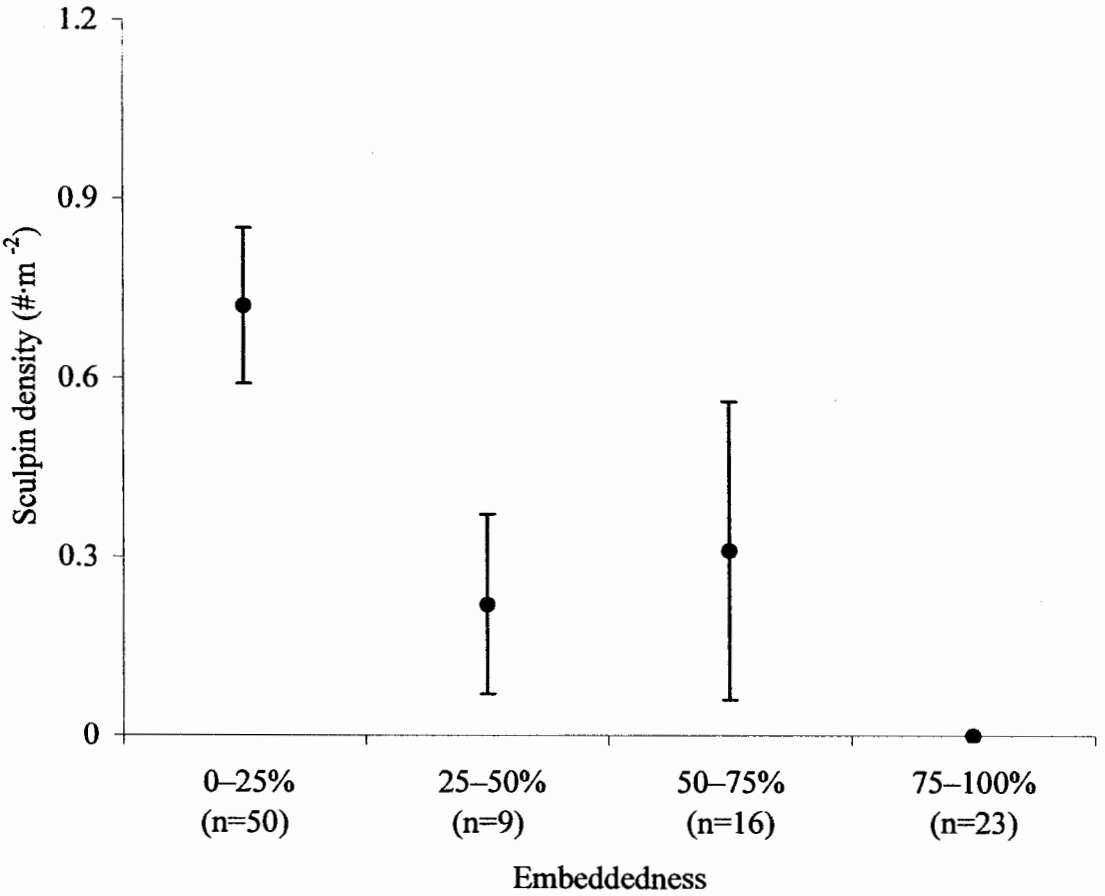

Figure 43. Average sculpin densities ± 1 S.E. for embeddedness. For substrate embedded 75–100 percent, the S.E. was less than the distance of the point.

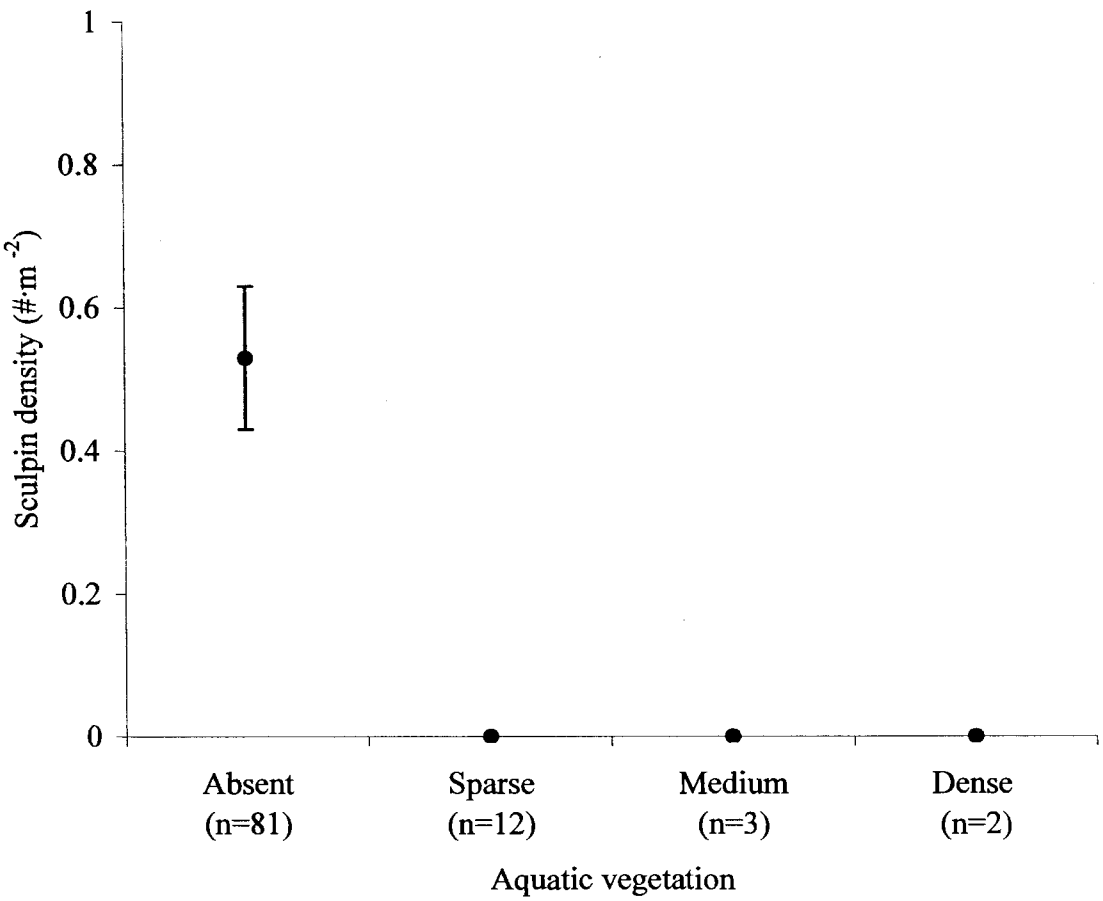

Figure 44. Average sculpin densities ± 1 S.E. for aquatic vegetation. For sparse, medium and dense aquatic vegetation, the S.E. was less than the distance of the point.

Sculpin densities showed little difference between shoreline areas with and without groundwater seepage, but the average density was slightly higher for shorelines with groundwater seepage when no other variables were included (Figure 45).

Current velocities greater than 0.1 $m \cdot s^{-1}$ had the highest average sculpin density. In current velocities less than 0.1 $m \cdot s^{-1}$, sculpin densities were 0.15 $sculpin \cdot m^{-2}$. Sculpin densities in current velocities 0.1–0.3 and greater than 0.3 $m \cdot s^{-1}$ were 1 and 0.82 $sculpin \cdot m^{-2}$, respectively (Figure 46).

The SAS PROC GLM result for the model composed of the 7 categorical habitat variables was significant ($p<0.0001$) in explaining a large portion of the variation ($R^2=0.74$) observed in sculpin densities (Table 28). Dominant substrate was the most significant factor affecting sculpin density ($p<0.0001$). Embeddedness ($p=0.0075$), groundwater seepage ($p=0.0366$), and current velocity ($p=0.0445$) were also significant in explaining sculpin densities. Unconsolidated substrate depth, subdominant substrate and aquatic vegetation were not significant factors for sculpin densities (Table 29).

