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Benthic Invertebrates and Sediment Characteristics in Main Channel Habitats in the Lower Columbia River

Abstract

Benthic invertebrate communities in the Columbia River between the lowermost dam and the upper estuary have been little studied. We describe the abundance of benthic invertebrates and sediment characteristics in main channel habitats in the lower Columbia River and examine the relationships between densities of specific benthic invertebrates and sediment characteristics and water depth. Using a 0.1-m^2 Van Veen grab sampler, we collected benthic samples in seven areas of the river from River Kilometer (RKm) 121 to 211 in April and September 1988 and 1989. Common taxa collected, included Turbellaria, Oligochaeta, the bivalve *Corbicula fluminea*, the amphipod *Corophium salmonis*, Chironomidae larvae, and Ceratopogonidae larvae. Overall, *Corbicula fluminea* and Ceratopogonidae larvae were consistently the most abundant benthic invertebrates. The relationship of benthic invertebrate densities between and within years, months, and areas varied substantially between the six predominant taxa. The effect of water depth and sediment characteristics on benthic invertebrate densities, after accounting for the influence of year, month, and area, varied between the six predominant taxa in this study. Water depth was significant ($P \leq 0.05$) for densities of three of the six taxa, sediment percent silt/clay significant for four, and sediment grain size and percent volatile solids significant for one each. Results from our study are probably applicable to a large area of main channel habitats in the Columbia River downstream from the lowermost dam. Because benthic invertebrates, particularly *Corophium salmonis*, are primary prey for many fishes, the sustained health of benthic invertebrate populations in the lower Columbia River is of concern.

Introduction

The Columbia River downstream from Bonneville Dam (River Kilometer [RKm] 234), the lowermost dam on the river, supports large populations of migrating juvenile salmon (*Oncorhynchus* spp.) and the largest population of white sturgeon (*Acipenser transmontanus*) in the world (DeVore et al. 1995). Studies of the diets of these and other fishes indicate that benthic amphipods and bivalves are often important prey for these fishes. Examples include the tube-dwelling amphipods *Corophium* spp. as primary prey for juvenile chinook (*O. tshawytscha*), coho (*O. kisutch*), and sockeye (*O. nerka*) salmon, steelhead (*O. mykiss*), and juvenile white sturgeon (Kirn et al. 1986; McCabe et al. 1983, 1986, 1993; Muir and Emmett 1988; Muir et al. 1988); and the introduced Asian bivalve *Corbicula fluminea* (= *C. manilensis*) as an important food for juvenile white sturgeon (McCabe et al. 1993).

Despite the importance of benthic invertebrates in the diets of juvenile salmon and white sturgeon, little is known of the distribution and ecology of benthic invertebrates in much of the lower river. Benthic invertebrate communities in the Columbia River downstream from RKm 50 have been studied more than upstream populations (e.g., Higley and Holton 1978; Durkin and Emmett 1980; Durkin et al. 1981, 1982; Emmett et al. 1986; Hinton et al. 1990; Jones et al. 1990). Upstream from RKm 50, benthic invertebrate studies have been limited primarily to short-term or geographically limited studies (e.g., Blahm and McConnell 1979, Blahm et al. 1979, McCabe and Hinton 1990, McCabe et al. 1990). Sanborn (1975) sampled the benthos of four areas in the Columbia River between RKm 29 and 167 in 1973-1974. McCabe and Hinton (1996) described the benthic invertebrate communities and sediment characteristics at 10 dredged-material disposal areas in the lower Columbia River between RKm 55 and 122. McCabe and Hinton's sampling stations were located within about 30 m of the high tide mark on the shore.

From 1987 through 1991, the spawning and early life history of white sturgeon in the lower Columbia River were studied (McCabe et al. 1993, Parsley et al. 1993, McCabe and Tracy 1994). Part of this research involved the collection of benthic invertebrates and sediment samples in eight areas of the lower Columbia River. A portion of this benthic invertebrate dataset was used in assessing the feeding ecology of juvenile sturgeon in two areas of the river and examining the relationships between juvenile white sturgeon abundance and abundances of two important benthic prey, *Corophium salmonis* and *Corbicula fluminea*, in eight areas (McCabe et al. 1993); however, important specific information about benthic invertebrates and sediment characteristics in the lower Columbia River was not presented.

To elucidate the ecological relationships between the benthos and feeding habits of juvenile salmon, white sturgeon, and other fishes, it is necessary to conduct systematic and long-term benthic invertebrate research throughout the river. To help achieve this goal, we describe the abundance of benthic invertebrate populations in main channel habitats in the lower Columbia River from RKm 121 to RKm 211 using data collected in seven areas. Data collected at one area downstream from RKm 50 are not included because benthic invertebrates have been studied much more in the river downstream from RKm 50 than upstream from RKm 50. We also examine the relationships between densities of specific benthic invertebrates and sediment characteristics and water depth.

Methods

Sampling

Sampling was conducted in seven areas distributed along the lower Columbia River between RKm 121 and RKm 211 in April and September 1988 and 1989 (Figure 1). At each area, designated by RKm, samples were collected along either two or three transects parallel to the shoreline. Transect 1 was closest to the Washington shore, Transect 2 was the middle transect, and Transect 3 was closest to the Oregon shore. In some river sections, only two transects (Transects 1 and 3) were established. Transects selected for benthic invertebrate sampling represented a portion of the total number of sampling transects that was used to determine the range of habitat use by juvenile white sturgeon.

