TASK 16. EFFECTS OF TEMPERATURE ON TIMING OF OUT-MIGRATION

16.1 OBJECTIVE

The objective of this study was to test the hypothesis that chinook salmon are stimulated to out-migrate from the Mokelumne River once they have accumulated a certain number of daily temperature units (i.e., the thermal sums hypothesis) rather than being stimulated by changes in flow, temperature or other environmental factors during the rearing period.

16.2 METHODS

The data used in this task included those collected during the 1990-1991 in-migration studies (Task 9), the 1991 fry emergence study (Task 12), the 1990-1992 outmigration studies (Task 14) and the 1991 smolt mortality study (Task 15). Daily water temperature was estimated by averaging the data recorded from 1 October 1990 to 2 July 1992 at three EBMUD datapod stations, Camanche Dam, Riffle and Mackville.

The existing data were used and relevant information gathered from the literature to simulate temporal distribution of chinook salmon at different life stages for the 1990-1991 and 1991-1992 year classes. The life stages included egg, fry and smolt. For the purposes of this analysis, egg was defined as just spawned; fry was just emerging from the gravel before rearing in the river; smolt was ready to out-migrate but still in the river.

For each year class, egg distribution was established using data collected in Task 9. Fry distribution was derived from the egg distribution by assuming a constant number of cumulative temperature units required for an egg to develop into a fry; the probability of egg survival was also taken into account. Smolt distribution was established using out-migration data collected in Task 14 and the mortality rate of the smolts passing through the river and Lake Lodi (Task 15). The number of temperature units required for fry to develop into smolts was examined to see if this is constant regardless of different flow, water temperature or other environmental factors during the rearing periods in both years.

Figure 16-1 summarizes the data, assumptions and approach used in the analysis. Because salmon did not start to in-migrate until mid-October in both year classes, 1 October was used as the date (i.e., Day 1) to begin standardizing the temporal scales for the analysis. The methodologies used for establishing temporal distributions of eggs, fry and smolts are described below.

16.2.1 Egg Distribution

On average, a female chinook salmon takes ten days to migrate up the Mokelumne River and spawn (Tasks 9 and 10). Because no sex ratio was available for daily in-migrating data, a