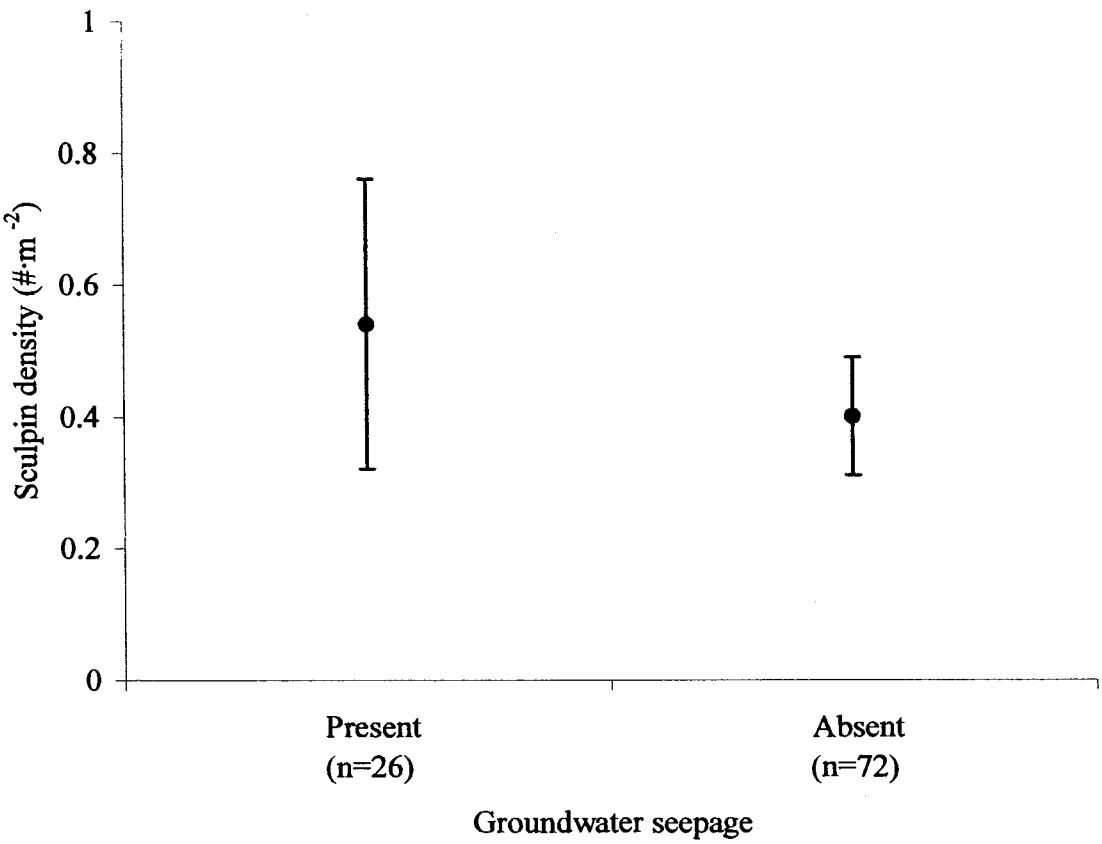

Figure 45. Average sculpin densities ± 1 S.E. for groundwater seepage.

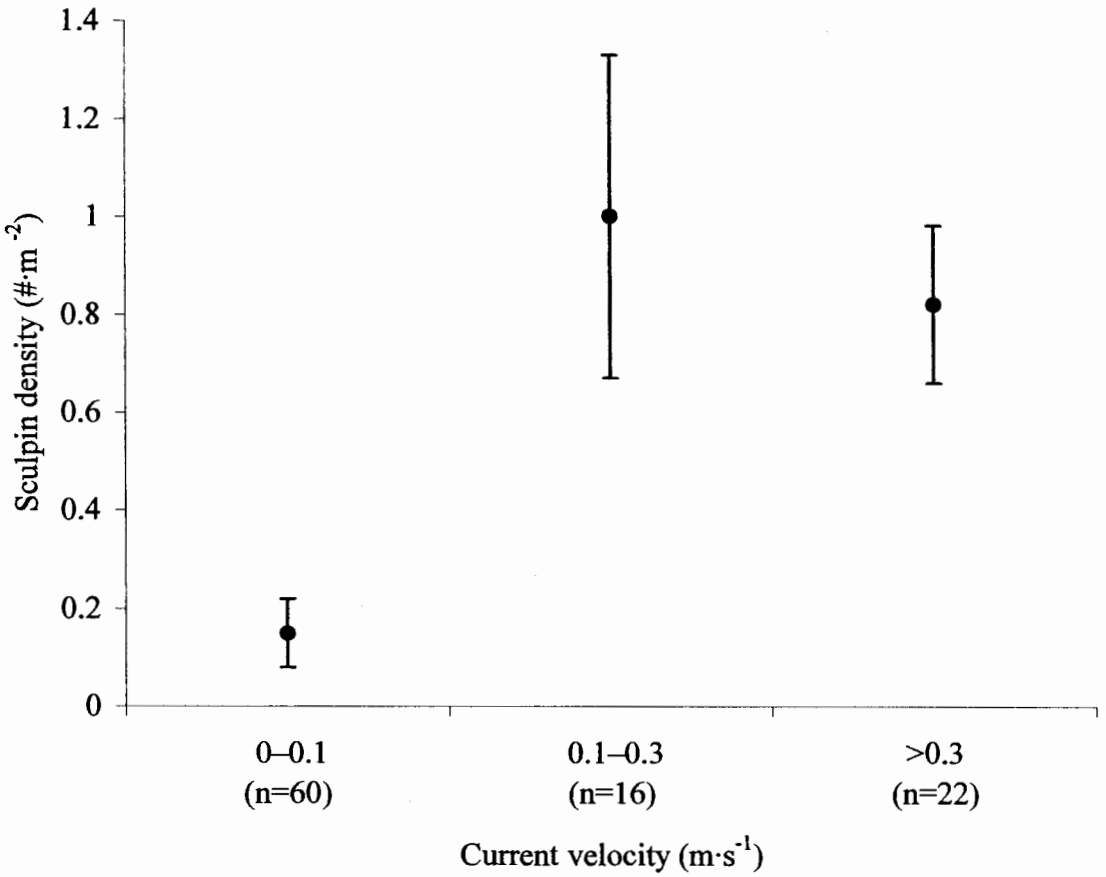

Figure 46. Average sculpin densities ± 1 S.E. for current velocity.

Table 28. The SAS PROC GLM results for sculpin density for the recorded habitat variables in the Hanford Reach, Columbia River.

Source	d.f.	Sum of squares	Mean square	F value	Pr > F
Model	25	51.7249	2.069	8.09	<0.0001
Error	72	18.4077	0.25566		
Corrected Total	97	70.1327			

Table 29. The SAS PROC GLM results for habitat variable significance in relation to sculpin density. Significant difference denoted by bold type.

Source	d.f.	Type III sum of squares	Mean square	F value	Pr > F
Dominant substrate	7	20.1161	2.87373	11.24	**<0.0001**
Subdominant substrate	7	3.01182	0.43026	1.68	0.1268
Unconsolidated substrate depth	2	1.45127	0.72564	2.84	0.0651
Embeddedness	3	3.30266	1.10089	4.31	**0.0075**
Aquatic vegetation	3	0.16526	0.05509	0.22	0.8854
Current velocity	2	1.662	0.831	3.25	**0.0445**
Groundwater seepage	1	1.15977	1.15977	4.54	**0.0366**

3.5 Species physical measurements

3.5.1 Asiatic clams

A total of 1,068 clams out of 3,090 collected had both shell height and shell weight recorded. The shell height-wet weight regression equation was: shell weight (g)=0.0012(shell height in mm)$^{2.7306}$ (Figure 47).