During each survey, five benthic invertebrate samples and one sediment sample were collected at each sampling station with a 0.1-m^2 Van Veen grab sampler (Word 1976). Two sampling stations about 185 m apart were established along each transect. When practical, each benthic invertebrate sample was sieved through a 0.5-mm screen in the field and the residue preserved in a buffered formaldehyde solution ($\geq 4\%$) containing rose bengal, an organic stain. If it appeared that most of the material would not wash through the sieve, the entire sample was preserved and sieved at a later time. Prior to sorting, all samples were washed with water and preserved in a 70% alcohol solution. Each benthic invertebrate sample was sorted and the invertebrates were identified to the lowest practical taxon and counted. Sediment samples were analyzed for sediment grain size, percent silt/clay, and percent volatile solids by the U.S. Army Corps of Engineers (North Pacific Division Materials Laboratory, Troutdale, Oregon). Each sediment sample was oven dried at 110°C for 24 h, then sieved. Hydrometer analysis was performed if more than 5% of the sample passed through a #230 sieve. Percent volatile solids were determined by weighing an oven-dried sample, then heating the sample in a muffle furnace at 600°C for 1 h. The sample was weighed before and after being placed in the muffle furnace, and the difference between the two weights was used to calculate percent volatile solids. The depth at each sampling station was measured using an electronic depth sounder; all depths were later standardized by converting them to mean lower low water (MLLW).

Data Analysis

Benthic invertebrate data were analyzed by individual sampling station and by combining stations in an area. Information calculated for each station included the number of taxa/categories and mean and standard deviation (SD) of the density (number/m^2) for each taxon/category and total invertebrates. Mean densities of invertebrates from individual sampling stations provided the data for statistical tests.

The relationship between water depth, sediment grain size, percent silt/clay, and percent volatile solids, as compared to year (1988 and 1989), month (April and September), and area were examined using three-factor analysis of variance (ANOVA). The Fisher's Protected Least Significant Difference (FPLSD) multiple comparison procedure was used to compare means from significant F-tests ($P \leq 0.05$) in the ANOVAs (Petersen 1985). The relationship between benthic invertebrate densities and year, month, and area was examined using three-factor analysis of

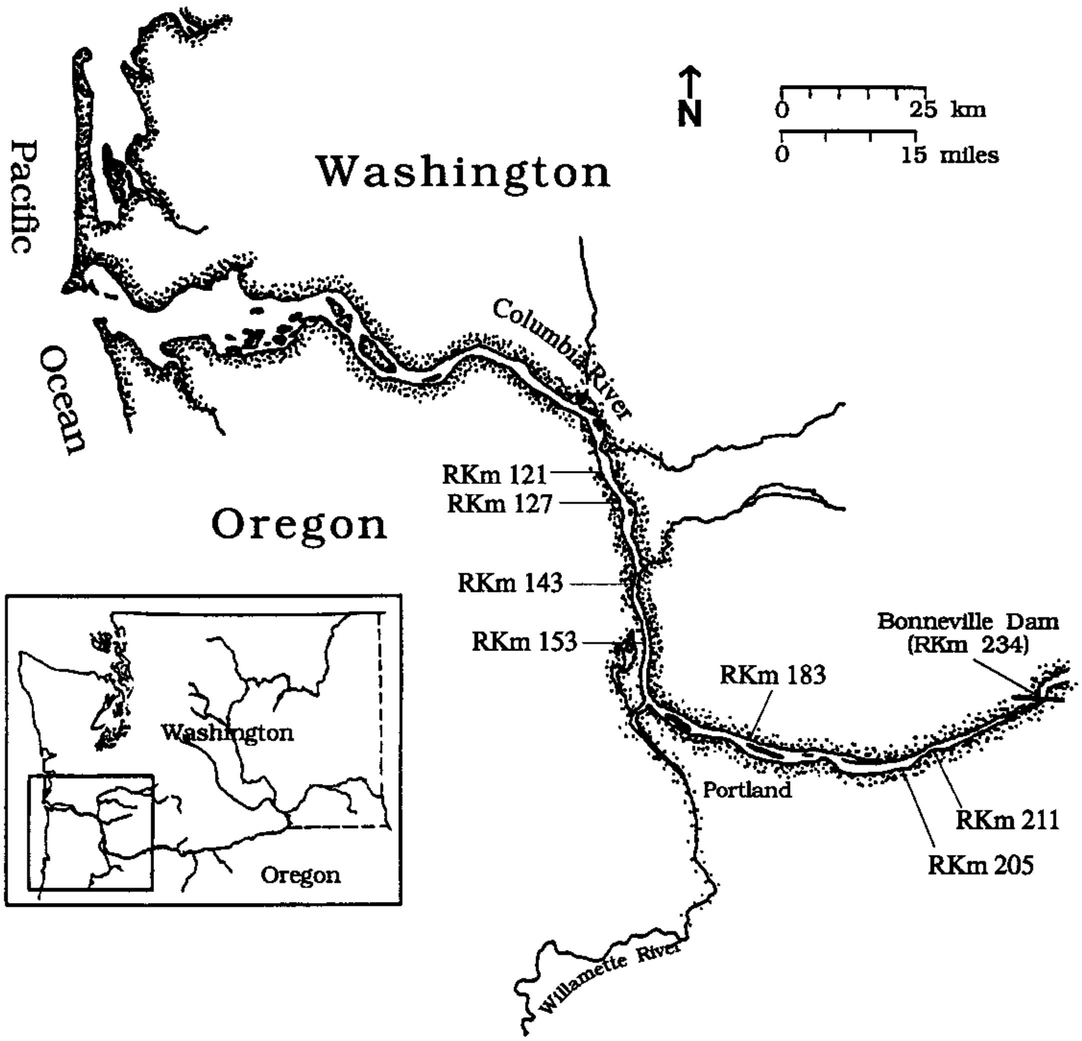

Figure 1. Map of the lower Columbia River showing the seven areas sampled for benthic invertebrates in April and September, 1988 and 1989.

covariance (ANCOVA) and the FPLSD procedure, with water depth, grain size, percent silt/clay, and percent volatile solids as the covariates. Regression equations were developed for significant covariates.

