AN ABSTRACT OF THE THESIS OF

Scott D. Lewis for the degree of Master of Science in Fisheries Science presented on 24 November 1997. Title: Life History, Population Dynamics, and Management of Signal Crayfish in Lake Billy Chinook, Oregon.

Abstract approved: Signature redacted for privacy.
Howard F. Horton

Signal crayfish *Pacifastacus leniusculus* were studied in Lake Billy Chinook, Oregon, during 1994 and 1995. Because little was known about the crayfish population, this study was conducted to obtain reliable estimates of life history and population parameters, document historic commercial harvests, and make management recommendations. Crayfish were captured with baited traps and by hand using SCUBA gear. Maturation of both male and female crayfish occurred during the fall of their third year at age 2+. Copulation of mature crayfish began during the first week of October in 1994 and 1995. In 1995, hatching began during the second week of April. The estimated mean days and thermal units required for egg incubation was 166 days and 2,208 degree-days, respectively. Mean pleopod fecundity during the incubation period was 105 ± 12 (mean ± 95% CI) eggs. Crayfish were captured as deep as 100 m, but 98% of the population was found at depths $\leq$ 70 m. The peak relative abundance of crayfish occurred at 10-20 m. Diel activity of crayfish was primarily nocturnal and was skewed towards sunset. Eight age classes were identified from analyses of length-frequency distributions. The sex composition of crayfish appeared to be a

50:50 ratio and only deviated because of behavioral changes related to hatching. The mean density of crayfish, estimated from transects, in five habitat types ranged from 0.24 crayfish/m^2 to 1.13 crayfish/m^2. The trappable population in Lake Billy Chinook was estimated to be 8,437,029 ± 2,252,332 crayfish. Total abundance, which included quadrat estimates for 0+ and 1+ crayfish, was estimated to be 35,940,145 ± 8,127,159. The mean molt increment of recaptured crayfish was 3.0 mm. The calculated population instantaneous mortality rate was Z = 0.67. Total estimated annual production and total biomass of crayfish was 21.16 g/m^2 and 33.80 g/m^2, respectively. The majority of tagged crayfish moved < 500 m; however, 21% moved > 1,000 m in one year. Of the total volume of smallmouth bass *Micropterus dolomieu* stomachs that had food items, crayfish represented 95.3%. The crayfish population in Lake Billy Chinook had been commercially harvested since 1970. Harvest peaked in 1987 at 69,967 kg. There was a strong correlation between the number of commercial licenses and kg of crayfish harvested from 1981 to 1995. Management recommendations include decreasing the commercial fishing season by 2 months and requiring trap-set information to be recorded with harvest sales tickets. If managed wisely, *P. leniusculus* in Lake Billy Chinook could continue to support a sustainable fishery.

Life History, Population Dynamics, and Management of Signal Crayfish in Lake Billy Chinook, Oregon.

by

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Dean of Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

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Scott D. Lewis, Author

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LIFE HISTORY, POPULATION DYNAMICS, AND MANAGEMENT OF SIGNAL CRAYFISH IN LAKE BILLY CHINOOK, OREGON.

INTRODUCTION

Wild populations of the indigenous signal crayfish *Pacifastacus leniusculus* in Oregon (Riegel 1959; Miller 1960; Taylor et al. 1996) have been commercially harvested since 1893 (Miller and Van Hyning 1970). A portion of a lotic population in the Deschutes River was inundated by Lake Billy Chinook (LBC) in 1964 with the completion of Round Butte Dam. The impounded water formed a three-armed reservoir that is comprised of the Crooked River, Deschutes River, and Metolius River arms. Because *P. leniusculus* can readily adapt to a range of aquatic environments (Hogger 1988; Lowery and Holdich 1988), this formerly lotic population now occupies and prospers in the lentic environment of LBC.

Commercial harvest of crayfish from LBC began in 1970 (C. D. Snow, Oregon Department of Fish and Wildlife, retired, personal communication); although, the most substantial annual harvests occurred during the 1980s. The mean annual harvest during the 1980s was 25,471 kg, peaking at 69,967 kg in 1987. Harvest decreased thereafter because of a drop in market price and an increase in the minimum legal size. Commercial harvest of crayfish is managed by the Oregon Department of Fish and Wildlife (ODFW) in the Crooked River and Deschutes River arms, and in the Metolius River arm it is managed by the Confederated Tribes of the Warm Springs Reservation of Oregon (CTWSRO).

To properly manage crayfish, knowledge about biology, population size and structure, habitat requirements, and ecological niche are needed (Hogger 1988). Because insufficient information for *P. leniusculus* in LBC was available, management regulations were based on information from other populations. This practice could be unreliable because life history and population characteristics of *P. leniusculus* can vary between environments (Flint 1975*a*, 1976; Cukerzis 1978; Kossakowski 1988; Westman et al. 1993). If the characteristics of a managed population differ significantly from the population that the regulations are based, detrimental effects may result at times of high sustained harvest. Therefore, regulations should be based on biological characteristics of the population for which they are intended.

Objectives

The fundamental objectives of this study were to obtain reliable estimates of life history and population characteristics of *P. leniusculus* in LBC, to determine aspects of the ecological significance of *P. leniusculus* in LBC, to document the historic commercial harvests and management practices, and to make recommendations to fishery managers responsible for the management of *P. leniusculus* in LBC. Specific research objectives and their respective sub-objectives are in Appendix 1.

Literature Review

Life History

Mating of *P. leniusculus* in other populations typically occurs in the fall as early as August and as late as December (Mason 1963; Biggs 1980). Mean pleopod fecundity estimates for *P. leniusculus* range from 110 to 201 eggs per female (Abrahamsson and Goldman 1970; McGriff 1983*a*). Fertilized eggs are attached to the pleopods of females where they are incubated until hatching in the spring, ranging from April to July (Mason 1963; Flint 1975*a*; Lowery and Holdich 1988). After hatching, dependent juveniles remain attached to the pleopods of the female until after the second molt, at which time the juveniles become independent (Hogger 1988). Estimated age at maturity for male and female *P. leniusculus* ranges from 2 to 4 years (Abrahamsson 1971; Shimizu and Goldman 1981). Growth rates also vary; for example, the carapace length of age 3+ *P. leniusculus* ranges from 28 to 62 mm (Goldman and Rundquist 1977; Lowery 1988).

There are many pathogens and parasites to which *P. leniusculus* is susceptible, but only a few are known to cause mass mortality in wild populations (Hogger 1988). The fungi *Aphanomyces astaci*, which decimated native crayfish populations throughout Europe, usually does not affect *P. leniusculus* because they are highly resistant to infection (Persson and Söderhäll 1981; Alderman and Polglase 1988). However, under the right conditions (e.g., high water temperatures and crayfish densities) *A. astaci* can cause significant mortalities

(Alderman and Polglase 1988). A characteristic sign of chronic *A. astaci* infection is melanisation of fungal hyphae in the musculature, which can be seen through the exoskeleton on the ventral side of the abdomen (Nylund and Westman 1981). The microsporidian *Thelohania contejeani* has been known to infect 3-30% of a crayfish population (McGriff and Modin 1983). Crayfish infected with *T. contejeani* develop a characteristic opaque white appearance from the accumulation of spores in the musculature, which can be observed through the exoskeleton on the ventral side of the abdomen (McGriff and Modin 1983; France and Graham 1985; Alderman and Polglase 1988). *T. contejeani* is thought to be spread only by ingestion of spores from infected crayfish (Alderman and Polglase 1988). Because of the cannibalistic nature of crayfish, an epizootic of *T. contejeani* in conjunction with high crayfish densities might lead to high mortality (Alderman and Polglase 1988). Although the majority of the leech-like annelid *Branchiobdella* species are considered to be ecto-commensals, infestations in high numbers can lead to secondary infections by other pathogens (Alderman and Polglase 1988).

Population Dynamics

P. leniusculus can occupy a range of habitats and environmental conditions (Lowery and Holdich 1988). Most investigators have found that high densities of crayfish are associated with greater amounts of large substrate (Flint 1975*b*; Shimizu and Goldman 1981; Davies 1989). Abrahamsson and Goldman (1970) found that crayfish density was greatest at a depth of 10-20 m during the summer. Flint (1975*a*) found that crayfish migrated to deeper water in winter and that horizontal movements of crayfish were no more than 200 m over a 4-week period.

Age estimation of *P. leniusculus* is difficult because crayfish do not have hard structures with annuli that age can be estimated from (Grant et al. 1987; France et al. 1991). The simplest method for estimating crayfish age is to interpret the principal peaks of a polymodal length-frequency distribution (called the "Peterson method") as representing different age classes (Grant et al. 1987). Due to population genetic variation and environmental conditions, the distribution of a single age class will begin to overlap with neighboring age classes after 3 to 4 years (France et al. 1991). When this occurs, other graphical and mathematical methods are available. France and Graham (1985) used the probability plot method of Cassie (1954) on a *P. leniusculus* population. Flint (1975*b*) and Shimizu and Goldman (1981) used the parabola method of Tanaka (1962) and determined that their *P. leniusculus* study populations had nine and six age classes, respectively. These methods share the same graphical bias for identifying age classes in that they are subjective, non-reproducible, and do not provide estimates of confidence intervals (Macdonald and Pitcher 1979; France et al. 1991). Somers (1987) used the mathematical computer program of Macdonald and Pitcher (1979) which reduces, but does not eliminate, subjectivity and allows for reproducible age classes, with true confidence intervals, to be estimated (France et al. 1991).

Sex ratios of captured *P. leniusculus* appear to fluctuate seasonally (Flint 1975*b*). Male crayfish dominate trap catches when females are ovigerous in the fall, winter, and spring. Females dominate for a period after young-of-the-year hatch in the late spring and females molt and resume feeding (Westin and Gydemo 1987).

Estimates of crayfish density and abundance have been made using many different methods (Abrahamsson and Goldman 1970; Flint 1975*a*; Quinn and Janssen 1989); although, the mark-recapture method is the most widely used. Flint (1975*a*) used the mark-recapture method with *P. leniusculus* in Lake Tahoe and obtained density estimates of 0.7-6.0 crayfish/m^2. Abrahamsson and Goldman (1970) used density estimates from quadrat counts of *P. leniusculus* in Lake Tahoe, obtained with SCUBA equipment, to develop an index for the catch per trap. This index was then applied to trap catches from other depths and resulted in a mean estimate of 0.9 crayfish/m^2.

Crayfish are important elements in the food web of all ecosystems that they occupy (Hogger 1988). They display opportunistic polytrophic feeding habits (i.e., carnivores, detritivores, and herbivores) and are thus key transformers of energy between several trophic levels in lakes (Momot et al. 1978; Goddard 1988). Crayfish are a food source for many teleost fish species including smallmouth bass *Micropterus dolomieu* (Stein 1977; Pflug and Pauley 1984), largemouth bass *M. salmoides* (Collins et al. 1983), rainbow trout *Oncorhynchus mykiss* (Hepworth and Duffield 1987), and northern squawfish *Ptychocheilus oregonensis* (Jeppson and Platts 1958). The majority of crayfish are consumed during the summer months (Stein 1977; Hepworth and Duffield 1987). The ages of crayfish most frequently found in stomachs of predatory fish are 0+ and 1+ (Stein 1977). In some cases, fish stomachs have been found to contain 100% crayfish (Hepworth and Duffield 1987).

Management

The most frequently used management methods to prevent overharvest of crayfish in commercial fisheries are minimum size and fishing season restrictions (Momot 1991; Thomas 1991). Overharvest occurs in two phases, growth overharvest and recruitment overharvest. Growth overharvest occurs when a population's mean size is reduced over successive fishing seasons. The more serious of the two, recruitment overharvest, occurs when the mean age of the crayfish population drops below the mean age at maturity. When this occurs, the stock may collapse. Growth overharvest does not effect recruitment because of compensatory responses in survival and growth (Momot 1991).

Study Area

Lake Billy Chinook is a reservoir located behind Round Butte Dam in central Oregon on the Deschutes River 179 km upriver from its confluence with the Columbia River (Figure 1). Round Butte Dam is owned and operated by Portland General Electric Company (PGE) under the Federal Energy Regulatory Commission license No. 2030. Based on LBC's limnological characteristics, it is classified as a eutrophic warm-monomictic reservoir (Wetzel 1983). LBC has a surface area of 1,585 ha, a shoreline of 100 km, and an elevation of 593 m at full pool (Johnson et al. 1985). The Crooked, Deschutes, and Metolius arms comprise 23%, 26%, and 51% of the total lake surface area, respectively. The corresponding length of each arm is 10.5 km, 14.0 km, and 19.5 km (Figure 1). LBC has a volume of 487,872,000 m^3 and a maximum and mean depth of 126 m and 31 m, respectively (Johnson et al. 1985). The reservoir has a narrow littoral zone, as is indicated by its shoal area (i.e., the lake surface area with a depth ≤ 3.3 m) of only 5% (Figure 2). The Deschutes River Basin above LBC encompasses 18,236 km^2 and receives an annual precipitation ranging from 25 to 229 cm (Johnson et al. 1985).

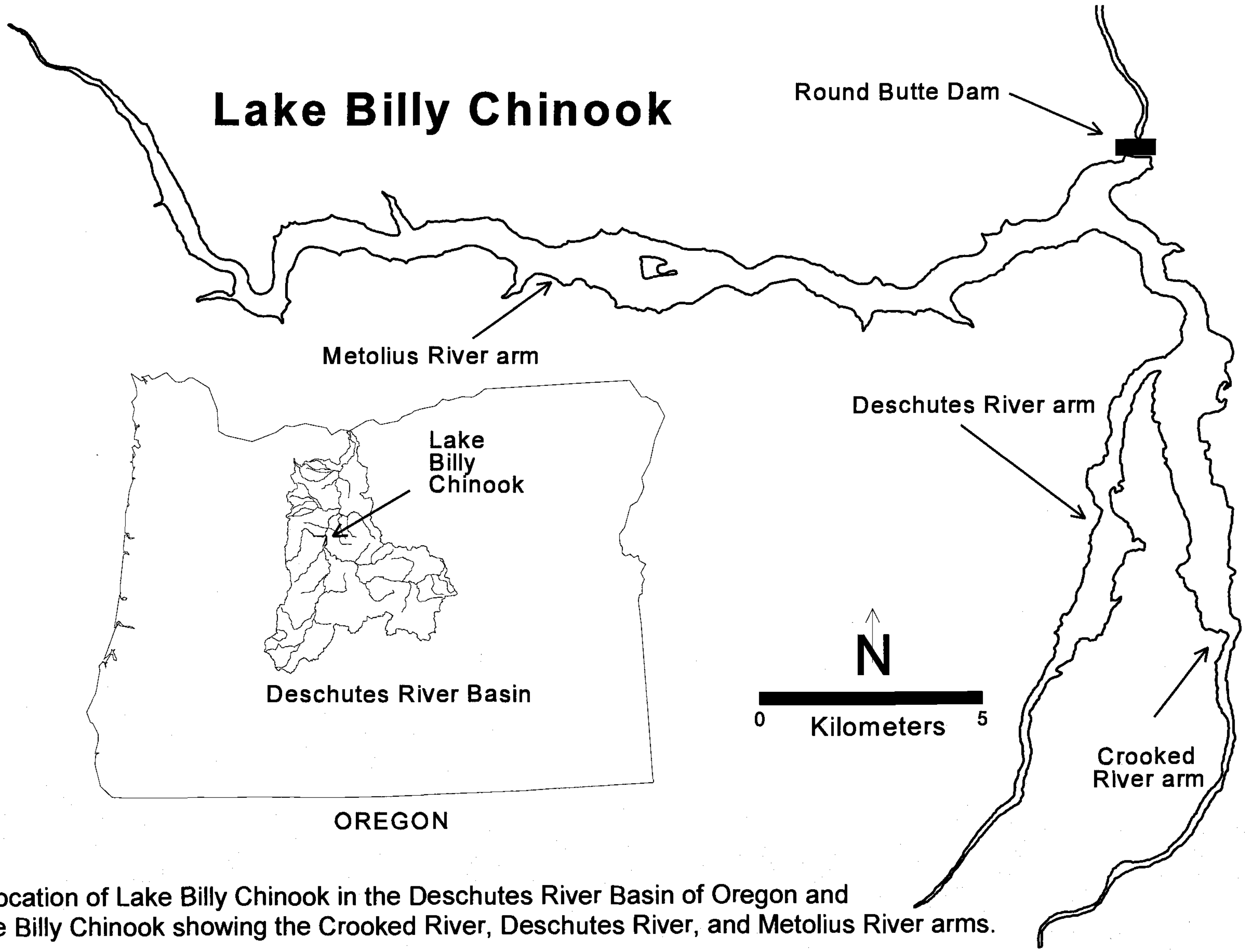

Figure 1. Location of Lake Billy Chinook in the Deschutes River Basin of Oregon and map of Lake Billy Chinook showing the Crooked River, Deschutes River, and Metolius River arms.

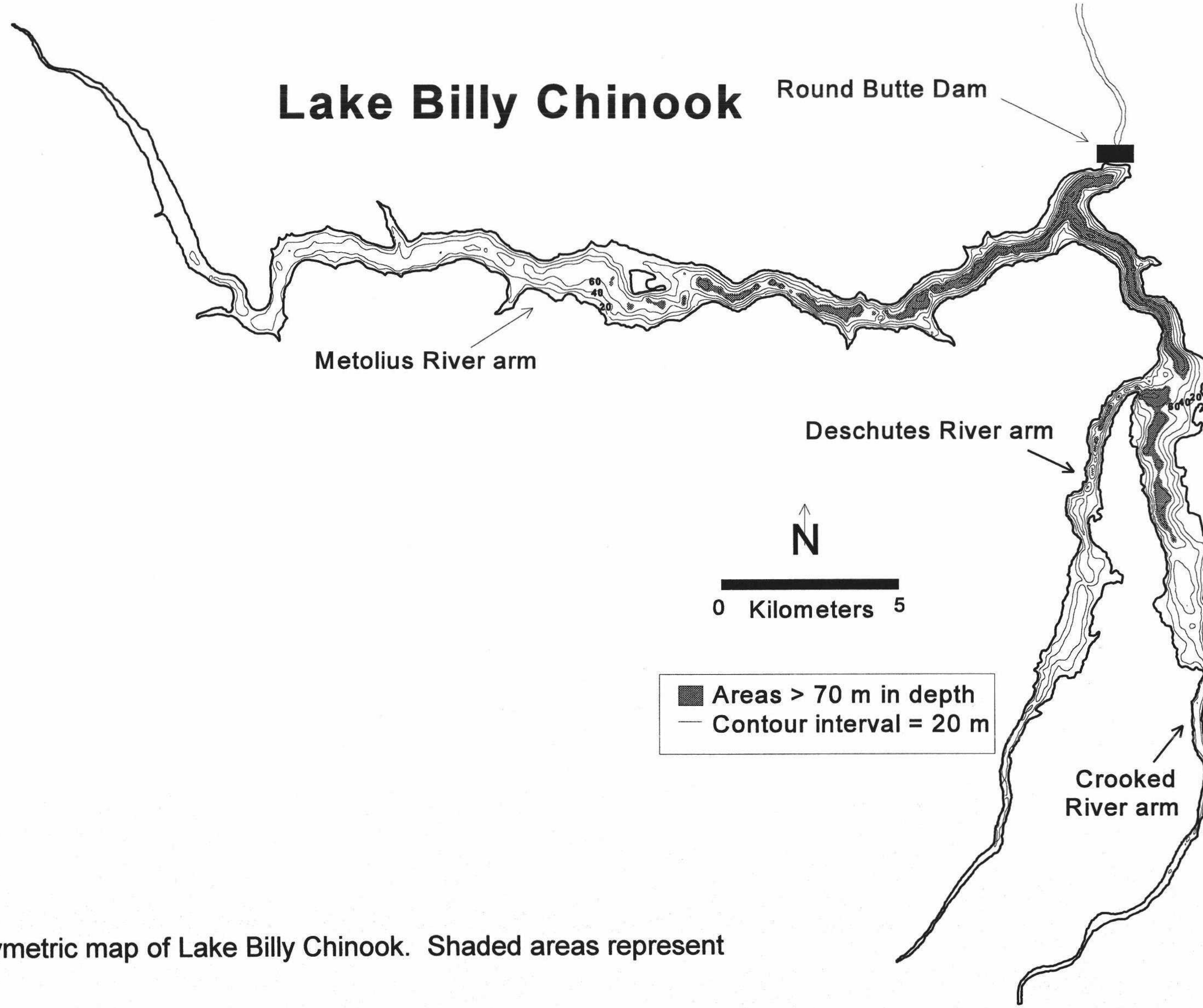

Figure 2. Bathymetric map of Lake Billy Chinook. Shaded areas represent depths > 70 m.

METHODS

General Methods

Crayfish were captured with cylindrical funnel traps baited with approximately 200 g of northern squawfish; ether whole or cut pieces. The traps were 61 cm in length by 28 cm in diameter and were made from either 1.3-cm^2 or 2.5-cm x 1.3-cm wire mesh. Funnel-entrance diameters ranged from 2.5 cm to 5.5 cm to reduce size and sex biases associated with trapping crayfish (Stuecheli 1991). Five to twenty traps were attached to a nylon rope in a longline-fashion and spaced at 5-m or 10-m intervals. Traps baited and set in the afternoon were retrieved the following morning. The mean time that traplines were in the water was 15 h. Metric coordinates for all traplines were recorded to the nearest 10 m using the Universal Transverse Mercator grid on U.S. Geological Survey 7.5 min topographical maps. Crayfish were also collected by hand using SCUBA equipment in water $\leq$ 10 m.

Post-orbital carapace length (POCL) was measured to the nearest 0.1 mm with calipers, which was the distance from the posterior portion of the eye socket to the posterior edge of the carapace. Total length (TL) was measured to the nearest 1.0 mm using a measuring board; which was measured from the anterior tip of the rostrum, called the acumen, to the posterior edge of the telson. Crayfish were weighed to the nearest 0.1 g with a digital scale.

Sex was determined by examining the pleopods on the ventral surface of the abdomen. On male crayfish, the first and second pairs of pleopods are modified into copulatory appendages. Conversely, the first pair of pleopods of female crayfish is vestigial. Three water temperature profiles were recorded monthly, one in each of the three arm of the lake. All analyses were considered significant at $\alpha = 0.05$. All error terms are 95% confidence intervals unless otherwise stated.

Life History

Reproduction

Maturation. — Male crayfish maturity was determined in September, just prior to mating, by the presence of mature white sperm in the vas deferens (Abrahamsson and Goldman 1970). Female maturity was also determined in September by the presence of mature eggs in the ovary (mature eggs become larger and change color from yellowish-white to brown as yolk is stored) or well-developed glare glands (developed glare glands are noticeably white) on the ventral surface of the abdomen (Abrahamsson and Goldman 1970; Mason 1970*a*). Color changes in the vas deferens and ovary of male and female crayfish, respectively, were observed by bending the abdomen under the carapace to expose the translucent exoskeleton between the carapace and the abdomen. Thus, maturity was determined without sacrificing crayfish. The median minimum size at sexual maturity of male and female crayfish was estimated by plotting the percent of mature crayfish on a probability scale against size (Wenner et al. 1975). The median minimum size was determined from the 50% intercept with linear regression lines for each sex.

Copulating and Spawning. — Time of copulating and spawning was determined from weekly samples of crayfish during the fall of 1994 and 1995. Females that had spermatophores attached to the fused sterna between the third pair of walking legs indicated that they had copulated (Mason 1970*b*). Spawning was determined by the occurrence of ovigerous female crayfish (female crayfish with eggs attached to their pleopods) in the catch (Mason 1970*a*). The time period between copulating and spawning was determined by the difference between the peak occurrence of copulated females and when 50% were ovigerous.

Hatching. — To determine hatching time, crayfish were trapped weekly during the spring of 1995 and females were examined for first- and second-stage dependent juveniles attached to the pleopods (Mason 1970*c*).