3.5.2 Crayfish

A total of 71 crayfish were obtained for physical measurements and sex determination. Forty-four crayfish had both carapace length and weight recorded. The weight-carapace length regression equation was weight(g)=0.0009(carapace length in mm)$^{2.7731}$ (Figure 48). Of the seventy-one crayfish obtained, 29 were male, 26 were female, and 16 were identified as juveniles. Female to male sex ratios were 1:1.12 (Figure 49).

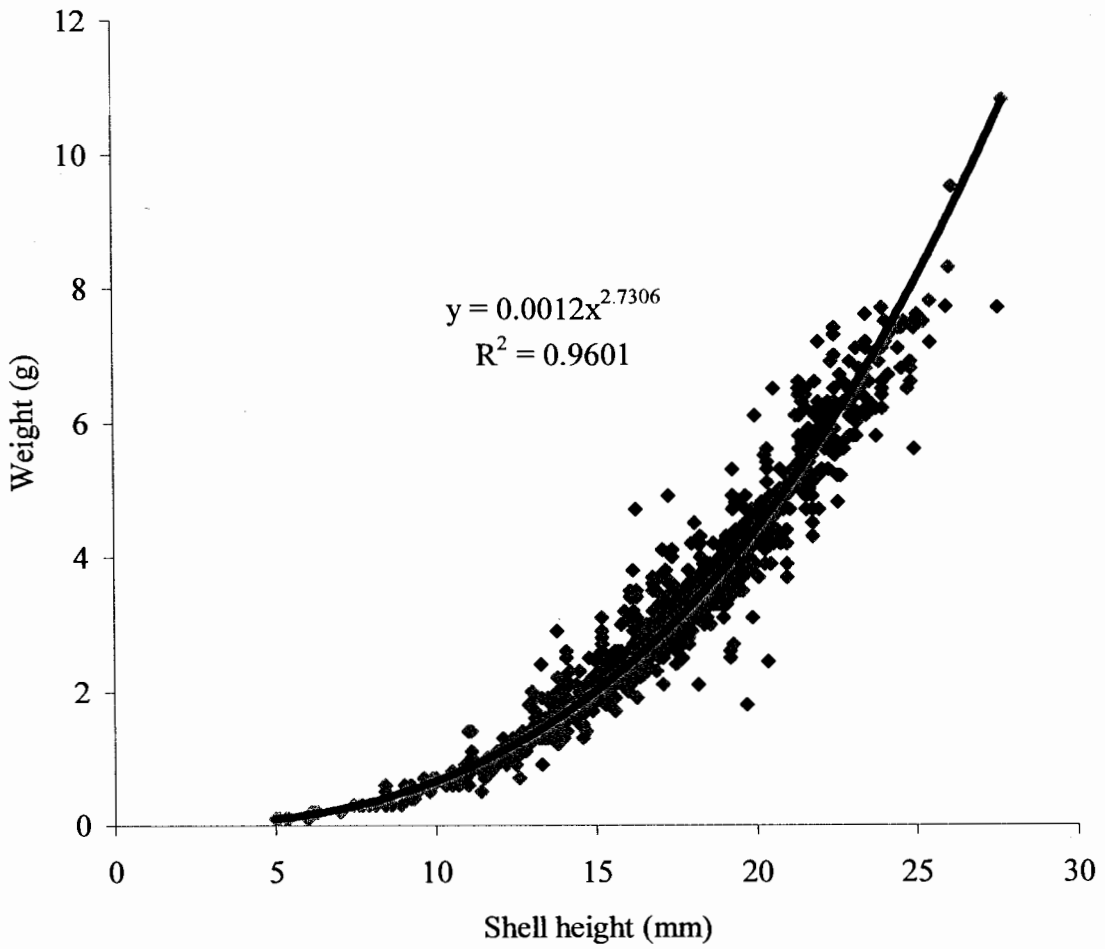

Figure 47. Asiatic clam shell height (0.1 mm) and wet weight (0.1 g) regression and R^2-value for 2002 collections (n=1068).

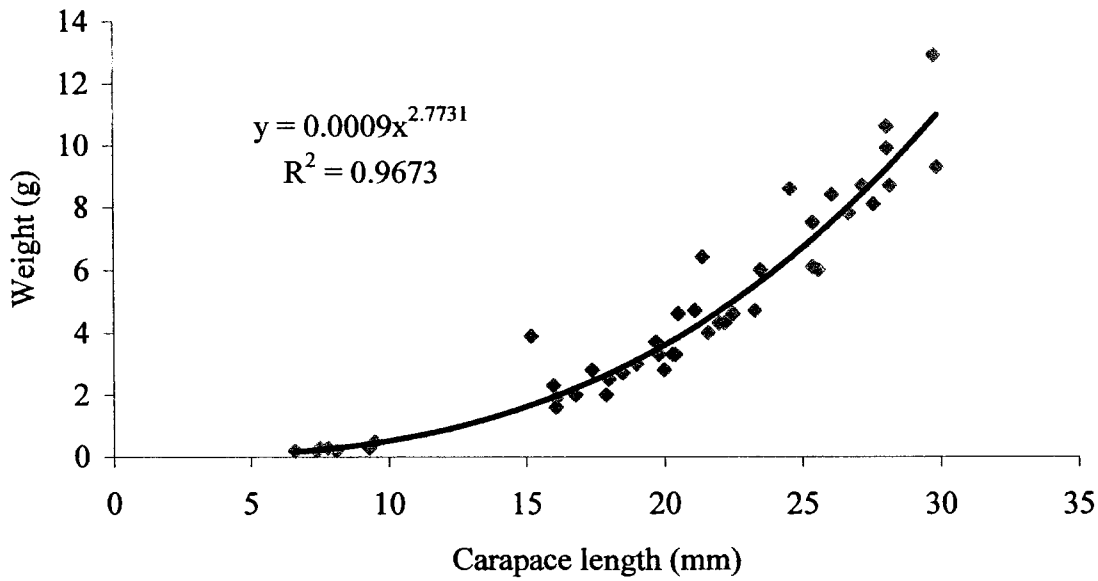

Figure 48. Crayfish carapace length and weight regression equation and R^2-value (n=44).

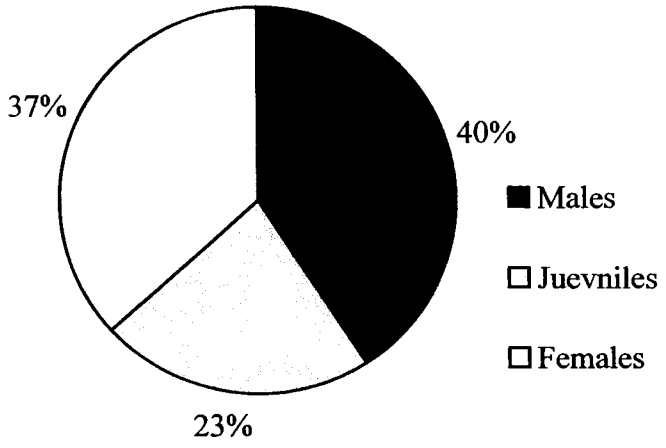

Figure 49. Crayfish male, female and juvenile proportions observed in 2002 (n=71).

4.0 Discussion

The shoreline environment of the Hanford Reach of the Columbia River has been altered over the last 60 years by the construction of large storage dams in the main stem Columbia River and tributaries in the United States and Canada. Water flows were regulated daily by power generation at upriver hydroelectric dams. The altered habitat has promoted the permanent established of exotic species of fish, e.g., carp (*Cyprinus carpio*), walleye (*Stizostedion vitreum*), smallmouth bass (*Micropterus dolomieui*), and the introduction of the Asiatic clam.

In addition, many contaminants now enter or are present in the Hanford Reach, Columbia River. Pesticides, herbicides and fertilizers from farmlands, municipal wastes from upstream towns and cities, as well as wastes from papers mills and smelters are released into the river and its tributaries. Fifty years of contaminants associated with plutonium production and related operations on the Hanford site now enter the Hanford Reach through contaminated groundwater (McCormack and Carlile 1984).

