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THE TOW-NET SURVEY ABUNDANCE INDEX FOR DELTA SMELT REVISITED

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INTRODUCTION

The delta smelt, *Hypomesus transpacificus*, is listed as threatened and has consequently become a key species affecting water management in the Sacramento-San Joaquin estuary (Moyle and others 1996). This paper reexamines the methods used for summer indexing of delta smelt abundance.

The Summer Tow-Net Survey (TNS) has been used to index striped bass (*Morone saxatilis*) abundance in the Sacramento-San Joaquin Delta since 1959 (Chadwick 1964; Turner and Chadwick 1972) and more recently delta smelt abundance (Stevens and others 1990; Moyle and others 1992). The method currently used to index delta smelt abundance differs from that used for indexing young-of-the-year striped bass. For striped bass, abundance is interpolated at a catch length of 38 mm from a regression of the $\log_{10}$ abundance on mean length of the catch for the two surveys that bracket the mean catch length of 38 mm (Turner and Chadwick 1972). This approach accounts for variability in spawning time and growth to set an index at a size that reflects these effects. This was not done for delta smelt because length data were inadequate, and in some years only two surveys were conducted (Stevens and others 1990; Sweetnam and Stevens 1993).

Wadsworth and Sommer (1996) attempted to develop a size-standardized index for delta smelt similar to the one used for striped bass, but found that abundance had no consistent relationship to the mean length. Another problem with this approach is that no delta smelt were measured before 1973. Therefore a length-based delta smelt index would be limited to the post-1973 period, even if feasible. This paper describes an evaluation of a new midsummer TNS delta smelt index based on the timing of the striped bass index, which reflects the synchrony of striped bass size with environmental conditions. Using the striped bass index period as a surrogate for the spawning and recruitment of delta smelt to the TNS gear could provide a more accurate index of abundance for delta smelt than the arbitrary use of the first two surveys to calculate the index. The young of both species have similar spatio-temporal distributions which make this approach plausible.

The new index was evaluated to determine if it would better reflect delta smelt abundance than the index currently used by comparing both indices to the Fall Mid-Water Trawl Survey (FMWT) delta smelt abundance index. Factors affecting the spawner-recruit relationship and summer-to-fall survival based on the new index are also explored.

METHODS

Calculation of the New Delta Smelt Tow-Net Index

Tow-net surveys are conducted every other week beginning in mid-June or early July. To calculate the new delta smelt index, only the two surveys that determine the striped bass 38-mm index are used. The surveys can vary annually in tandem combinations from the first and second to the fourth and fifth. To calculate each survey's index, the sum of the catch in three tows at each station is weighted by the estimated water volume in acre-feet at the station. These products are summed over all stations and divided by 106 for reporting convenience. The mean of the two indices is the annual index. The old delta smelt index was calculated using the same methods, except only the first two surveys are used. The percent increase or decrease in the new index relative to the old index was calculated to evaluate changes in the two indices. The new annual index was also calculated for the six areas of the estuary reported by Stevens and others (1990): Montezuma Slough, Suisun Bay, Lower Sacramento River, Lower San Joaquin River, South Delta, and East Delta. In 1966, no survey was conducted, and in 1967 and 1968 delta smelt catches were not recorded.

Factors Affecting the Timing of the Striped Bass Abundance Index

The first step in justifying the new index was to demonstrate the relationship between the timing of the striped bass index and environmental conditions. The Julian calendar date (days past January 1) when the striped bass mean size reaches 38 mm was correlated with mean flows and temperatures. These Julian dates ranged from day 173 to day 242. Flow data were used from the California Department of Water Resources (DWR) DAYFLOW data base. Temperatures used were those of record for April to June 1983–1998 from DWR's continuous recorder data collections made on the Sacramento River (station RSAC101) at Rio Vista and on the San Joaquin River (station RSAN007) at Antioch.