Incubation. — The mean incubation period was estimated by determining the number of elapsed days between when 50% of the females were ovigerous after copulation in the fall of 1994 and when 50% of the females were ovigerous before hatching occurred in the spring of 1995. The mean water temperature (°C) was estimated by calculating the combined mean of all three arms. The degree-days required for egg incubation was calculated using the equation (Keller 1988):

$$°D = I \times \overline{T} \tag{1}$$

Where:

$$°D = \text{Degree - days required for egg incubation.}$$
$$I = \text{Mean incubation period (days).}$$
$$\overline{T} = \text{Mean water temperature (°C) during incubation period.}$$

Fecundity. — Females were sampled monthly from November 1994 to March 1995 to estimate pleopod egg numbers as a measure of reproduction potential (Mason 1977). The months of October and April were excluded to ensure that the majority of females were ovigerous so fecundity estimates would not be biased.

<u>Pathogens and Parasites</u>

Crayfish were visually examined throughout the duration of the study for presence of *Branchiobdella* sp. and gross signs of infection from *A. astaci* and *T. contejeani* (Alderman and Polglase 1988; Hogger 1988). When crayfish were observed with gross signs of infection from *T. contejeani*, wet-mount microscope slides of abdominal tissue were examined to verify field observations (McGriff and Modin 1983). Pathogen and parasite observations were summarized for each month.

Population Dynamics

Habitat

The substrate of LBC was divided into large-scale habitat types using pre-Round Butte Dam aerial photographs taken in 1956 and 1961. These habitat types were field checked using SCUBA equipment, a fathometer, and an Ekman dredge. Habitat types were mapped out and the surface areas were measured with a compensating polar planimeter and expanded based on the mean slope of the lake bottom. To determine the depth distribution of crayfish, 5-trap traplines were set at 5-m depth intervals from the surface to 90 m (Abrahamsson and Goldman 1970).

Age and Sex Composition

Length-frequency distributions of trapped and hand captured crayfish were analyzed using the computer program Mix (Macdonald and Pitcher 1979). The program dissects a mixed length-frequency distribution into components and fits a normal curve to each component that represents a single age class (Grant et al. 1987; France et al. 1991). Initial estimates of the number of age classes were required. The first fitted curve represents the 0+ age class and the last represents the nth age class. Cohort and population mean sizes were calculated from the resulting length-frequency analyses.

Crayfish were trapped and sexed weekly during the summer, biweekly during the fall and spring, and monthly during the winter to determine seasonal changes of sex ratios.

Density

Density of crayfish, for each habitat type, was estimated by counting crayfish on underwater transect lines (Helfman 1983; Quinn and Janssen 1989) during the period of night when they were most active. To determine when crayfish were most active, diel activity was estimated by trapping crayfish from similar habitat in the lower 6 km of the Metolius River arm continually for 24 hours to estimate mean catch per hour. Using SCUBA equipment, all crayfish within 1 m on each side of 50-m transect lines were counted at night between 2300 h and 0300 h. The total count per transect was divided by 100 m^2 to yield the crayfish/m^2 density estimate. Transect lines were set in water $\leq$ 10 m.

The density of crayfish at all depths of LBC could not be estimating using the transect method because of SCUBA diving limitations. Therefore an additional method was used, in combination with the transect method, to estimate crayfish density at all depths in LBC. This method uses the capture range (CR) of a trap, which is the area in m^2 around a trap that attracts and captures crayfish for a given period of time. This enabled the use of trap catch from any depth to estimate crayfish density. Traps were set adjacent to the transect lines after the crayfish had been counted. The resulting mean catch per trap (C) was divided by the crayfish density (D), estimated from the transect count, to obtain the mean capture range. Capture ranges were calculated for habitats that traps could be set on. The equation used was:

$$CR_H\ (m^2) = \frac{\overline{C}_H = \dfrac{\sum_{i=1}^{n_C} x_{i,C}}{n_C}\ (\text{No.})}{\overline{D}_H = \dfrac{\sum_{i=1}^{n_D} x_{i,D}}{n_D}\ (\text{No./m}^2)} \qquad (2)$$

Where:

CR_H = Estimated trap capture range for habitat type H.
$\overline{C}_H$ = Mean catch per trap for habitat type H.
$\overline{D}_H$ = Mean crayfish density for habitat type H estimated from transects.

The estimated capture range provided an index to estimated mean density over the entire depth distribution of crayfish for each habitat type (Abrahamsson and Goldman 1970). The mean crayfish density was estimated by dividing the mean number of crayfish captured per trap, over the entire crayfish depth distribution for a specific habitat type, by the estimated capture range for that habitat type. For the mean density estimates, the mean crayfish catch per trap from the depth distribution was used instead of the transect catch per trap, and equation (2) was rewritten to solve for density (D):

$$\overline{D}_H = \frac{\overline{C}_H}{CR_H} \qquad (3)$$

Abundance

The resulting mean density estimate, using equation (3), for crayfish over their depth distribution was multiplied by the bottom surface area to estimate total abundance for each habitat type. Total abundance, using this method alone, was determined by summing the different abundance estimates for each habitat type. Abundance estimate error terms were derived by using the mean percent error, from 95% confidence intervals, of transect counts and catch per trap estimates for each respective habitat type.

Due to the size-selective bias of crayfish traps, the abundance estimates using this method did not include 0+ and 1+ age crayfish. Age 0+ and 1+ crayfish densities were estimated with quadrat sampling at depths $\leq$ 10 m (Lamontagne and Rasmussen 1993). A 1-m^2 quadrat was placed on the bottom and all loose substrate was removed while 0+ and 1+ age crayfish were captured by hand. Assuming that 0+ and 1+ age crayfish densities would be proportional to the densities of older crayfish in other non-sampled habitats allowed the total abundance of 0+ and 1+ age crayfish in LBC to be estimated. The total abundance of 0+ and 1+ age crayfish was estimated by expanding the quadrat estimates to other non-sampled habitats proportionally to the abundance estimates obtained for the combined transect and trapping method. Abundance estimate error terms were derived by using the mean percent error, from 95% confidence intervals, of quadrat density estimates.

Growth and Mortality

Growth in length was estimated using the analyzed length-frequency data fitted with a von Bertalanffy growth curve (Tyler and Gallucci 1980). The best fit of the growth curve was determined by using parameters that yielded the smallest residual sum of squared deviations between the model and the analyzed length-frequency data. The equation for the von Bertalanffy growth curve was:

$$l(t) = L_{\infty}(1 - e^{-K(t-t_0)}) \qquad (4)$$

Where:

L_{∞} = Asymptotic length.
K = Growth constant.
t_0 = The time at which $l(t) = 0$.

Growth in weight was determined from linear regression of log-transformed weight-length measurements. Growth was also estimated using linear regression from a pre-molt and post-molt relation (i.e., molt-increment) derived from mark-recapture data (Flint 1975*a*).

The annual molting pattern was determined by dissecting gastroliths of adult crayfish monthly (n = 40/month) and measuring their thickness to the nearest 0.1 mm. Crayfish have two gastroliths in their foregut that function as calcium storage structures. As a molt nears, the two gastroliths become larger as calcium is absorbed from the old exoskeleton and incorporated into the gastroliths. During a molt, part of the foregut is molted causing the two gastroliths to be shed in to the stomach where they are broken down and the calcium re-absorbed. Although the gastroliths only account for about 10% of the total calcium needed to re-harden the new exoskeleton, the mouth parts are hardened first so feeding can commence and the remaining calcium requirements can be acquired from the environment (Lowery 1988).

A survivorship curve was constructed from recruitment estimates, quadrat sampling, and length-frequency distributions. The recruitment estimate was derived by multiplying the density of mature females at the beginning of the copulation period by the mean fecundity of females in LBC then accounting for a hatching success of 22% (Mason 1970*c*) and first- to second-stage mortality of 87.5% (Flint 1975*a*). Recruitment occurs shortly after the first molt during the second-stage (Mason 1970*c*). Because of trapping bias, age 2+ and 3+ cohorts were estimated by interpolation from linear regression of density estimates between age 0+ and 1+ from quadrats and age 4+ to 7+ from trapping, using a natural log transformation. Using these estimates, mortality (Z) was calculated using the equation (Ricker 1975):

$$Z = -(\log_e N_{t+1} - \log_e N_t) \qquad (5)$$

Where:

Z = Instantaneous rate of total mortality.
N = Number of individuals, of each age, in a representive sample.

Production and Biomass

Crayfish production (P) was estimated using the removal-summation method of Hynes and Coleman (1968) as described by Waters and Crawford (1973) and used with crayfish by Shimizu and Goldman (1981). This method calculates annual production (g/m^2) as the sum of losses in weight between all age classes. Production was estimated from one habitat type and extrapolated to others by assuming that production differences would be proportionally the same as density differences between habitats.

Live-weight biomass (B) was estimated from the mean weight of crayfish in each age class multiplied by crayfish density for each habitat type and expressed in terms of g/m^2. Total biomass (kg) of crayfish in LBC was estimated by summing the biomass estimates for each habitat type.

The annual turnover ratio (P/B) was calculated by dividing annual production by total biomass (Wetzel 1983). Determining turnover ratios is useful in making comparisons between populations and their environments and for monitoring the same population over time (Shimizu and Goldman 1981).

Movements and Migrations

Crayfish captured with traps were marked with Floy FTSL-23 streamer tags in 1994. The tags were inserted through the membrane between the carapace and the abdomen on the dorsal side. Tags were numbered and had a return address to aid in their recovery from the commercial fishery. A total of

2,948 crayfish were tagged in 1994 with the following distribution: Crooked River arm n = 2,348; Deschutes River arm n = 200; and Metolius River arm n = 400. More crayfish were tagged in the Crooked River arm with the intent of doing a mark-recapture population estimate, but it was determined to be too labor intensive. Tagged crayfish were recovered in 1994, 1995, and 1996. Horizontal movements were determined from the location of recaptured crayfish obtained during the mark-recapture process, during systematic spatial trapping from tag release points, and from the catch of commercial crayfishers. Seasonal vertical migration of crayfish was determined using the method already described for determining depth distribution, but was repeated over time.

Smallmouth Bass Predation

Smallmouth bass were sampled nocturnally with an electrofishing boat (Reynolds 1983) on a monthly schedule from May to September of 1995. Total length was recorded to the nearest 1.0 mm. Smallmouth bass stomachs were evacuated, using the gastric lavage method, (Giles 1980) and filtered thought a 1.0-mm screen, and the residual contents were preserved in 10% formalin. Smallmouth bass were released after stomach contents and data were collected. Stomach contents were later identified and analyzed using the volumetric method (Windell 1971; Bowen 1983). When possible, the consumed crayfish's carapace and chelipeds were measured to the nearest 0.1 mm so age could be determined.

Management

Past Harvest and Management

Data on commercial harvest were obtained from ODFW and CTWSRO and summarized for the years 1981-1995. Crayfish were sampled by ODFW during three years. They were: In 1970, when interest in harvesting crayfish first began; in 1982, when larger numbers of licensees first began to harvest crayfish; and in 1988, the year after the largest harvest to date. To determine if any changes in population size structure could be detected as a result of harvest, these three sample years were compared with 1994 data from this study. The comparisons were restricted to similar locations in the Crooked River arm.

In 1971, ODFW sampled crayfish from LBC and had the abdominal musculature (n = 24) tested for mercury. The results of the 1971 mercury tests indicated that some of the crayfish had concentrations that approached the Food and Drug Administration (FDA) limit of 0.5 ppm. To compare with these earlier results, 10 crayfish from each of the three inflow areas were captured during August 1995 and supplied to the Oregon Department of Environmental Quality (DEQ) for mercury testing.

Management Recommendations

The results from this study were compared to the current management methods to assess their biological effectiveness, and recommendations were made accordingly.

RESULTS

Life History

Reproduction

Maturation. — Maturity was first observed at the size class of 26 mm POCL for both males and females and represented 11.0% and 16.7% of each size class, respectively. All males ≥ 36 mm and all females ≥ 38 mm were mature (Figure 3). The median minimum size at maturity for male and female crayfish was not significantly different (P = 0.46, t-test) and was 29.2 mm and 29.5 mm, respectively (Figure 4).

Copulation and Spawning. — In 1994, copulated females were first observed on 7 October and last on 12 November. Ovigerous females were first observed on 22 October (Figure 5). In 1995, copulated females were first observed on 6 October and last on 22 October. Ovigerous females were first observed on 13 October (Figure 5). The highest percent of captured females with spermatophores was 17.0% and occurred on 7 October 1994. The mean time from copulation to spawning for 1994 and 1995 was 8.5 days (Figure 5).

Hatching. — In 1995, females with dependent first- and second-stage 0+ age juveniles attached to pleopods were first observed on 8 April and last on 22 April (Figure 6). The highest percent of captured females with dependent juveniles was 9.0% and occurred on 22 April (Figure 6).

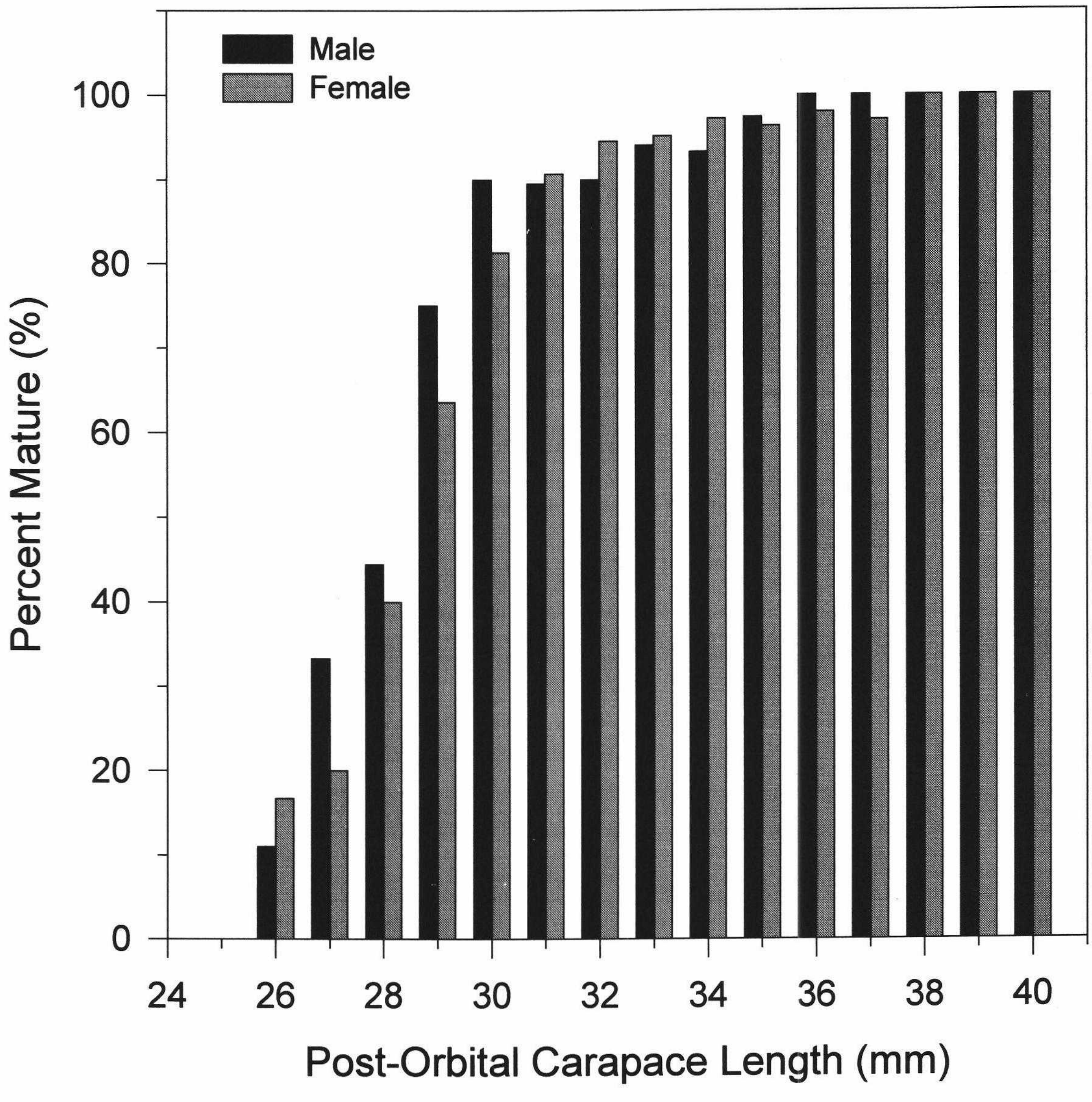

Figure 3. Percent mature male (n = 263) and female (n = 502) crayfish per size class.

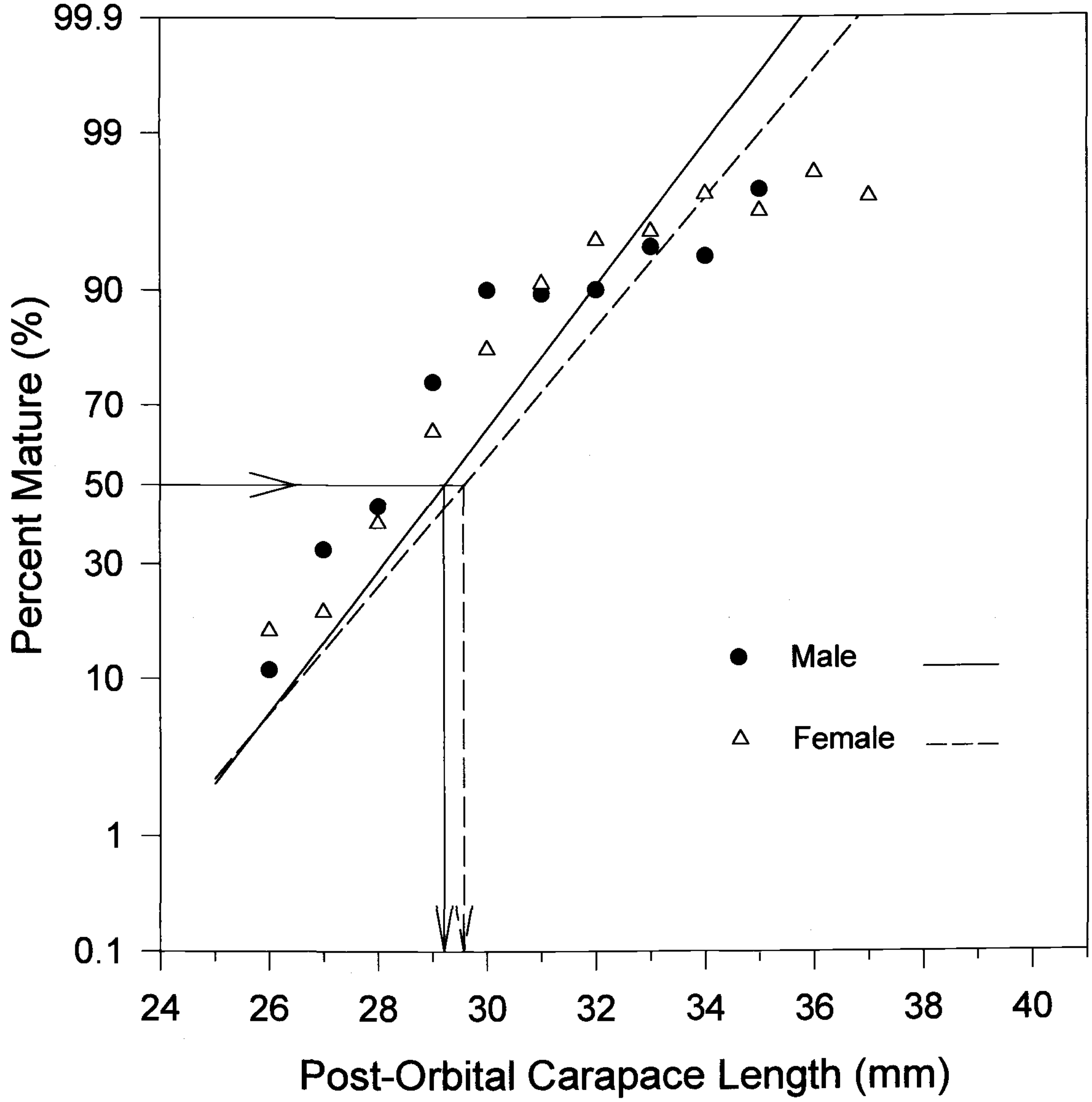

Figure 4. Percent mature male and female crayfish plotted on probability scale. The line originating from 50% on the y axis intersects with linear regression lines for male and female crayfish. Drop lines from intersect points identify median minimum size at maturity for males (29.2 mm) and females (29.5 mm).

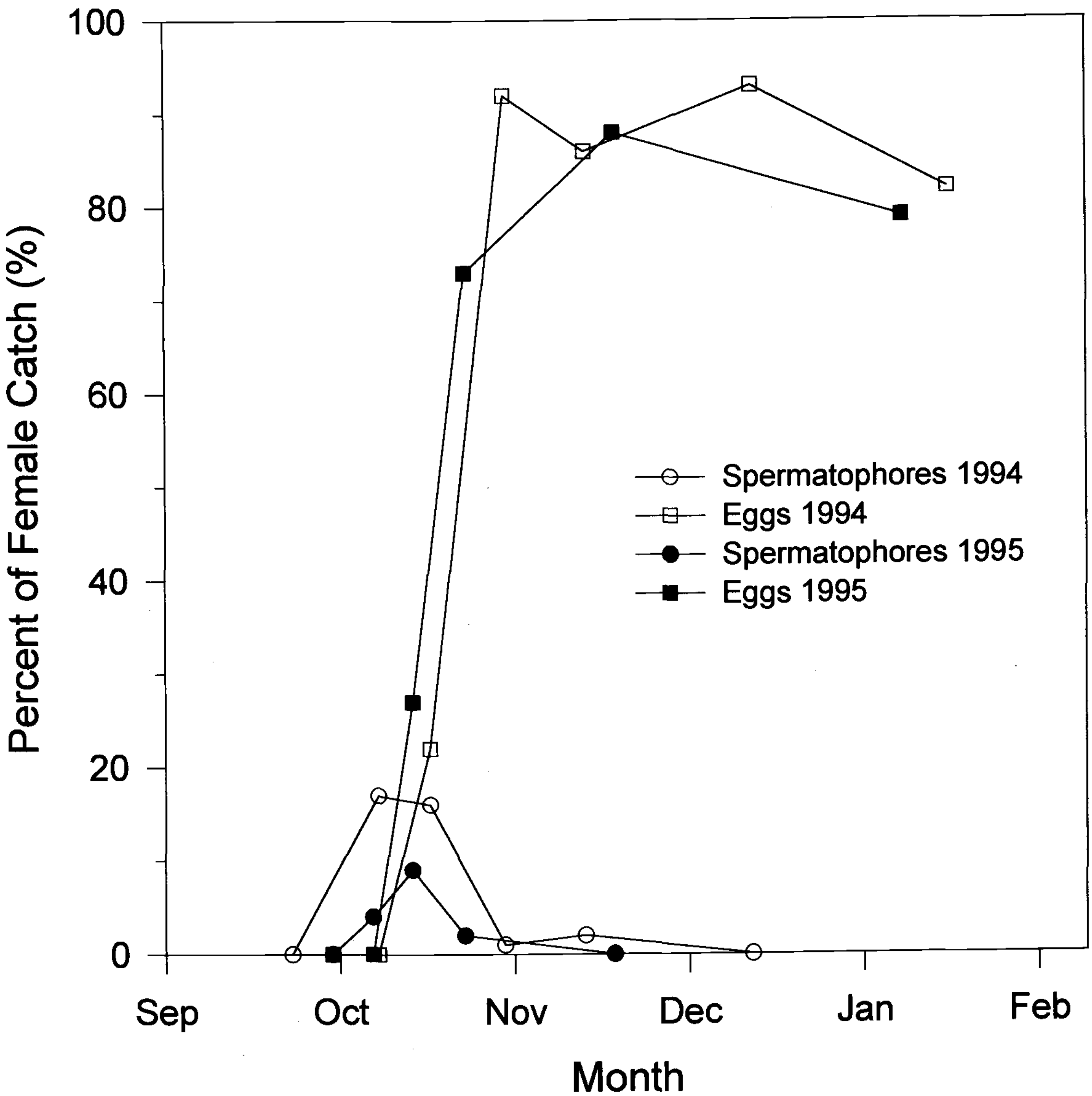

Figure 5. Percent of total female catch for 1994 (n = 797) and 1995 (n = 1,442) that had spermatophores or eggs attached from September to January.