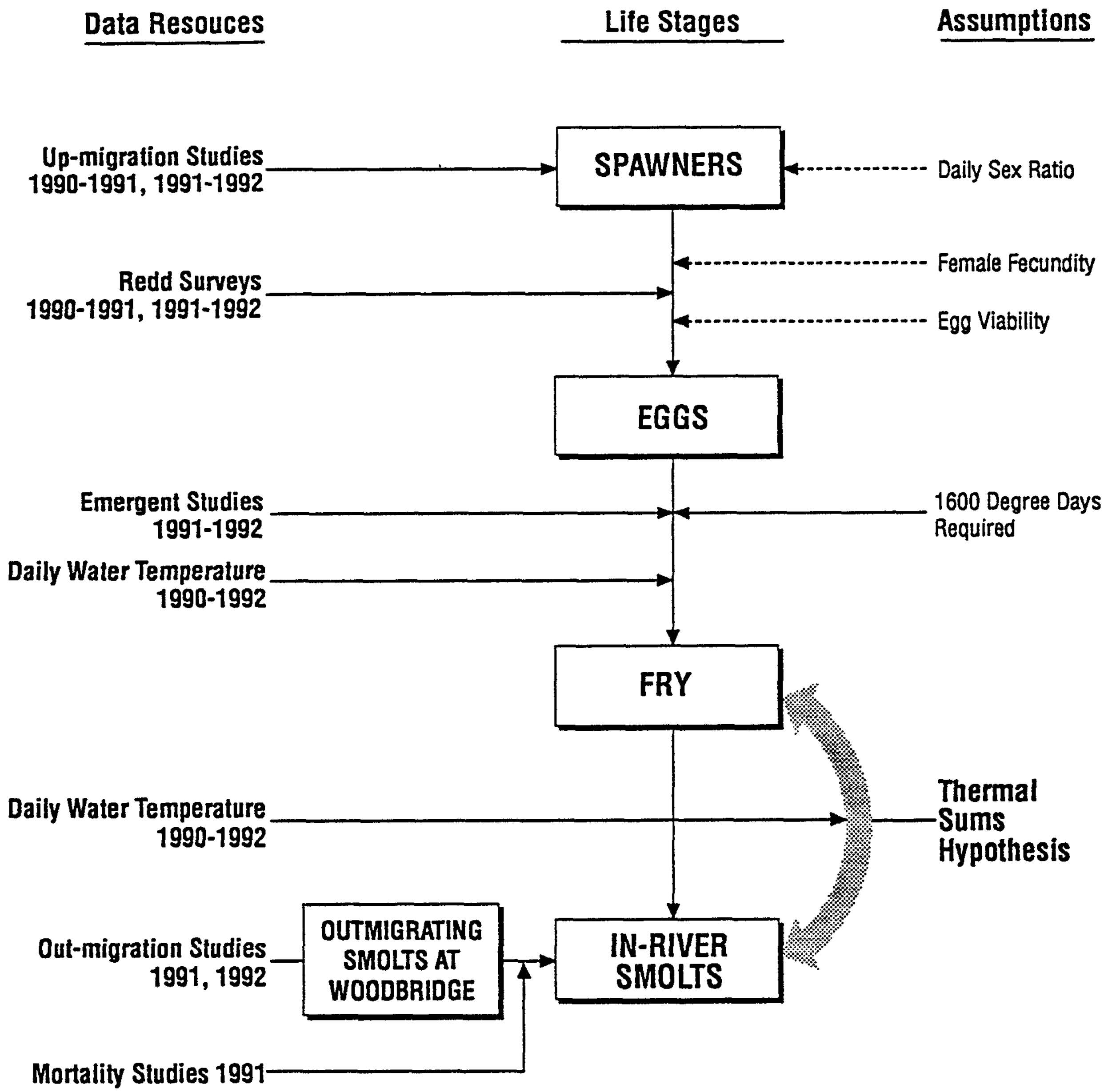

Figure 16-1. Temporal distribution of chinook salmon life stages.

constant daily sex ratio was assumed throughout the entire in-migration season. In addition, no information on reproduction status (i.e., fecundity) of each female was available, so each female was assumed to have produced the same quantity and quality of eggs. Using these assumptions, egg distribution can be established by shifting the time series of daily salmon escapement forward ten days and multiplying by a constant sex ratio as well as a constant number of eggs per female. For each year class, the entire egg population was standardized to one (1.0) and the daily relative percentage of the total was used to plot the distribution.

16.2.2 Fry Distribution

One daily temperature unit (DTU) equals 1° Fahrenheit above freezing (32°F) for a 24-hour period. For a given period of time, the number of accumulated DTU during that period can be expressed as degree-days (DD) (Johnson et al. 1989). The number of DD has been widely used by hatchery managers to estimate the length of time required for salmonid egg development (Alderdice and Velsen 1978; Leitritz and Lewis 1980; Piper et al. 1982). According to Piper et al. (1982), the DD required for chinook salmon egg development is 450 to the eyed stage, 750 to hatch, and 1,600 to fry.

All eggs spawned on the same day were considered one daily-cohort. For each cohort, a total of 1,600 DD was assumed to be needed for the eggs to develop into fry (Piper et al. 1982). Using the daily water temperature data, the DTU was calculated; for each cohort, the number of days to reach 1,600 DD was recorded as the day when eggs become fry. The fry distribution was then established by shifting each cohort to the day when eggs become fry.

Experiments conducted by BioSystems in 1991 (Task 12) showed that egg survival was significantly affected by water temperature. If no daily water temperature exceeded 15° C during the development of a daily-cohort, the survival rate from egg to fry was 0.405 (i.e., cold water cohort); otherwise, it was 0.095 (i.e., warm water cohort). To establish fry distribution, these different survival rates were taken into account.

Daily water temperature was examined over the egg-to-fry development period to identify cold and warm cohorts. The magnitude of fry distribution was established by adjusting the egg survival rate for each cohort. The entire fry population was standardized to one (1.0) and the daily percentage of the total was used to analyze the distribution.

