Estimation of the Reduction in Recruitment of Winter Flounder in the Niantic River Associated with Operations at Millstone Nuclear Power Station.

By

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Introduction-

Winter flounder (*Pseudopleuronectes americanus*) stocks on Georges Bank and in the Southern New England stock area declined to low abundance in the early 1990's (NEFSC 1999). The decline was associated with a period of high fishing mortality rates from 1985 to 1993. With substantial reductions in exploitation, both stocks have exhibited biomass recoveries although not yet to former levels of abundance (NEFSC 1999). Inshore stocks of winter flounder are vulnerable to anthropogenic impacts in addition to overfishing (ASMFC 1992). Steam electric power plants use large volumes of condenser cooling water which results in the entrainment and impingement of larval and juvenile fishes in the area of the intake structures (Vaughan 1988). The significance of these early life stage losses relates to the proportion of cohorts destroyed and the magnitude and timing of a stocks compensatory response (Savidge et al. 1988). Other impacts include elevated temperature from thermal discharges and toxicity from biocides used to remove fouling agents (Madenjian et al. 1986).

Gibson (1994) and NUSCo. (1998) showed through simulation modeling that a winter flounder population subject to both overfishing and entrainment losses would decline to low levels. Survey abundance data for winter flounder in Mt. Hope Bay, Narragansett Bay and Niantic River, Connecticut conform to the simulated pattern. Winter flounder relative larval mortality rates in Mt. Hope Bay were correlated with coolant flow at Brayton Point Station (Gibson 1994). NUSCo. (1998) reported on a correlation between entrainment and larval mortality rate. An intervention analysis using time series methods showed that the collapse of fish populations in Mt. Hope Bay in the vicinity of Brayton Point Station was correlated with a large increase in condenser coolant flow (Gibson 1996). Scientists for the utilities and for government regulatory agencies have disputed the impacts of power generation on local fish stocks (Christensen and Klauda 1988). More recently, recreational fishing associations have tried through litigation to hold power companies responsible for the declines. In the case of Niantic River winter flounder, the utilities have steadfastly maintained that overfishing is responsible for the stock decline and that power plants have minimal impacts (NUSCo. 1998). Government scientists responsible for overseeing environmental impacts have indicated the potential for more significant impacts (Crecco and Howell 1991, Crecco 1994). In this paper, I reanalyze stock-recruit data from the Niantic River stock and, with the inclusion of condenser cooling flow, estimate the loss in recruitment associated with plant operation. Diagnostics from the fitted model are compared with trends in pre-recruit fishing mortality rates estimated for winter flounder in the southern New England area.

Methods and Data Sources-

Stock Abundance, Mortality Rates, and Plant Flow Data- All data for the Niantic River winter flounder stock and flow data for Millstone Station were taken from NUSCo. (1999). Estimates of spawning stock and subsequent recruitment are available for the 1977 to 1994 year classes of winter flounder in the Niantic River (NUSCo. 1999, Table 31). These estimates were based on Jolly-Seber mark recapture data and trawl catch per unit effort (CPUE) along with age-length relationships for the stock. Winter temperature data in February was obtained from continuous recorders at the station intakes and is summarized in NUSCo. (1998, Table 6). Records of condenser coolant flow usage at the station by unit were taken from NUSCo. (1998, Table 5) and NUSCo (1999, Table 36). Fishing mortality rate estimates at age for southern New England (SNE) winter flounder were taken from the virtual population analysis (VPA) calibration in NEFSC (1999). This peer reviewed work is the definitive statement on the stock status of winter flounder in the area. Spawning stock and recruitment estimates for SNE and Georges Bank from VPA were also examined for comparison to the Niantic River population which is a component of the regional stock. Age 4 abundance in year t+4 was divided by spawning stock number in year t and the recruit per spawner ratios plotted against time. Trawl survey data from the states of Massachusetts, Rhode Island, and Connecticut were taken from NEFSC (1999) and used to further examine trends in recruit per spawner ratios in the region. Age disagregated survey data were used to compute the ratio of age 4 CPUE in year t+4 to the age 4+ CPUE in year t. This calculation is consistent with the spawner-recruit lag in NUSCo. (1998).