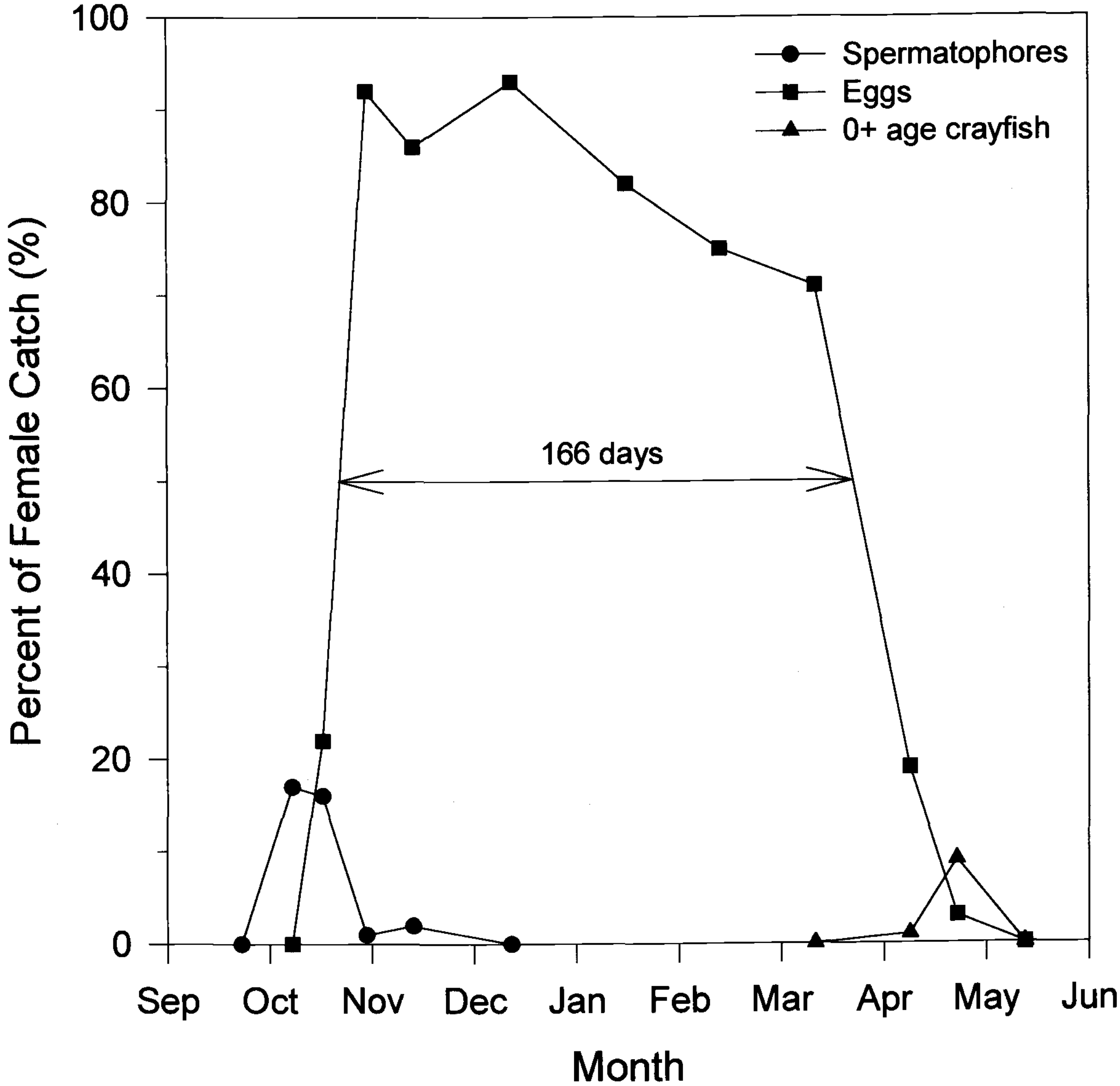

Figure 6. Percent of total female catch (n = 1,048) with spermatophores, eggs, or 0+ age crayfish attached from 19 September 1994 to 12 May 1995. The mean incubation period of 166 days is indicated by the arrowed line.

Incubation. — The estimated mean incubation period for eggs was 166 days (Figure 6). The mean water temperature during the incubation period was 13.3°C (Appendix 2, 3, and 4). Using equation (1), the calculated incubation required for hatching of eggs was 2,208 degree-days.

Fecundity. — The estimated mean number of pleopodal eggs per female from November 1994 to March 1995 was 105 ± 12 eggs for female ≥ 30 mm. The highest monthly estimate was in November at 132 ± 29 eggs and the lowest was March at 64 ± 29 eggs (Figure 7). The maximum individual egg count was 280 eggs for one female in November 1994. In March 1995, 20% of the females sampled had no eggs. Mean monthly estimates were significantly different ($P < 0.001$, ANOVA F-test). This difference was not due to the size of females sampled because there was no significant difference between months for POCLs of females ($P = 0.36$, ANOVA F-test). The mean monthly fecundity estimates appeared to decrease during the incubation period. However, the decrease was not statistically significant ($P = 0.36$, linear regression). The months of October and April were not included in the fecundity analysis because there was a large percentage of females still spawning or hatching eggs during those months. Fecundity increased with size ($P < 0.0001$, $r^2 = 0.25$, $n = 80$, linear regression) of the female crayfish (Figure 8). Females without pleopodal eggs or with low numbers (< 30 eggs) were not included in the regression analysis because it was thought that they were not representative. This mainly occurred in March just prior to hatching.

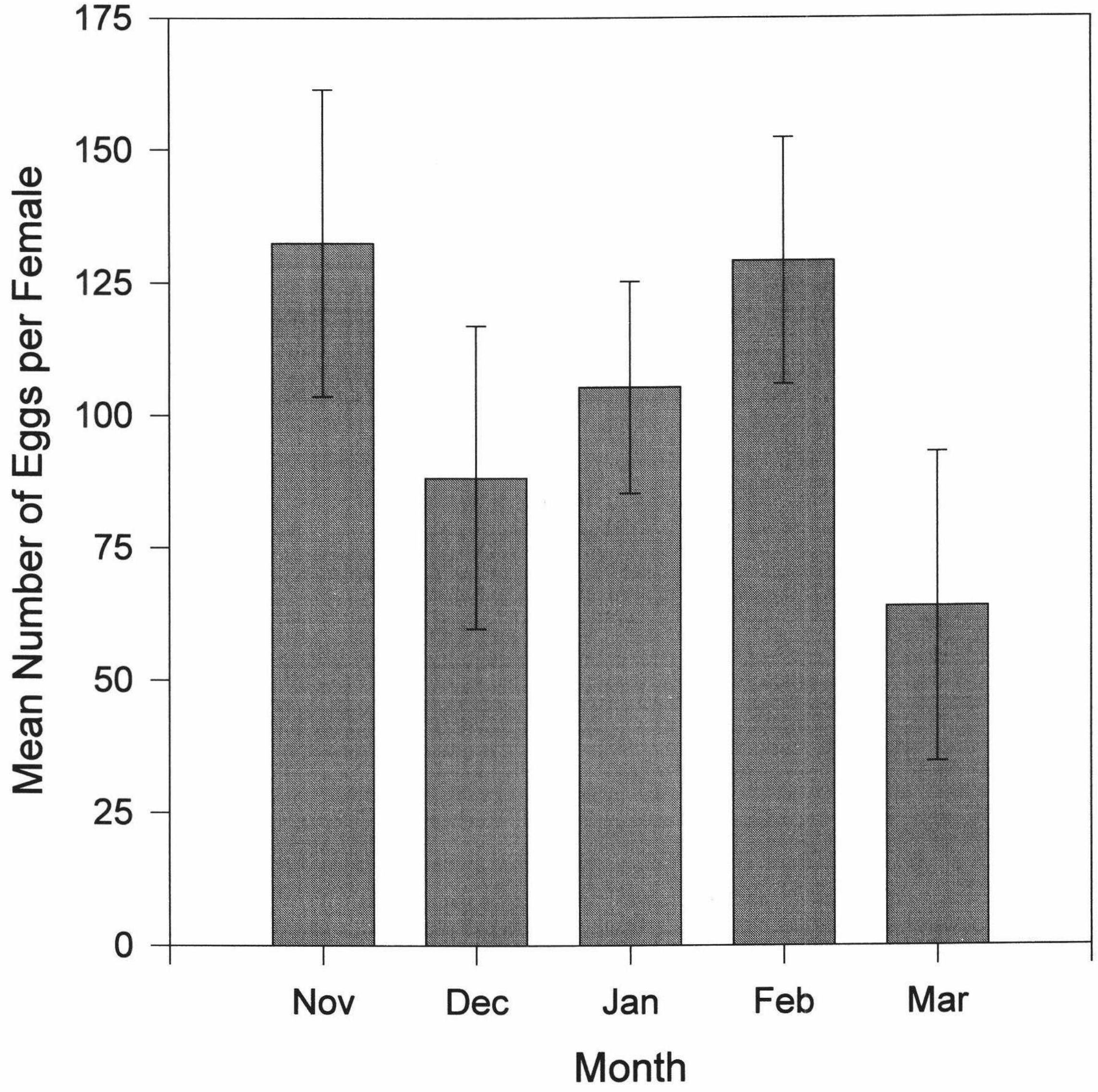

Figure 7. Mean number of pleopodal eggs, with 95% confidence intervals, for female crayfish captured with traps from November 1994 to March 1995. Mean for all five months was 105 ± 12 eggs/female (n = 101).

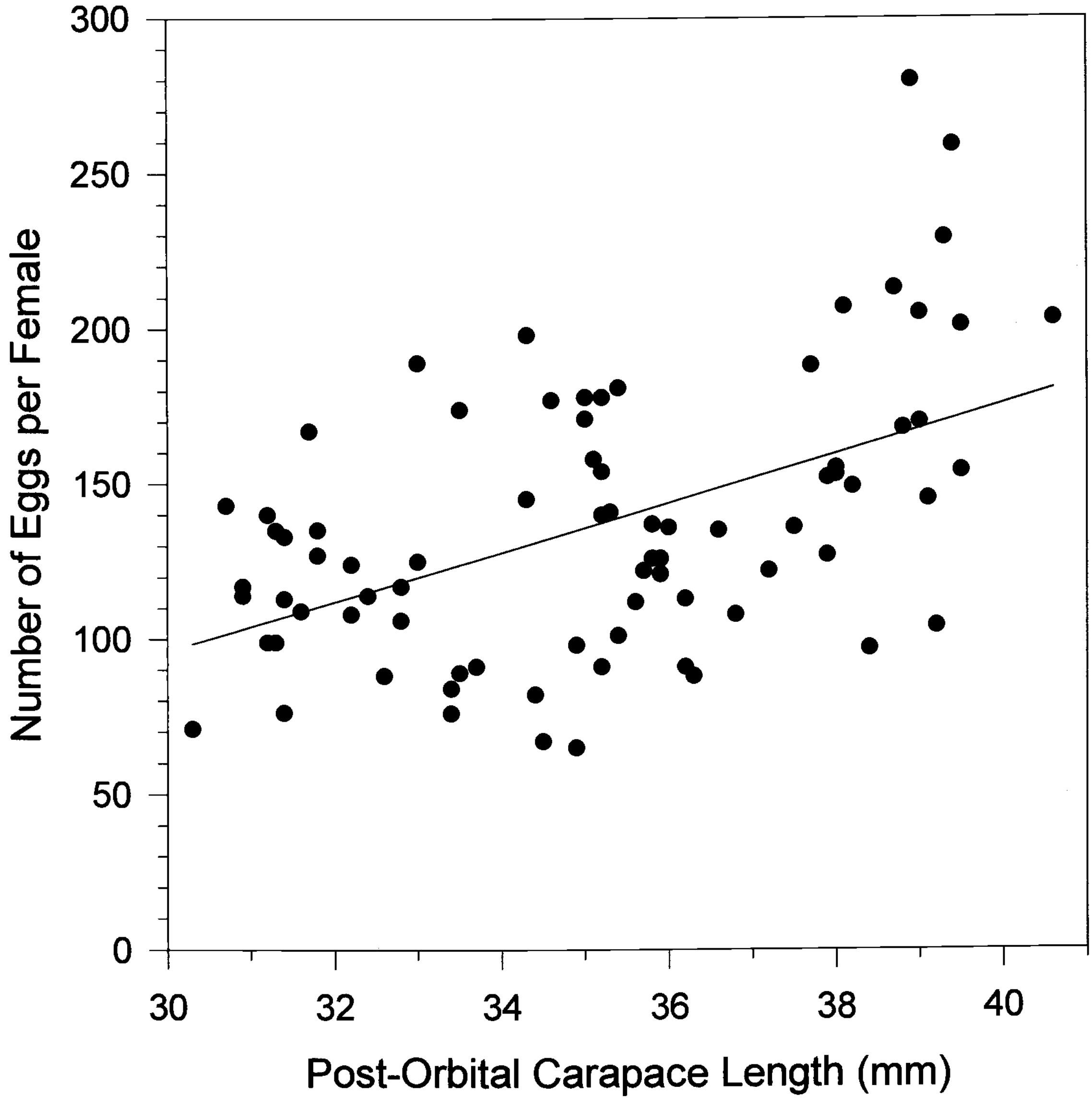

Figure 8. Linear regression of pleopodal eggs and post-obital carapace length (mm). The regression equation is: (No. of eggs) = -142.5 + 7.95(POCL),P < 0.0001, $r^2 = 0.25$, n = 80.

<u>Pathogens and Parasites</u>

No signs of gross infection by the fungi *A. astaci* were observed at any time during the study. The microsporidian *T. contejeani* occurred in 25% of the monthly samples from June 1994 to January 1996. Of the five months that had an occurrence (October 1994; April, June, and October 1995; and January 1996), the percent of crayfish infected ranged from 0.45% to 0.81% and the mean was 0.65%. The annelid *Branchiobdella* spp., or cocoons containing eggs and young worms, were found on 100% of the crayfish observed that were 1+ and older (n ≈ 150,000). Only 0+ age crayfish were observed to be free of branchiobdellids and cocoons. They were free from infestations through their first summer and winter.

Population Dynamics

<u>Habitat</u>

The substrate of LBC was stratified into five principal habitat types: (1) Vertical basalt cliffs (Cliff); (2) boulder and cobble talus accumulations (B/C); (3) sand/silt (S/S); (4) a mixture comprised of sand/silt habitat with varying densities of boulders and cobbles (Mix); and (5) a ring of boulders and cobbles (Draw-Down) around the margin of the reservoir extending down to the 4.5-m contour (Figure 9). In figure 9, S/S and Mix habitats are combined, and Draw-Down habitat is not visible due to the lack of graphical resolution. The Draw-Down

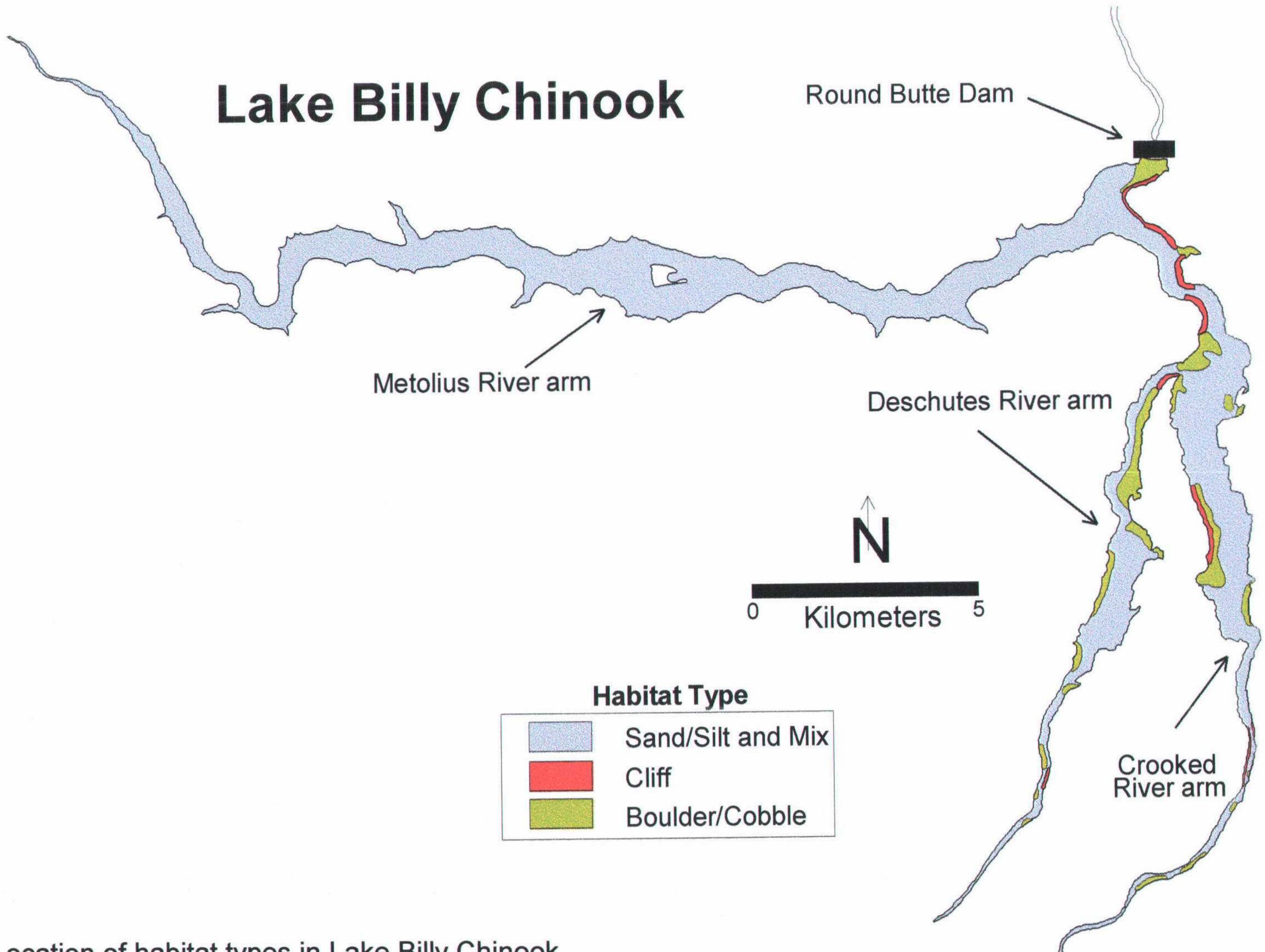

Figure 9. Location of habitat types in Lake Billy Chinook.

habitat was formed from reservoir surface level fluctuations and wave action that removed fine sediments from this zone.

The bottom surface area for depths ≤ 70 m were calculated for habitat types previously described. In the Crooked, Deschutes, and Metolius arms, these habitats comprised 20.1%, 29.4%, and 50.5% of the total habitat ≤ 70 m, respectively (Table 1).

Table 1. Lake bottom surface areas (m^2) of habitat types ≤ 70 m deep for the three arms of Lake Billy Chinook.

	Habitat type				
Arm	Cliff	Boulder Cobble	Sand/Silt and Mix	Draw-Down	Total
Crooked	76,380	542,159	2,972,178	118,730	3,709,447
Deschutes	116,130	1,209,746	3,979,746	116,654	5,422,276
Metolius	0	0	8,938,158	396,022	9,334,180
Total	192,510	1,751,905	15,890,082	631,406	18,465,903

The crayfish depth distribution in LBC extended from the surface to 100 m; although, 98% of the crayfish were captured in water ≤ 70 m (Figure 10). The percent of total catch peaked at 10-20 m for all months, with the overall distributions skewed towards deeper water (Figure 10).

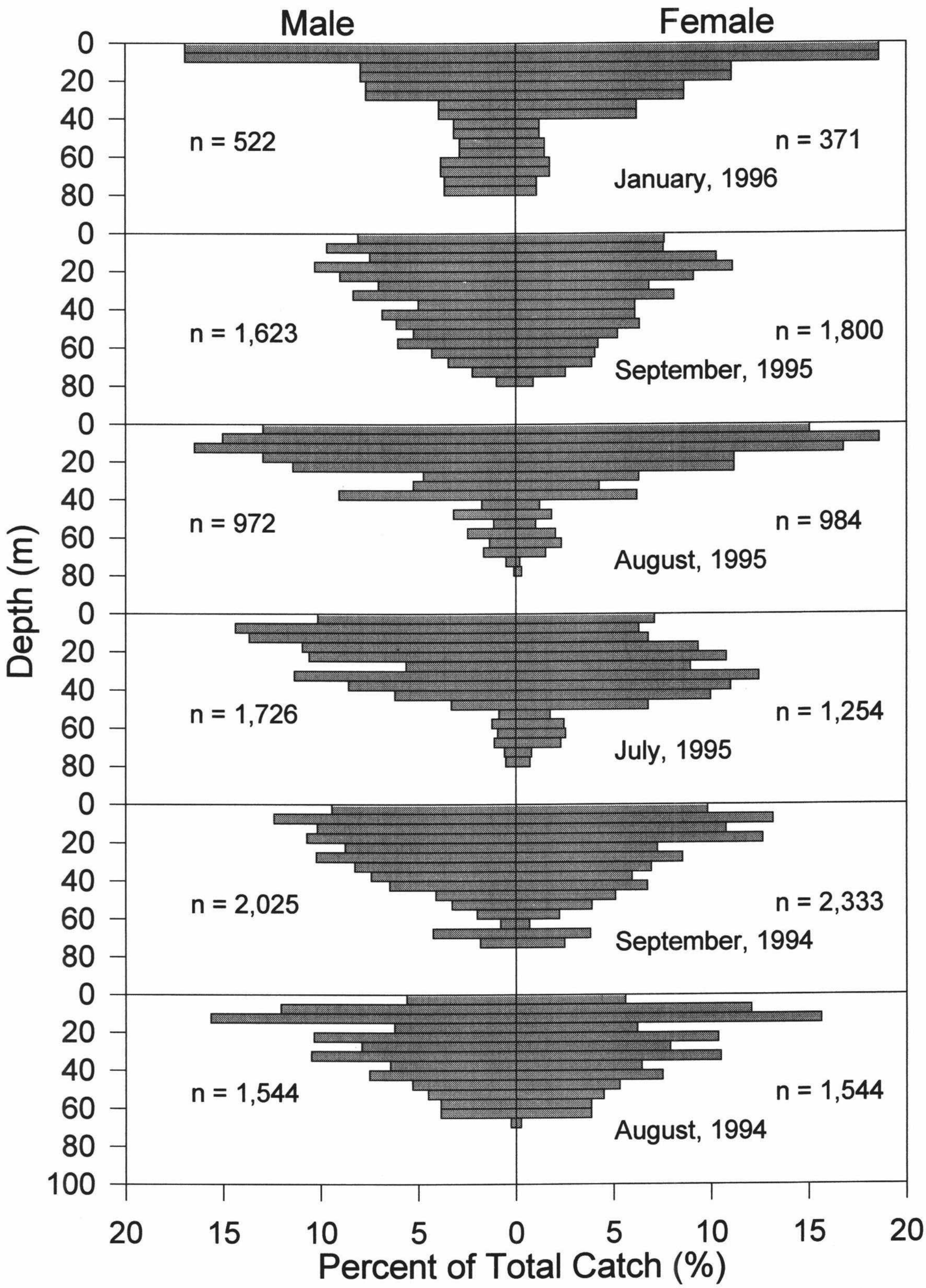

Figure 10. Depth distribution by 5-m intervals of male and female crayfish captured from August 1994 to January 1996. The sample in August 1994 were not sexed and a 50:50 ratio was assumed.

Diel sampling from 2 to 3 August revealed a nocturnal activity pattern (Figure 11). The trapping was conducted in S/S and Mix habitat in the lower 6 km of the Metolius River arm. From sunset, catch gradually rose from about 6 crayfish/hour to about 12/hour at 0000 h. Catch remained at 12/hour until 0500 h, and then dropped sharply to 6/hour (Figure 11). The nocturnal activity distribution was skewed towards the sunset (Figure 11).