Benthic invertebrate densities were transformed ($\log_{10}$) prior to analyses (Elliott 1977), and sediment characteristics and water depth were transformed ($\sin^{-1}\sqrt{}$) as needed to achieve approximate normality and equal variance of the model residuals.

Results

Water Depth and Sediment Characteristics

Four sediment characteristic values were considered extreme outliers after visual inspection of the data and normality plots: 1) median grain size was 2.22 mm in September 1989 at one station at RKm 205; 2) percent silt/clay was 38.7% in September 1988 at one station at RKm 153; 3) percent silt/clay was 90.4% in September 1989 at one station at RKm 143; and 4) percent volatile solids was 4.7% in September 1989 at one station at RKm 211. These values were excluded from the analyses.

Significant differences between areas were detected for water depth ($P = 0.004$), median grain size ($P = 0.005$), $\sin^{-1}\sqrt{}$ percent silt/clay ($P < 0.001$), and $\sin^{-1}\sqrt{}$ percent volatile solids ($P < 0.001$). No significant interactions ($P > 0.05$) between year, month, and area or significant differences between years or between months were detected for any of the four variables. RKm 183 had a significantly lower mean water depth than the other areas; depths at RKm 183 averaged less than 7.3 m during all months (Table 1). RKm 143, 183, and 205 had significantly larger mean median grain sizes than RKm 211. Also, RKm 183 had a significantly larger mean median grain size than RKm 121, 127, and 153. RKm 211 had both a significantly higher percent silt/clay and a significantly higher percent volatile solids than the other areas; percent silt/clay and percent volatile solids values averaged $\geq$1.0% during all months (Table 1). Rkm 205 had a significantly higher percent volatile solids than RKm 121, 127, and 183. There were no other significant differences.

Benthic Invertebrates

The number of benthic invertebrate taxa/categories collected in the lower Columbia River ranged from a low of 17 in September 1989 to a high of 20 in April 1989. In both April and September 1988, 19 taxa/categories were collected (Table 2). The number of taxa/categories at individual stations ranged from 4 to 13 in April and September 1988; from 3 to 13 in April 1989; and from 5 to 8 in September 1989. In each area, two to five taxa/categories were numerically dominant during each survey.

Common taxa/categories collected throughout the lower river included Turbellaria (flatworms), Oligochaeta (annelids), *Corbicula fluminea* (bivalve), *Corophium salmonis* (amphipod), Chironomidae larvae (midges), and Ceratopogonidae larvae (biting midges) (Tables 2 and 3). All these taxa/categories were collected in all seven areas during each survey, except for Turbellaria at RKm 205 in September 1988 and Oligochaeta in April 1988 at RKm 205. Overall, *Corbicula fluminea* and Ceratopogonidae larvae were consistently the most abundant benthic invertebrates during the study. Mean densities (by geographic area) of *Corbicula fluminea* ranged from 15 to 733 organisms/m^2. Usually mean densities of *Corbicula fluminea* were less than 500 organisms/m^2 in each area in 1988 and generally less than 300 organisms/m^2 in 1989. Mean densities (by area) of Ceratopogonidae larvae ranged from 48 to 979 organisms/m^2. In 1988, mean densities of Ceratopogonidae larvae were generally less than 650 organisms/m^2 in each area, and in 1989, usually less than 300 organisms/m^2.

For Turbellaria mean densities, there was a significant interaction between year and month ($P < 0.001$) and between year and area ($P = 0.036$), but not between month and area ($P = 0.258$). The mean density of Turbellaria was significantly higher in April 1988 than densities during the other three surveys, which were not significantly different from each other. In 1988, the mean density of Turbellaria at RKm 205 was significantly lower than mean densities at RKm 121, 143, 183, and 211; densities at the other areas were not significantly different from each other. However, in 1989, the mean density at RKm 211 was significantly lower than mean densities at RKm 127, 143, and 183, and mean densities at RKm 153 and 205 were significantly lower than the mean density at RKm 183. Another perspective of the year/area interaction was that at RKm 153 and 211, 1988 had significantly higher mean densities than 1989, whereas there were no significant differences between years for the other areas. Turbellaria density was positively related to water depth after accounting for year, month, and area ($P < 0.001$); however, depth explained only 10% of the variation in Turbellaria density (Table 4).

There were no significant interactions between year, month, and area for Oligochaeta mean densities. Significant differences occurred between months ($P = 0.010$) and areas ($P = 0.019$), but not between years ($P = 0.405$). The Oligochaeta mean density in September was significantly higher than that in April. The mean densities for RKm 183 and 205 were significantly lower than those for RKm 143 and 153. Also, the mean Oligochaeta density at RKm 205 was significantly lower than that at RKm 121. Oligochaeta density was positively related to water depth ($P = 0.025$), grain size ($P = 0.034$), and percent silt/clay ($P < 0.001$) after accounting for year, month, and area; however, these physical characteristics explained only 16% of the variation in Oligochaeta density (Table 4).

TABLE 1. Mean depths (mean lower low water), median grain sizes (GS), percents silt/clay (S/C), and percents volatile solids (VS) at seven sampling areas (RKm-transect) of the lower Columbia River between RKm 121 and 211. Two stations were sampled along each transect.