Historically, the annual discharge of the Columbia River was marked by a massive spring flood followed by gradual decreasing flows in late summer and autumn (Figure 50). As the river receded, cobblestone beaches dried out as they were exposed to air and sunlight. Unlike most rivers, the shoreline vegetation was essentially clear of trees. Instead, the plant communities of the exposed beaches were dominated by shoreline shrubs, such as sandbar willow (*Salix exigua*), low-growing herbs [e.g., wire grass (*Eleocharis* sp.)] and showy-flowered forbs (e.g., *Coreopsis atkinsonia, Aster Hesperus, Gaillardia aristata, Allium schoenoprasum*) (Rickard and Gray 1995).

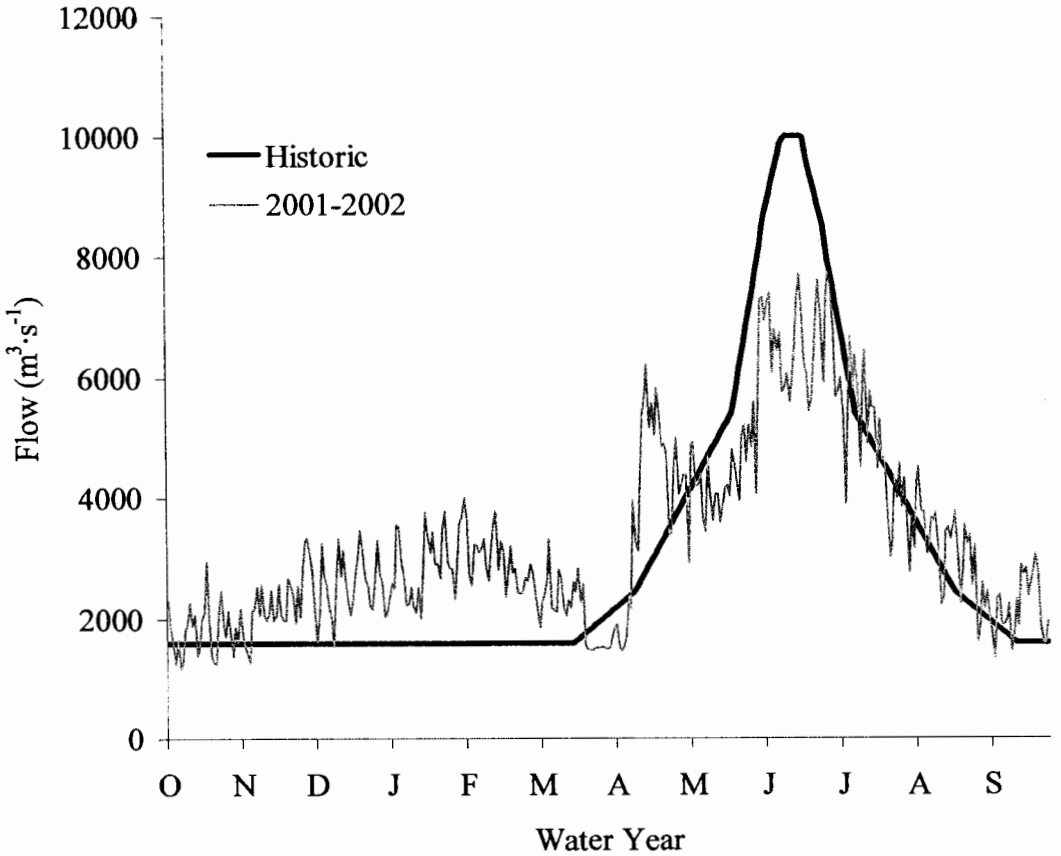

Figure 50. A depiction of hypothetical historic flows and regulated river flows from water year 2001–2002 (October through September) in the Hanford Reach, Columbia River. Daily flows of were from Priest Rapids Dam (Columbia River Dart 2002). Historic flows were depicted from FCRPS 2001.

A similar trend in river flows throughout the water year still occurs today, but the gradual flow reductions witnessed historically no longer occur. A series of hydroelectric dams stores large volumes of water that are released during power demands. The variability in such regulated flows was observed in daily flows from October 2001–September 2002 (Figure 50). Superimposed on the annual flow fluctuations were daily fluctuations that resulted in daily changes in surface elevation of up to four meters in the river channel below Priest Rapids Dam (Figure 51). Due to the variable flows, the historic Columbia River moving littoral zone, which is the most productive part of river a system (Horne and Goldman 1994), did not exist in the Hanford Reach. Repeated episodes of dewatering prevented primary and secondary aquatic production in the near-shore areas of the Hanford Reach and other regulated rivers (Kroger 1973; Blinn et al. 1995; Benenati 1998; Stark 2001). Thus, aquatic primary and secondary productivity was located primarily below the low-water level where periphyton and aquatic invertebrates persisted.

As a result of the hydraulic operations from a series of upriver hydroelectric dams, the Hanford Reach shoreline was marked by three distinct zones of vascular vegetation, non-vegetated substrates and periphyton. The occurrence of vascular vegetation declined as the shoreline was submerged for greater amounts of time. Vascular vegetation was observed in more than half the observations in shoreline areas above the 1,970 $m^3 \cdot s^{-1}$ flow level, which was covered with water less than 80 percent of the time. Non-vegetated substrate was present in shoreline areas submerged 80–95 percent of the time (between flow levels of 1,353–1,970 $m^3 \cdot s^{-1}$). Persistent periphyton was restricted to shoreline areas submerged more than 95 percent of the time.

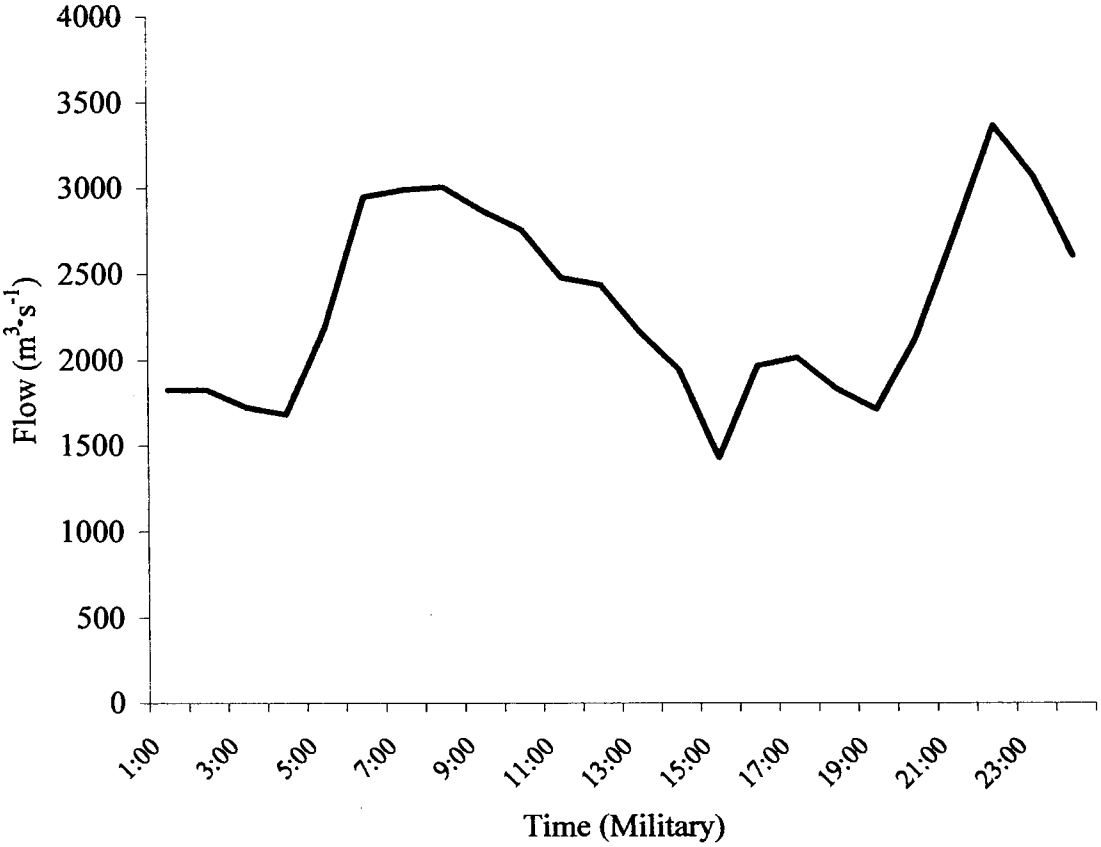

Figure 51. Hourly flows released from Priest Rapids Dam on September 17, 2002 (USACENWD 2002).