Age and Sex Composition

Eight cohorts were identified from length-frequency analysis of hand-captured crayfish (Table 2). The POCL of all cohorts were significantly different from adjacent cohorts (all P-values < 0.001, t-tests and ANOVA F-tests with Student-Newman-Keuls and Dunn's multiple-comparison tests).

Table 2. Age and mean post-orbital carapace length (mm), with 95% confidence intervals, of cohorts determined from length-frequency analysis of crayfish captured during August and September 1995.

	Age							
	0+	1+	2+	3+	4+	5+	6+	7+
Mean POCL (mm)	12.5	23.8	29.3	33.8	37.5	41.3	44.3	47.0
95% CI	± 0.5	± 0.5	± 0.5	± 0.4	± 0.3	± 0.4	± 0.7	± 0.7

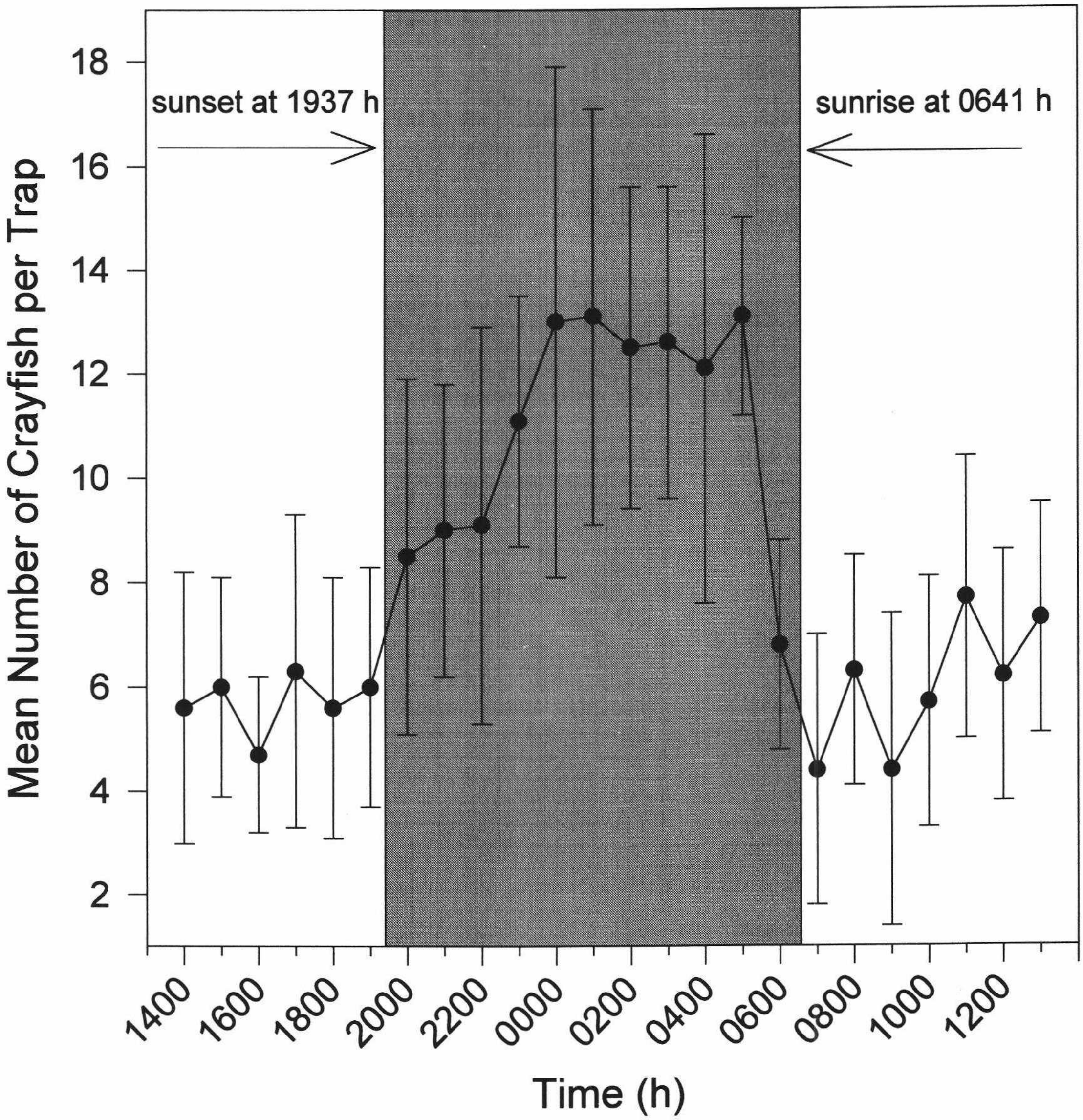

Figure 11. Diel activity of crayfish expressed as mean number of crayfish, with 95% confidence intervals, captured per 10 traps per hour for 24 continuous hours (n = 1,971). Shaded area indicates time period from sunset to sunrise.

Analysis of trap length-frequency data could not successfully identify distinct cohorts because of the biases associated with that method of capturing crayfish. However, a comparison of length-frequency data from traps identified other differences between habitat types. The mean sizes of crayfish from each habitat type were: B/C, 35.4 ± 0.2; S/S, 39.4 ± 0.3; Mix, 38.7 ± 0.3; and Draw-Down, 38.5 ± 0.2 (Figure 12), and were significantly different ($P < 0.0001$, ANOVA F-test). The mean size of crayfish from the Mix and Draw-Down habitat were not significantly different; whereas, crayfish from B/C habitat were significantly smaller and crayfish from S/S habitat were significantly larger than crayfish from other habitats ($P < 0.05$, Dunn's multiple-comparison test).

The sex composition of crayfish in LBC appeared to be 50:50 ratio during all months but three (Figure 13). During the months of March and April, males dominated trap catches, and females dominated during May (P-values < 0.001, Chi-square analyses). Sex ratios of crayfish for all other months were not significantly different from a 50:50 ratio (Figure 13).

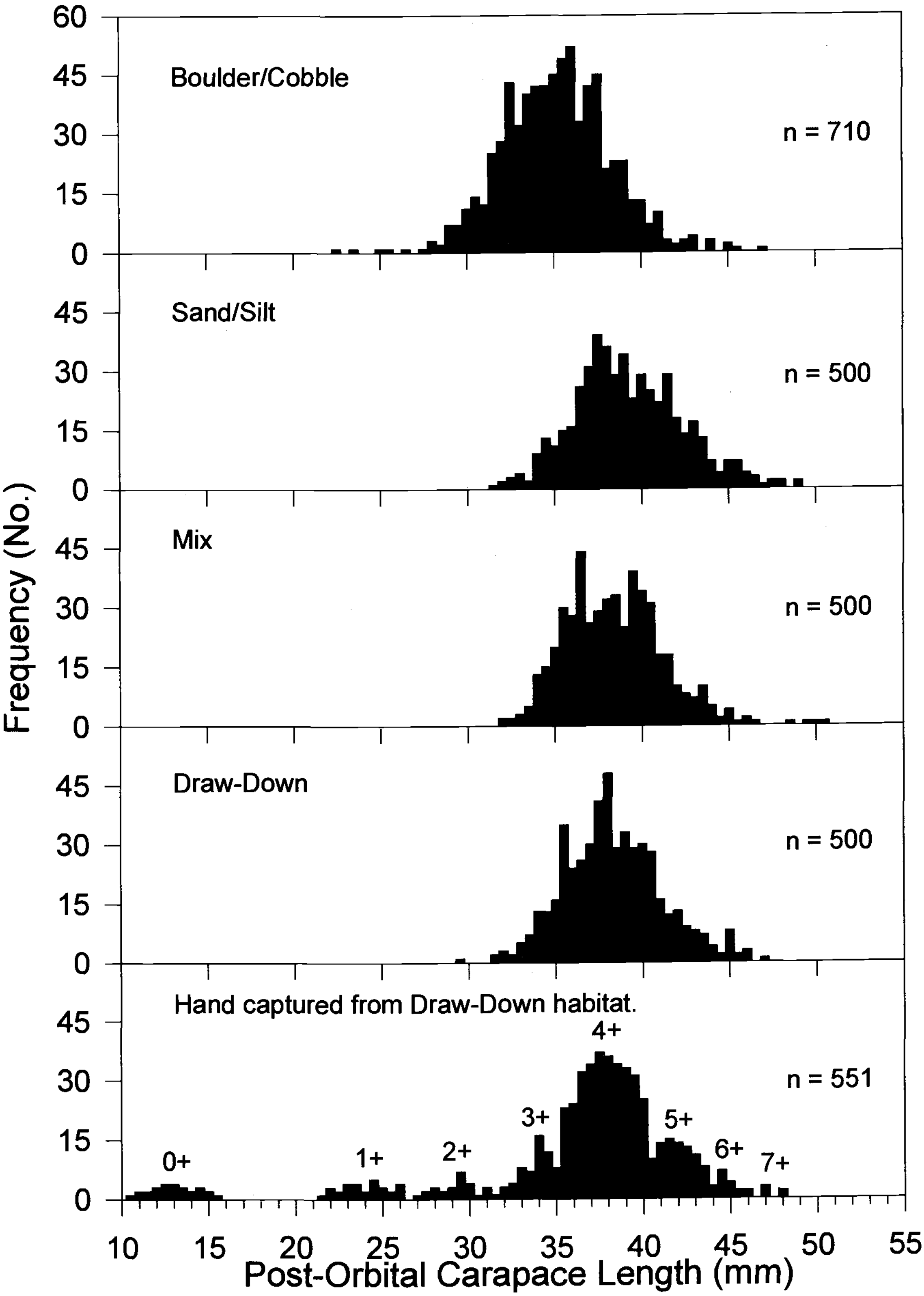

Figure 12. Length-frequency distributions of crayfish captured with traps from Boulder/Cobble, Sand/Silt, Mix, Draw-Down, and captured by hand from a combination of Draw-Down habitat.

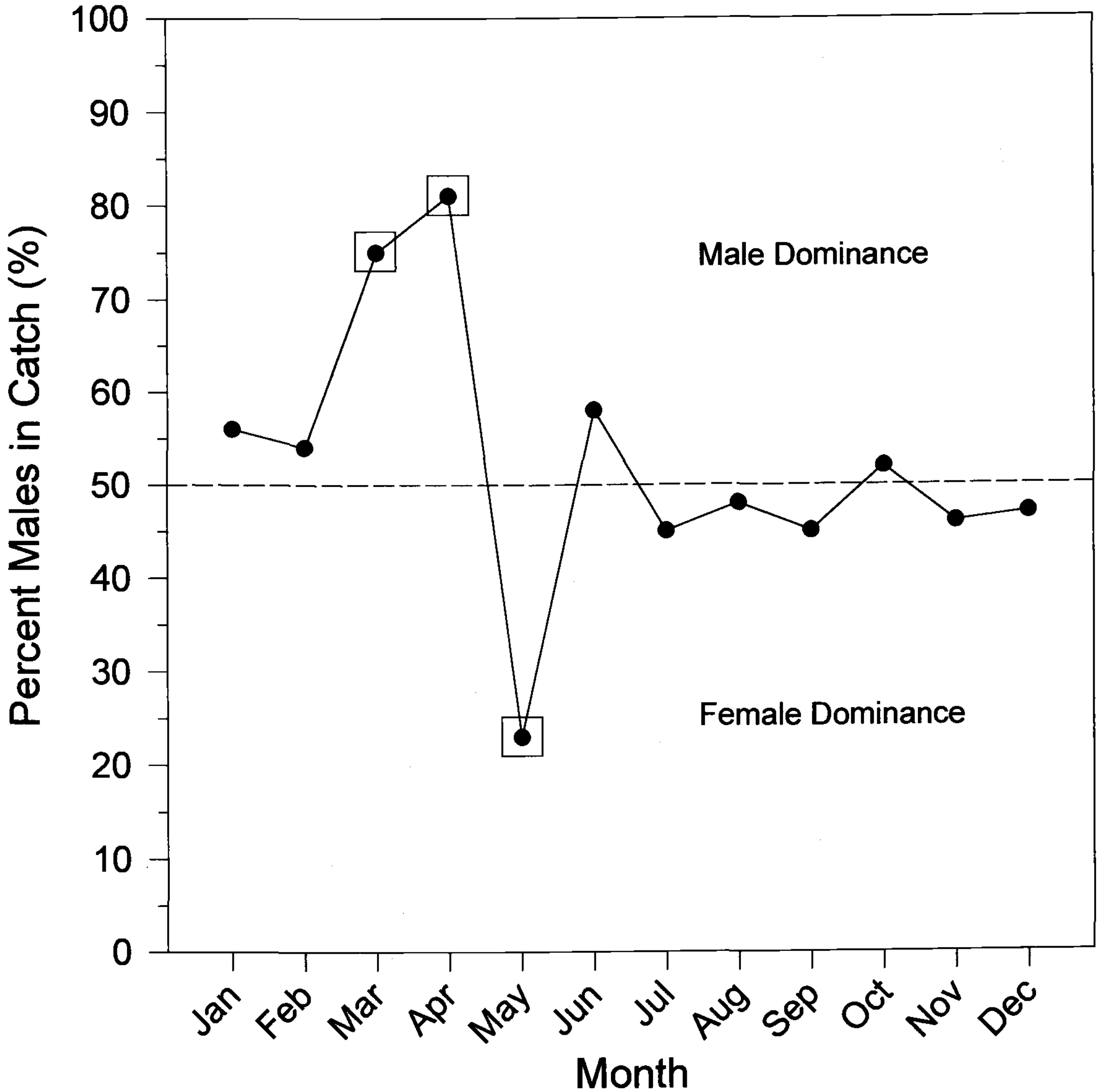

Figure 13. Monthly sex composition of crayfish catch from traps. Boxes indicate significant deviations from an expected 50:50 sex ratio (P-values < 0.001, Chi-square analyses, n = 2,866 for all 12 months).

Density

Crayfish densities were significantly different between habitat types ($P < 0.0001$, ANOVA F-test) from transects counts (Figure 14). No significant differences occurred between Cliff and B/C habitats ($P > 0.05$) and between S/S and Mix habitats ($P > 0.05$, Student-Newman-Keuls multiple-comparison test). Because S/S and Mix habitats were not significantly different, they were pooled for all other analyses. The highest mean density (1.13 ± 0.08 crayfish/m^2) occurred in Draw-Down habitat, and the lowest mean density (0.24 ± 0.07 crayfish/m^2) occurred on Cliff habitat.

Because traps could not be set on the Cliff habitat, only transect counts were used to estimate density. Transects were set vertically from the surface to 30 m. In the 0- to 5-m interval, density was 0.1 crayfish/m^2 (Figure 15). Density peaked at 0.53 crayfish/m^2 in the 10- to 15-m interval, than decreased to 0.1 crayfish/m^2 in the 25- to 30-m interval. The lower limit of crayfish on Cliff habitat was estimated to be 29 ± 6 m (Figure 15).

Trap capture ranges (CR) were calculated for B/C and the combined S/S and Mix habitat types using equation (2). The mean catch per trap adjacent to transects lines in those two habitat types was 23.3 ± 9.8 crayfish/m^2 and 52.3 ± 15.6 crayfish/m^2, respectively. The calculated capture range for B/C habitat was 92 ± 30 m^2 and the combined S/S and Mix habitat was 116 ± 34 m^2. The mean crayfish density over their depth distribution was calculated using equation (3).

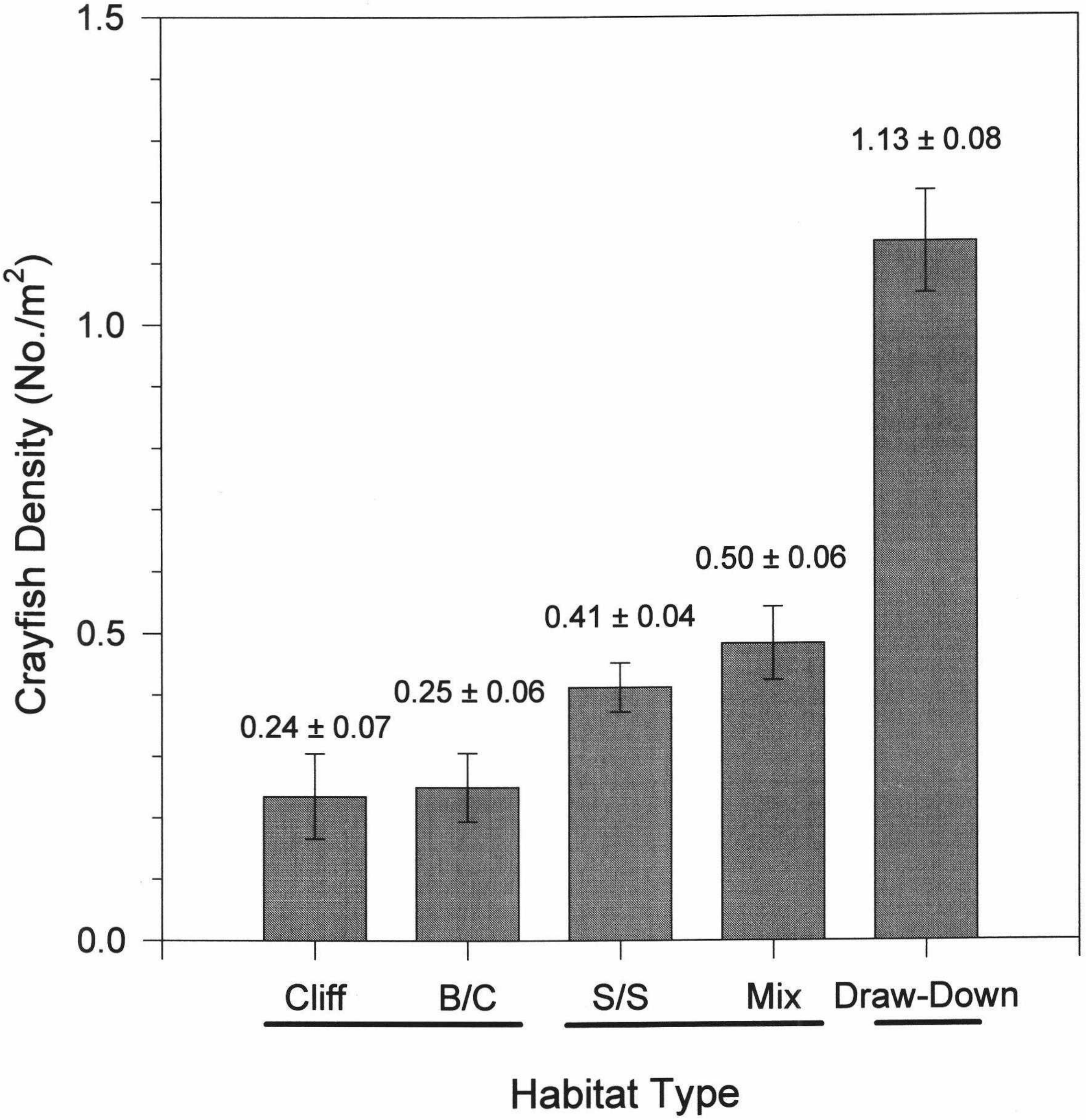

Figure 14. Mean density of crayfish (No./m^2), with 95% confidence intervals, from transect counts for Cliff (n = 4), Boulder/Cobble (n = 10), Sand/Silt (n = 10), Mix (n = 10), and Draw-Down (n = 10) habitat types. Horizontal lines indicate non-significant differences (ANOVA with Student-Newman-Keuls multiple-comparison test).

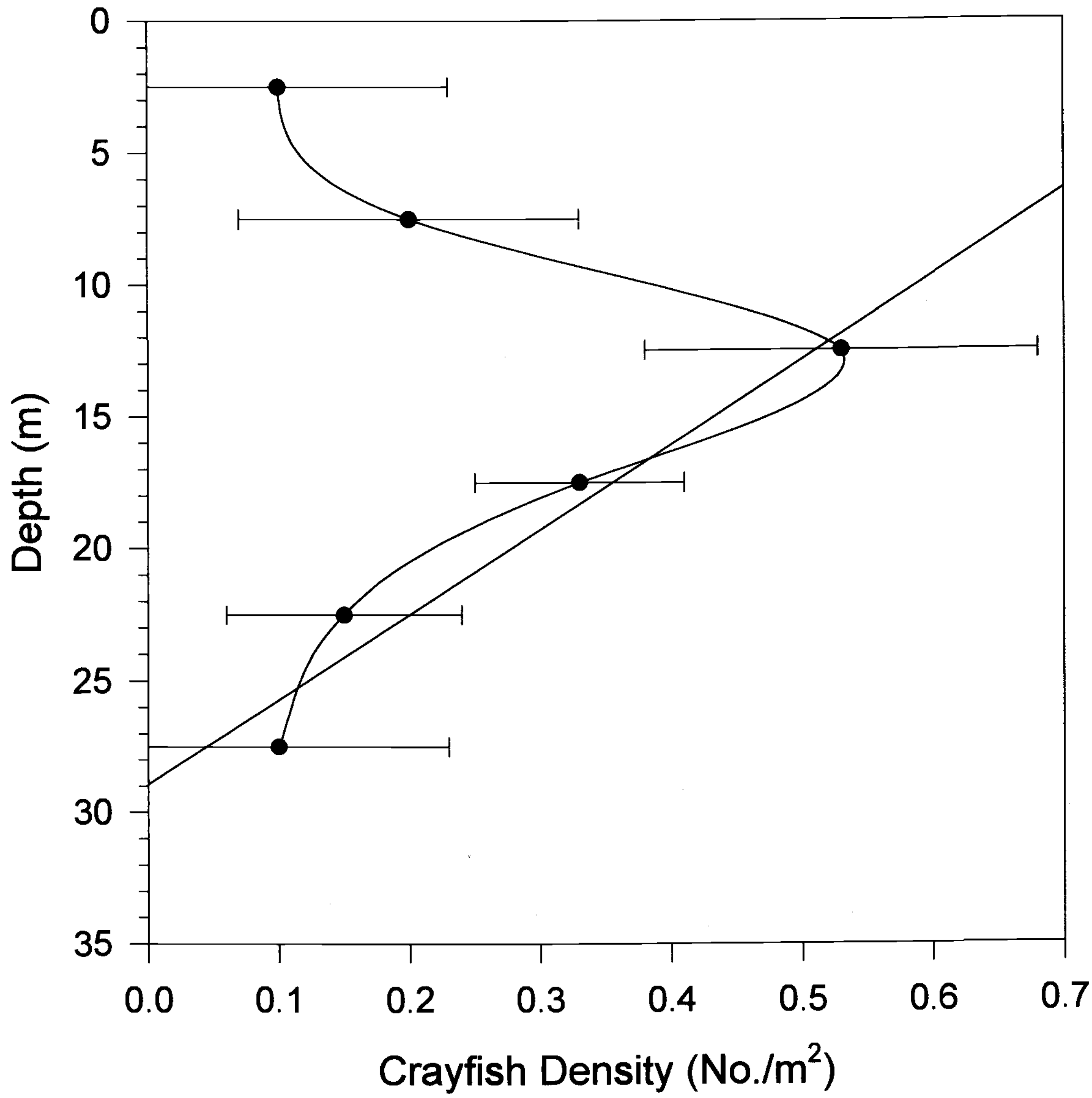

Figure 15. Mean density of crayfish, with 95% confidence intervals, at 5-m depth intervals on Cliff habitat. Linear regression, with 95% confidence band, of four deepest intervals to estimate maximum depth distribution of crayfish on Cliff habitat. The regression equation is: (depth) = 28.9 - 32.2(density), $P = 0.028$, $r^2 = 0.95$, $n = 4$.

The mean catch was 19 crayfish/trap for B/C and 53 crayfish/trap for the combined S/S and Mix habitats. The estimated densities of crayfish over their depth distribution for B/C and the combined S/S and Mix habitat types were 0.21 ± 0.07 crayfish/m^2 and 0.46 ± 0.13 crayfish/m^2, respectively.