	April 1988				September 1988				April 1989				September 1989			
RKm-trans.	Dep. (m)	GS (mm)	S/C (%)	VS (%)	Dep. (m)	GS (mm)	S/C (%)	VS (%)	Dep. (m)	GS (mm)	S/C (%)	VS (%)	Dep. (m)	GS (mm)	S/C (%)	VS (%)
121-1	14.0	0.42	0.1	0.7	14.0	0.45	0.0	0.6	15.4	0.58	0.1	0.6	13.6	0.48	0.1	0.7
121-3	11.1	0.32	0.1	0.5	11.0	0.40	0.1	0.6	11.4	0.39	0.1	0.6	10.4	0.42	0.1	0.7
Area	12.6	0.37	0.1	0.6	12.5	0.42	0.1	0.6	13.4	0.48	0.1	0.6	12.0	0.45	0.1	0.7
127-1	20.0	0.64	0.1	0.6	18.0	0.49	0.1	0.6	18.7	0.62	0.1	0.5	17.5	0.58	0.1	0.6
127-2	13.3	0.57	0.1	0.4	11.0	0.41	0.2	0.6	12.0	0.49	0.1	0.6	11.4	0.41	0.1	0.6
127-3	8.8	0.26	0.1	1.0	8.0	0.28	0.1	0.6	9.1	0.32	0.1	0.6	7.3	0.26	0.3	0.6
Area	14.0	0.49	0.1	0.7	12.3	0.39	0.1	0.6	13.3	0.48	0.1	0.6	12.1	0.42	0.2	0.6
143-1	5.9	0.41	0.1	0.6	6.2	0.40	0.4	1.0	5.9	0.34	0.2	0.6	4.0	0.37	0.1	0.8
143-3	15.9	0.56	0.0	0.6	14.5	0.60	0.1	0.7	15.7	0.65	0.1	0.8	14.6	0.70	45.3	1.1
Area	10.9	0.48	0.1	0.6	10.4	0.50	0.2	0.8	10.8	0.50	0.2	0.7	9.3	0.54	22.7	1.0
153-1	19.0	0.65	0.1	0.8	18.7	0.52	0.3	0.8	20.3	0.64	0.0	0.6	18.9	0.61	0.2	0.8
153-2	11.7	0.40	0.0	0.4	12.2	0.34	0.1	0.8	12.8	0.38	0.1	0.7	11.3	0.40	0.1	0.6
153-3	5.9	0.40	0.3	0.6	5.8	0.22	19.4	2.1	5.6	0.36	<0.1	0.6	4.3	0.38	0.6	0.7
Area	12.2	0.48	0.1	0.6	12.2	0.36	6.6	1.2	12.9	0.46	<0.1	0.6	11.5	0.46	0.3	0.7
183-1	7.6	0.86	0.0	0.7	7.2	0.58	0.1	0.6	7.5	0.79	0.1	0.7	6.9	0.94	0.1	0.7
183-3	6.9	0.46	0.1	0.5	5.8	0.40	0.1	0.5	6.7	0.39	0.1	0.6	5.6	0.36	0.1	0.7
Area	7.2	0.66	<0.1	0.6	6.5	0.49	0.1	0.6	7.1	0.59	0.1	0.6	6.2	0.65	0.1	0.7
205-1	8.7	0.28	0.2	0.7	6.5	0.28	0.1	0.5	9.4	0.30	0.2	0.7	6.1	0.26	0.1	0.4
205-3	17.2	0.42	0.0	1.1	14.5	0.82	0.1	1.4	16.8	0.98	0.1	1.4	15.4	1.40	0.1	1.3
Area	13.0	0.35	0.1	0.9	10.5	0.55	0.1	1.0	13.1	0.64	0.2	1.0	10.7	0.83	0.1	0.8
211-1	14.5	0.64	0.1	1.4	13.9	0.46	0.2	1.0	15.7	0.50	0.1	1.1	13.9	0.57	0.1	2.8
211-2	17.7	0.36	0.2	1.2	16.0	0.39	0.1	1.1	17.4	0.18	0.2	0.8	16.3	0.22	1.8	0.8
211-3	5.9	0.17	4.0	1.7	6.4	0.18	2.8	1.4	6.9	0.17	2.8	1.9	3.5	0.18	2.2	1.5
Area	12.7	0.39	1.4	1.4	12.1	0.34	1.0	1.2	13.3	0.28	1.0	1.3	11.2	0.32	1.4	1.7

TABLE 2. Occurrence of benthic invertebrates in the lower Columbia River between RKm 121 and 211, 1988-1989. Presence is indicated by a "+" and absence by a "0."

Taxon/category	1988		1989	
	April	September	April	September
Turbellaria	+	+	+	+
Nemertea	0	+	+	+
Nematoda	+	0	0	0
Nematomorpha	+	+	+	+
Polychaeta	+	0	0	0
Neanthes limnicola	0	+	+	+
Oligochaeta	+	+	+	+
Hirudinea	0	0	+	0
Bivalvia				
Anodonta spp.	0	0	0	+
Corbicula fluminea	+	+	+	+
Gastropoda				
Fluminicola spp.	0	0	+	0
Juga spp.	0	+	0	0
Ostracoda	+	+	+	+
Isopoda				
Gnorimosphaeroma oregonensis	0	0	+	0
Asellus occidentalis	0	+	0	0
Porcellio scaber	0	+	+	0
Amphipoda				
Gammaridae	+	0	0	+
Corophium spp.	0	0	+	+
Corophium salmonis	+	+	+	+
Corophium spinicorne	+	+	+	+
Ramellogammarus oregonensis	+	0	+	0
Hyalella azteca	0	+	+	0
Arachnoidea (aquatic)	0	+	0	+
Ephemeroptera nymph	+	0	0	0
Odonata nymph	0	+	0	+
Trichoptera larvae	+	+	0	0
Diptera				
Diptera pupae	+	0	0	0
Tipulidae larvae	+	0	0	0
Chironomidae larvae	+	+	+	+
Chironomidae pupae	+	+	+	+
Ceratopogonidae larvae	+	+	+	+
Ceratopogonidae pupae	+	0	+	0
Total number	19	19	20	17

Month and area had a significant interaction for *Corbicula fluminea* mean densities ($P < 0.001$), and there was a significant difference between years ($P < 0.001$). Mean densities of *Corbicula fluminea* in 1988 were higher than those in 1989. In April, mean densities at RKm 121, 127, and 205 were significantly lower than densities at RKm 153, 183, and 211, and the mean density at RKm 205 was significantly lower than that at RKm 143. However, in September, the mean density of *Corbicula fluminea* at RKm 205 was significantly lower than the densities at RKm 121 and 127, and the density at RKm 153 was significantly lower than that at RKm 127. Another perspective of the month/area interaction was that mean densities of *Corbicula fluminea* in September were significantly lower than those in April for RKm 121, 127, and 205, but not significantly different for the other four areas. *Corbicula fluminea* density was significantly related to percent silt/clay

TABLE 3. Mean densities (number/m^2) and standard deviations (SD) of benthic invertebrates collected in April and September of 1988 and 1989 between RKm 121 and 211 in the Columbia River. Less common taxa are included in totals, but are not listed individually. Depending upon the number of transects, generally 20-30 samples were collected at each area.