Diagnostic Evaluation of NUSCo. S-R Model- The stock regenerating function which forms the basis of the NUSCo. simulation procedure is a Ricker type stock-recruit curve which employs a secondary explanatory variable in the form of winter temperature:

$$R=\alpha P \exp(-\beta P-\phi T) \exp(\epsilon) \quad (1)$$

where:

R= *recruitment*
P= *parental stock*
T= *February water temperature*
α= *curve slope at the origin*
β= *compensatory mortality parameter*
ϕ= *temperature mortality parameter*
ϵ= *multiplicative error term.*

The model relates future recruitment in the population to present spawning stock and environmental conditions during the spawning period. The α parameter represents the density independent recruitment rate at very low stock abundance and is in units of recruits per spawner. It is the maximum rate of recruit production by the population. The recruitment time lag is approximately 4 years as some fish mature at age 3 and some have not matured by age 5 (NUSCo. 1998). The β parameter is the instantaneous rate of decrease in recruitment per unit increase in spawning stock. The per unit change in recruitment due to temperature is given by ϕ. The error term (ϵ) is a collection of both measurement errors and process deviations. Measurement error occurs in the estimation of spawning stock and other explanatory variables. Process error occurs when recruitment deviates from the assumed population dynamics process because of factors other than those accounted for in the model. Rewriting eq. 1, it is shown that the two factors in the exponential term serve as multipliers of the maximum recruitment rate:

$$R=\alpha P\ exp(-\beta P)\ exp(-\phi T)\ exp(\epsilon) \qquad (2)$$

Dividing both sides of eq.2 by P gives:

$$R/P=\alpha\ exp(-\beta P)\ exp(-\phi T)\ exp(\epsilon). \qquad (3)$$

In this form, recruitment per unit spawner is a survival ratio with a maximum value of α at low stock density unless modified by environmental factors. Since total survivorship from spawned egg to recruiting adult at age 4 can be cast as a product of many stage specific survival rates, it should be clear that α can be decomposed into many components. Walters and Hilborn (1992) give the appropriate caveats to such an analysis, the most important of which is that nice correlations between environmental factors and survival often breakdown with the addition of new data. Additional variables in a stock-recruit model should have an experimental basis or at least a strong theoretical one.

When eq. 2 is parameterized and allowances are made for variability in parameters and winter temperature, it can be used to drive a simulation exercise. In order to be reliable, several assumptions in addition to those above must hold. Measurement errors in the independent variable need to be small relative to process errors (Walters and Ludwig 1981). Hilborn and Walters (1992) recommend high precision in estimates of spawning stock and a 10 fold range to minimize the impact of measurement errors. The fitted model must also explain a substantial portion of the variability in recruitment and the estimated parameters must be stable over time. Specifically, it is assumed that model residuals are normally distributed with zero mean and constant variance. Diagnostic evaluation of residuals can identify where model assumptions may be invalid. Time trends in residuals may indicate nonstationarity in the production parameters caused by factors external to the model (Walters 1987). Model predictions under these conditions will be biased and the simulations unreliable.

To evaluate the properties of the NUSCo. stock-recruit model, it was refit in an

EXCEL spreadsheet environment using the SOLVER function. SOLVER uses a generalized, reduced gradient algorithm to find solutions to nonlinear problems. Once parameters were estimated, residuals were calculated as observed recruitment minus model predicted. Residuals were plotted in time sequence and against other plausible explanatory variables such as prerecruit fishing mortality rate and plant condenser coolant flow. Correlations between model residuals and candidate variables were calculated. Uncertainty in the parameter estimates was evaluated by bootstrapping (Efron 1982). Residuals from the original model fit were resampled randomly and added to the predicted values to create alternate realizations of the recruitment series. The model was then successively refit 500 times and parameter estimates accumulated in frequency tables. Confidence bounds on the parameters were based directly on the cumulative bootstrap frequencies. This is a more reliable procedure than the nonlinear, small sample approximations used by NUSCo. (Hilborn and Walters 1992). Parameter correlations were calculated from the bootstrap outcomes.