Abundance

Using the combined transect and trapping method, crayfish abundance in LBC was estimated to be 8,437,029 ± 2,252,332. The highest crayfish abundance was estimated for the Metolius River arm at 4,559,058 ± 1,193,642 and the lowest estimate was for the Crooked River arm at 1,633,551 ± 439,179 (Table 3). The highest habitat type crayfish abundance occurred in the combined S/S and Mix habitats at 7,309,438 ± 2,065,711 and the lowest was in Cliff habitat at 46,202 ± 13,476 (Table 3).

These abundance estimates did not include 0+ and 1+ age crayfish. Quadrats were used to estimate 0+ and 1+ age crayfish. The mean density/m^2 of 0+ and 1+ age crayfish in Draw-Down habitat was 2.13 ± 0.54/m^2 and 1.53 ± 0.32/m^2, respectively. These densities were extrapolated to all Draw-Down habitat in LBC and resulted in an estimate of 1,344,895 ± 340,959 and 966,051 ± 202,050 crayfish in the 0+ and 1+ age classes, respectively. Since quadrats sampling was done in August and September, considerable summer mortality had lowered densities from what might have been expected earlier in the summer. The assumption was made that 0+ and 1+ age crayfish densities would be the same proportionally as older crayfish in other habitats. This assumption was partially validated by the fact that ovigerous females were found proportionally in other habitat and depths as other crayfish. Also, length-frequency distributions indicated that a similar age structure was present in all habitats. This assumption allowed the combined abundance of 0+ and 1+ age crayfish in LBC to be estimated at 27,503,116 ± 5,874,827.

Table 3. Estimated abundance of crayfish ≤ 70 m deep in the three arms and four different habitat types in Lake Billy Chinook using the combined transect and trapping method. Error terms were derived by using the mean percent error, from 95% confidence intervals, of transect counts and catch per trap estimates.

	Habitat type				
Arm	Cliff	Boulder/ Cobble	Sand/Silt and Mix	Draw-Down	Total
Crooked	18,331 ± 5,347	113,853 ± 37,951	1,367,202 ± 386,383	134,165 ± 9,498	1,633,551 ± 439,179
Deschutes	27,871 ± 8,129	254,047 ± 84,682	1,830,683 ± 517,367	131,819 ± 9,332	2,244,420 ± 619,511
Metolius	0	0	4,111,553 ± 1,161,961	447,505 ± 31,682	4,559,058 ± 1,193,642
Total	46,202 ± 13,476	367,900 ± 122,633	7,309,438 ± 2,065,711	713,489 ± 50,512	8,437,029 ± 2,252,332

Growth and Mortality

The mean POCLs, derived from cohort length-frequency analyses, were fitted with a von Bertalanffy growth curve using equation (4). The calculated parameters of the von Bertalanffy growth curve were L_∞= 49, K = 0.38, and t_0 = -0.5 (Figure 16). Growth in weight of male and female crayfish was not significantly different (P = 0.13, t-test of slopes from linear regression) and were therefore combined (Figure 17).

The mean molt increment of re-captured crayfish was 3.0 mm (Figure 18) and was not significantly different between males and females (P = 0.26, t-test of slopes from linear regression). The predicted molt increment, based on linear regression analysis, increased with POCL and ranged from 2.5 mm at 30.6 mm POCL to 4.2 mm at 42.1 mm POCL.

The annual molting pattern of crayfish ≥ 30.0 mm, as indicated by gastrolith size, had a bimodal distribution for both males and females (Figure 19). The first mode occurred in April and a second smaller mode in August.

Using equation (5) for data collected in Draw-Down habitat, the estimated crayfish survivorship (Z = 0.67) in LBC displayed a type III curve, where there is high mortality early in life followed by lower and relatively constant mortality for the remainder of their life span (Krebs 1985). Of the total mortality that occurred, 68% was in the first four months while the remaining 32% occurred through age 7+ (Figure 20).

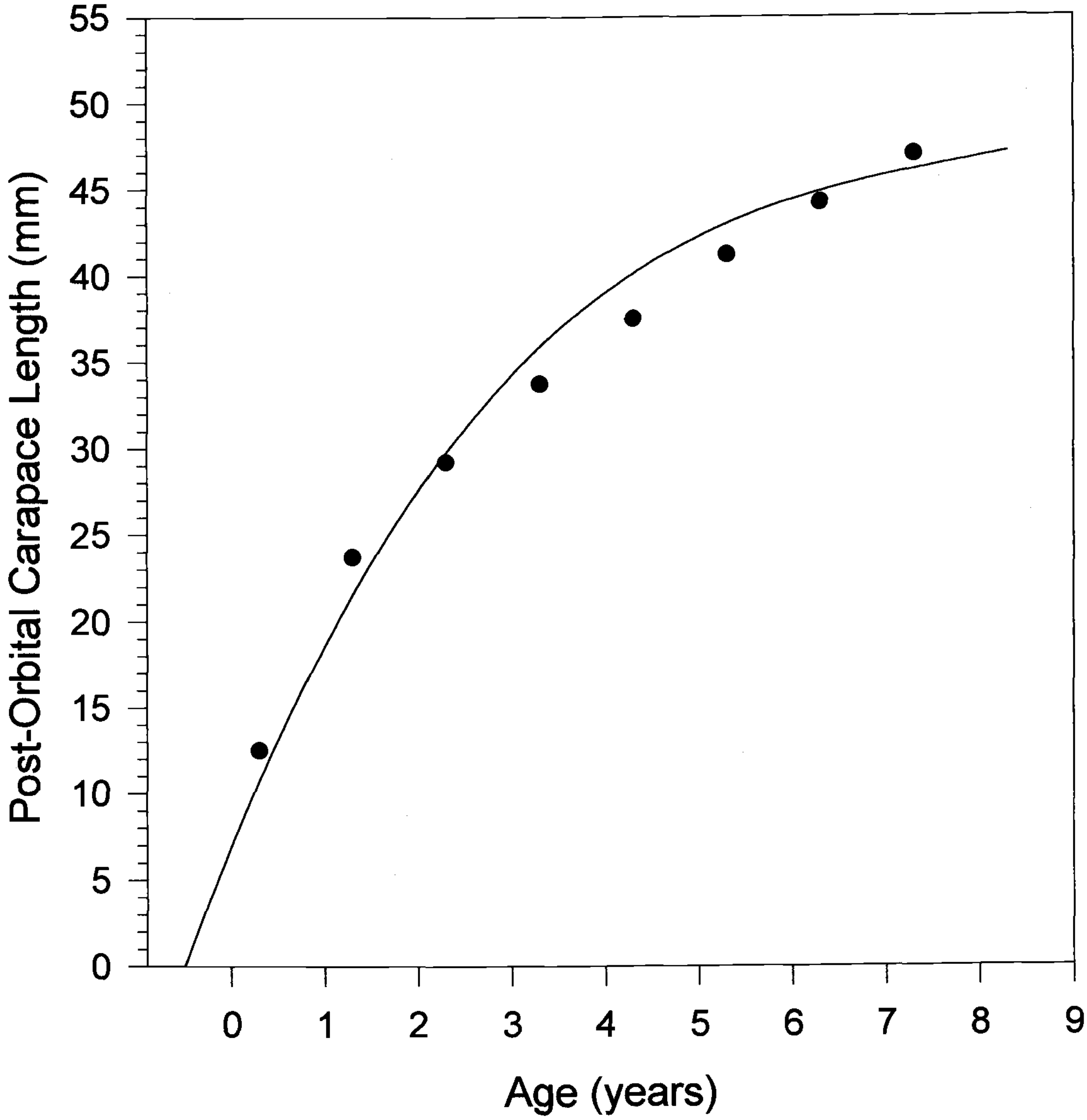

Figure 16. Mean post-orbital carapace lengths (mm), derived from cohort length-frequency analyses, fitted with a von Bertalanffy growth curve, with $L_{\infty} = 49$, $K = 0.38$, and $t_0 = -0.5$. Crayfish were captured by hand from Draw-Down habitat.

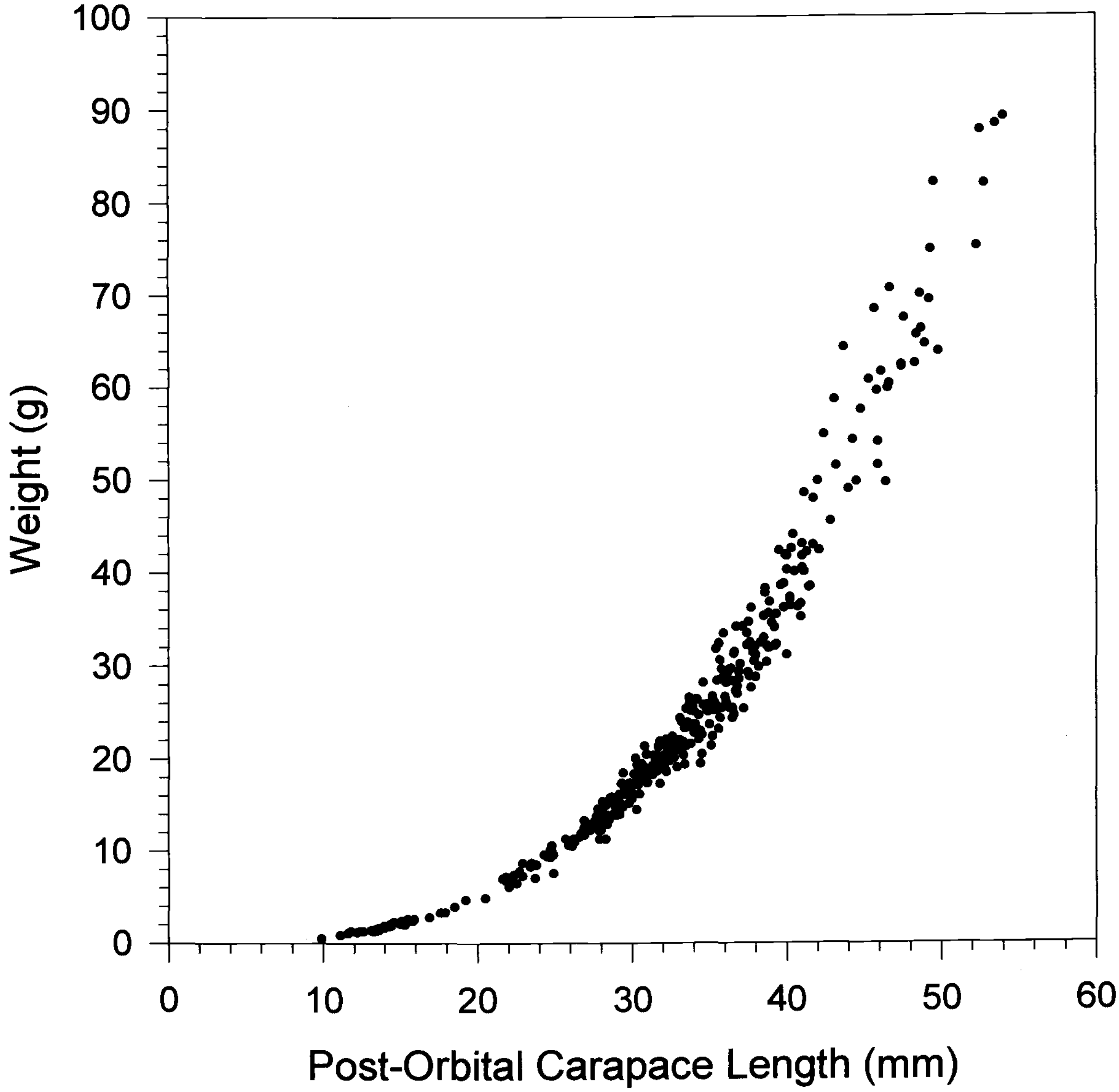

Figure 17. Weight-length relation for male (n = 205) and female (n = 150) crayfish. The regression equation is: log(weight) = -3.11 + 2.93 log(POCL), $P < 0.0001$, $r^2 = 0.99$, n = 355.

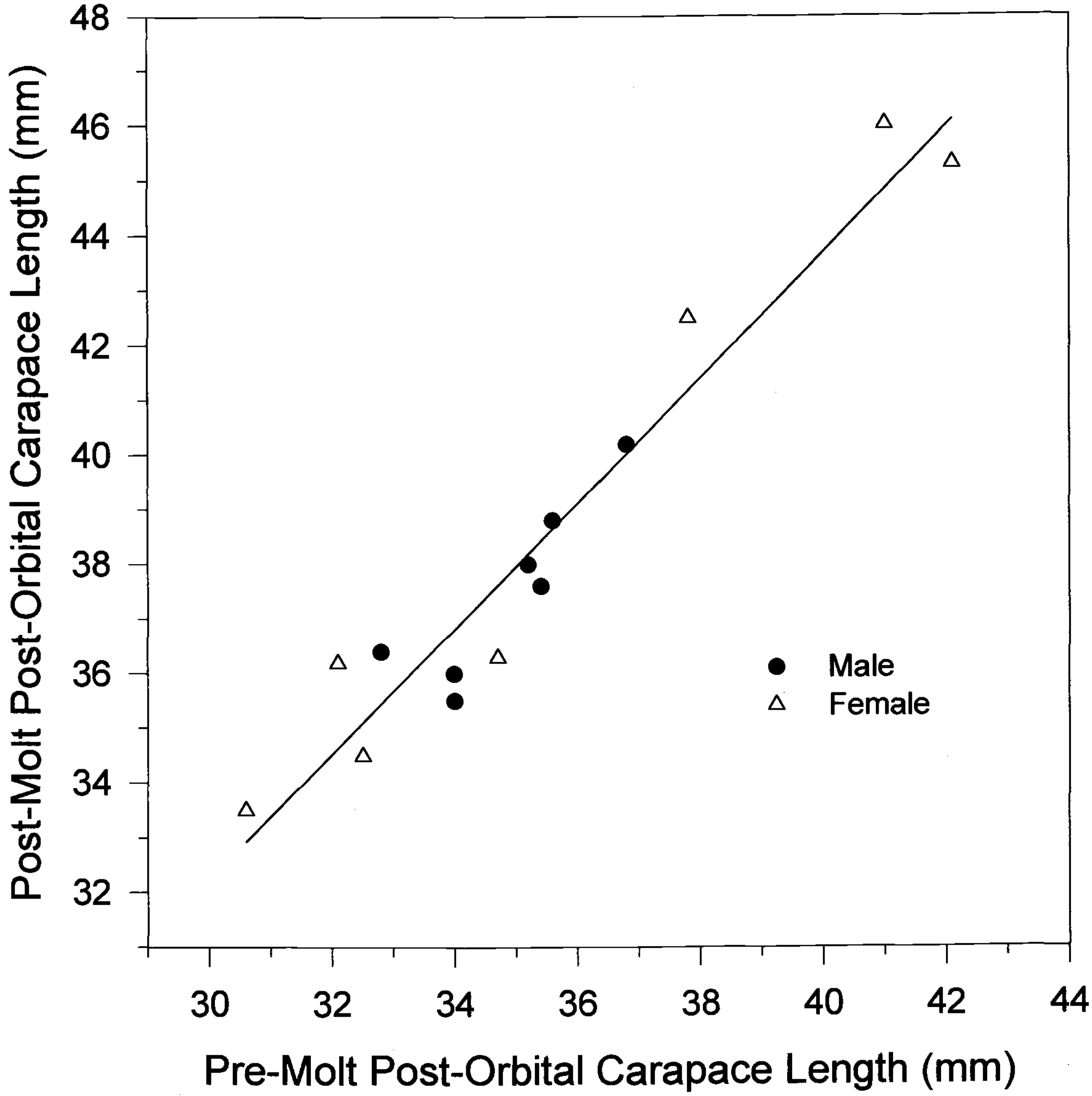

Figure 18. Linear regression of post-molt post-orbital carapace length (mm) and pre-molt post-orbital carapace length (mm) for male (n = 7) and female (n = 7) crayfish. The regression equation is: (post-molt POCL) = -2.11 + 1.15(pre-molt POCL), $P < 0.0001$, $r^2 = 0.94$, n = 14.

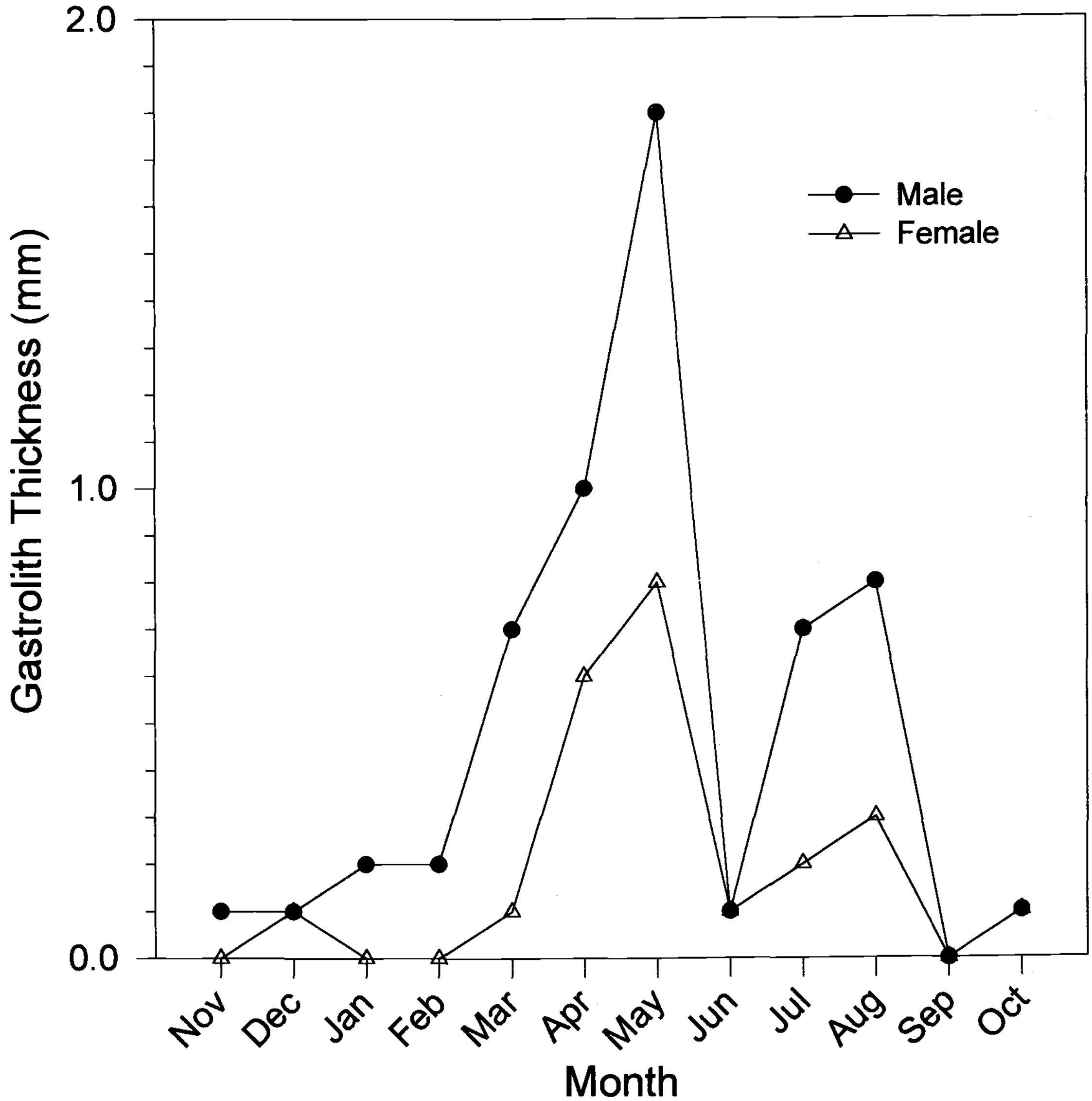

Figure 19. Mean gastrolith thickness (mm) for male (n = 240) and female (n = 240) crayfish from November 1994 to October 1995.

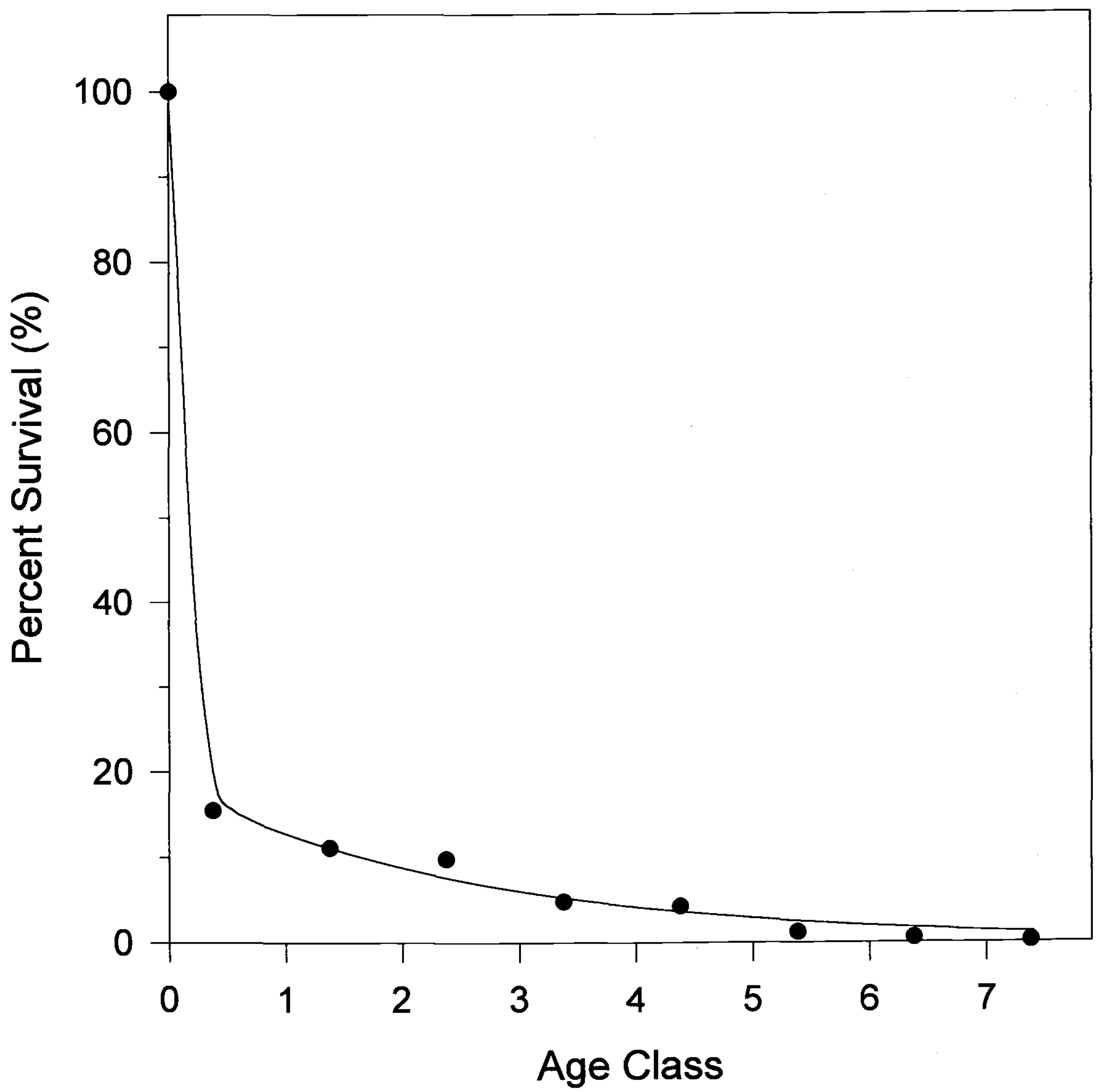

Figure 20. Estimated survivorship curve for crayfish in Draw-Down habitat. The instantaneous mortality rate was (Z) = 0.67.

Production and Biomass

Total annual production of crayfish in Draw-Down habitat was 52.39 g/m^2 and the total biomass was 83.67 g/m^2 (Table 4). The greatest biomass was found in the 2+ age class. Using the production and biomass estimates, the calculated turnover ratio was 0.63. The total mean production, weighted for each habitat type, for LBC was 21.16 g/m^2; the weighted mean biomass was 33.80 g/m^2. The estimated annual production for all ages in LBC was 390,807 kg and the total biomass was 624,175 kg (Table 5). Approximately 86% of the production and biomass occurred in the combined S/S and Mix habitats.