Survey mean lengths of delta smelt were regressed on striped bass mean lengths to determine if both increased together indicative of a similar period of recruitment to the gear. Delta smelt 61 to 126 mm fork length (FL) were assumed to be from the previous year class based on a plot of length frequencies (Figure 1). These comprised 1.9% of all delta smelt measured and were excluded from length analyses. However, because not all fish counted were measured, no attempt was made to account for their small contribution to the abundance index.

Spawner-Recruit Relationship

The new index was evaluated for a spawner-recruit relationship using a Beverton-Holt model (Beverton and Holt 1957, as cited in Ricker 1975):

$$\text{Recruits} = 1/(\text{Alpha} + (\text{Beta}/\text{Spawners}))$$

The previous year's (FMWT) delta smelt abundance was used as an estimate of spawners and the new TNS index as a measure of recruits. The FMWT abundance index is based on sampling 100 stations in the estuary monthly from September to December. An abundance index is calculated monthly by summing the products of mean catch per tow and water volume for 17 subareas of the estuary. The total fall index is the sum of the four monthly indices (Stevens and others 1990). Regression relationships between log transformed spawner and recruit data were calculated for both the old and new indices to compare them.

Residuals from the spawner-recruit model were correlated with several environmental and prey variables. For example, copepods have been identified as the major prey of delta smelt (Nobriga and Lott, submitted; Lott and Nobriga, submitted). To estimate prey abundance where delta smelt occur, mean zooplankton densities were calculated from the California Department of Fish and Game's (DFG) zooplankton survey data for the specific conductance range where 95% of delta smelt abundance was sampled. For methods and distribution of sampling stations, see Orsi and Mecum (1986).

Survival between Summer and Fall

Summer-to-fall survival for both the new and old indices was evaluated for the period between the TNS and the FMWT. The survival index was calculated by adjusting both the FMWT index and the TNS index to their full volume weighted size and dividing the FMWT index by the TNS index. The FMWT index was divided by four to compute an average index value and multiplied by 104. The TNS index was multiplied by 106 to restore the index to its original size. Differences between decline and predecline periods in mean survival were tested using the Wilcoxon two sample test. Statistical analyses were done with SAS (1988) software. A significance criterion of • = 0.05 was used for all tests.

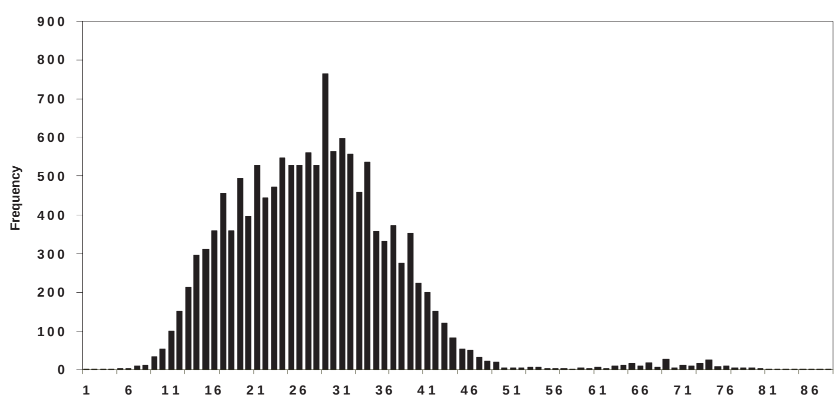

Figure 1 Length-frequency distribution of all delta smelt caught in the midsummer tow-net surveys. Fork lengths greater than 86 mm were omitted for clarity.

RESULTS

Factors Affecting the Timing of the Striped Bass Abundance Index

The striped bass index is set later in years of low temperature and high flows. The striped bass index date showed a significant negative correlation with both the Antioch and Rio Vista water temperatures for April, May, and June and was positively correlated with San Joaquin River and Sacramento River flows for the same months (Table 1). The relationship of the index date to San Joaquin River flows was weaker than the relationship with Sacramento River flows. Sacramento River flow and temperature at Rio Vista are strongly correlated ($r = –0.84$ for April, $r = –0.76$ for May, and $r = –0.90$ for June); mainly because in wetter years with spring storm events, water temperatures tend to be cooler than in dry, non-stormy springs. Therefore, the striped bass index date varies over a range of calendar dates in response to these conditions.