Area		April 1988		September 1988		April 1989		September 1989	
(RKm)	Taxon/category	Mean	SD	Mean	SD	Mean	SD	Mean	SD
121	Turbellaria	41	68	2	7	19	36	2	5
	Oligochaeta	51	103	117	161	27	44	28	49
	Corbicula fluminea	59	112	480	490	30	37	177	207
	Corophium salmonis	46	86	44	71	4	7	39	48
	Chironomidae larvae	26	37	7	12	10	9	3	7
	Ceratopogonidae larvae	146	126	979	1,003	258	263	318	250
	Total	374	293	1,633	1,533	348	318	570	364
127	Turbellaria	33	82	2	6	27	61	12	24
	Oligochaeta	32	68	306	516	70	251	140	269
	Corbicula fluminea	154	218	320	528	15	18	318	350
	Corophium salmonis	27	39	127	158	1	3	256	332
	Chironomidae larvae	11	13	3	9	7	8	4	8
	Ceratopogonidae larvae	161	161	302	371	238	383	205	201
	Total	420	304	1,065	1,150	358	528	936	565
143	Turbellaria	105	144	1	3	6	13	6	23
	Oligochaeta	149	379	48	57	13	18	15	22
	Corbicula fluminea	198	129	336	378	38	51	91	56
	Corophium salmonis	117	197	11	16	29	86	651	532
	Chironomidae larvae	14	18	2	4	1	3	8	13
	Ceratopogonidae larvae	635	563	323	266	164	228	48	43
	Total	1,218	700	722	530	251	264	844	519
153	Turbellaria	28	45	2	4	2	6	1	2
	Oligochaeta	151	321	619	967	227	546	211	371
	Corbicula fluminea	733	980	107	135	263	489	138	181
	Corophium salmonis	122	226	184	298	54	76	359	663
	Chironomidae larvae	36	67	2	5	5	7	14	23
	Ceratopogonidae larvae	606	780	213	264	228	232	190	196
	Total	1,694	1,527	1,128	1,161	779	935	914	628
183	Turbellaria	9	19	3	7	6	13	3	9
	Oligochaeta	1	2	21	38	1	3	7	14
	Corbicula fluminea	189	148	476	494	90	115	60	84
	Corophium salmonis	5	8	43	56	5	8	8	18
	Chironomidae larvae	5	11	38	59	21	29	7	23
	Ceratopogonidae larvae	472	643	886	941	189	144	291	195
	Total	681	753	1,486	1,285	312	223	380	205
205	Oligochaeta	0	0	20	39	129	291	195	436
	Corbicula fluminea	307	532	371	504	16	37	298	663
	Corophium salmonis	23	29	4	7	13	16	12	20
	Chironomidae larvae	40	142	1	3	2	4	33	48
	Ceratopogonidae larvae	73	45	553	818	161	251	360	216
	Total	450	536	950	1,288	323	518	907	996
211	Turbellaria	31	80	10	20	2	7	1	2
	Oligochaeta	144	228	238	457	321	693	131	122
	Corbicula fluminea	640	813	266	303	70	50	106	164
	Ostracoda	20	60	2	5	2	7	14	39
	Corophium salmonis	116	165	79	113	241	337	141	146
	Chironomidae larvae	33	39	21	38	33	47	32	41
	Ceratopogonidae larvae	349	492	314	349	65	74	143	189
	Total	1,338	1,055	955	657	752	968	574	324

TABLE 4. Regression equations and r^2 values relating benthic invertebrate densities to water depth, sediment grain size (GS), percent silt/clay (S/C), and percent volatile solids (VS) after accounting for year, month, and area. Depth is in meters and grain size is in millimeters. Variables were only included if their coefficients from analysis of covariance were significant ($P \leq 0.05$). Transformations are indicated in parentheses. When the $\sin^{-1}\sqrt{}$ transformation was used, the decimal form of the variable was required for calculation (e.g., 0.01 was used for a percent silt/clay of 1.0%).

		Coefficient				
Taxon ($\log_{10}$)	Constant	Depth	GS	S/C ($\sin^{-1}\sqrt{}$)	VS ($\sin^{-1}\sqrt{}$)	r^2
Turbellaria	-0.242	0.064				0.101
Oligochaeta	-0.548	0.053	1.228	10.755		0.163
Corbicula fluminea	1.335			-3.981	6.513	0.046
Corophium salmonis	1.613	-0.060		5.104		0.089
Chironomidae larvae	1.272					0.000
Ceratopogonidae larvae	1.997			-7.115		0.120

($P = 0.005$) and percent volatile solids ($P = 0.049$) after accounting for year, month, and area. *Corbicula fluminea* density was positively correlated with percent volatile solids and negatively correlated with percent silt/clay; however, these physical characteristics explained only 5% of the variation in *Corbicula fluminea* density (Table 4).