Movements and Migrations

Horizontal movements of crayfish tagged in 1994, even though highly variable in distance, generally increased with time (Figure 21). Crayfish captured in 1994, 14 days after tagging, moved 107 ± 67 m (n = 11). In 1995, 411 ± 28 days after tagging, the mean distance moved from the release point was 588 ± 271 m (n = 14). The mean distance moved by the only two crayfish recaptured in 1996 was 1,375 ± 300 m over a period of 674 days. The mean net movement of recaptured crayfish was 1.5 m/day. There was no significant movement in either the upstream or downstream direction of recaptured crayfish (P = 0.89, Chi-square analyses).

Table 4. Annual production and biomass estimates for all ages of crayfish from Draw-Down habitat.

Age	No./m^2	Mean wt (g)	Biomass (g/m^2)	Loss (No./m^2)	Wt at loss (g)	Wt loss (g/m^2)
0	13.75[a]	0.06	0.83	11.62	0.67	7.73
0.38	2.13[b]	1.27	2.71	0.60	4.83	2.90
1	1.53[b]	8.38	12.82	0.18	11.90	2.14
2	1.35[c]	15.41	20.80	0.69	19.42	13.40
3	0.66[c]	23.43	15.46	0.08	27.60	2.21
4	0.58[d]	31.76	18.42	0.41	36.95	15.15
5	0.17[d]	42.14	7.16	0.10	46.95	4.70
6	0.07[d]	51.76	3.62	0.04	56.66	2.27
7	0.03[d]	61.55	1.85	0.03	63.51[e]	1.91

Total Biomass = 83.67 g/m^2 Total Production = 52.39 g/m^2

[a]Estimated from pleopod fecundity with pre-recruitment mortality.
[b]Estimated from quadrat sampling.
[c]Estimated from linear regression interpolation.
[d]Estimated from length-frequency data of hand-captured crayfish from a known area.
[e]Weight at loss between 61.55 g and observed maximum of 65.47 g.

Table 5. Production (g/m^2) and biomass (g/m^2) estimates for crayfish in different habitat types and total production (kg) and biomass (kg) for available habitat in Lake Billy Chinook.

	Production		Biomass	
Habitat	Production (g/m^2)	Total production in LBC (kg)	Biomass (g/m^2)	Total Biomass in LBC (kg)
Cliff	11.13	2,143	17.77	3,421
B/C	11.59	20,305	18.51	32,428
S/S and Mix	21.10	335,281	33.70	535,496
Draw-Down	52.39	33,079	83.67	52,830
Weighted mean	21.16	390,807	33.80	624,175

Although there were significant differences between crayfish depth distributions by season and crayfish gender, no clear migration pattern was apparent. The means of the depth distributions for male crayfish were 7 m and 2 m deeper than the females depth distributions in January 1996 and August 1995, respectively (P-values < 0.01, Mann-Whitney rank-sum U-tests). In July 1995, the female mean depth distribution was 7 m deeper than the male ($P < 0.01$, Mann-Whitney rank-sum U-test). There was a significant difference between the depth distributions of male crayfish for all months sampled ($P < 0.05$, ANOVA on ranks). There were no significant differences between the

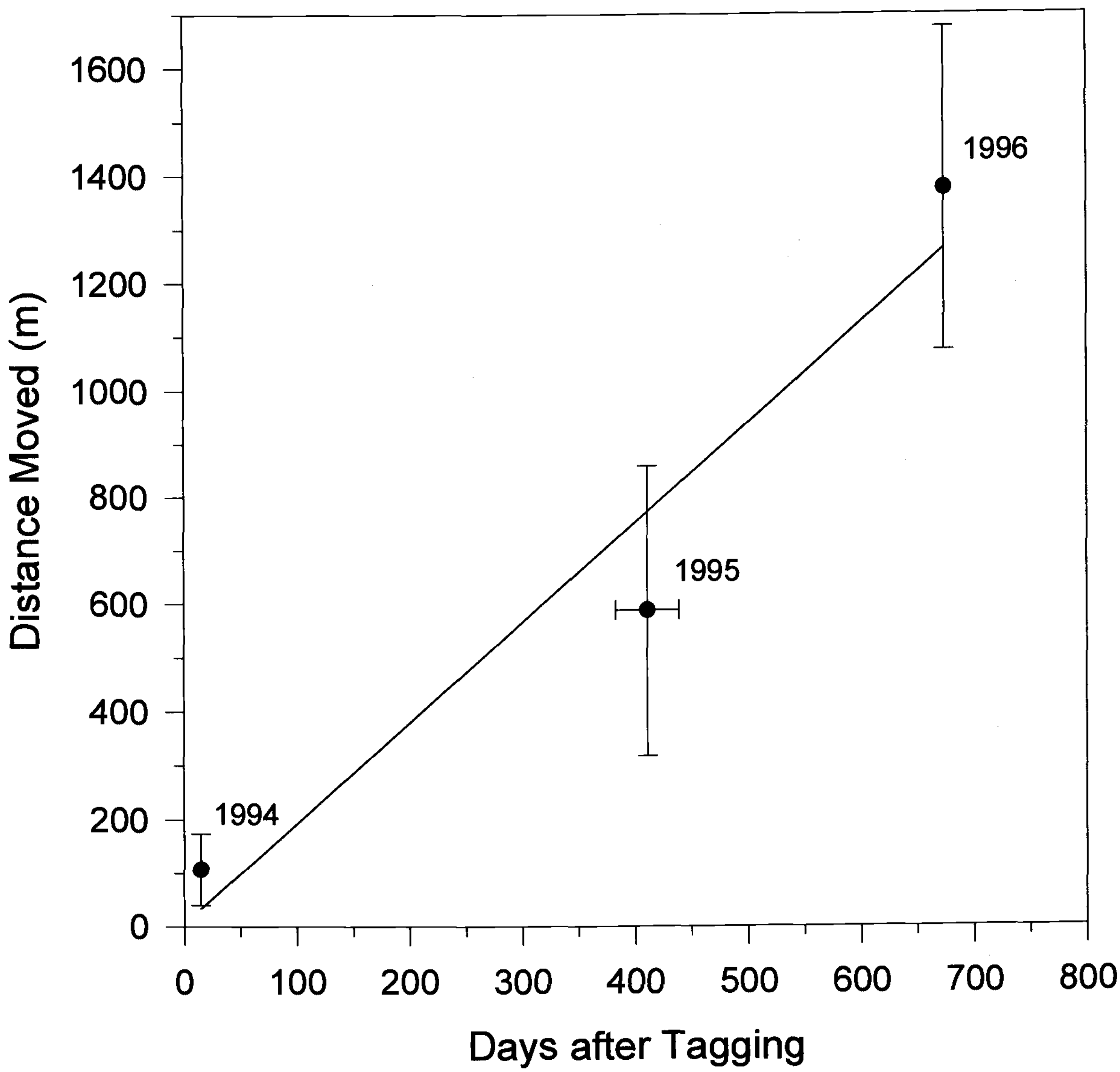

Figure 21. Linear regression of the mean distance moved (m) and the mean number of days after tagging, with 95% confidence intervals, by crayfish tagged in 1994 and recaptured in 1994 (n = 11), 1995 (n = 12), and 1996 (n = 2). The regression equation is: (meters moved) = 45.0 + 1.51(days after tagging), $P < 0.0001$, $r^2 = 0.49$, n = 25.

means of the male distributions for January 1996 and July 1995 and also between January 1996 and September 1994 (P-values > 0.05, Dunn's multiple-comparison test). There was a significant difference between the depth distributions of female crayfish for all months sampled ($P < 0.05$, ANOVA on ranks). There were no significant differences between the means of the female distributions for January 1996 and August 1995 and also between September 1995 and July 1995 (P-values > 0.05, Dunn's multiple-comparison test).

Smallmouth Bass Predation

During the months of May through September, the diet of smallmouth bass was primarily crayfish (Figure 22). Of the smallmouth bass that had ingested items, the mean volume represented by crayfish was 95.3% for the months sampled. Of the total volume of crayfish that was consumed, 95.0% was 1+ age crayfish or older with a mean POCL of 20 mm. The mean number of crayfish consumed decreased during the five months sampled, from a high of 2.7 crayfish per smallmouth bass sampled in May to a low of 0.3 crayfish in September. The analysis included smallmouth bass with empty stomachs, which was 30.0% of the smallmouth bass sampled. Other notable taxa consumed included Diptera, Hemiptera, and Amphipoda that represented only 2.4%, 1.3%, and 1.0% of the total volume, respectively. Other taxa found were Arachnid, Coleoptera, Hymenoptera, Lepidoptera, Hirudinea, and smallmouth bass. Each of these taxa were only found once and were excluded from the analysis.

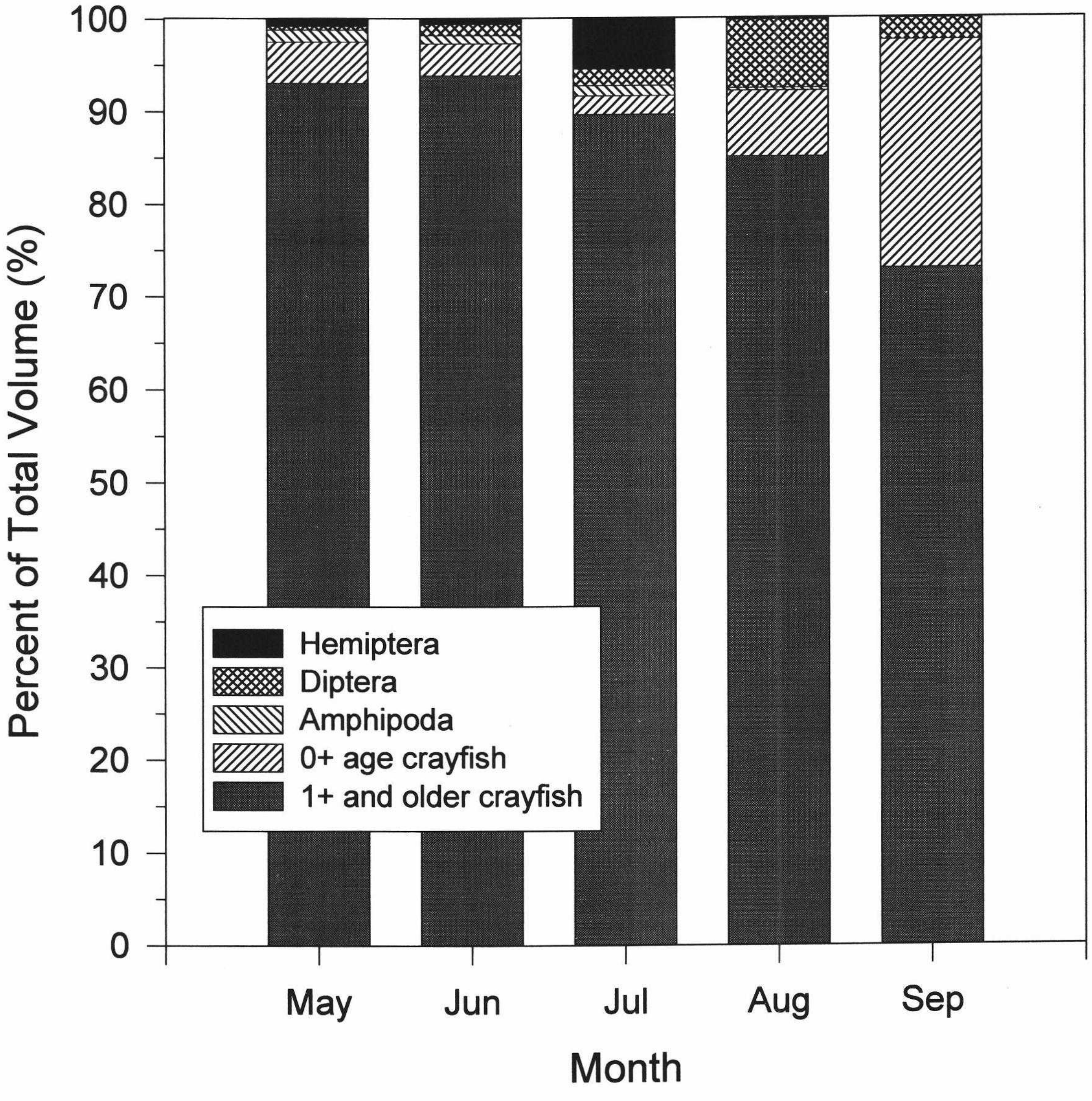

Figure 22. Percent of food items (by volume) contained in stomachs of smallmouth bass (n = 203) from May to September of 1995.

Management

Past Harvest and Management

Commercial harvest of crayfish in LBC began in 1970; although, catch statistics were not kept by ODFW until 1981. Total annual harvest peaked in 1987 at 69,967 kg, and the mean annual harvest during the 1980s was 25,471 kg (Figure 23). Through 1995, the lowest harvest occurred in 1993 at 1,283 kg (Figure 23). A tribal commercial crayfish fishery began in the Metolius River arm in 1987. This coincided with the largest tribal harvest at 24,025 kg. The tribal harvest decreased thereafter to only 23 kg in 1993 (Figure 23). The drop in harvest after 1987 corresponded with a drop in the market price for crayfish and an increase in the minimum legal size from 89 mm to 92 mm TL. The total number of commercial crayfishing licenses issued that harvested crayfish from LBC ranged from 1 to 35 during the period of record from 1981 to 1995, and the mean number of licenses per year was 14 (Figure 23). The number of licenses peaked twice at 35, once in 1982 and again in 1987 (Figure 23).

The mean market price for crayfish from 1981 to 1995 ranged from \$2.20/kg in 1994 to \$3.06/kg in 1987, and the mean price was \$2.52/kg (Figure 24). The number of commercial licenses appeared to be correlated with the mean market price. After excluding the year 1982, because it was too much of an influential outlier, the correlation was significant (No. of licenses = -35.1 + 19(mean \$/kg), $P = 0.01$, $r^2 = 0.43$, $n = 14$). The mean annual harvest per license ranged from 428 kg/license to 5,670 kg/license, which occurred during

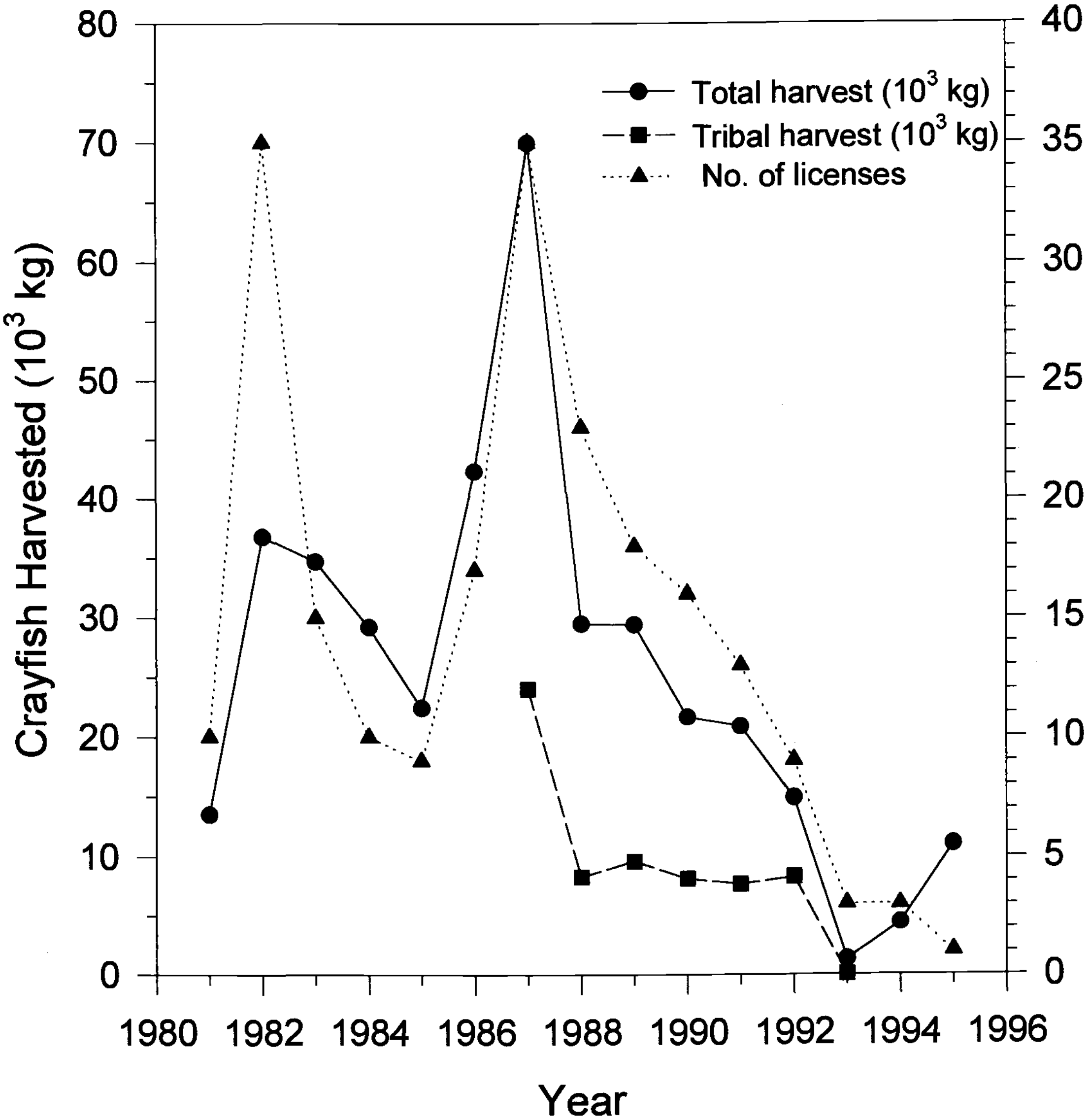

Figure 23. Total commercial and tribal harvest (10^3 kg) of crayfish and total number of commercial fishing licenses from 1981 to 1995.

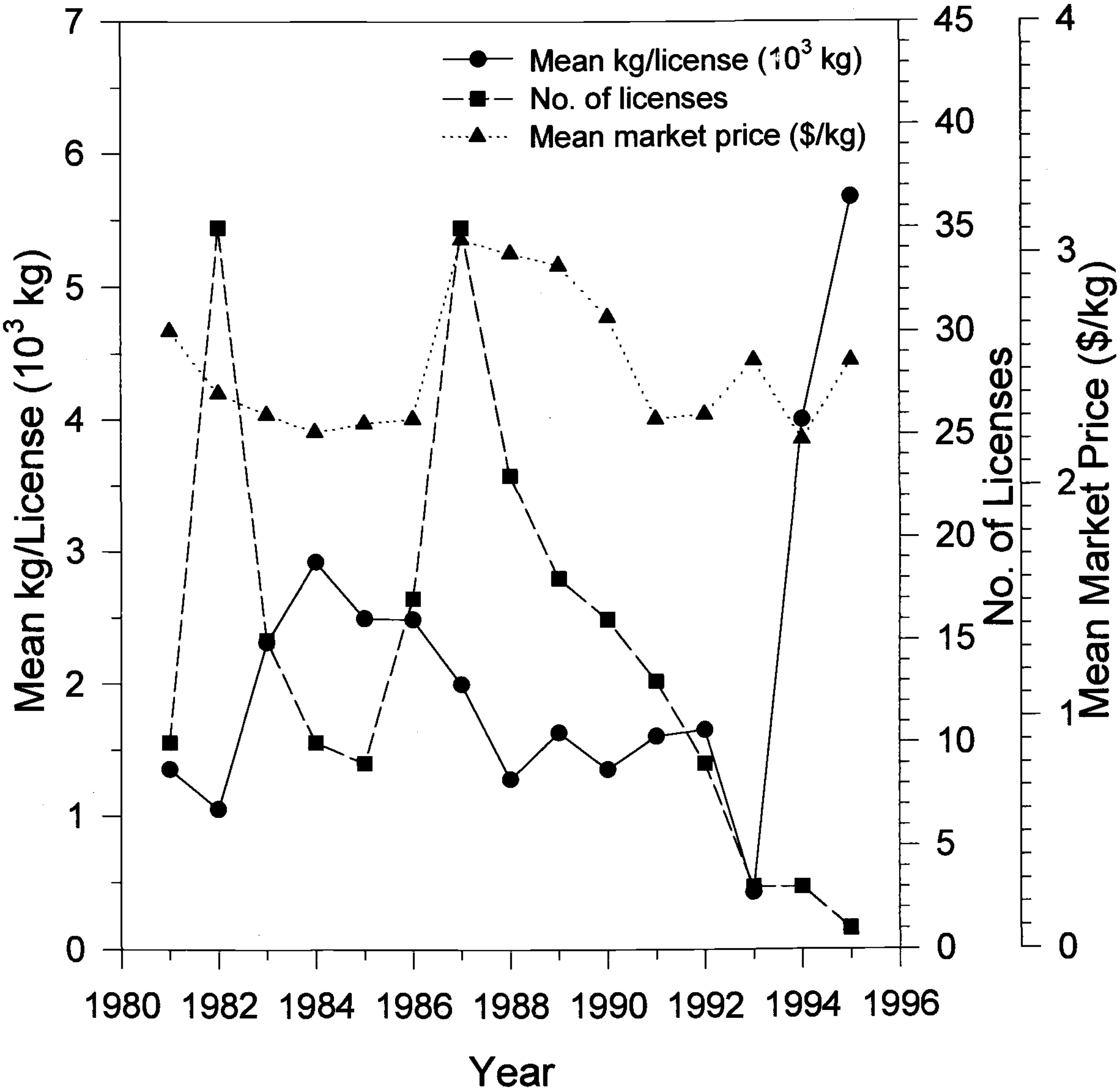

Figure 24. Mean kg/license (10^3 kg), number of licenses, and mean market price for crayfish from 1981 to 1995.

1993 and 1995, respectively. The mean from 1981 to 1995 was 2,150 kg/license (Figure 24). The number of licenses was significantly correlated with the mean kg/license ($P = 0.017$, $r^2 = 0.39$, $n = 14$, linear regression). The year 1993 was excluded from the analysis because it was not representative. As the number of licenses increased, the mean kg/license decreased (Figure 24).

The total quantity of crayfish commercially harvested from LBC increased with the number of licensees fishing. The mean harvest increase was 1,761 kg for every one licensee (Figure 25). The catch-per-unit-effort (CPUE) appeared to be linear for the years 1981-1995. The year 1982 was again excluded from the analysis because of its influence. In 1982 the number of licenses was high, but harvest was abnormally low (Figure 25).

The ODFW crayfish samples from 1970, 1982, and 1988 were converted from TL to POCL using a relation estimated from linear regression (Figure 26). There was a significant difference ($P < 0.0001$, ANOVA F-test) between mean lengths of the sampled years (Figure 27). However, there was no significant difference between mean lengths for 1983 and 1988 ($P > 0.05$, Dunn's multiple-comparison test). Although there was no difference between the mean POCL of these two years, the percent of crayfish $\geq$ 35 mm (current minimum size) was 22% in 1983 and 14% in 1988 (Figure 27). The current minimum size of crayfish for commercial harvest is 92 mm TL, which corresponds to 35 mm POCL, was changed from 89 mm TL in 1988. The sample from 1970 was assumed to be representative, but it may have been taken from the upper 3 km of the Crooked River arm where crayfish are larger (Figure 28).