16.2.3 Smolt Distribution

In 1991, BioSystems conducted in-river and Lake Lodi mortality studies by releasing marked smolts in the river at Camanche Dam, at the confluence of the river and Lake Lodi at Bruella Road, and in Lake Lodi near the WID Canal (Task 15). Smolts were then recaptured in fish traps in the upper and lower fish ladders at Woodbridge Dam. Because chinook salmon were trapped at Woodbridge Dam (forming Lake Lodi), the daily captures reflected any losses incurred as smolts passed through the river and Lake Lodi. Exponential functions used to estimate the survival rates for smolts passing through the river (i.e., in-river survival) and

Lake Lodi (i.e., Lake Lodi survival), according to the survival rates on each releasing dates, Days 223 (11 May), 235 (23 May) and 248 (5 June), can be expressed as the equation below:

$$\begin{aligned} &\textit{if} \;\; x_i \le x_0 \quad \textit{then} \;\; y_i = 1 \\ &\textit{otherwise} \;\; y_i = e^{a+bx_i} \quad 0 \le y_i \le 1 \end{aligned} \tag{1}$$

where x_i is a given day (e.g. x_i= 223 at Day 223), x_0 is the day when the survival rate starts to decline, and y_i is the survival rate at Day *i*. *a* and *b* are constants.

The number of smolts estimated to have died in-river and in Lake Lodi were added to the number of smolts collected daily at Woodbridge Dam to establish smolt distribution. The entire smolt distribution was also standardized to one (1.0). The daily percentage of the total was used to standardize the distribution for analysis.

16.2.4 DD Required from Fry to Smolt Development

According to the established fry and smolt distributions, the DD required for chinook salmon to develop from fry to smolt in the Mokelumne River was estimated. Each accumulated population was divided into ten parts and then the required DD was estimated for every part. For this, the following logistic functions were used to express cumulative fry and smolt distributions over time:

$$y = \frac{\exp(\beta_0+\beta_1 x)}{1+\exp(\beta_0+\beta_1 x)} \tag{2}$$

where *y* is the cumulative percentage of the population and *x* is a given day (e.g. *x*= 223 at Day 223). β_0 and β_1 are constants.

For both 1990-1991 and 1991-1992 year classes, the number of DD between the dates for every part of the cumulative fry and smolt distributions was calculated. An F-test was used to examine the difference between the numbers of DD required for both year classes.

16.3 RESULTS

16.3.1 Egg Distribution

The daily count of salmon escapements lasted from 17 October (Day 17) to 17 December (Day 78) for the 1990-1991 year class and from 28 October (Day 28) to 29 December (Day 90) for the 1991-1992 year class (Figure 16-2). The distributions of daily salmon escapement in the two year classes were both shifted ten days forward to become the egg