For *Corophium salmonis* mean densities, significant interaction was detected between year and month ($P = 0.033$) and between month and area ($P < 0.001$), but not between year and area ($P = 0.056$). Mean densities in September 1989 were significantly higher than those during the other three surveys, which were not significantly different from each other. In September, mean densities at RKm 183 and 205 were significantly lower than those at the other areas, and the mean density at RKm 211 was significantly lower than that at RKm 127. In April, the mean density of *Corophium salmonis* at RKm 183 was significantly lower than mean densities at RKm 143, 153, 205, and 211, and the mean density at RKm 127 was significantly lower than that at RKm 153. Another perspective of the month/area interaction was that mean densities for September were significantly higher than those for April at RKm 121 and 127, but were not significantly different for the other areas. *Corophium salmonis* density was significantly related to water depth ($P < 0.001$) and percent silt/clay ($P = 0.001$) after accounting for year, month, and area. *Corophium salmonis* density was positively correlated with percent silt/clay and negatively correlated with water depth; however, these physical characteristics explained only 9% of the variation in *Corophium salmonis* density (Table 4).

A three-way interaction between year, month, and area was detected for mean densities of Chironomidae larvae ($P < 0.001$). In April 1988, the mean density of Chironomidae larvae at Rkm 183 was significantly lower than mean densities at RKm 121 and 211. In September 1988, the mean density of Chironomidae larvae at RKm 183 was significantly higher than mean densities at RKm 127, 143, 153, and 205. In April 1989, the mean density at RKm 143 was significantly lower than mean densities at RKm 121, 127, 183, and 211. Finally, in September 1989, mean densities of Chironomidae larvae at RKm 121, 127, and 183 were significantly lower than those at Rkm 205 and 211, and the mean density at RKm 121 was significantly lower than that at RKm 153. Density of Chironomidae larvae was not significantly related to water depth and sediment characteristics after accounting for year, month, and area (Table 4).

There were no significant interactions between year, month, and area for mean densities of Ceratopogonidae larvae. There were significant differences for mean densities of Ceratopogonidae larvae between years ($P = 0.007$) and months ($P = 0.009$), but not between areas ($P = 0.131$). The mean density in 1988 was significantly higher than that in 1989. The mean density of Ceratopogonidae larvae in September was significantly higher than that in April. Density of Ceratopogonidae larvae was negatively related to percent silt/clay after accounting for year, month, and area ($P < 0.001$); however, percent silt/clay explained only 12% of the variation in Ceratopogonidae larvae density (Table 4).

Discussion

It is often difficult to compare data from benthic invertebrate studies done by different investigators. Frequently, there are differences in samplers, sieve sizes, sampling designs, and analyses used by researchers. Given these caveats, we will generally compare findings from the present study to other large-river benthic invertebrate studies. In our study, we observed benthic invertebrate densities somewhat similar to those reported for the Fraser River, British Columbia, and the Hudson River, New York (Northcote et al. 1976, Ristich et al. 1977). In the mainstem of the Fraser River, Northcote et al. (1976) found that annual densities of benthic organisms (including lamprey ammocoetes) usually averaged about 1,000 organisms/m^2, with seasonal averages generally highest in the spring. Dipteran larvae and oligochaetes were the dominant taxa in the mainstem of the Fraser River. Ristich et al. (1977) observed that densities of benthic invertebrates at freshwater stations in the lower Hudson River generally averaged less than 1,000 organisms/m^2 during the four sampling periods. Dominant taxa in freshwater areas of the Hudson River included oligochaetes, chironomids, and other insect species. In the lower Columbia River between RKm 121 and RKm 211, benthic invertebrate densities at individual areas (by survey) often exceeded 1,000 organisms/m^2 in 1988. However, in 1989, benthic invertebrate densities never averaged more than 936 organisms/m^2. Overall, *Corbicula fluminea* and Ceratopogonidae (Diptera) larvae were consistently the most abundant benthic invertebrates in the benthos of main channel areas of the lower Columbia River (Table 3).

Our comparisons of benthic invertebrate densities by area, month, and year highlight the temporal and spatial variabilities in benthic invertebrate populations in the lower Columbia River. Other studies of benthic invertebrates in the lower Columbia River have produced similar findings (e.g., Hinton et al. 1995, McCabe and Hinton 1996, McCabe et al. 1996). For example, McCabe et al. (1996) observed that densities of *Corbicula fluminea* and Ceratopogonidae larvae were significantly different ($P < 0.05$) between surveys and areas in a study conducted near RKm 70 and 73, and *Corophium* spp. densities were significantly different between surveys ($P < 0.05$).

Results from our regression analysis indicated that the density of *Corophium salmonis* was negatively correlated with water depth and positively correlated with percent silt/clay (Table 4). Similarly, McCabe and Hinton (1991) observed that mean densities of *Corophium salmonis* at shallow-water stations (2-5 m deep) at RKm 153 from June through September 1990 frequently exceeded 1,200 organisms/m^2, whereas at nearby channel areas (11-21 m), mean densities of *Corophium salmonis* never exceeded 355 organisms/m^2. McCarthy (1973) observed that *Corophium salmonis* was most frequently found in mud (<0.25 mm), although it also lived in coarser sediments. Hinton et al. (1995) and McCabe and Hinton (1996) noted significant ($P < 0.05$) regression relationships between median grain size and *Corophium* spp. density. In both studies, there was a negative correlation between median grain size and *Corophium* spp. density.

In our study, the density of *Corbicula fluminea* was negatively correlated with percent silt/clay and positively correlated with percent volatile solids (Table 4). In a laboratory and field-laboratory study, fine sand (predominantly between 0.25-0.70 mm particle size in the laboratory and 0.35-0.60 mm in the field-laboratory) was the preferred substrate for *Corbicula fluminea*; however, the clam can use a wide range of substrates, from fine sand to coarser material (Belanger et al. 1985). Fine sand was preferred over organically enriched fine sand. Median grain sizes at many of sampling sites in the seven areas we sampled in the lower Columbia River were within the 0.25-0.70 mm range (Table 1).