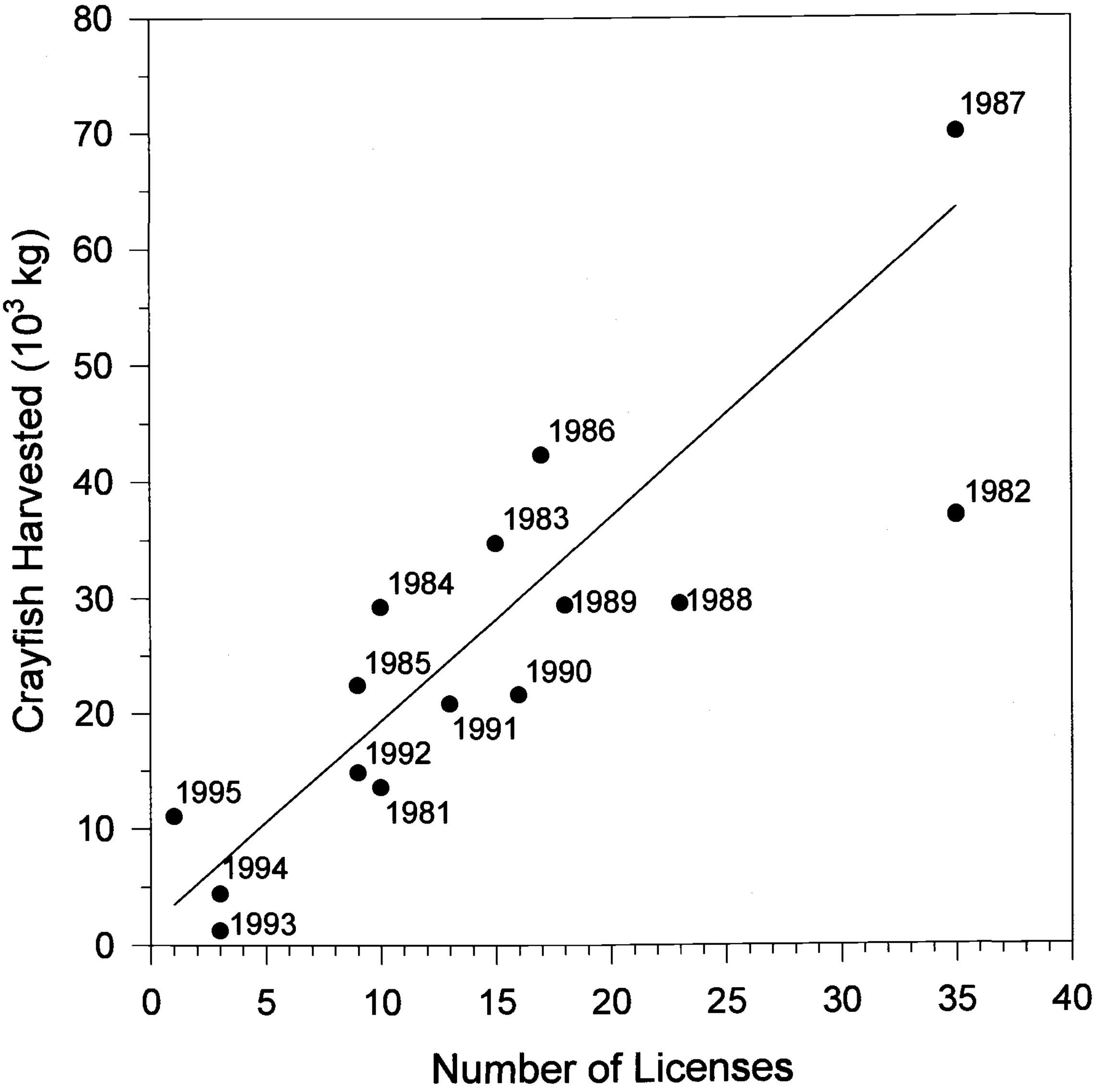

Figure 25. Linear regression of commercially harvested crayfish (10^3 kg) and the number of commercial licenses from 1981 to 1995. The regression equation is: (kg) = 1763.4 + 1761.3(No. of licenses), $P < 0.0001$, $r^2 = 0.82$, $n = 14$. The year 1982 was excluded from the regression.

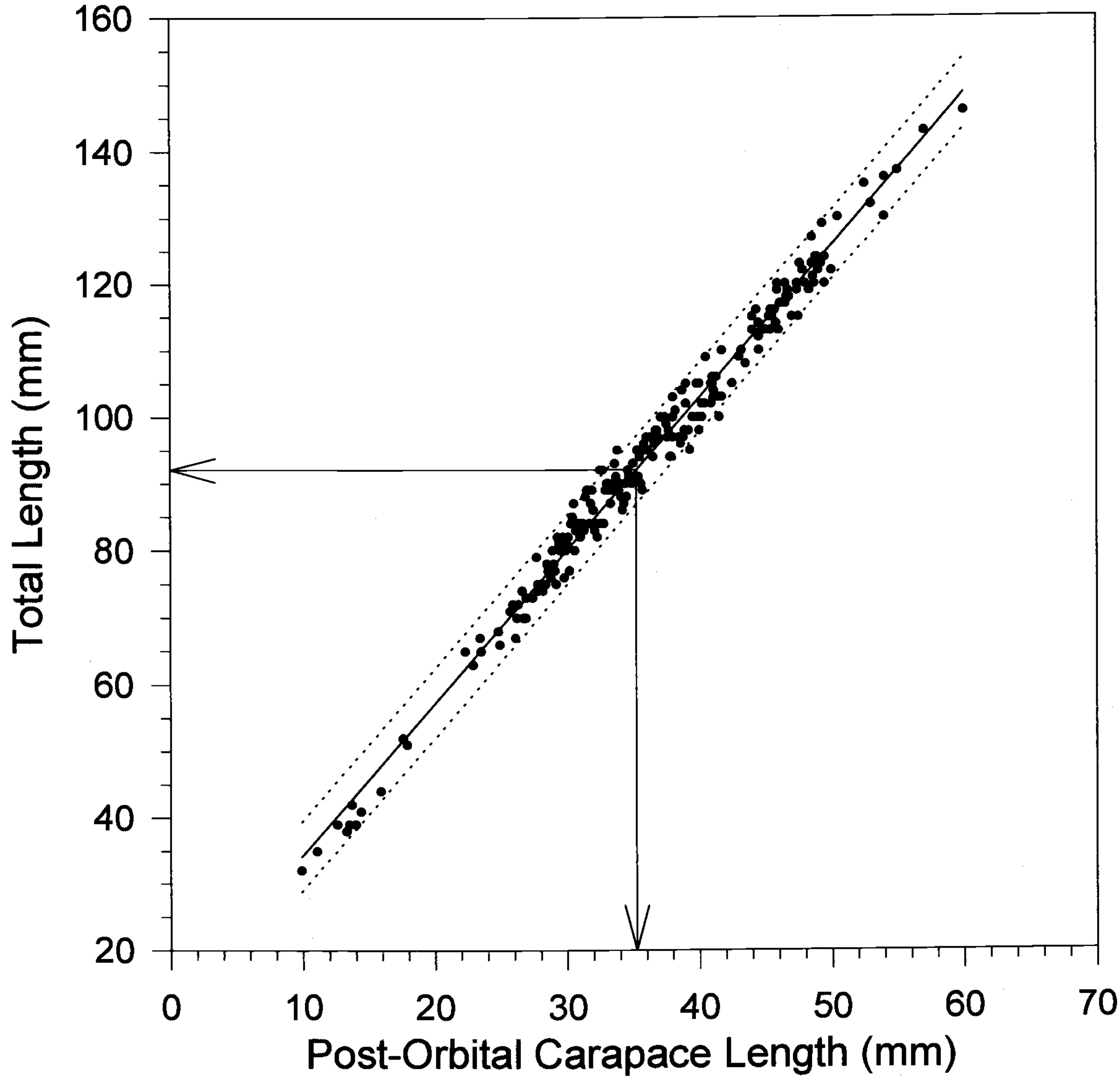

Figure 26. Linear regression of crayfish total length and post-orbital carapace length, with 95% prediction interval, for male (n = 125) and female (n = 90) crayfish. The regression equation is: (TL) = 11.49 + 2.29(POCL), $P < 0.0001$, $r^2 = 0.98$, n = 215. Drop lines point to current minimum total length (92 mm) and post-orbital carapace length (35 mm) of commercially harvestable crayfish.

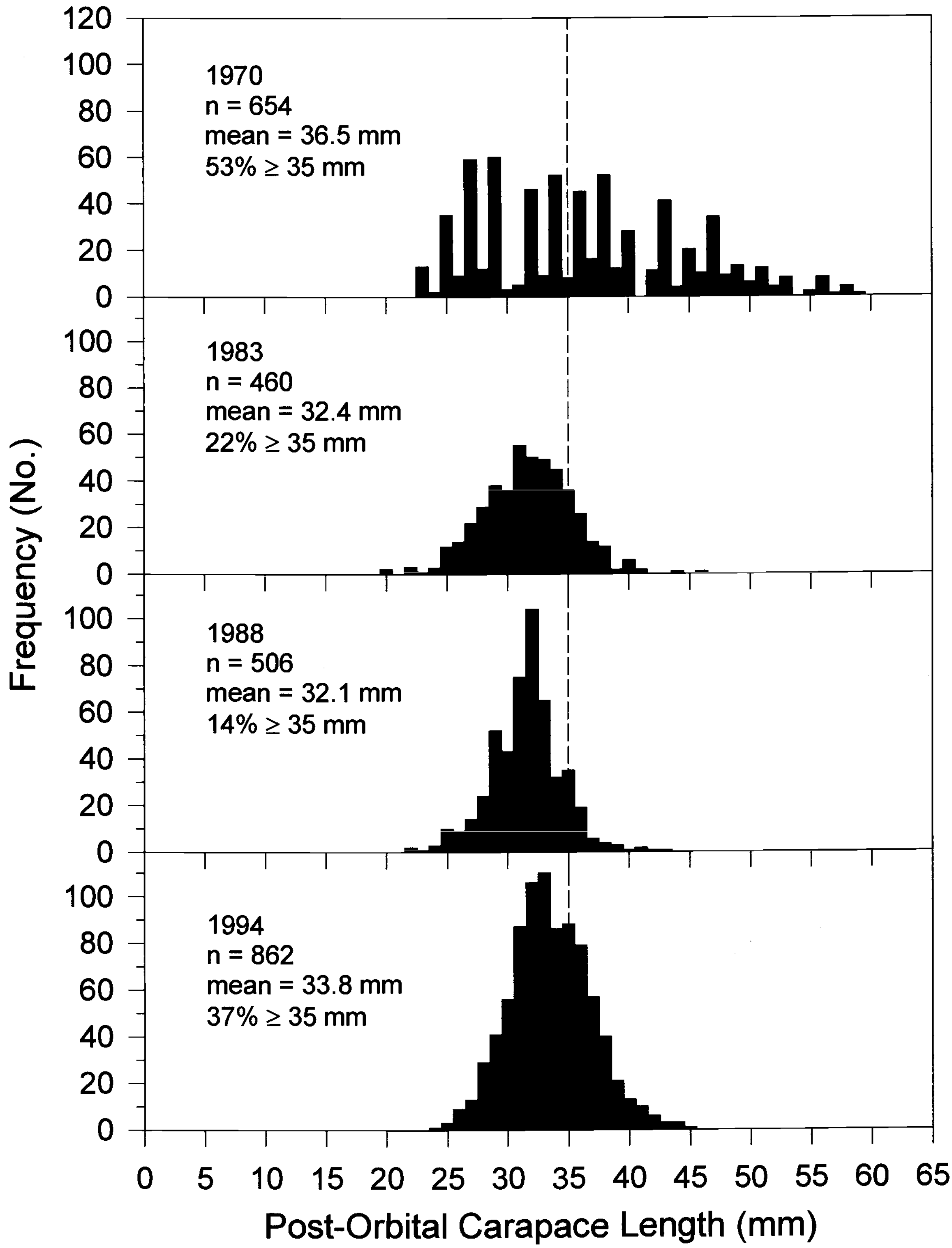

Figure 27. Length-frequency distributions of crayfish from 1970, 1983, 1988, and 1994 samples. The vertical dashed line indicates current minimum post-orbital carapace length (35 mm) for commercial harvest.

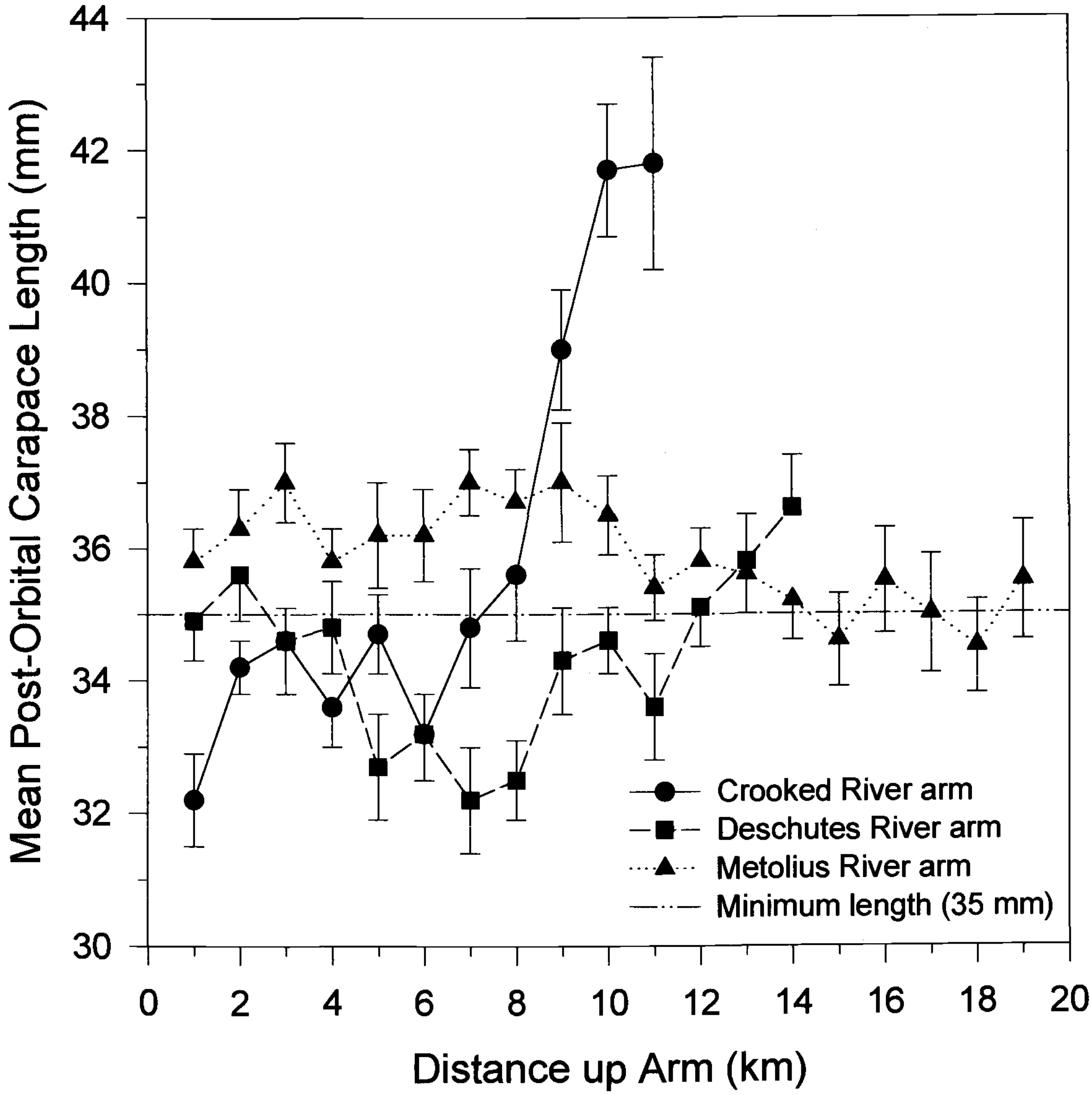

Figure 28. Mean post-orbital carapace length (mm) of crayfish, with 95% confidence intervals, per km in the Crooked River (n = 1,100), Deschutes River (n = 1,400), and Metolius River (n = 1,900) arms. Horizontal dashed line equals current minimum post-orbital length (35 mm) for commercial harvest.

Comparisons of mercury concentrations in abdominal musculature of crayfish tested in 1971 and 1995 from each arm of LBC were significantly different. The mean concentration of mercury in crayfish from 1995 in the Crooked River arm was 0.124 ± 0.033 ppm and was significantly higher ($P < 0.01$, t-test) than the concentration detected in 1971 at 0.077 ± 0.039 ppm. In the 1995 sample from the Deschutes River arm, the mercury concentration was 0.114 ± 0.018 ppm and was significantly lower than the 1971 sample at 0.276 ± 0.076 ppm ($P < 0.001$, Mann-Whitney rank-sum U-test). In the Metolius River arm, there was no significant difference between the 1995 sample of 0.114 ± 0.029 ppm and the 1971 sample at 0.063 ± 0.061 ppm ($P = 0.10$, Mann-Whitney rank-sum U-test).

In Oregon, the current minimum size restriction of commercially caught crayfish is 92 mm (TL). The fishing season extends from 1 April to 31 October. The minimum size of 92 mm TL is thought to allow female crayfish to mate and produce offspring at least once before becoming available for harvest. The fishing season is designed to protect ovigerous females during incubating (A. K. Smith, ODFW, personal communication). Other commercial regulations include: purchase of a commercial license, using only traps to capture crayfish, labeling of all gear (e.g., boats, traps, and holding pens) with an identification number issued by ODFW, and returning all ovigerous females and undersized crayfish immediately to the water. There is no limit on the crayfish that can be harvested by a licensee, or for the total harvest from any specific body of water.

Commercial harvest in the Metolius River arm of LBC is open only to tribal members of CTWSRO. In addition to the regulations on the other two arms of LBC, tribal fishery managers also set a limit of 1,000 traps that can be fished in the Metolius River arm. The arm is divided into 12 zones that are awarded to tribal members though a lottery system. A minimum of two zones are maintained as sanctuaries on a rotating basis.

Management Recommendations

The current minimum size limit of 92 mm TL is accomplishing its intended goal of allowing a cohort to complete one reproductive cycle before recruitment into the harvestable population. Unless management objectives of the fishery change, the current minimum size limit is adequate.

The current fishing season from 1 April to 31 October is not accomplishing its intended goal to protect ovigerous females during the incubation period. If full protection of ovigerous females is to be accomplished, the commercial fishing season should be shortened two months and extend only from 1 May to 30 September.

The tribal regulations in the Metolius River arm of LBC generally seem sufficient. The method of drawing fishing zones is a good way to limit harvest to a desired level. The rotation of two sanctuaries throughout the arm is not biologically necessary because the current regulations serve the purpose of conservation.

Currently there is no limit on the quantity of crayfish that can be harvested from LBC. To protect the long-term sustainability of the fishery, the total annual harvest should not exceed 50,000 kg. This is the natural production, minus 22% to account for molted exoskeleton production (Mason 1975), of harvestable-size crayfish estimated from the depths that are usually fished (< 15 m). Half of this harvest, 25,000 kg, could come from the Metolius River arm alone, and the other half from the combined Crooked River and Deschutes River arms. All other biologically related regulations appear to be reasonable.

The recommendation is also made that commercial licensees be required to keep a record of the effort (trap-sets) expended to capture the crayfish sold at market. Currently, only the license number, total catch, and body of water is recorded on a sales ticket submitted to ODFW. The recording of the number of trap-sets would allow the computation of CPUE for a more reliable measurement of effort to help manage the fishery. One trap-set is defined as one trap baited, set overnight, and pulled the next day.

It is also recommended that index sites be established in LBC to ensure that any differences between future crayfish samples would be related to factors other than the habitat from which the samples were taken. There should be at least two index sites per arm and a sample of at least 500 crayfish lengths per site. Depth of traps for samples should also be standardized (e.g., 5-15 m). One sample per year during the first 2 weeks of June, after most harvestable size crayfish have molted, would be sufficient to monitor the population. During high harvest years, a second sample could be taken at the end of September.

DISCUSSION

Life History

Reproduction

Maturation. — Maturation of *P. leniusculus* in LBC displayed the expected positive relation of increased percent maturity with increased size (Figure 3). Males and females matured in the fall of their third year at age 2+. This was the same as exhibited by a *P. leniusculus* population in the Sacramento River (McGriff 1983*a*), but a year earlier than a population in Lake Tahoe (Flint 1975*a*). The difference in age at maturity is most likely the result of differential growth rates between populations (McGriff 1983*a*), i.e., crayfish that grow faster mature earlier.

Copulating and Spawning. — *P. leniusculus* in LBC began copulation at the same time (first week of October) in 1994 and 1995 (Figure 5). Photoperiod was likely the main factor initiating copulation. The date at fall turnover was 12 days earlier and the temperature was 2°C lower in 1995 than in 1994. Nevertheless, copulation occurred at the same time both years. Wild populations of *P. leniusculus* in western North America copulate at about the same time. Most copulation occurs in October (Mason 1963; 1970*a*; Flint 1975*a*; Shimizu and Goldman 1981; McGriff 1983*a*). Very similar copulation times have been documented for introduced *P. leniusculus* in Sweden (Söderbäck 1995). However, lotic populations seem to initiate copulation 14-21 days earlier than lentic populations (McGriff 1983*a*). Perhaps physical cues used to initiate copulation change with environments. Temperature in lentic environments changes less rapidly than in lotic environments and therefore crayfish may rely on photoperiod more as a cue.

Hatching. — Date at egg hatching (Figure 6) for *P. leniusculus* in LBC was within the range (March to July) reported for other populations (Miller 1960; Mason 1963; Flint 1975*a*; Shimizu and Goldman 1981; McGriff 1983*a*). Temperature differences likely account for this range. Hatching times are earlier in warmer environments and later in colder environments. For example, in the Sacramento River hatching occurs as early as March (McGriff 1983*a*), but in Lake Tahoe it occurs as late as July (Flint 1975*a*). Based on hatching times, LBC's mean water temperature would be colder than the Sacramento River but warmer than Lake Tahoe. This agrees with the present temperature characteristics of the respective environments.

Incubation. — Incubation of *P. leniusculus* eggs in LBC required 2,208 degree-days. This concurs with Mason's (1977) mean estimate of 2,249 degree-days for *P. leniusculus* in a laboratory experiment, a difference of only 41 degree-days.

Fecundity. — Even though the apparent decrease of the mean number of pleopod eggs from November through March was not significant (Figure 7), considerable over-winter losses of pleopodal eggs can occur (Mason 1977). The mean estimate of 105 ± 12 pleopodal eggs for this study was lower than estimates for other populations. Mean pleopod egg counts normally range from

110 to 201 (Abrahamsson and Goldman 1970; McGriff 1983*a*; Söderbäck 1995). However, researchers typically estimate pleopod eggs only in the fall after spawning and do not included the rest of the incubation period. This variation in methodology may account for the differences.

Pathogens and Parasites

Infections and infestations from pathogens and parasites of *P. leniusculus* in LBC appear to be low in frequency and intensity. Because of natural resistance, the fungi *A. astaci* does not have the same detrimental effects on *P. leniusculus* populations as it does on European species (Alderman and Polglase 1988). Even though no gross infections were observed during the course of this study, *A. astaci* was most likely present in a low chronic state. The occurrence of the microsporidian *T. contejeani* in a low percentage of the LBC crayfish population is similar to what has been found in other crayfish populations (Persson and Söderhäll 1981). Because infection is dependent on ingestion of *T. contejeani* spores (i.e., cannibalism) it has a density-dependent nature (Brown and Bowler 1977). At current crayfish densities in LBC, it does not appear that *T. contejeani* will cause substantial mortalities. The ubiquitous presence of branchiobdellids on *P. leniusculus* in LBC did not appear to affect the population significantly. The extent of secondary infections as a result of branchiobdellids was not quantified, but did seem to be low. The overall health of *P. leniusculus* in LBC appeared to be good.

Population Dynamics

Habitat

The Crooked River and Deschutes River arms have similar habitats (i.e., many Cliff and B/C habitat areas) because of recent geological events. About 1.2 million years ago, a large intra-canyon basalt lava flow filled the then existing Crooked River and Deschutes River canyons (Bishop and Smith 1990; Orr et al. 1992). When the Crooked and Deschutes rivers eroded though the basalt, many areas with large vertical cliffs remained. At the bottom of the vertical basalt cliffs, talus accumulations of boulders and cobbles formed (Bishop and Smith 1990). This same intra-canyon basalt flow only partially extended up the Metolius River canyon (Smith 1986), and thus its habitat is composed of mostly S/S and Mix (Figure 9).