Enhanced Stock-Recruit Model- Given some diagnostic deficiencies in the NUSCo. stock-recruit model and an inverse correlation between residuals and flow, an attempt was made to improve the model. The enhanced model was used to estimate the reduction in realized recruitment associated with plant operation. Entrainment at the station is correlated with coolant flow and larval abundance. A linear regression model regressing the $\log_e$ of entrainment on $\log_e$ coolant flow and $\log_e$ 7 mm larval abundance explained 61% of the variance and was highly significant ($F=15.43$, $df=20$, $p<0.01$). Both parameters were significant at $P<0.01$. This finding indicates that the relationship between the plant and larval entrainment is conceptually similar to the log catch model commonly used in separable fisheries assessment models (Deriso 1985). The logarithm of larval "catch" is a function of larval abundance and plant "fishing" effort. Accordingly, it was hypothesized that the plant functions as a predator, killing Niantic River winter flounder directly through impingement and entrainment. Additional indirect mortality occurs through elevated temperature and biocide effects on vital processes. Walters et al. (1986) shows how a stock-recruit models may be extended to include the effects of predation on recruitment. In the case of Millstone Station, plant morality rate was assumed to be proportional to condenser coolant flow in the same manner that fishing mortality is assumed proportional to fishing effort. As such, eq.1 can be extended to include a third explanatory variable as:

$$R=\alpha P \exp(-\beta P-\phi T-\theta F) \exp(\epsilon) \qquad (4)$$

where:

$R=$ *recruitment*
$P=$ *parental stock*
$T=$ *February water temperature*
$F=$ *Mean March-May flow*
$\alpha=$ *curve slope at the origin*
$\beta=$ *compensatory rate parameter*

ϕ = *temperature effect parameter*
θ = *coolant flow effect parameter*
ϵ = *multiplicative error term.*

The θ parameter estimates the instantaneous rate with which recruitment changes per unit change in plant coolant flow. It is analogous to the catchability coefficient in fishery models if flow is considered an estimator of plant fishing effort. Eq. 4 specifies an inverse effect, that is recruitment falls as coolant flow increases. The form of mortality is not specifically identified so that θ estimates the aggregate plant impact between spawned eggs and recruiting adult. The statistical hypothesis tested is that the estimate of θ is significantly greater than zero. If plant coolant flow effects recruitment to the population, variance explained by the enhanced model should increase and uncertainty in the other stock dependent parameters (α, β) should decline. It should be pointed out that entrainment estimates are not appropriate for inclusion in the stock-recruit model. Entrainment is a function of both larval abundance and plant fishing rate. It should be clear from eq. 3 that the exponential terms are conditional survival rates which modify α. Survival rates are obtained as the ratio of two abundances or the exponentiation of an instantaneous mortality term. Substitution of entrainment for plant flow is conceptually erroneous since it equates a survival rate with the exponentiation of a constant multiplied by an abundance term.

The remaining issue is which coolant flow series best indexes plant winter flounder predation rate. Since entrainment is likely a greater source of mortality than impingement, the March to May flow series was selected. Exploratory model fits with different unit combinations showed that the unit 3 flow series produced a better model in terms of variance explained and residual behavior than total flow. This is consistent with the findings of Gibson (1996) who used an intervention analysis to model the effect of a dramatic increase in flow at Brayton Point Station. Coolant flow at Millstone Station exhibits a similar step increase whereby flow approximately doubles when unit 3 was activated. The unit 3 flow variable essentially acts as an on-off switch in the model. Recruitment varies as a step rather than a monotonic function of flow. It should be noted that in the fitting of eq. 3, absolute flow levels are used rather than centered data since there are no conditions under which entrainment would benefit the stock. The proportional reduction in realized recruitment due to unit 3 operation is estimated by:

$$m_3 = 1 - exp(-\theta F) \qquad (5)$$

where: m_3 = *proportional reduction*
F = *unit 3 flow*
θ = *flow parameter.*

Only the impact of unit 3 can be estimated directly with the above formulation. Units 1 and 2 have operated since 1977 so their impact is imbedded in the stock-recruit data and is reflected in a reduced slope parameter (α). NUSCo. (1998) notes that estimates of the slope have been less than a theoretical value based on life history attributes. The average impact of unit 1 and 2 operation can be estimated indirectly. When the impact of unit 3 operation is accounted for in eq. 3, the slope estimate will rise above that given by NUSCo. (1999) for the S-R model without flow. If it is assumed that the remaining difference between the estimated value and the utilities theoretical value of 5.87 is due to the combined effects of fishing mortality and unit 1-2 operation, the latter can be estimated with data on the former:

$$m_{1\text{-}2}=(1- \alpha/\alpha' \exp(-\sum_{i=1}^{3} F_i)) \qquad (6)$$

where:
$m_{1\text{-}2}$= *proportional reduction in recruitment*
α= *estimated stock-recruit slope*
α'= *theoretical stock-recruit slope*
F= *instantaneous fishing mortality rate*
i= *age.*

Cumulative fishing mortality rates over ages 1 to 3 on cohorts of winter flounder were taken from NEFSC (1999). It is assumed that the mean age at recruitment to the spawning population is 4 years. Since spawning occurs in the winter, little fishing mortality occurs at age 4 prior to spawning.

Results-

Niantic River Winter Flounder Abundance- Trawl abundance indices and absolute population estimates for the Niantic River stock are summarized in Table 1. The data clearly show a collapsed stock. Trawl CPUE for both large and small winter flounder is at historic low levels (Figure 1). The 1997 and 1998 values are about 5% of peak abundances. The trawl CPUE trends are corroborated by the Jolly-Seber mark and recapture estimates of absolute population size. Stock size declined from a maximum of 79,607 fish in 1985 to only 6829 in 1997 (Figure 2). The trawl CPUE of fish greater than 15 cm is highly correlated with the Jolly-Seber estimates of stock size ($r=0.95$, $df=12$, $P<0.01$). Hindcasted estimates of stock size using the trawl CPUE and fitted regression equation average 155,427 fish from 1977 to 1983 or about 22 times current population size. Jolly-Seber estimates of recruitment have declined from 47,000 in 1984 to less than 5000 in 1995-1996. Trawl CPUE of fish less than 15 cm in length was highly correlated with Jolly-Seber recruitment the next year ($r=0.80$, $df=11$, $P<0.01$). Fish less than 15 cm in the spring trawl survey would likely recruit to the greater than 20 cm class the next year so the correlation is logical. Hindcasted estimates of Jolly-Seber recruitment averaged 48,266 fish from 1977 to 1983 or about 12 times current levels. The trawl CPUE indices indicate that absolute abundance and recruitment will remain low in 1998. Stock size in 1998 was predicted at 4027 fish and recruitment at 5892 fish.

Stock-Recruitment Estimates and Environmental Data- Estimates of female spawning stock and realized recruitment in future years is given in Table 2 for the 1977 to 1994 year classes as reported in NUSCo. (1999). Similar to the Jolly-Seber estimates, spawning stock and realized recruitment are at very low levels (Figure 3). The recruit per spawner ratio fluctuated between 0.40 and 2.22 from 1976 to 1986 and then declined steadily to a historic low of 0.17 in 1994. The time sequence of these data are important. Recruitment in the stock began to collapse with the 1986 year class which was the first to fall below 20,000 fish. Spawning stock did not decline to consistently low levels until several years later. This pattern does not support an overfishing hypothesis which would be expected to reduce spawning stock first. The February temperature deviation increased from 1977 to 1990 and then began to decline (Figure 4). The value in 1994 was the lowest since 1982. Condenser coolant flow data for Millstone station are summarized in Table 3. Mean flows by generating unit during the March to May larval winter flounder period are given along with total flow used by the units combined. Total flow fluctuated around 600 million cubic meters from 1977 to 1985 and then increased to around 1200 million cubic meters from 1986 to 1994 (Fig.5). The doubling of flow occurred as a result of unit 3 activation.