A) 1990-1991

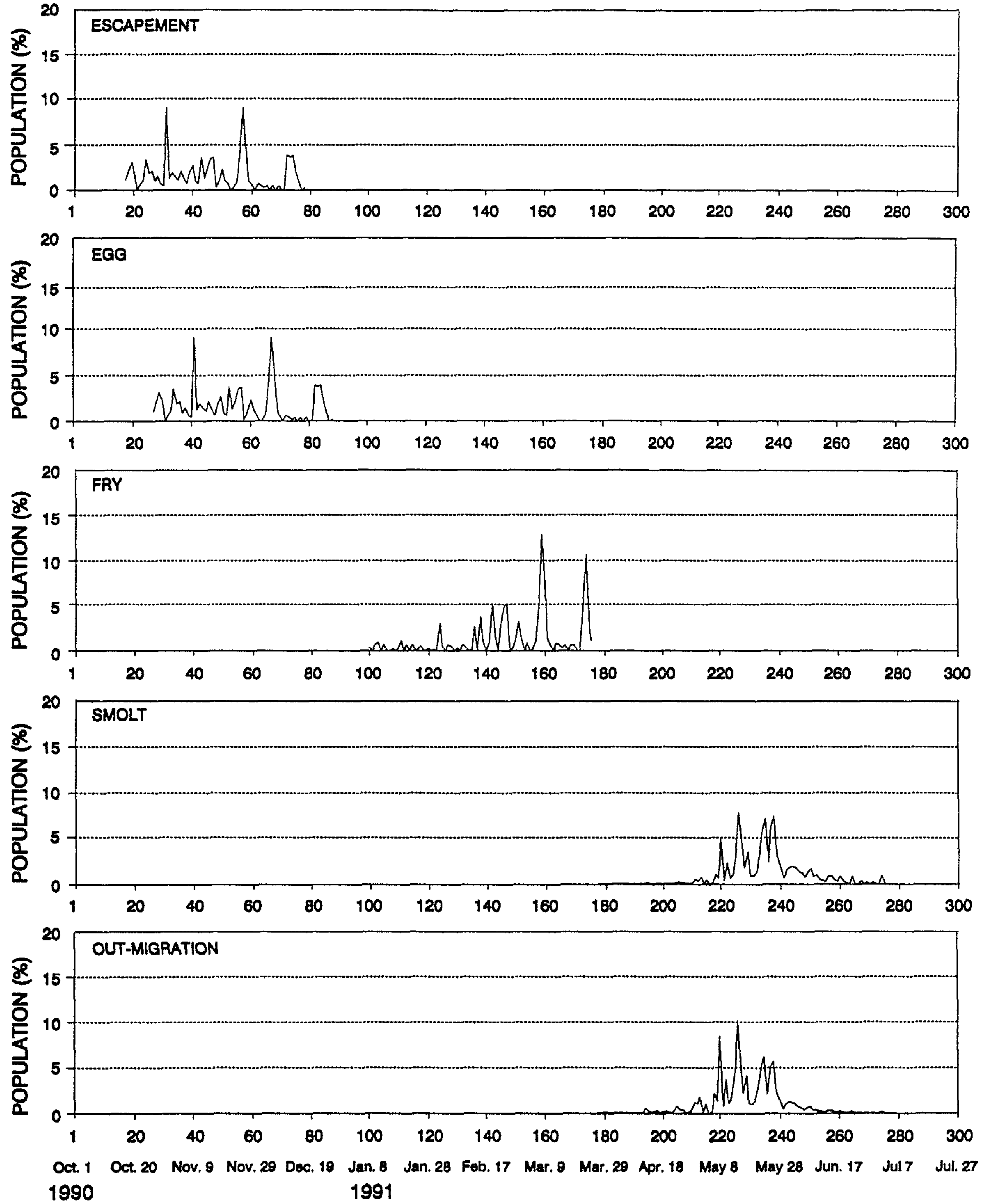

Figure 16-2. The temporal distributions of the Mokelumne River salmon escapement, egg, fry, smolt, and out-migration in A) 1990-1991 and B) 1991-1992 year class.