Table 1 Correlations of the 38-mm striped bass index set date with temperature (1983–1999) and with river flow (1959–1998)

April	*May*	*June*	*April*	*May*	*June*
Temperature at Rio Vista			**Temperature at Antioch**		
–0.687	–0.8245	–0.8098	–0.70260	–0.68364	–0.74820
$P = 0.046$	$P < 0.0001$	$P < 0.0001$	$P = 0.0051$	$P = 0.0050$	$P = 0.0013$
$n = 15$	$n = 16$	$n = 16$	$n = 14$	$n = 15$	$n = 15$
Sacramento River flow at Sacramento			**San Joaquin River flow at Jersey Pt.**		
–0.582	–0.673	–0.676	–0.562	–0.597	–0.630
$P < 0.0001$	$P < 0.0001$	$P < 0.0001$	$P < 0.0002$	$P < 0.0001$	$P < 0.0001$
$n = 39$	$n = 39$	$n = 39$	$n = 39$	$n = 39$	$n = 39$

New Delta Smelt Index

The new delta smelt index was higher than the old index in 21 years, lower in only six and the same in ten years (years when surveys 1 and 2 were used). In 1959, 1965, 1972, 1977, 1987, 1988, and 1991, the new index was more than double the old index (Table 2). The new and old indices were strongly correlated ($r = 0.801$, $P < 0.0001$, $n = 37$). The delta smelt is most abundant in Suisun Bay and the Lower Sacramento River. The decline in abundance is evident in all areas (Table 3). The new index was significantly though weakly correlated with the FMWT survey indices except for November, whereas the old index was significantly correlated only with the December FMWT index (Table 4).

The relationship between the survey mean lengths of delta smelt and striped bass was significant and positive ($R^2 = 0.329$, $P < 0.0001$) (mean delta smelt length: 29.5 + 0.318 mean striped bass length) (s.e. = 1.72 and 0.049) with means increasing over time (Figure 2). However, the average survey mean size of delta smelt for all surveys was about half as variable as that of striped bass (c.v. = 2.1 for delta smelt compared to 27.7 for striped bass). The rate of increase in the mean length over the surveys was about three times greater for striped bass than for delta smelt. The mean delta smelt lengths were greater than those of striped bass in the early surveys but this difference decreased with later surveys (Figure 3). This convergence of mean lengths and the progressive changes in length frequencies for the two species, as well as the change in the delta smelt abundance, are illustrated using the four 1975 surveys (Figure 4).

Spawner-Recruit Relationship

The spawner-recruit relationship for the new index was not strong (Figure 5). The standard errors of the estimates for Alpha (0.026, s.e. = 0.0145) and Beta (12.4, s.e. = 9.92) were large relative to the estimates. A linear regression of the $\log_{10}$ recruits (new TNS index) to $\log_{10}$ spawners was significant ($r^2 = 0.326$, $P = 0.003$) and explained more of the variation than a similar regression using the old TNS index ($r^2 = 0.189$, $P = 0.02$). The regression relationship between the $\log_{10}$ FMWT index (spawners) and the $\log_{10}$ FMWT of the previous year's index (recruits) was not significant ($r^2 = 0.022$, $P = 0.47$). Therefore, the new TNS index provides a better, although weak spawner-recruit relationship than the relationship between the fall indices lagged by one year.

Eurytemora affinis density was the only variable significantly correlated with the residuals of the new index spawner-recruit relationship (Table 5). This relationship was driven by the high residual variation in four years which were associated with high *E. affinis* densities (Figure 6). The residuals from a spawner-recruit relationship based on the years before 1988, before the collapse of the *E. affinis* population, are also significantly correlated with *E. affinis* density ($r = 0.64$, $P = 0.013$). Hence, the residual abundance relationship with *E. affinis* is driven by the trends in the population before 1988 and not by the low *E. affinis* abundance after 1987. The residual variation in the spawner-recruit index for the old TNS index was also significantly correlated only with *E. affinis* abundance ($r = 0.48$, $P = 0.014$).