Higher bottom water velocities in the main channels than in shallow littoral areas, backwaters, and side channels, probably result in less favorable habitat for specific invertebrates, particularly the tube-building amphipod *Corophium salmonis*. The higher water velocities could limit standing crops of benthic invertebrates by periodically scouring them out of the main channel habitats during periods of high river flow. Periodic scouring and disruption of the bottom sediments may also not allow sufficient buildup of detritus and fine material to support high standing crops of benthic invertebrates.

Because the primary focus of our study was juvenile white sturgeon habitat, our benthic sampling was limited to main channels of the lower Columbia River; consequently, we did not sample a wide range of depths and sediment types. For example, we generally collected no samples in habitats less than 4 m deep. Sampling of a wider range of depths and sediments may have resulted in better regression relationships between densities of benthic invertebrates and water depth and sediment characteristics.

The lower Columbia River is a navigational channel for commercial ships and barges and requires periodic dredging to maintain adequate depths. Dredged material is often disposed of at deep inwater areas in the lower river. Dredging or disposal operations could impact benthic invertebrates in channel areas downstream from RKm 205.

In general, results from our study are probably applicable to a large area of the Columbia River downstream from Bonneville Dam (RKm 234). The main channel habitats that we sampled are representative of a large area of the lower Columbia River between the estuary (RKm 0-75) and Bonneville Dam (see NOAA Navigational Charts 18523, 18524, and 18531). Much of the river in this reach consists of channel habitat with depths frequently exceeding 10 m. In addition, the substrate in most of the Columbia River between the mouth and Bonneville Dam is sand (0.062-<2 mm). Parsley and Beckman (1994) estimated that the predominant substrate in about 99% of this river reach was sand.

A comprehensive benthic invertebrate study of all aquatic habitat types in the lower Columbia River should be conducted to adequately describe the distribution, abundance, and ecology of these organisms. For example, more research should be concentrated on shallow littoral habitats of the lower Columbia River. These shallow areas, which often support higher standing crops of benthic invertebrates than main channel areas, are generally more susceptible to human impacts than the main channel areas. Besides sampling all habitat types, it is important to establish long-term studies of benthic invertebrate populations in the lower Columbia River in order to recognize natural temporal variations. These studies are necessary to determine the effects of man-made and natural perturbations on the benthos in the lower Columbia River. Within the last 18 years, there have been two major oil spills (1978 and 1984) and one natural disaster, the eruption of Mount St. Helens in 1980, which impacted the benthos of the lower Columbia River. Without long-term studies, it is impossible to determine the extent of the effects of such perturbations on benthic invertebrate communities. Because benthic invertebrates, particularly *Corophium salmonis*, are primary prey for many fishes, the sustained health of benthic invertebrate populations in the lower Columbia River is of concern.

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Literature Cited

Belanger, S. E., J. L. Farris, D. S. Cherry, and J. Cairns, Jr. 1985. Sediment preference of the freshwater Asiatic clam, *Corbicula fluminea*. The Nautilus 99(2-3):66-73.

Blahm, T. H., J. T. Durkin, R. J. McConnell, L. G. Davis, and T. C. Coley. 1979. Portland Harbor predredge and disposal study. Final Rep. to U.S. Army Corps of Eng. by U.S. Natl. Mar. Fish. Serv., Seattle, Washington. 30 p.

Blahm, T. H., and R. J. McConnell. 1979. Impact of flow-lane disposal at Dobelbower Bar. Final Rep. to U.S. Army Corps of Eng. by U.S. Natl. Mar. Fish. Serv., Seattle, Washington. 25 p.

DeVore, J. D., B. W. James, C. A. Tracy, and D. A. Hale. 1995. Dynamics and potential production of white sturgeon in the unimpounded lower Columbia River. Trans. Amer. Fish. Soc. 124:845-856.

Durkin, J. T., T. C. Coley, K. Verner, and R. L. Emmett. 1981. An aquatic species evaluation at four self scouring sites in the Columbia River estuary. Final Rep. to U.S. Army Corps of Eng. by U.S. Natl. Mar. Fish. Serv., Seattle, Washington. 46 p.

Durkin, J. T., and R. L. Emmett. 1980. Benthic invertebrates, water quality, and substrate texture in Baker Bay, Youngs Bay, and adjacent areas of the Columbia River estuary. Final Rep. to U.S. Fish Wildl. Serv. by U.S. Natl. Mar. Fish. Serv., Seattle, Washington. 44 p. plus appendices.

Durkin, J. T., R. L. Emmett, K. Verner, T. C. Coley, W. Muir, G. T. McCabe, Jr., and R. J. McConnell. 1982. Benthic macroinvertebrates and substrate of Cathlamet Bay, Oregon. Final Rep. to U.S. Fish Wildl. Serv. by U.S. Natl. Mar. Fish. Serv., Seattle, Washington. 87 p.

Elliott, J. M. 1977. Some methods for the statistical analysis of samples of benthic invertebrates. Freshwater Biol. Assoc. Sci. Publ. 25. 160 p.

Emmett, R. L., G. T. McCabe, Jr., T. C. Coley, R. J. McConnell, and W. D. Muir. 1986. Benthic sampling in Cathlamet Bay, Oregon—1984. Final Rep. to U.S. Army Corps of Eng. by U.S. Natl. Mar. Fish. Serv., Seattle, Washington. 11 p. plus appendices.

Higley, D. L., and R. L. Holton. 1978. A grab-sample study of the benthic invertebrates of the Columbia River estuary—supplemental data report 1 November 1975 through 29 February 1976. Supplement to Reference 76-3. Oregon State Univ., Corvallis. 27 p.