The distribution of Asiatic clams, crayfish and sculpin were related to the percentage of time the shoreline was submerged on an annual basis and the three shoreline zones of vascular vegetation, non-vegetated substrate and periphyton. The presence of Asiatic clams was greatest at shoreline areas submerged more than 80 percent of time. No clams were found in shoreline areas that were submerged less than 50 percent of the time (shoreline areas submerged by flows greater than 3,463 $m^3 \cdot s^{-1}$).

Clams were found in all three of the shoreline zones, but the percentage of clams in each size class were not uniform for the three shoreline zones. Clams 11–22 mm in shell length were the most frequently observed clam in all three shoreline zones. Clams 5–11 mm in shell length were seldom found in the shoreline zones of periphyton and non-vegetated substrate. For the shoreline zones of periphyton and non-vegetated substrate, clams 5–11 mm in shell length were one and two percent of the total clams observed. However, in the vascular vegetation zone, clams 5–11 mm in shell length were 41 percent of the total clams observed. Clams greater than 22 mm in shell length were most abundant in the periphyton zone.

Factors found to affect Asiatic clam densities were dominant substrate, subdominant substrate, embeddedness and current velocity. In dominant substrate, the highest densities of Asiatic clams were in substrates 51–200 mm where the average density was 503 clams$\cdot m^{-2}$ and ranged from 5–1,835 clams$\cdot m^{-2}$. Substrates larger than 300 mm averaged 71 clams$\cdot m^{-2}$ and ranged from 0–295 clams$\cdot m^{-2}$.

Subdominant substrate was identified as a factor affecting the clam density. For all subdominant substrate groups except substrate 251–300 and 301–350 mm, clam densities were between 227 and 410 clams m^{-2}. Subdominant substrate classes of 251–

300 and 301–350 mm were each represented with one observation with densities of 1,835 and 825 clams·m^{-2}.

Asiatic clams densities were highest in areas with current velocities 0.1–0.3 m·s^{-1} with an average of 710 clams·m^{-2} and ranged from 295–1,835 clams·m^{-2}. The lowest densities occurred in current velocities less than 0.1 m·s^{-1} (142 clams·m^{-2}). Clam densities averaged 427 clams·m^{-2} in current velocities greater than 0.3 m·s^{-1}.

On the average, clam densities decreased when substrate embeddedness became greater than 50 percent. Densities in substrate 0–50 percent embedded averaged 388 clams·m^{-2} and ranged from 0–1,835 clams·m^{-2}. Substrate embedded 50–75 percent had an average density of 268 clams·m^{-2}. Substrate embedded more than 75 percent had an average density of than 76 clams·m^{-2} and ranged from 0–190 clams·m^{-2}.

Crayfish were predominantly found in shoreline areas submerged with water 85 percent of the time. At shoreline depths with periphyton, crayfish were found in 81 percent of the observations. While crayfish were found in non-vegetated substrate, crayfish were only found in 33 percent of the observations. No crayfish were found in vascular vegetation.

Factors found to affect crayfish densities were dominant substrate, unconsolidated substrate depth and groundwater seepage. An average crayfish density of 10.7 crayfish·m^{-2} were observed in dominant substrate 151–250 mm with a range of 6–23 crayfish·m^{-2}. As substrate became either larger or smaller, densities declined. Crayfish densities increased as unconsolidated substrate depth increased. Only one crayfish was found in 41 observations with unconsolidated substrate less than 5 cm in depth. Unconsolidated substrate 5–10 cm in depth had an average density of 2.06 crayfish·m^{-2}

and ranged from 0–10 crayfish·m^{-2}. Unconsolidated substrate greater than 10 cm averaged 9.31 crayfish·m^{-2} and ranged from 1–23 crayfish·m^{-2}. Given similar habitat, higher crayfish densities were observed in the presence of groundwater seepage.

Sculpin distributions did not differ between the established percentages of time the shoreline was submerged , but sculpin distributions differed between the shoreline zones of vascular vegetation, non-vegetated substrate and periphyton. Sculpin were found more frequently at shoreline depths with periphyton than in vascular vegetation. Only eight percent of the observations in vascular vegetation had sculpin observed; whereas sculpin were found in 33 percent of the observations in periphyton.

Habitat factors found to affect the densities of sculpin were dominant substrate, embeddedness, current velocity, and groundwater seepage. Sculpin densities increased as substrate classes increased from less than 50 mm to 251–300 mm. Dominant substrate 251–300 mm averaged 2.5 sculpins·m^{-2} and ranged from 1–4 sculpin·m^{-2}. No sculpin were found in dominant substrate greater than 300 mm. Substrate embedded less than 25 percent had the highest sculpin densities with an average density of 0.72 sculpins·m^{-2} and ranged from 0–4 sculpin·m^{-2}. No sculpin were found in substrate embedded more than 75 percent. Sculpin densities were highest in current velocities greater than 0.1 m·s^{-1} where the density averaged 0.9 scuplin·m^{-2} and ranged from 0–4 sculpin·m^{-2}. Velocities less than 0.1 m·s^{-1} had the lowest average density with 0.15 sculpin·m^{-2}. In velocities less than 0.1 m·s^{-1}, only one of the 60 observations possessed a sculpin, and 4 sculpin were found in that one observation, which was influenced by the presence of groundwater seepage. Given similar habitat, higher sculpin densities were found in the presence of groundwater seepage.

4.1 Distributions of vascular vegetation, non-vegetated substrate and periphyton

The Hanford Reach shoreline was broken into the three shoreline zones of vascular vegetation, non-vegetated substrate and periphyton. This shoreline pattern could be attributed to a combination of frequent watering and dewatering episodes that inhibited periphyton and vascular vegetation establishment in the band of bare substrate. The vascular plant communities in the Hanford Reach were found to change as the amount of shoreline submergence increased. Reed canarygrass (*Phalaris arundinacea*) occurred where substrate was occasionally wetted. As the shoreline extended further into the river, transitions from common spikerush (*Eleocharis palustris*) to water smartweed (*Polygonum amphibium*) were found (Fickeisen et al. 1980). Due to the shoreline substrate and steepness in the study area, Indian hemp (*Apocynum cannabinum*) was the dominant vascular vegetation that extended furthest into the river. Below hydroelectric dams, sediments become coarser than that of the original riverbed due to fine sediment being removed from shoreline areas that experienced frequent watering and dewatering (Leopold et al. 1964). Thus, a lack of fine substrate was probably another factor preventing the establishment of vascular vegetation in the study area.

Between the shorelines zones of vascular vegetation and periphyton, a non-vegetated substrate zone composed of non-embedded cobble unable to sustain neither periphyton nor vascular vegetation was present. Kroger (1973) found that periphyton communities perished after short episodes of dewatering. However, the periphyton community in the Hanford Reach was diatomaceous (Fickeisen et al. 1980), and diatomaceous periphyton was reported to tolerate short-term dewatering (Benenati 1998).