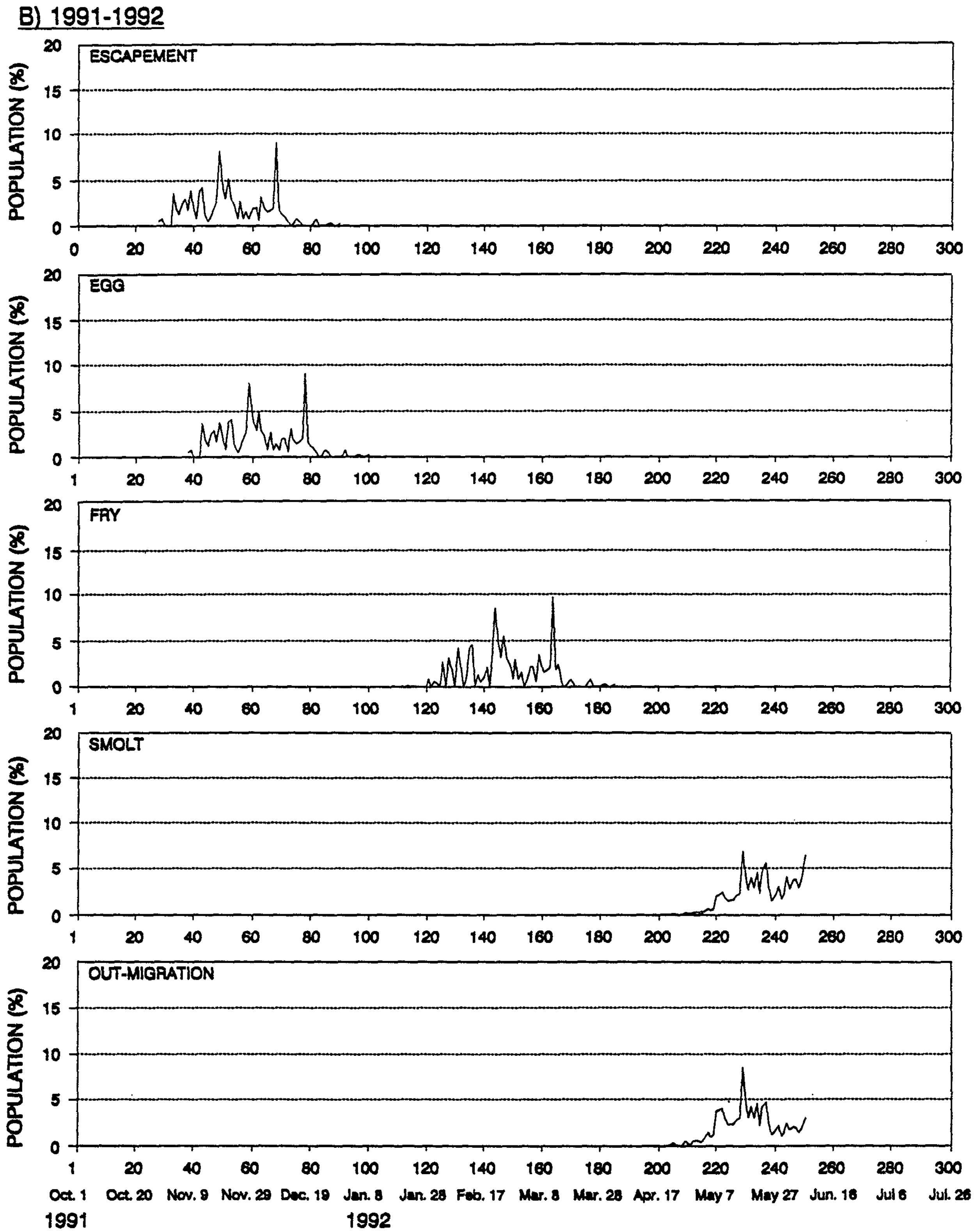

Figure 16-2. The temporal distributions of the Mokelumne River salmon escapement, egg, fry, smolt, and out-migration in A) 1990-1991 and B) 1991-1992 year class (cont.).

distributions. The egg distribution started on 27 October (Day 27) for the 1990-91 year class, and on 7 November (Day 38) for the 1991-1992 year class.

16.3.2 Fry Distribution

For the 1990-1991 year class, the cohorts before Day 49 (18 November 1990) were warm and those after Day 49 were cold. For 1991-1992 year class, the warm cohorts were spawned before Day 46 (15 November 1991). The survival rate was 0.095 for warm cohorts and 0.405 for cold cohorts. Accordingly, the fry distributions were established for both year classes (Figure 16-2).

16.3.3 Smolt Distribution

Figure 16-3 shows that the in-river and Lake Lodi survival rates were exponentially decayed across time. Using the exponential functions listed in Table 16.1, the number of smolts estimated to have died in-river and in Lake Lodi were added to the number of daily smolts collected at Woodbridge Dam and the smolt distributions established for 1990-1991 and 1991-1992. Smolt distributions for each year class are shown in Figure 16.2.

Table 16.1. The relationships of survival rates over time for smolts passing through the river (i.e., in-river survival) and through Lake Lodi (i.e., Lake Lodi survival).

			Exponential Relationship	R^2
In-river	if $x_i \leq 200$	then $y_i = 1$	otherwise $y_i = exp\ (8.93\text{-}0.045\ x_i)$	0.98
LakeLodi	if $x_i \leq 224$	then $y_i = 1$	otherwise $y_i = exp\ (0.43\text{-}0.002\ x_i)$	0.99

16.3.4 DD Required from Fry to Smolt Development

The cumulative fry and smolt distributions (Figure 16-4) were expressed as logistic functions for each year class. Using 1 October as Day 1, Table 16.2 shows the reference dates to identify each tenth (10%, 20%, etc.) of cumulative fry and smolt distributions. The DD required to develop from fry to smolt for each ten percent were estimated and listed in Table 16.2.

The DD required ranged from 1,851 to 2,015 with an average of 1,948 (SD= 53) for 1990-1991; it ranged from 1,887 to 1,971 with an average of 1,928 (SD= 29) for 1991-1992. The DD required by these two year classes was not significantly different (F-value= 0.94, $p > 0.05$). Therefore, it was concluded that there is a constant number of DD required for chinook salmon development regardless of other environmental factors during the rearing period in the Mokelumne River.