Survival Between Summer and Fall

The survival of delta smelt was higher for the post-decline years (after 1982) compared to pre-decline years (Figure 7). The mean survival index was 0.101 for the pre-decline years and 0.237 for post decline years and these means were significantly different (Wilcoxon $Z = -2.576$, $P = 0.01$). Survival was significantly but negatively correlated with *E. affinis* density (Table 6), a relationship inconsistent with the positive correlation expected between survival and food supply. This result likely reflects the time trends in both survival and *E. affinis* abundance. Survival was not significantly correlated with flows or other food variables, but the correlation with water transparency (Secchi disc) was nearly significant. Using the old index, the differences in mean survival between the two time periods was also significant (Wilcoxon $Z = -2.344$, $P = 0.02$).

Table 2 Relationship between the new and old delta smelt abundance indices [a]

Year	*Old Index*	*New Index*	*Difference*	*Percent Change*
1959	12.1	39.6	27.5	227.3
1960	25.4	24.7	–0.7	–2.8
1961	21.3	12.9	–8.4	–39.4
1962	24.9	24.9	0.0	0.0
1963	1.8	2.1	0.3	16.7
1964	24.6	42.4	17.8	72.4
1965	6.0	12.2	6.2	103.3
1969	2.5	4.2	1.7	68.0
1970	32.5	44.9	12.4	38.2
1971	12.5	24.2	11.7	93.6
1972	11.1	70.7	59.6	536.9
1973	21.3	23.4	2.1	9.9
1974	13.0	16.2	3.2	24.6
1975	12.2	14.7	2.5	20.5
1976	50.6	50.6	0.0	0.0
1977	25.8	52.0	26.2	101.6
1978	62.5	75.6	13.1	21.0
1979	13.3	15.7	2.4	18.0
1980	15.8	13.1	–2.7	–17.1
1981	19.8	19.8	0.0	0.0
1982	10.7	9.2	–1.5	–14.0
1983	2.9	2.9	0.0	0.0
1984	1.2	1.2	0.0	0.0
1985	0.9	1.0	0.1	11.1
1986	7.9	7.9	0.0	0.0
1987	1.4	3.2	1.8	128.6
1988	1.2	3.2	2.0	166.7
1989	2.2	2.2	0.0	0.0
1990	2.2	1.5	–0.7	–31.8
1991	2.0	7.9	5.9	295.0
1992	2.6	2.6	0.0	0.0
1993	8.2	12.1	3.9	47.6
1994	13.0	8.5	–4.5	–34.6
1995	3.2	4.4	1.2	37.5
1996	11.1	11.1	0.0	0.0
1997	4.0	4.0	0.0	0.0
1998	3.3	4.3	1.0	30.3

[a] No delta smelt were enumerated in 1967 and 1968, and no survey was conducted in 1966.

Table 3 Delta smelt new tow-net survey abundance index by area [a]