Estimates of Fishing Mortality Rate- Fishing mortality rates at age for winter flounder in the Southern New England stock region are summarized in Table 4. The mean age at recruitment to the Niantic River spawning population is about 4 years. Prerecruit flounder will be exposed to fishing mortality at age 1, age 2, and age 3. By convention, age 4 is reached on January 1 and spawning is shortly thereafter so little F occurs prior to spawning. Fishing mortality increases from age 1 to age 3. Cumulative, pre-recruit mortality on the cohorts average 0.91 but showed a strong time trend (Figure 6). Cohort cumulative mortality rose for the 1977 to 1983 year classes but then began to drop. Mortality fell sharply for the 1989 to 1994 year classes. The 1990-1994 year classes suffered reduced mortality relative to the historic levels (< 0.80). These reductions in F correspond with management measures which increased minimum sizes and mesh regulations. The history of winter flounder regulations in Connecticut waters is given in NUSCo. (1998, Table 2). The time sequence of regulatory changes matches well with the reduction in cohort F in the VPA. Size limit increases began in 1983 and commercial mesh regulation began in 1989. Both measures would reduce mortality rate on young fish consistent with the SARC 28 VPA results. The mortality rates used by NUSCo. (1998, Table 41) on the other hand do not match SARC 28 estimates nor the history of DEP regulations.

NUSCo. S-R Model- Spawning stock estimates varied by a factor of seven and the coefficients of variation on trawl survey estimates were less than 0.10 in all years. Jolly-Seber estimates of adult stock had CV's ranging from 0.11 to 0.20 for years corresponding to the stock-recruit analysis. These attributes indicate that the abundance data were suitable for developing a recruitment curve. The stock-recruit data for the Niantic River population are plotted by year class in Figure 7. The 1977 to 1986 year classes display a typical pattern with occasional strong cohorts interspersed with stable recruitment over a range of spawning stocks. The 1987 year class begins a transition to a different regime. Year class strength declines markedly despite adequate levels of spawners in 1987 to 1991. Subsequent further reductions in spawning stock in 1991-1994 were associated with very low recruitment. This regime shift is not as pronounced in VPA estimates of stock and recruitment for either the Southern New England or Georges Bank stocks (Figures 8 and 9). While there is some evidence of low recruitment in 1989-1991 for these stocks, recruitment of the 1992-1994 year classes improves while the Niantic remains at critically low levels. This can be seen more clearly in a time plot of standardized recruitment ratios (Figure 10). Recruitment per spawner continues to decline in the Niantic River while the other two stocks show increases. The atypical pattern of the Niantic population is further emphasized by data from state agency trawl surveys. Recruit per spawner ratios have increased in recent years in surveys conducted by Massachusetts, Rhode Island, and Connecticut (Figure 11). These regional data indicate that local factors are responsible for the poor recruit per spawner ratios in the Niantic River 1987-1994 year classes. Results of fitting the NUSCo. version of the stock-recruit curve are given in Table 5. The EXCEL solver routine found essentially the same parameter estimates as the SAS nonlinear regression procedure used by NUSCo. (1999). Bootstrap frequency distributions for the parameter estimates are shown in Figures 12-14. Parameter 95% confidence intervals were estimated directly from the cumulative bootstrap distributions. The alpha parameter was estimated 1.19 with a confidence bound of 0.70-1.62. The compensatory mortality parameter (β) was estimated at 0.000020 with a confidence bound of 0.000011-0.000029. The winter temperature effect parameter (ϕ) was estimated at 0.39 (95% CI: 0.23-0.57).