Regardless of periphyton community structure, once periphyton communities and the benthic fauna within them were destroyed, complete recovery of the benthic community in other rivers required several months of consistent submergence. Blinn et al. (1995) reported that after two 12-hour exposure periods, more than four months was required for the benthos mass to equal that of permanently submerged benthos, and one month was required for the chlorophyll *a* levels to recover. Thus, in the Hanford Reach, the periphyton community may reestablish itself after a month of consistent submergence, but the benthic macroinvertebrates may require an additional three months of consistent submergence for complete recovery from short-term shoreline dewatering episodes.

Periphyton sometimes was found in areas prone to repeated dewatering. In these areas, groundwater seepage along the shoreline permitted periphyton patches to persist. In addition, crayfish and clams were sometimes found living within these groundwater seepages able to support periphyton.

4.2 Distribution of Asiatic clams, crayfish and sculpin

4.2.1 Asiatic clams

In the Hanford Reach, clams became more abundant as shoreline areas were submerged for greater periods of time, but clams were found throughout the three shoreline zones of vascular vegetation, non-vegetated substrate and periphyton. In other rivers, Asiatic clams were reported intolerant of aerial exposure and were not found in shoreline areas that experienced dewatering (Junk 1975; McMahon 1979). For Asiatic clams, mortality rates of 50 percent resulted after four consecutive days of dewatering, and 98 percent mortality rates resulted after 12 consecutive days of dewatering (White 1979; White and White 1977). High mortalities were also reported in dewatered shoreline areas during an 11-day reservoir drawn down of the Rhone River, France (Mouthon 2001a). Yet despite these findings, in the Hanford Reach clams were found in shoreline areas that experienced several days of dewatering with air temperatures above 35°C. One reason that clams survived in areas of the Hanford Reach that experienced dewatering was the presence of groundwater seepage. Bank storage returning to the river may have also kept substrate moist and clams alive when the river flows decreased. The other explanation for the clam distribution could be attributed to a mobility mechanism exhibited by this species.

The Asiatic clam has the ability to become buoyant and drift in the river currents. Prezant and Chalerwat (1984) reported clams 14 mm in shell length could maintain buoyancy and drift in currents greater than 0.1 $m \cdot s^{-1}$ by secreting a long mucous thread that acted like a parachute. Thus, clams observed at shoreline areas in and near vascular

vegetation were probably deposited when high flows diminished. This activity would explain how clams 5–11 mm in shell length composed 41 percent of the clams observed in the vascular vegetation zone. In addition, the inability of larger clams to relocate would explain the abundance of larger clams where periphyton persisted.

The three size classes identified in the Hanford Reach were similar to size classes reported in other river systems. Cataldo and Boltovskoy (1999) reported clams 15.3–22.4 mm were on their second year of growth, and clams 23.5–27 mm were on their third year of growth. Thus, the three size classes (5–11, 11–22 and >22 mm in shell length) identified in the Hanford Reach were probably representative of clams during first, second and third year of growth. Clams 5–11 mm in shell length were seldom observed because these clams were probably young of the year and not very abundant at the time of the study.

Clam populations in most rivers experience two spawning periods initiated by water temperatures between 19–26°C (Aldridge and McMahon 1978), thus clams typically spawn in the spring and fall. However, water temperatures in the Hanford Reach were between 19–21°C from only mid-August through mid-September (Columbia River DART 2002), so it was probable that only one annual spawning event occurred in the Hanford Reach. Thus, with only one cohort per year, a length frequency histogram could be used to identify Asiatic clam age. However, for length frequency analysis to be used as a method to identify clam age, clams used in the histogram should be collected from the persistent periphyton zone. Stresses associated with repeated dewatering likely result in retarded growth. Boltovskoy et al. (1997) reported dwarf clam populations in areas with environmental stress.

4.2.2 Crayfish

The vast majority of the crayfish were found at depths with periphyton. Periphyton is an important food for crayfish (Flint 1975; Flint and Goldman 1977). In adult signal crayfish, 90 percent of their diet was plant material, i.e, detritus and periphyton (Mason 1975). In the Hanford Reach, the presence of periphyton identified areas not prone to repeated dewatering. Stark (2001) found that benthic aquatic insects in the Hanford Reach were restricted shoreline areas that did not experience dewatering. Thus, the macroinvertebrate community was also located where periphyton persisted and crayfish were most abundant. Mason (1975) found that animal materials composed 65 percent subyearling *P. leniusculus* diets. Therefore, most of the crayfish food source was readily available in areas not prone to dewatering so food availability was not a reason for crayfish to move up the shoreline into areas prone to dewatering.

Despite the fact a large majority of the crayfish food source was at shoreline areas rarely dewatered, some crayfish were found in shoreline areas that experienced daily dewatering, and river fluctuations were known to strand and kill crayfish (Becker et al. 1981). This finding could be attributed to nocturnal crayfish activity coinciding with high water flows that typically occurred after sunset and before sunrise (Abrahamssom 1983; Ranta and Lindstrom 1992; Columbia River DART 2002). Crayfish probably foraged up the shoreline during the night. Clams were probably the dominant food item available in shoreline areas dewatered on a daily basis. Asiatic clams were a known food item of crayfish. Metal bioaccumulation studies have monitored contaminant trophic transfers between Asiatic clams and crayfish (Simon et al. 2000).

Crayfish were not observed in submerged shoreline areas with vascular vegetation, which is another crayfish food item (Mason 1975; Guan and Wiles 1998). The lack of crayfish at submerged vascular vegetation can again be attributed to rapid shoreline watering and dewatering. Daily movements of *P. leniusculus* were reported to be 1.5 $m \cdot day^{-1}$ (Lewis 1998), but the distance between periphyton and vascular vegetation was conservatively 10 m or more depending on the slope of the shoreline. Therefore, crayfish that traveled up the shoreline to possibly feed on vascular vegetation would probably be stranded and die during rapid dewatering episodes.

4.2.3 Sculpin

Sculpin movements up and down the shoreline with the river elevation could be attributed to depth and velocity preferences (Finger 1982; Brown 1991; Brown et al. 1995; White and Harvey 1990). All observations occurred at depths less than 1.5 m. Prickly sculpin (*C.* asper), mottled sculpin (*C. bairdi*), piute sculpin (*C. beldingi*) and torrent sculpin (*C. rhotheus*) were reported to occur in the Hanford Reach, Columbia River (Gray and Dauble 1977), but sculpin were not identified to specific epithets because sculpin identification required access to morphological features on the ventral side of the fishes (Wydoski and Whitney 2003). Such information was difficult to obtain while sculpin were nestled against substrate.

In the Hanford Reach, sculpin movement up and down the shoreline could be associated with a combination of flood response, depth preferences, currently velocity preferences and predator avoidance (Finger 1982; Brown et al. 1995; Wydoski and Whitney 2003). Sculpin tend to prefer shallow water areas away from fast waters (Wydoski and Whitney 2003). In the Hanford Reach, the hydraulic operations at Priest

Rapids Dam can suddenly increase the flow rate more than 400 percent within an hour. Such increases in water flow greatly altered the river and shoreline environment, and fish species must respond to such changes. In the Eel River, California, prickly sculpin preferred a depth of 0.27 m (Brown et al. 1995). Brown (1991) reported that three species of sculpin in an artificial stream all preferred depths less than 1 meter. Northern pike minnow (*Ptychocheilus oregonensis*) and small mouth bass (*Micropterus dolomieui*) and common predators in the Hanford Reach (Gray and Dauble 1977), and their presence could have caused sculpin to follow shallow depths up the shoreline as the river stage increased in order to avoid predation in the increasingly deeper waters.