Year	Area 1	Area 2	Area 3	Area 4	Area 5	Area 6
1959	0.0	3.5	34.5	1.6	0.1	0.1
1960	0.3	3.4	20.1	0.6	0.2	0.3
1961	0.0	0.3	10.5	1.0	0.1	1.1
1962	0.3	4.8	18.6	1.2	0.0	0.0
1963	0.0	1.0	1.0	0.2	0.0	0.0
1964	0.0	3.6	36.2	1.8	0.1	0.8
1965	0.1	2.8	8.6	0.6	0.2	0.2
1969	0.0	2.3	1.7	0.3	0.0	0.0
1970	0.0	3.8	39.2	1.3	0.2	0.4
1971	0.5	19.7	1.6	1.4	0.0	1.1
1972	0.0	1.0	68.7	0.8	0.1	0.2
1973	0.0	15.2	6.1	2.0	0.0	0.1
1974	0.1	14.3	0.2	1.5	0.0	0.1
1975	0.7	12.6	0.8	0.5	0.1	0.1
1976	0.1	4.8	41.2	4.1	0.1	0.4
1977	0.0	0.7	48.3	3.0	0.0	0.0
1978	1.3	27.2	46.9	0.2	0.0	0.0
1979	0.0	0.9	14.6	0.1	0.0	0.0
1980	0.3	8.5	3.2	1.3	0.0	0.0
1981	0.2	2.3	16.3	1.1	0.1	0.0
1982	0.4	7.7	1.0	0.2	0.0	0.0
1983	0.2	2.8	0.0	0.0	0.0	0.0
1984	0.0	0.9	0.3	0.1	0.0	0.0
1985	0.0	0.1	0.8	0.1	0.0	0.0
1986	0.1	1.0	6.6	0.1	0.1	0.0
1987	0.0	0.0	2.5	0.7	0.1	0.0
1988	0.0	0.2	2.9	0.2	0.0	0.0
1989	0.1	0.2	1.7	0.1	0.0	0.1
1990	0.0	0.3	1.1	0.2	0.0	0.0
1991	0.0	0.2	7.5	0.3	0.0	0.0
1992	0.0	0.3	1.8	0.5	0.0	0.0
1993	0.0	5.5	5.7	0.9	0.0	0.0
1994	0.0	1.4	6.3	0.8	0.0	0.0
1995	0.0	3.6	0.6	0.2	0.0	0.0
1996	0.1	7.1	3.4	0.6	0.0	0.0
1997	0.0	1.7	2.3	0.2	0.0	0.0
1998	0.0	4.3	0.0	0.0	0.0	0.0

[a] Areas: (1) Montezuma Slough, (2) Suisun Bay, (3) Sacramento River, (4) San Joaquin River, (5) South Delta, and (6) East Delta.

Table 4 Correlation of old and new tow-net delta smelt abundance indices with the fall midwater trawl delta smelt abundance index for 28 years of record

Tow-Net Delta Smelt Abundance Index	FMWT Delta Smelt Abundance Index				
	Total	Sep	Oct	Nov	Dec
Old	0.267	0.263	0.074	–0.037	0.589 [b]
New	0.425 [a]	0.492 [b]	0.373 [a]	–0.056	0.516 [b]

[a] significant at P = 0.05 to 0.01.
[b] significant at P < 0.01.

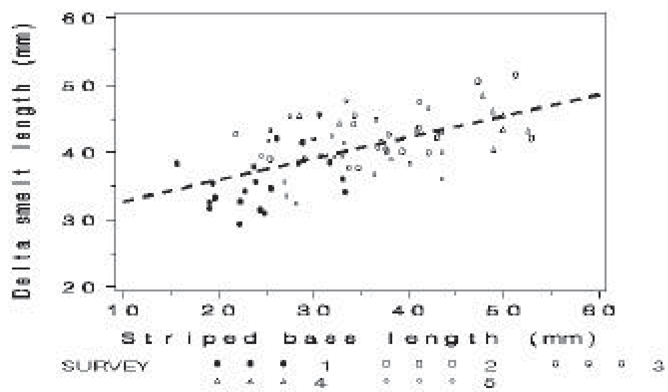

Figure 2 Relationship of delta smelt mean length to striped bass mean length for the midsummer tow-net surveys where the samples size of delta smelt was >30 fish per survey