Observed and predicted recruitment for the NUSCo. S-R model fit are graphed in Figure 15. Both series decline but predicted values reach a low point in 1990 and then begin to increase much like observed recruitment in other stock areas. Actual recruitment in the Niantic River however collapses to low levels giving rise to a very noticeable residual pattern (Figure 16). The residuals switch from positive values in 1983-1987 to negative values in 1988-1994. Residuals were significantly correlated in an inverse manner with time ($r=0.62$, $df=16$, $P<0.01$). A residual trend, when plotted in the time domain, is a general diagnostic of an inadequate model (Draper and Smith 1981). In stock-recruit models, this pattern likely means that there are external variables producing systematic change (Hilborn and Walters 1992). Model residuals were significantly correlated with cumulative cohort fishing mortality rate but in a nonsensical manner (Figure 17; Table 6). The positive correlation suggest that high recruitment to the spawning stock follows high pre-recruit fishing mortality rates and vice versa. This is clearly illogical and occurs simply because fishing mortality rates were declining while recruitment was failing for other reasons. Stock-recruit model residuals were inversely correlated with total condenser coolant flow at Millstone Station (Figure 18, Table 7). The large increase in coolant flow in 1986 begins a trend of failing recruitment in the Niantic River winter flounder stock (Table 2). The inverse correlation is logical since increased entrainment-impingement rate, mediated through flow increases, would remove a higher proportion of potential recruits from the population. As noted by NUSCo. (1999), the Niantic River stock-recruit parameters are not stable over time. There is a strong downward trend through time for the alpha parameter of the Ricker curve as data points are added (Table 8, Figure 19). This is a classic case of nonstationarity in the production parameters which means that NUSCo predictions about future stock behavior are unreliable (Hilborn and Walters 1992). They will overestimate the stocks ability to rebound since the serial erosion of the productivity parameter is ignored.

Enhanced Stock-Recruit Model- Results of fitting the S-R model including a coolant flow parameter are found in Table 9. The model fit was greatly improved with a reduction in residual sums of squares of nearly 60%. Bootstrap distributions for the parameter estimates are given in Figures 20-23. The stock-recruit slope (α) was estimated at 2.02 with a 95% confidence interval of 1.46-2.50. The compensatory mortality parameter (β) was estimated at 0.000026 with a 95% confidence interval of 0.000019 to 0.000031. The estimate of the winter temperature parameter (ϕ) was 0.225 (95% CI: 0.125-0.325). The estimate of the coolant flow parameter (θ) was 0.017 (95% CI: 0.009-0.025). A comparison of the parameter estimates between the NUSCo. and the enhanced S-R model is given in Table 10. Both the slope and compensatory mortality parameters increased in magnitude for the model including plant coolant flow. Precision on the two stock dependent parameters also improved. The magnitude of the winter temperature parameter declined with no change in precision. The coolant flow parameter was well estimated with a bootstrap CV of 23%. The bootstrap outcomes indicated that there was virtually zero chance that this parameter was zero. The alpha and beta parameters were highly correlated for 16 degrees of freedom ($r=0.81$, $P<0.01$). This indicates that higher productivity ($\alpha=R/S$) at low stock sizes is associated with smaller populations for maximum recruit production ($1/\beta$). The environmental effects parameters (temperature, flow) were also correlated with α ($r=-.56$, $P<0.05$ $r=0.47$, $P=0.05$). This is not surprising since inclusion of other explanatory values in a stock-recruit model is in effect a partitioning of the α parameter. The temperature and flow parameters were not significantly correlated with β nor with each other. This indicates a good ability to discriminate the effects of temperature and flow on recruitment.