4.3 Habitat factors were found to affect the densities of Asiatic clams, crayfish and sculpin

4.3.1 Asiatic clams

Substrate, embeddedness and current velocities affected clam densities. In this study, clam densities averaged 209·m^{-2} and ranged 0–825 clams·m^{-2} in substrate less than 50 mm (i.e., sand and gravel), and less than 100 clams·m^{-2} in substrate highly embedded (primarily sand). These densities were similar to Asiatic clam densities reported on like substrates in other rivers. Mouthon (2001a, 2001b) reported between 100–200 clams·m^{-2} for clams greater than 10 mm in shell length on coarse sand and silt substrates in the Rhone River and Saone River, both located in France. Cataldo and Boltovskoy (1999) reported densities 200–500 clams·m^{-2} in fine gravel and sand substrates for clams greater than 1 mm in shell length in the Parana River, Argentina.

In the Hanford Reach, the highest densities were found in a mix of unembedded large gravel–cobble substrate (51–200 mm) with scattered rubble substrate (251–350 mm) in areas with current velocities between 0.1–0.3 $m \cdot s^{-1}$. The combination of slower pocket water behind the rubble substrates coupled with the mucus-thread mobility mechanism may explain why densities were greatest within these habitat parameters. This environment may simply be where a large portion of the clams settled.

High clam densities were probably able to sustain themselves in such habitats because such current velocities probably provided abundant food. Diatomaceous filamentous periphyton was the dominant primary producer on the substrate and diatoms were the dominant phytoplankton in the water column (Fickeisen et al. 1980; Gray and Rickard 1989). River currents sheer filamentous periphyton from the substrate, but pocket water behind large cobble and rubble substrates probably had velocities slow enough to permit phytoplankton to settle for clams to forage upon.

Density information in large gravel–cobble substrates was not available for comparison. One reason Asiatic clam density data in cobble substrates were not reported in the literature was benthic samplers were incapable of consistent and accurate density measurement in gravel–cobble substrates that jam such devices.

In larger substrates, clams became less abundant. One reason clams declined in larger substrates was because crayfish became more abundant and less habitat was available for clams to burrow. Regardless of unconsolidated substrate depth, clams were found on top of the sand or burrowing in the sand surrounding rocky substrate. Large substrate meant less area was available for clams to burrow. In larger substrates, clams

were found laying on bare rock making them readily available for crayfish or other predators to forage.

Clam densities were lowest in current velocities less than 0.1 $m \cdot s^{-1}$. Low current velocities were positively correlated with the presence of fine substrate (Leopold et al. 1964). Current velocities of 0.1–0.3 $m \cdot s^{-1}$ supported the highest clam densities, but clam densities declined as currents exceeded 0.3 $m \cdot s^{-1}$. Because Asiatic clams can become buoyant by expelling a mucus substance, this dispersal mechanism probably did not favor relocation into areas with high current velocities.

4.3.2 Crayfish

It was not surprising that dominant substrate, unconsolidated substrate depth and groundwater seepage were habitat features shown to affect crayfish density. Substrate size and the amount of substrate cover were greatly correlated with crayfish densities (Flint and Goldman 1977; Shimizu and Goldman 1983; Guan and Wiles 1996). Cobble substrate 151–250 mm had the highest crayfish densities (10.7 crayfish$\cdot m^{-2}$) in the Hanford Reach, but as substrates became larger and smaller, densities decreased. This same trend was observed in Lake Tahoe. Flint and Goldman (1977) reported crayfish densities were highest in cobble–boulder substrates, but densities declined in larger substrates, and Guan and Wiles (1996) found crayfish densities were lowest in areas with small substrate, such as gravel.

The deepest unconsolidated substrate category (>10 cm) supported the high crayfish density. A four-fold increase in density was found between unconsolidated substrate depth 5–10 cm (2.06 crayfish$\cdot m^{-2}$) and substrate greater than 10 cm deep (9.31

crayfish·m^{-2}). Only one crayfish was found in substrate less than 5 cm in depth where densities were 0.02 crayfish·m^{-2}. These findings were similar Guan and Wiles (1996) who found substrates with the greater density of potential shelters had the highest crayfish densities.

Greater food availability attracted greater numbers of crayfish in Lake Tahoe (Flint and Goldman 1977). Groundwater seepage may have introduced nutrients thereby increasing the periphyton standing crop. In Lake Tahoe, Abrahamson and Goldman (1970) reported greater crayfish numbers where primary productivity was increased through the introduction of nutrients. The Hanford Reach is a nutrient poor section of the Columbia River (Miles et al. 1992). Any nutrients arriving through groundwater would have increased the primary productivity of that shoreline zone, thereby potentially providing an area capable of supporting greater numbers of crayfish.

4.3.3 Sculpin

Dominant substrate, embeddedness, current velocity and groundwater seepage were factors significantly related to sculpin densities. This study found that sculpin preferred cobble–boulder substrates up to 300 mm in diameter, but no sculpin were found in substrates larger than 300 mm. Although four species of sculpin were reported to reside to in the Hanford Reach (Gray and Dauble 1977), none of these species were reported to prefer large boulder substrate. Torrent, mottled and piute sculpin preferred cobbles substrates, and densities were reported to decline in substrate greater than 80 mm (Finger 1982). Prickly sculpin were found prefer rubble substrates (Wydoski and Whitney 1979; Brown et al. 1995; White and Harvey 1990).

Sculpin were typically associated with some kind of cover, but in the study area the only cover available was from the substrate. Macrophyte patches, primarily Eurasion milfoil (*Myriophyllum spicatum*), were found in sand and highly embedded gravel substrate, and no sculpin were found in areas that supported macrophytes.

Sculpin were found in low velocity areas with cobble substrate 25–75 percent embedded, such habitat is utilized predominantly by prickly sculpin (White and Harvey 1990). In other lotic systems, mottle sculpin were found to prefer rubble substrates in areas with current velocities greater than 0.28 $m \cdot s^{-1}$ (Bailey 1952; Matheson and Brooks 1983).

Groundwater seepages could have attracted sculpin by either an increased food source from nutrient introduction, or sculpin could be attracted to cooler temperatures. Wydoski and Whitney (1979) described sculpin as cool water fishes. Torrent, mottled and piute sculpin were found to prefer cooler water temperature (Finger 1982). In addition, three species of sculpin from the Pit River, California, preferred temperatures between 11.2–13.5°C (Brown 1989), and the freshwater sculpin (*Cottus cognatus*) preferred temperature between 9–12°C (Otto and Rice 1977). Wydoski and Whitney (1979) reported prickly sculpin were usually in water 10–17.7°C.

In the Hanford Reach, groundwater was found to be cooler than the ambient river temperature. During pilot sampling in August 2002, the ambient river temperature was 21.2°C, which in 1.5°C below the lethal limit reported for prickly sculpin (Wydoski and Whitney 2003). In a shoreline area influenced by groundwater seepage, the river water temperature just above the substrate was 19.4°C. The temperature of groundwater coming from the shoreline above the river surface was 13.5°C. Because ambient river

temperatures approached sculpin lethal limit temperatures, sculpin were probably attracted to the cooler groundwater entering the Columbia River.

4.4 Crayfish physical traits

The crayfish population in the Hanford Reach was similar to many other signal crayfish populations. Length-weight regressions were similar to reported findings in other populations, but larger crayfish in the Hanford Reach appeared to exhibit reduced weights (Figure 52). The sex ratios were nearly 1 male per 1 female. Identical sex ratios were reported as the natural equilibrium for *P. leniusculus* populations (Lewis 2002).