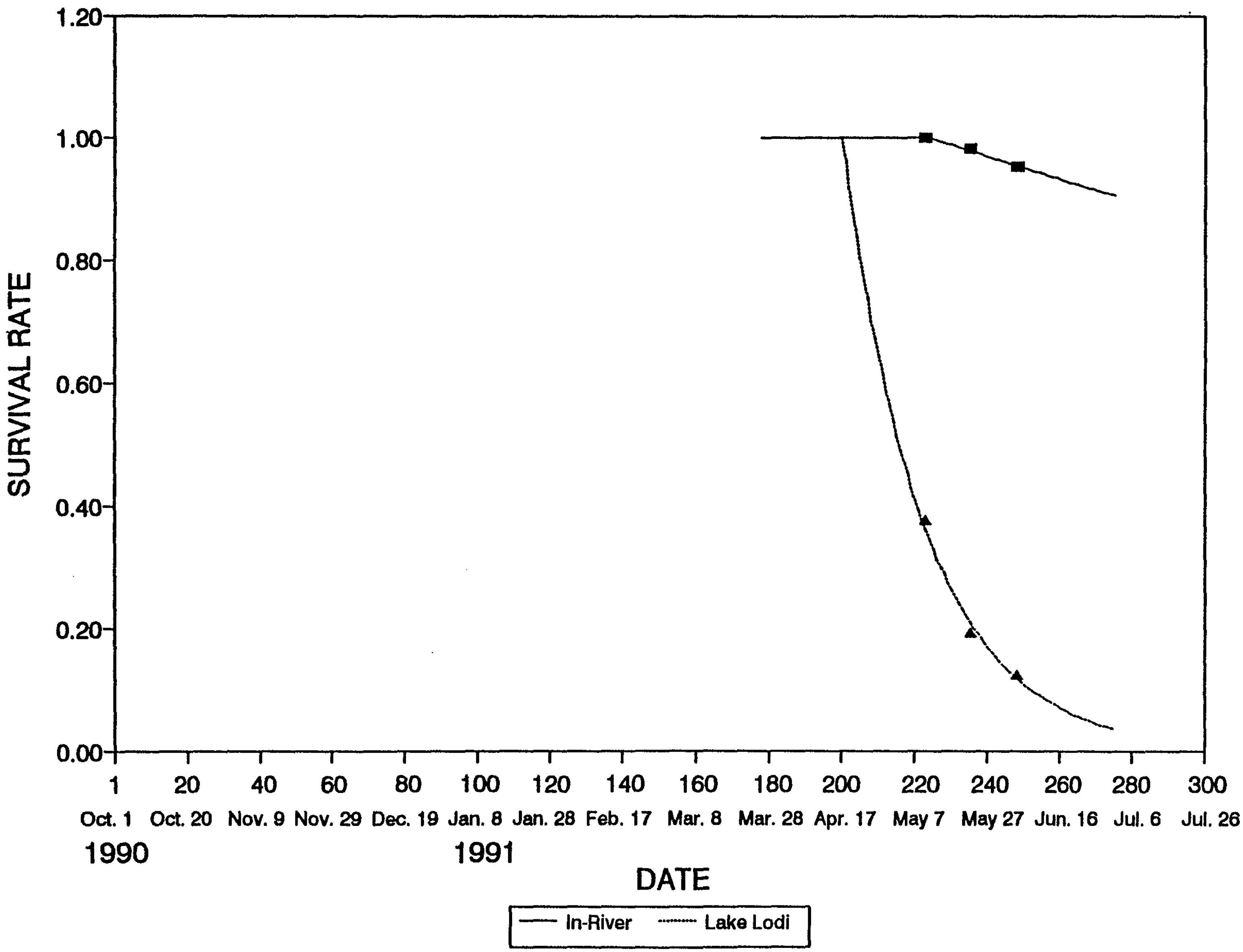

Figure 16-3. The in-river and Lake Lodi survival rates over time during the smolt out-migration in 1991.