Observed and model predicted recruitment are plotted in Figure 24. There was closer agreement for the 1977-1985 and 1988-1994 year classes in the flow enhanced model than the NUSCo. version. Because of the on-off action of the unit 3 flow variable, the model predicted 1986 year class was below the observed value. A review of NUSCo. (1999) indicated that unit 3 began commercial operation in April of 1986, part way into the larval season. Possibly, the impact of unit 3 in 1986 was not as great as indicated by March-May coolant flow. Madenjian et al. (1986) have discussed the problem of modeling intervention effects at the point of impact and suggested ramp functions as a means to spread the initial population adjustment over several years. Reducing 1986 flow to 25.0 instead of the 49.8 to simulate only part of a larval season provided for a further 19% reduction in residual sums of squares and a smoother pattern in predicted year class abundance. Without more detailed data on plant operations in 1986, further refinements to the enhanced S-R model are speculative. Residuals for the enhanced model are plotted against time in Figure 25. They did not demonstrate a significant time trend ($r=-0.29$, $df=16$, $P=0.24$). Further, estimates of alpha and beta did not decline with respect to terminal data year (note difference in scale, Figures 19 and 26).

Estimates of the proportional reduction in year class strength due to unit 3 operation ranged from 0.47 to 0.62 with a mean of 0.57. This means that on average, 57% of a cohort is lost prior to recruitment through the combined effects of entrainment, impingement, and indirect impacts of plant operation. The average pre-recruit cumulative fishing mortality rate was 0.91. Based on eq. 4, the mean reduction in realized recruitment due to operation of units 1 and 2 was 0.14. Using a conditional probability equation, the mean reduction in realized recruitment from operation of all units was 0.63. These estimates are considerably higher than in NUSCo. (1999). They report a pre-unit 3 production loss which averages 7.7% using mass balance calculations. This increased to an average of 17.6% with the addition of unit 3. It is not surprising that the utilities estimate is lower since it reflects only entrainment losses. The estimate from the enhanced stock-recruit model encompasses all losses which can be statistically associated with increased power output at Millstone station. Also, the NUSCo. calculations of production loss refer to larvae without consideration of survival value to potential recruit. Since survival rate increases with larval stage, the NUSCo. calculations would underestimate the potential recruitment lost.

Alternative Explanations for Low R/S Ratio- The statistical correlation of low recruitment per unit spawner with plant coolant flow does not establish causality. Having ruled out fishing mortality as the cause, it is objective to examine other potential explanations. To be plausible, they need to operate on local scales since the behavior of the Niantic population is at odds with regional data. The NUSCo. stock-recruit model accounts for changes in spawning stock and water temperature during the spawning period. The enhanced model adds the influence of unit 3 condenser coolant flow. Other factors which could cause abnormally low recruitment include; increased predation, pollutants or habitat loss, and regime shifts. Several potential predators of YOY and juvenile winter flounder have increased greatly in abundance in the past decade. Piscivorous fishes and birds such as striped bass and cormorants are frequently implicated in contemporary fish stock problems. Atlantic coast striped bass stock biomass increased from 8087 mt in 1982 to 63,844 by 1996 (NEFSC 1998). Cormorant populations in Connecticut and Rhode Island have exhibited exponential growth in the past decade (Howell 1995, RIDFW- Bird Surveys). NUSCo. (1998) also identify harbor seals as a potential source of predation on adult winter flounder. The resurgence of the above species however has been a regional phenomenon so they are unlikely to be responsible for uniquely low recruitment per unit spawner in the Niantic River. NUSCo. (1998) summarized literature on predation by Crangon spp. of shrimp on newly settled winter flounder and other flatfishes. These small crustaceans exhibit size selective and density dependent predation and are therefore potential regulators of juvenile flatfish abundance. No abundance data on Crangon spp. is available but it is doubtful that they have multiplied only in the Niantic River. A redundant sequence of population regulation mechanisms has been suggested by NUSCo. (1998) whereby first order adjustment of winter flounder cohorts is achieved in the egg-larval stage followed by fine tuning of young of the year abundance. This is a reasonable hypothesis supported by winter flounder modeling studies (Rose et al. 1995) and observations on the similar North Sea plaice (Bax 1999). However, the stock-recruit data for the Niantic population indicate that compensatory mechanisms have been overwhelmed. Recruitment per spawner continues to fall (Table 2) and is at historic low levels despite reductions in fishing mortality and improvements in February temperatures.