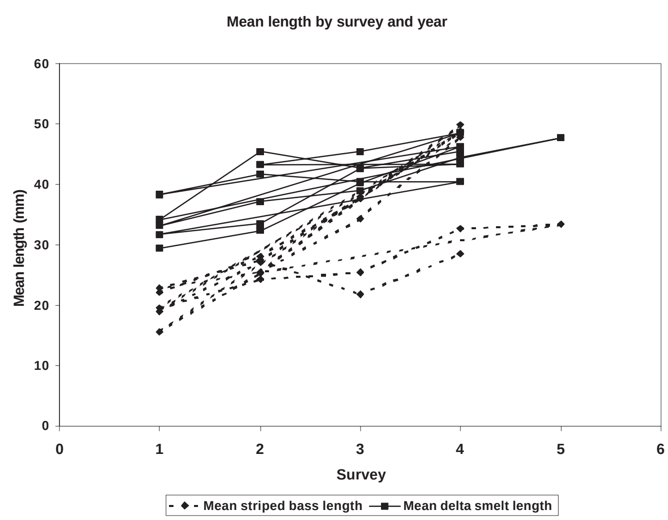

Figure 3 Annual plots of the mean lengths of delta smelt and striped bass over survey for those years when at least four or five surveys were conducted

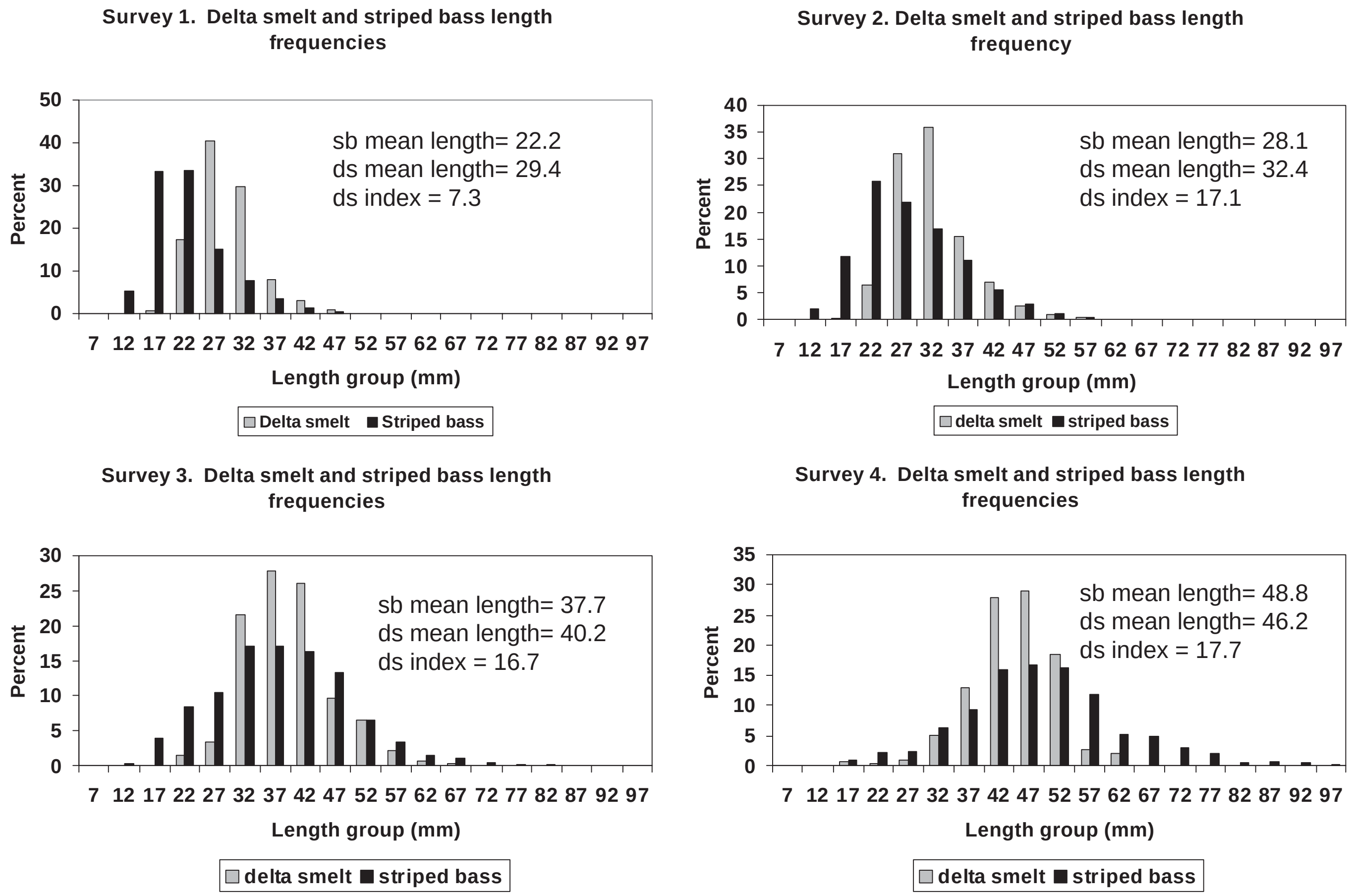

Figure 4 Length frequency distributions for striped bass and delta smelt for summer tow-net surveys conducted in 1975

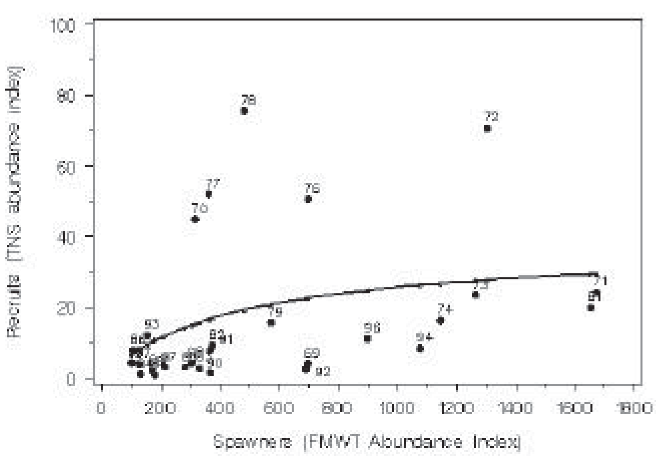

Figure 5 Beverton-Holt Spawner-Recruit model fit for delta smelt based on the new tow-net index as a measure of recruits and the previous FMWT abundance index as a measure of spawning stock

Table 5 Correlations of residual variation of recruit abundance for the new delta smelt index with annual means of environmental variables from April to June