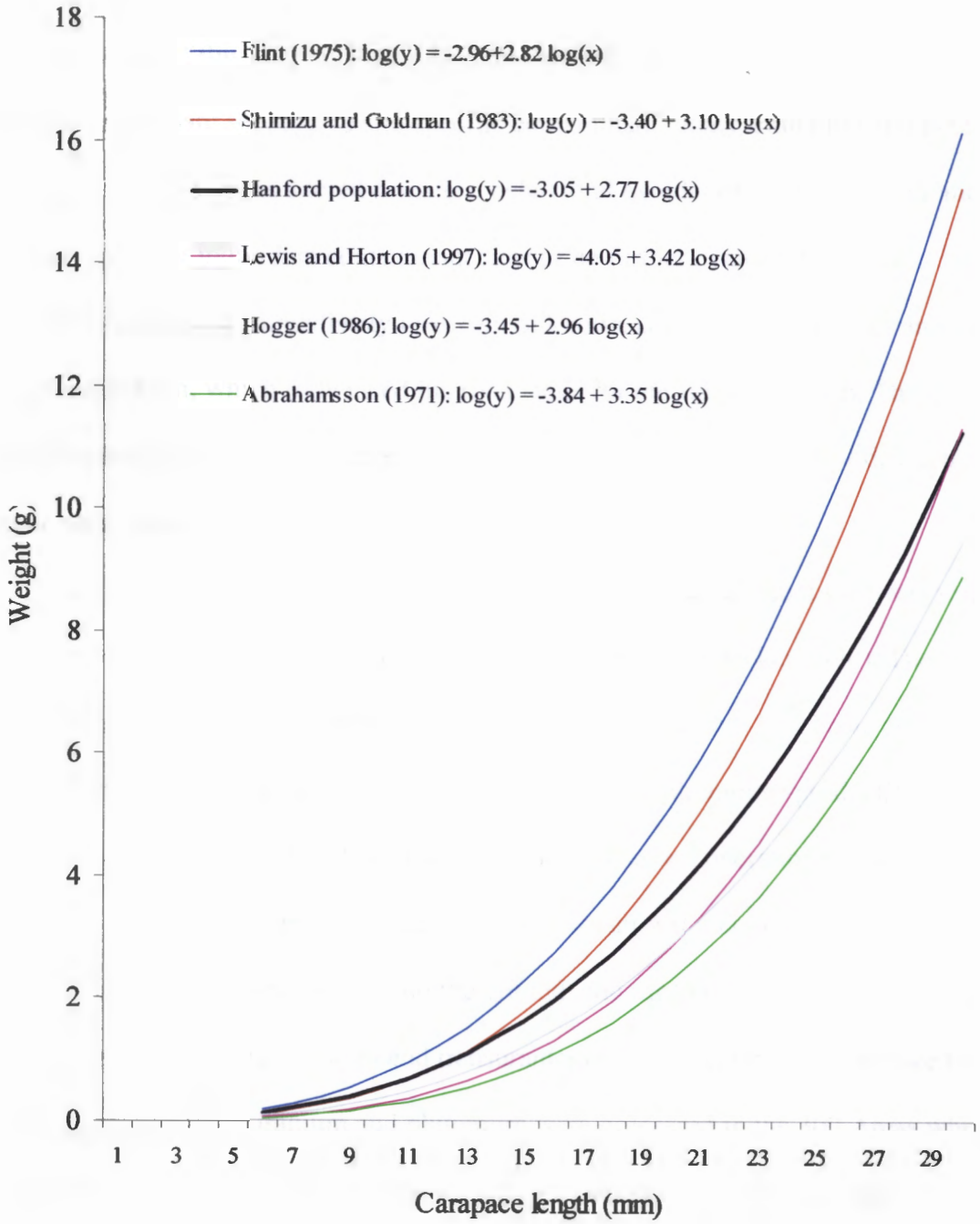

Figure 52. Weight length relationships of signal crayfish from Hanford Reach and several other populations reported in Lewis (2002).

4.5 Ecological studies at Hanford sites of concern

The goal of this study was to obtain data on populations not effected by known Hanford contaminant seepage so site-specific contaminant bioaccumulation and potential ecological effects, such as altered densities, behavioral avoidance or size class anomalies, could be studied at individual contaminant sites or be further evaluated for study. The study site was selected immediately upstream of known contaminant seepages and below Priest Rapids Dam, which influenced the river stage for the Hanford Reach. The study area was selected under the assumption that habitats were representative of downstream contaminant areas.

In 1943, the Hanford Reach of the Columbia River and adjacent land was selected as the site to produce plutonium for the first nuclear weapons (Becker 1990). The Hanford Nuclear Reservation operational zones are classified into four basic areas (i.e., 100, 200, 300, and 400) (Figure 2). In the 100 Areas, nine plutonium-production reactors were built along the river shoreline. The 200 Areas possessed operational procedures that released large amounts of process chemicals and coolant water containing low-level radioactive waste (nontransuranic) into the ground, and the 200 Areas also stored high-level radioactive waste (plutonium and transuranics) in large underground storage tanks of which some leaked. Uranium and plutonium were processed in the 300 Areas where wastes, such as cooling water, pickling rinses, and caustics from the processes of plutonium-uranium extraction and uranium fuel rod fabrication, were discharged into settling ponds near the river. The 400 Area possessed a commercial nuclear power plant and the Fast Flux Test Facility, which was used to test fuels and materials for advanced nuclear technology for the United States Department of Energy (Becker 1990).

Operational procedures for weapons-grade plutonium production created contaminants such as acids, radionuclides, and heavy metals. Acid contaminants were primarily nitrates. Some radionuclide contaminants were tritium, strontium-90, cesium-137, cobalt-60, uranium-235/238, plutonium-239/240, and technetium-99. Examples of heavy metal contaminants were chromium, cadmium, copper, lead, nickel, zinc, mercury, and antimony (Becker 1990; Patton 1998; Newcomer and Hartman 2001). Environmental surveillance proved that Hanford Site contaminants were bioaccumulating in the near shore aquatic fauna. Asiatic clams, sculpin, and crayfish were found to accumulate such Hanford contaminants (Poston et al. 1998; Patton et al. 2003).

Delistraty and Yokel (1998, 1999) showed spring water and sediments collected at contaminant seepages were toxic to the selected test organisms in the laboratory, but the actual riverine environment was not incorporated into these analyses. Large volumes of river water rapidly diluted contaminants. Only 0.02 percent of the Columbia River annual river flow average was composed of the Hanford Site aquifer (Newcomer and Hartman 2001), which was well below the 3.00 percent dilutions reported in laboratory tests. The degree of contaminant seepage water and river water mixing varied with river stage elevation and site-specific hydraulics, but datasets showed dilution increased as the seepages approached the river shoreline (Arntzen 2001; Peterson and Connelly 2001).

Since plutonium production has stopped, it was unlikely that Hanford contaminants were eliciting a major effect on the entire Hanford Reach of Columbia River, but effects may occur at localized contaminant seepage areas where contaminant concentrations in the river were at their highest levels. At these sites of concern, field investigations were required to determine if any effects were occurring. However, the

fluctuations in river elevation affect contaminant concentrations and where they entered the river. In addition, variable river hydraulics affect the distribution and movements of species, such as clams, crayfish and sculpin—species most likely to be exposed to contaminants.

The distributions of clams, crayfish and sculpin and factors affecting their densities were previously unknown along the Hanford River shoreline, thus potential ecological effects from contaminants also remained unknown. This thesis was conducted to provide background information of the studied benthic species for such ecological investigations.

In summary, research performed on Asiatic clams, crayfish and sculpin, should be preformed during predictable low flow conditions (September–October) for two reasons. First, studies should be performed at depths not influenced by dewatering, i.e., samples should be taken at depths with persistent periphyton, and shoreline areas not influenced by dewatering were only accessible during low flow conditions. And second, contaminant concentrations entering the river are most concentrated during low flow periods (Arntzen 2001; Peterson and Connelly 2001).

The variable flows released from Priest Rapids Dam have marked the shoreline with the three distinct zones of vascular vegetation, non-vegetated substrate and periphyton. In the study area, the distribution of periphyton marked the low water level. At sites of concern, the periphyton line should be used to identify shoreline areas not affected by dewatering. Further studies on benthic aquatic species should occur at depths not affected by dewatering.

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Vita

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During his undergraduate and graduate studies at Eastern Washington University, Behr was awarded four research fellowships at Battelle Pacific Northwest National Laboratory, Richland, Washington. Behr presently continues aquatic research at Battelle Pacific Northwest National Laboratory for the U.S. Department of Energy.