Hinton, S. A., G. T. McCabe, Jr., and R. L. Emmett. 1990. Fishes, benthic invertebrates, and sediment characteristics in intertidal and subtidal habitats at five areas in the Columbia River estuary. Final Rep. to U.S. Army Corps of Eng. by U.S. Natl. Mar. Fish. Serv., Seattle, Washington. 92 p. plus appendices.

Hinton, S. A., G. T. McCabe, Jr., and R. L. Emmett. 1995. In-water restoration between Miller Sands and Pillar Rock Island, Columbia River: environmental surveys, 1992-93. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-NWFSC-23. 47 p.

Jones, K. K., C. A. Simenstad, D. L. Higley, and D. L. Bottom. 1990. Community structure, distribution, and standing stock of benthos, epibenthos, and plankton in the Columbia River estuary. Prog. Oceanog. 25:211-241.

Kim, R. A., R. D. Ledgerwood, and A. L. Jensen. 1986. Diet of subyearling chinook salmon (*Oncorhynchus tshawytscha*) in the Columbia River estuary and changes effected by the 1980 eruption of Mount St. Helens. Northw. Sci. 60(3):191-196.

McCabe, G. T., Jr., R. L. Emmett, and S. A. Hinton. 1993. Feeding ecology of juvenile white sturgeon (*Acipenser transmontanus*) in the lower Columbia River. Northw. Sci. 67(3):170-180.

McCabe, G. T., Jr., R. L. Emmett, W. D. Muir, and T. H. Blahm. 1986. Utilization of the Columbia River estuary by subyearling chinook salmon. Northw. Sci. 60(2):113-124.

McCabe, G. T., Jr., and S. A. Hinton. 1990. Benthic infauna and sediment characteristics in the Columbia River near Westport, Oregon, August 1989. Final Rep. to U.S. Army Corps of Eng. by U.S. Natl. Mar. Fish. Serv., Seattle, Washington. 14 p.

__________. 1991. Report D. *In* A. A. Nigro (ed.), Status and habitat requirements of the white sturgeon populations in the Columbia River downstream from McNary Dam. Annu. Rep. to Bonneville Power Admin. (Project 86-50), Portland, Oregon. Pp. 145-180.

__________. 1996. Benthic invertebrates and sediment characteristics in freshwater, beach habitats of the lower Columbia River, 1994-95. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-NWFSC-26. 111 p.

McCabe, G. T., Jr., S. A. Hinton, and R. L. Emmett. 1996. Benthic invertebrates and sediment characteristics in Wahkiakum County Ferry Channel, Washington, before and after dredging. Final Rep. to U.S. Army Corps of Eng. by U.S. Natl. Mar. Fish. Serv., Seattle, Washington. 32 p.

McCabe, G. T., Jr., S. A. Hinton, R. L. Emmett, and R. J. McConnell. 1990. Benthic invertebrates, sediment characteristics, and demersal fishes off Cottonwood Island, Columbia River, before and after rock groin construction, 1987-1988. Final Rep. to U.S. Army Corps of Eng. by U.S. Natl. Mar. Fish. Serv., Seattle, Washington. 17 p. plus appendices.

McCabe, G. T., Jr., W. D. Muir, R. L. Emmett, and J. T. Durkin. 1983. Interrelationships between juvenile salmonids and nonsalmonid fish in the Columbia River estuary. Fish. Bull., U.S. 81:815-826.

McCabe, G. T., Jr., and C. A. Tracy. 1994. Spawning and early life history of white sturgeon, *Acipenser transmontanus*, in the lower Columbia River. Fish. Bull., U.S. 92:760-772.

McCarthy, J. E. 1973. The distribution, substrate selection and sediment displacement of *Corophium salmonis* (Stimpson) and *Corophium spinicorne* (Stimpson) on the coast of Oregon. Doctoral Thesis, Oregon State Univ., Corvallis. 61 p.

Muir, W. D., and R. L. Emmett. 1988. Food habits of migrating salmonid smolts passing Bonneville Dam in the Columbia River, 1984. Regul. Rivers Res. & Manage. 2:1-10.

Muir, W. D., R. L. Emmett, and R. J. McConnell. 1988. Diet of juvenile and subadult white sturgeon in the lower Columbia River and its estuary. Calif. Fish Game 74(1):49-54.

Northcote, T. G., N. T. Johnston, and K. Tsumura. 1976. Benthic, epibenthic and drift fauna of the lower Fraser River. Westwater Res. Cent. Tech. Rep. 11. Univ. British Columbia, Vancouver. 227 p.

Parsley, M. J., and L. G. Beckman. 1994. White sturgeon spawning and rearing habitat in the lower Columbia River. N. Amer. Jour. Fish. Manag. 14:812-827.

Parsley, M. J., L. G. Beckman, and G. T. McCabe, Jr. 1993. Spawning and rearing habitat use by white sturgeons in the Columbia River downstream from McNary Dam. Trans. Amer. Fish. Soc. 122:217-227.

Petersen, R. G. 1985. Design and analysis of experiments. Marcel Dekker, Inc. New York. 429 p.

Ristich, S. S., M. Crandall, and J. Fortier. 1977. Benthic and epibenthic macroinvertebrates of the Hudson River. I. Distribution, natural history, and community structure. Estuarine Coastal Mar. Sci. 5:255-266.

Sanborn, H. R. 1975. Benthic infauna observed at five sites in the Columbia River from August 1973 to July 1974. Final Rep. to U.S. Army Corps of Eng. and Columbia River Fish. Prog. Office (Natl. Mar. Fish. Serv.) by U.S. Natl. Mar. Fish. Serv., Seattle, Washington. 21 p.

Word, J. Q. 1976. An evaluation of benthic invertebrate sampling devices for investigating feeding habits of fish. *In* C. A. Simenstad and S. J. Lipovsky (eds.), Fish food habits studies, 1st Pacific Northwest technical workshop. Washington Sea Grant WSG-WO 77-2, University of Washington, Seattle. Pp. 43-55.

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