The lower limit and overall depth distribution of *P. leniusculus* in LBC (Figure 10) appeared to correspond to the amount of light penetration that would be expected for a reservoir of LBC's eutrophic classification (Wetzel 1983). Abrahamsson and Goldman (1970) suggested the lower limit of *P. leniusculus* in Lake Tahoe was determined by low water temperatures (< 6.8 °C), which interfered with the ability of eggs to hatch. This could not explain the distribution of crayfish in LBC because the winter low isothermal temperature was > 10 °C.

The lower trap catches of crayfish in the 5-10 m interval of LBC may indirectly be a result of water temperature stratification. Temperature stratification creates a surface layer of warmer water (epilimnion) that is about 10 m deep in LBC (Appendix 2, 3, and 4). Smallmouth bass, which appear to be the most significant crayfish predator in LBC, are typically found in the epilimnetic water of littoral areas in lakes and reservoirs (Scott and Crossman 1973; Carlander 1977). The concentration of smallmouth in the littoral area probably increases predation on crayfish relative to deeper areas. Increased fish predation might explain the lower trap catches in the 5-10 m interval (Collins et al. 1983). This same pattern was apparent from the transect density estimates on Cliff habitat (Figure 13). During the winter, a time when smallmouth bass are less active (Scott and Crossman 1973; Carlander 1977), this same pattern was not seen (Figure 10). In winter, most crayfish were captured in the top 10 m. In addition to less predation, the winter distribution may also be explained by greater activity of crayfish in the upper 10 m and less in deeper water and not by a net movement of crayfish to shallower water.

Nocturnal activity of *P. leniusculus* in LBC suggested a skewed distribution toward sunset (Figure 11). *Orconected virilis and O. propinquus* crayfish populations in Lake Michigan appear to display this same behavior (Quinn and Janssen 1989). This distribution would support a behavioral hypothesis that crayfish are reluctant to leave cover at dusk to forage and are eager to seek cover at dawn.

Age and Sex Composition

The number of cohorts (eight) that were identified from length-frequency analysis in this study (Table 2) were the same as a *P. leniusculus* population in the Sacramento River (Shimizu and Goldman 1981). In other environments, *P. leniusculus* have been observed to have as many as 9 (Mason 1975) to 12 (Flint 1975*a*) cohorts. Even with large sample sizes (n = 710), length-frequency distributions obtained from trap catches were difficult, at best, to analyze. Therefore, when age structure is an important objective in a study, capturing crayfish by hand is the preferred method because the cohorts are more accurately separated (France et al. 1991).

The smaller mean size of crayfish in B/C habitat (Figure 12) may be due to slower growth, as a result of a poor food source, for crayfish in that habitat type (Svärdson 1949). The larger crayfish in the S/S habitat may indirectly reflect effects of fish predation. Not only are smaller crayfish eaten, but larger crayfish are able to selectively use S/S habitat due to their resistance to fish predation (Stein 1977; Mather and Stein 1993).

The sex ratio of *P. leniusculus* in LBC was estimated to be 50:50 (Figure 13). Deviations from this ratio were probably the result of seasonal behavioral differences between male and female crayfish (Westin and Gydemo 1987). The sex ratios of trapped crayfish for the months of March and April significantly deviated, in favor of males, from an expected 50:50 ratio one month before and during egg hatching. This result would suggest that females are more reclusive just prior to and during hatching of their eggs. During May, just after eggs hatch, females dominated the catch suggesting that they were aggressively seeking food to replenish reserves lost during the hatching period.

Density

Densities of *P. leniusculus* in LBC (Figure 14) were below those estimated for other studies, especially in the B/C habitat type. Shimizu and Goldman (1981) speculated that densities of *P. leniusculus* in similar rocky substrate could be 77.2 crayfish/m^2, which is much higher than the 0.25 crayfish/m^2 in B/C habitat from this study. This disparity may be the result of differences in the extent and character of these habitats. The B/C habitat areas in LBC are up to 400 ha in size. Even though there was adequate cover for crayfish, periphyton appeared to be the only significant food source available and probably was not capable of sustaining high crayfish densities. In Draw-Down habitat, which had higher densities, crayfish were observed migrating to adjacent S/S areas at night to forage for invertebrates and other consumable items. A plausible hypothesis might be that habitat complexity is more important than cover alone in determining crayfish densities.

Abundance

The estimated trap capture ranges of 92 m^2 for B/C habitat and 116 m^2 for the combined S/S and Mix habitats were larger than the 12.7 m^2 for cobble and bolder habitat calculated by Abrahamsson and Goldman (1970), but were much smaller than the 1,452 m^2 for sand flats calculated by Flint (1975*a*). There are many sources of variation in the trap capture range method that could explain the differences, e.g., kind of bait used in traps, habitat type, crayfish densities, and length of time traps are set. Nonetheless, this method is a useful tool to estimate crayfish densities at water depths that otherwise would not be obtained.

The combined transect and trapping method used to estimate crayfish abundance (Table 3) was biased because it could not effectively sample the smaller age classes. The resulting abundance estimates were in effect estimates of the crayfish susceptible to trapping. Even after adding 0+ and 1+ age class density estimates from quadrat sampling, the total abundance estimate of 35,940,145 ± 8,127,159 was still an underestimate of the total population because ages 2+ and 3+ were still underrepresented. The under representation of 2+ and 3+ age crayfish was because the biases associated with trapping cause more larger crayfish to be caught, and also because of the small quadrat sample size that could not account for lower densities of the older crayfish. One of the key assumptions that had to be made was that the age structures were similar between habitat types. This assumption held up well enough to use in this context, based on the results of length-frequency comparisons between habitats, even though clear age classes could not be defined. The only habitat in which age structure might have been different enough was B/C, where the age structure appeared to be shifted toward the smaller crayfish (Figure 12).

Growth and Mortality

Growth in length of *P. leniusculus* in LBC exceeded estimates for populations in both Lake Tahoe (Flint 1975*a*) and Berry Creek (Mason 1963), but was slightly less than that for populations in the Sacramento River (Shimizu and Goldman 1981) and Finland (Westman et al. 1993). The fit of the von Bertalanffy growth curve to the estimated cohort POCLs was generally acceptable (Figure 16). The curve better described the first three years of growth. Growth between cohorts after that was more linear than the curve could fit. This same phenomenon was found in populations from Lake Tahoe (Flint 1975*b*) and the Sacramento River (Shimizu and Goldman 1981). The linear growth of the last four cohorts was probably because from age 4+ on, *P. leniusculus* only molt once per year (Flint 1975*b*; Shimizu and Goldman 1981). Growth in weight of males and females (Figure 17) was very similar even though they are quite different morphologically (Miller 1960). This apparent lack of difference between sexes is probable because the disproportionate growth of male chelae is offset by growth of female abdomens (Flint 1975*a*). The mean molt increment of 3.0 mm (Figure 18) is similar to the 2.3 mm increment estimated for *P. leniusculus* in the Sacramento River (Shimizu and Goldman 1981).

The molting pattern, as indicated by gastrolith thickness, with its two modes was likely the result of age of the crayfish sampled (Figure 19). The first mode in April represented the period when age 3+ and older crayfish all molted. The second and smaller mode represented mostly 3+ crayfish that molted a second time during the growing season. Age 4+ and older crayfish typically molt only once a year (Flint 1975*b*; Shimizu and Goldman 1981).

The mortality rate for *P. leniusculus* in LBC ($Z = 0.67$) was identical to that estimated for *P. leniusculus* in the Sacramento River (Shimizu and Goldman 1981). This rate was twice the mortality rate ($Z = 0.324$) estimated for *P. leniusculus* in the colder Lake Tahoe environment (Flint 1975*a*). These rates support the fact that *P. leniusculus* in Lake Tahoe live an additional four years (Flint 1975*b*).

Production and Biomass

The annual crayfish production in LBC of 21.16 g/m^2 (Table 5) was similar to most other estimates of *P. leniusculus* from other environments. Mason's (1975) calculated annual production for *P. leniusculus* in a small western Oregon stream was 23.4 g/m^2, and Flint's (1975*a*) estimated annual production in Lake Tahoe for the most abundant habitat was 20.14 g/m^2. However, a population of *P. leniusculus* in the Sacramento River had a much higher estimate of 235.78 g/m^2 (Shimizu and Goldman 1981).

Movements and Migrations

Movements of tagged *P. leniusculus* in LBC during the first 14 days after release (107 ± 67 m) were similar to movements found in Lake Tahoe of about 100 m during a similar period of time (Flint 1975*a*). One and two years after release, the total distance moved increased (Figure 21). However, no clear spatial pattern evolved and led to the conclusion that the movements were random. Evidence of seasonal depth migrations was not conclusive. More samples were probably needed to identify any patter that may be present. However, Flint (1975*a*) concluded that there was a shift to deeper water of *P. leniusculus* in Lake Tahoe during the winter. The one sample in January from LBC indicated just the opposite, a shift to shallower water. This observation was probably due to a difference in crayfish activity between depths and not a net movement of crayfish.

Smallmouth Bass Predation

P. leniusculus was a large dietary component of smallmouth bass in LBC (Figure 22). The age classes most heavily preyed upon were 0+ and 1+. Smallmouth bass selected for these ages based on size and abundance and acted as optimal foragers, minimizing energy expenditures against energy acquisition of prey items, i.e., cost/benefit minimization (Stein 1977). Any effect of smallmouth predation on *P. leniusculus* in LBC was probably offset by compensatory increases in survival and growth (Momot 1967; Gowing and Momot 1979; Momot 1991). It is doubtful, given the habitat that smallmouth bass occupy in LBC, that they could ever exploit crayfish enough to cause any significant population declines.

Initially, other resident fish were to be examined for dietary habits, but the methods employed to capture fish and obtain stomach contents were biased. Boat electrofishing is more efficient for species inhabiting the shallow water along the margin of a lake (≤ 3 m), and fish that inhabit the littoral area of a lake typically do not represent the entire fish community (Reynolds 1983). Because of LBC's small shoal area (5%), smallmouth bass were the primary fish captured during electrofishing. Also, gastric lavage is a method of obtaining stomach contents without sacrificing the fish and has its greatest success with the Centrarchidae and Percidae families (Bowen 1983; Reynolds 1983).

Management

Past Harvest and Management

The *P. leniusculus* fishery in LBC appeared to be market driven. When the market price for crayfish increased, the number of commercial crayfishers closely followed (Figure 24). The majority of commercial crayfishers were from the local area and the income derived from fishing was typically supplemental. As the mean market price for crayfish and the number of commercial licenses increased, the mean harvest per license decreased. Most of this effect was probably the result of more inexperienced and less well-equipped crayfishers entering the fishery when there was a high market price for crayfish. Whereas, the more subsistent crayfishers were likely less affected by decreased market prices and continued to fish; they were probably more efficient as well. This same effect was found in the Sacramento River (McGriff 1983*b*). Also, as more crayfishers entered the fishery, physical competition for the same fishing areas likely reduced the harvest per license (McGriff 1983*b*).

Comparisons of the three sample years from ODFW and the one from this study suggested that harvest effects were apparent in the 1988 sample (Figure 27). The 1970 sample did appear to be unsorted catch from traps, but was skewed in the positive direction and suggested that the sample came from the upper 3 km in the Crooked River arm where the crayfish are larger (Figure 28). The more important sample years were 1983, 1988, and 1994. The 1994 sample was significantly different from both 1988 and 1983, but there was no significant difference between the 1988 and 1983 samples. However, when comparisons were made between the percent of legal size crayfish, differences were more apparent. In 1983, 1988, and 1994, 22%, 14%, and 37% of the crayfish sampled were of harvestable size, respectively (minimum size of 92 mm TL). However, the 1983 and 1988 samples were taken from a population that had a minimum size limit of 89 mm TL. The percent of legal size crayfish under the old minimum size was 32%, 20%, and 47%, which was a change in the percent of legal size crayfish by 10%, 6%, and 10%, respectively. This indicated that the 1988 sample frequency distribution was more leptokurtic, i.e., a distribution having many values around the mean (Zar 1974), than the 1983 and 1994 samples. This was also apparent in a comparison of the frequency distribution standard deviations (3.6, 2.9, and 3.3). A hypothesis for the leptokurtic distribution of the 1988 sample might be that as harvest removed larger crayfish it reduced the intraspecific competition with smaller crayfish and increased their age specific survival and growth rates (Momot 1991). However, with the reduction in harvest since 1988, the crayfish have shown to be quite resilient as indicated by an even larger percent of legal size crayfish from the 1994 sample (37%).

The results from mercury testing indicated that concentrations in crayfish have increased in Crooked River, decreased in the Deschutes River, and remained about the same in the Metolius River since 1970. While the results may have been indicative of changes from anthropogenic sources higher in the watersheds, they may also lack accuracy simply due to the testing methods used during 1971 (D. Drake, DEQ, personal communication). The area that had the highest concentrations from the 1971 testing was from within the boat marina on the Crooked River arm. Due to limits on the number of crayfish that could be tested in 1995, crayfish samples from this area were not tested because it was felt that the other areas were more representative of the LBC crayfish population. Nonetheless, the results from the 1995 testing indicated that mercury concentrations in crayfish were all below the FDA limit of 0.5 ppm.

Management Recommendations

The minimum size limit of 92 mm TL for commercial harvest appears to be accomplishing its stated goal. But whether it is biologically justifiable to allow a cohort only one reproductive cycle before recruitment into the commercial fishery was not determined. Most minimum size limits of crayfish in the western United States appear to be based on sizes that are acceptable at market for human consumption and have no biological basis (Momot 1991; Thomas 1991). Under the past harvest regime, the current minimum of 92 mm TL appears to have ensured enough recruitment. However, if harvest levels were to be sustained at high levels in the future, fishery managers might consider increasing the minimum size limit to 95 mm TL to ensure that a cohort can complete two reproductive cycles before recruitment into the harvestable population. Recruitment overharvest would not occur at the current minimum size; however, growth overharvest probably would occur on a seasonal basis but would recover seasonally as well. As long as the mean size did not continue to drop over several fishing seasons and the population was allowed to recover, harvest could continue.

The recommended shortening of the fishing season by two months probably would not reduce total harvest by a large amount. The months of April and October of the current fishing season are also the months with the lowest harvest and represent about 5-8% of the total catch in a season (ODFW commercial crayfishing statistics, 1981-1995). Crayfish catches are lower in April because of egg hatching and lower in October because of copulating and spawning. Also, the commercial crayfishers tend to avoid the sometimes-extreme environmental conditions that can occur during those two months.

Information on trapping effort from the commercial fishery in the form of trap-sets, in combination with regular annual sampling of the population, could help managers better estimate gear saturation and growth overharvest. If CPUE were to decrease while population parameters remained constant, then gear saturation would have occurred (McGriff 1983*b*). If both were to decrease, then the fishery would be into the growth overharvest phase.

The life history and population characteristics of *P. leniusculus* in LBC are the result of many abiotic environmental factors. Because of this, the often-used method of managing all populations with the same regulations should not be applied to commercially exploited populations. For exploited populations, management regulations should be population specific. The ability of *P. leniusculus* to adapt its life history and population characteristics to a wide range of environments has allowed it to take advantage of the lentic environment of the reservoir. If managed wisely, the crayfish population in LBC could continue to support a sustainable fishery.

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APPENDICES

Appendix 1. Specific objectives and their respective sub-objectives for *Pacifastacus leniusculus* research in Lake Billy Chinook, Oregon.

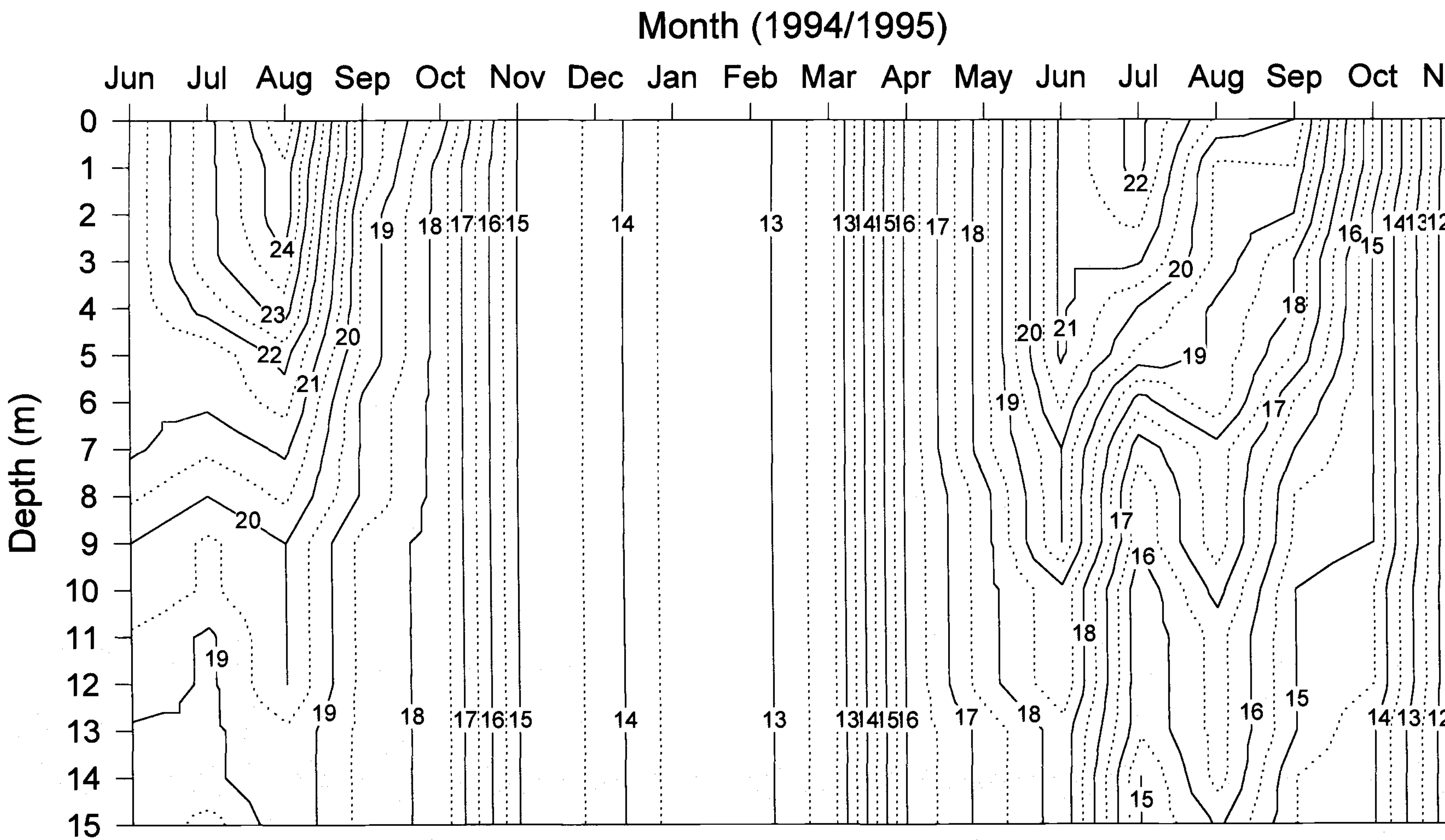
1. **Identify life-history characteristics of *P. leniusculus* in LBC.**
    a. Estimate median minimum age and size at sexual maturity.
    b. Determine time of mating and hatching.
    c. Estimate female fecundity.
    d. Determine the occurrence of gross pathogens and parasites.

2. **Describe the population dynamics of *P. leniusculus* in LBC.**
    a. Determine habitat use.
    b. Estimate age and sex composition.
    c. Estimate density and abundance.
    d. Estimate growth and mortality rates.
    e. Estimate production and biomass.
    f. Determine movements and migrations.

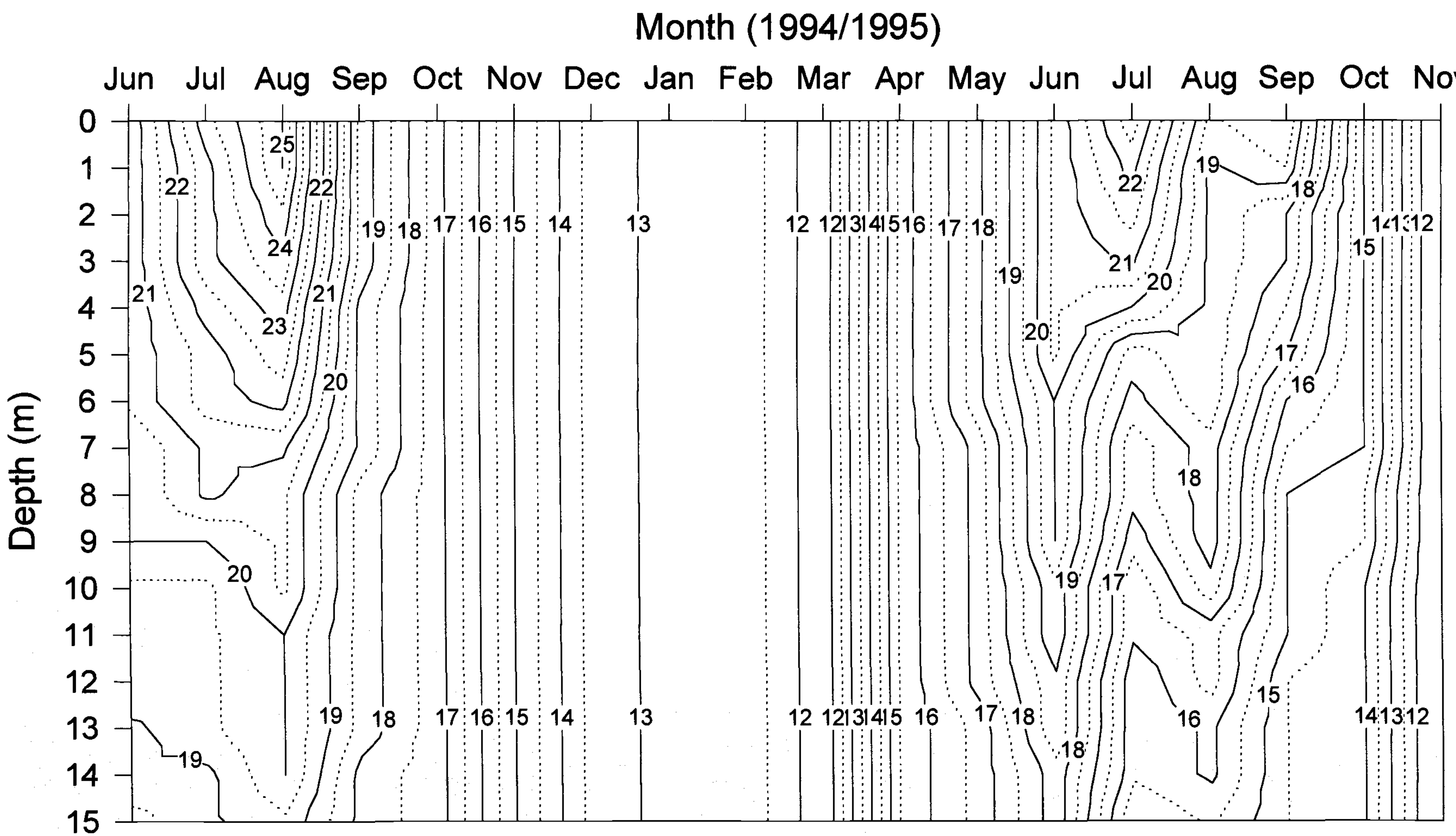
3. **Determine aspects of the ecological significance of *P. leniusculus* in LBC.**
    a. Determine use of crayfish as a food source by smallmouth bass *Micropterus dolomieu*.

4. **Document the historic commercial harvests and management practices of *P. leniusculus* in LBC and make management recommendations.**
    a. Document the historic commercial harvests and management practices.
    b. Recommend management strategies for commercial harvest and population monitoring.

Appendix 2. Depth-time isotherms (°C) for the Crooked River arm, June 1994 to November 1995.



Appendix 3. Depth-time isotherms (°C) for the Deschutes River arm, June 1994 to November 1995.



Appendix 4. Depth-time isotherms (^{o}C) for the Metolius River arm, June 1994 to November 1995.