Variable	*Correlation Coefficient*
Delta water exports	–0.091
Mean flow at Jersey Point on the San Joaquin River (Qwest)	–0.106
Log_{10} Delta outflow	–0.165
Water transparency (Secchi disc)	–0.390
Eurytemora affinis density at <6000 • S/cm EC	0.677 [a]
Calanoid copepod density at <6000 • S/cm EC	0.139
Cyclopoid copepod density at <6000 • S/cm EC	–0.101

[a] significant at $P < 0.01$.

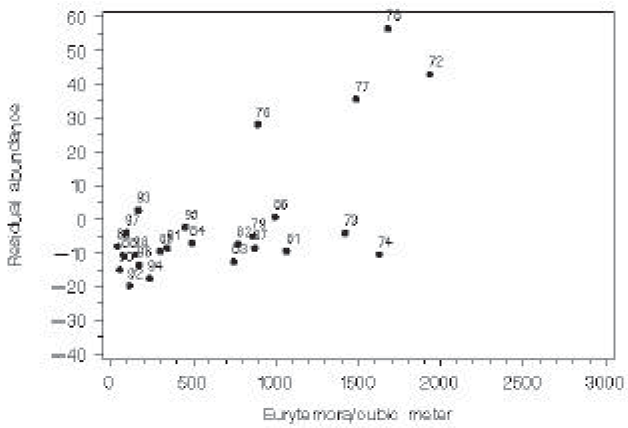

Figure 6 Relationship of residual abundance variation in recruits with *Eurytemora affinis* density

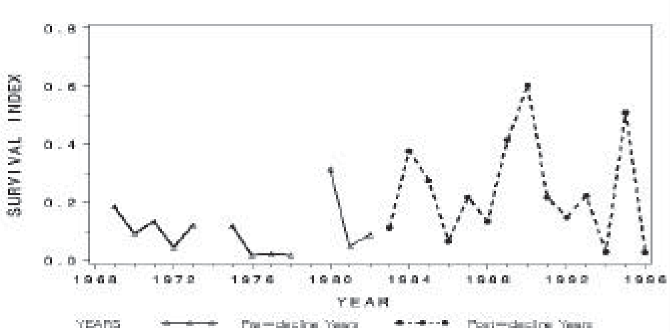

Figure 7 Trends in annual survival indices for delta smelt based on the midsummer tow-net survey and the FMWT abundance indices.