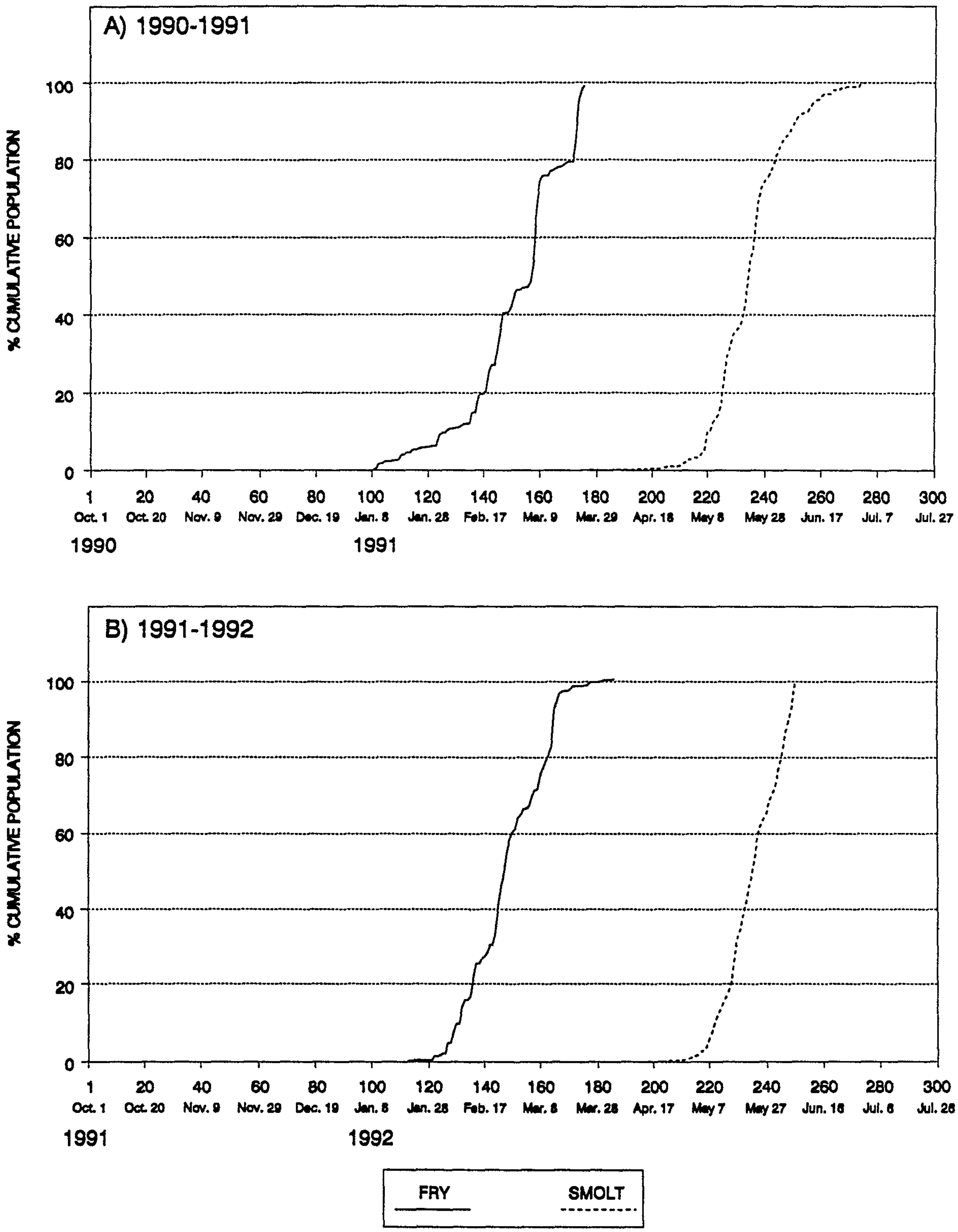

Figure 16-4. The cumulative fry and smolt distributions over time for A) 1990-1991 and B) 1991-1992 year classes.

Table 16.2. The date at which each 10 percent of the salmon population becomes fry and smolts for 1990-1991 and 1991-1992 year classes. The number of degree days required by newly-emerging fry to become out-migrating smolts is also given for each year class. 1 October 1990 and 1 October 1991 were, respectively, as Day 1 for the two year classes.

% Population	1990-1991[1]					1991-1992[2]				
	Fry		Smolt		DD	Fry		Smolt		DD
	Day	Date	Day	Date		Day	Date	Day	Date	
10	127	Feb 4	222	May 10	2015	135	Feb 12	226	May 13	1917
20	136	13	228	16	2003	140	17	230	17	1964
30	142	19	231	19	1967	143	20	232	19	1949
40	147	24	234	22	1956	146	23	234	21	1932
50	151	28	237	25	1962	149	26	236	23	1918
60	155	Mar 4	240	28	1963	151	28	238	25	1925
70	160	9	243	31	1929	154	Mar 2	239	26	1887
80	166	15	246	Jun 3	1883	157	5	242	29	1898
90	175	24	252	9	1851	160	8	245	Jun 1	1910

[1] All dates in this group are in 1991.
[2] All dates in this group are in 1992.

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