Table 6 Correlations of survival indices with mean environmental conditions for July through October

Variable	*Correlation Coefficient*
Delta water exports	0.249
Mean San Joaquin flow at Jersey Point (Qwest)	–0.076
Log_{10} Delta outflow	0.058
Water transparency (Secchi disc)	0.390
mean *Eurytemora affinis* density at • 12 mS/cm EC [a]	–0.402 [b]
mean calanoid copepod density at • 12 mS/cm EC	0.235
mean cyclopoid copepod density at • 12 mS/cm EC	–0.006

[a] Over 95% of all FMWT delta smelt were captured at • 12 mS/cm EC.
[b] Asterisk indicates an inconsistent relationship. See text for details.

Discussion

Population parameters, such as spawning time and growth that determine the striped bass index date are likely affected by temperature. Therefore, the new delta smelt index more likely reflects seasonal timing by using the time of striped bass indexing as a surrogate for seasonal variation. Delta smelt mean lengths tend to be larger than those of striped bass in the first two surveys but converge in later surveys. This pattern suggests delta smelt may have a more prolonged spawning period or spawn earlier than striped bass. Delta smelt apparently spawn at lower temperature than striped bass. Delta smelt larva have been captured at temperatures as low as 11 °C, whereas striped bass eggs are first captured at temperatures of 14 to 15 °C (unpublished DFG Egg and Larva Survey data).

The conclusion that the new index is better is based on several findings. The new index tends to be higher than the old one because delta smelt tend to be more abundant when later surveys can be included. The positive correlations, albeit weak to moderate, between the new TNS index and the FMWT indices suggest the new index better reflects the relative abundance at midsummer than the old index which was weakly correlated with the FMWT in only one month. The new index when used in a spawner-recruit regression produces a stronger relationship than the old index.

The positive correlation of Beverton-Holt residuals with *E. affinis* may not be cause and effect but reflect coincident time trends. However, further research on this relationship is merited because *E. affinis* was the major delta smelt food item before its abrupt decline in abundance in 1988 (Lott and Nobriga) following the invasion of an Asian clam *Potamocorbula amurensis* (Kimmerer and others 1994). Before the sharp decline in *E. affinis* in 1988, there was a long-term decline in abundance (Obrebski and others 1992). Delta smelt feed mainly on calanoid copepods, including the introduced *Pseudodiaptomus forbesi*, which has become abundant since *E. affinis* declined. However, residual recruit abundance was not significantly correlated with total calanoid density (*E. affinis* plus *P. forbesi*). Total calanoid density did not decline after 1987 due to the increase in *P. forbesi*.

Average summer to fall survival increased significantly in the post-decline years, but the reason is not clear.

One possibility is that survival is higher because density has declined. Correlation of survival with food abundance and flow conditions were not significant and revealed no potential mechanisms for the change in summer to fall survival.

Abundance changes in the new index relative to the old one would not affect previous conclusions regarding the general decline in delta smelt abundance in all areas of the estuary or the timing of the decline as both become marked after 1982. Although the new index may not be as accurate as a size-standardized index, it is likely the most rational index possible with the data limitations. The new index and methods for calculating it should be used in future consultations and data analysis. Although the new indexing method is an apparent improvement, the new index sheds little new light on environmental conditions controlling delta smelt abundance or survival.

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The Interagency Ecological Program for the Sacramento–San Joaquin Estuary
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California Department of Water Resources
State Water Resources Control Board
US Bureau of Reclamation
US Army Corps of Engineers
California Department of Fish and Game
US Fish and Wildlife Service
US Geological Survey
US Environmental Protection Agency

National Marine Fisheries Service