No data on habitat quality and quantity in the Niantic production system are available to examine trends. It is clear that fisheries production depends on both. Gibson (19) has shown that winter flounder population abundance is related to the size of habitat area on a logarithmic scale. For example, the Niantic River which is a small estuary perhaps numbered 155,000 fish during peak abundance years while the Georges Bank stock numbered about 20 million fish during peak years (NEFSC 1999). While habitat loss or deterioration cannot be ruled out, a reduction in population size to about 5% of former levels implies a massive habitat impact. This would seem to be unlikely since other flatfish species sampled in the Niantic River have not declined in abundance (NUSCo. 1998, appendix VI).

There is considerable evidence that trends in fish population abundance are linked to trends in climate (Bakun 1999). Periods of similar recruitment which are synchronous with climate stanzas are termed "regimes" (Beamish et al. 1999). Regime shifts occur when recruitment levels change synchronous to a climate shift. Research on Pacific salmon indicates that large scale climatic factors influence aggregate production but individual stocks may vary from the aggregate pattern. A change in the Ricker productivity parameter was used by Adkinson et al. (1996) to explain changes in the abundance of Bristol Bay sockeye salmon stocks. This suggests a parallel with Niantic River winter flounder in that a regime shift and decline in the stock-recruit slope are evident. However, given that the Niantic population is the outlier within regional data, it is difficult to invoke large scale, climatic regime shifts as an explanation.

Collie and Spencer (1993) have shown how the above factors may combine to influence the abundance of fish stocks. A production model including low frequency environmental forcing, depensatory predator-prey relationships, and overfishing was developed. Simulations showed that certain parameter combinations could produce multiple equilibria or alternating periods of high and low abundance. Increased fishing pressure made stocks more vulnerable to a shift to low abundance and increased the level of favorable environment needed to return the stock to high productivity. An important element of the model is the type III predation function of Holling (1965). Predation rate is maximized at intermediate prey density so that prey populations, once depressed by other factors, may become "trapped" in the low abundance state. Although, NUSCo. (1998) ruled out depensatory behavior based on the work of Meyers et al. (1995) it should be given more consideration. The Niantic stock-recruit data is beginning to resemble a depensatory curve with a cluster of points to the right of the origin in recent years. Given the trajectory of the trawl CPUE and the regression relationships noted above, it is likely that spawning stock and recruitment will decline further. In Figure 27, several new S-R data pairs have been added based on predictions from the trawl CPUE. The new points augment the cluster to the right of the origin. It is not hard to visualize a depensatory curve which rises from the origin, declines into a pit, before rising again. It is possible that overfishing and plant impacts have reduced winter flounder abundance to such a low point that a depensatory predator, perhaps the Crangon spp., has trapped the population at low levels. The decadal increase in winter temperatures may have been a predisposing factor. If this scenario is true, much larger reductions in fishing mortality and plant impacts along with improved climatic conditions may be needed to move the population to a high productivity phase.

Discussion-

There is clear and compelling evidence that the Niantic River winter flounder population is exhibiting atypical population dynamics when compared to other stocks in the region. Recruitment and spawning stock are collapsing. The recruit per spawner ratio continues to decline despite reductions in fishing mortality and improvements in winter temperatures. Peer reviewed data and assessment modeling for other stocks show increasing recruit per spawner ratios in recent years and a general stock recovery. The Ricker stock-recruit model used by the utilities exhibits diagnostic flaws in the form of serial correlation in the model residuals. This invalidates its use in population projection exercises as the assumption of random error with zero mean and constant variance (NUSCo. 1998, page 26) is not met. The net effect is that predictions of population recovery are overly optimistic. This conclusion does not rest on the above analysis. The companies own projections show a stock which declines to a low point in 1993 and then begins a recovery (NUSCo. 1998, page 91, Figure 40). Indeed, the companies simulation trajectory resembles that of other regional stocks. Their own monitoring data however show a stock which continues to decline after 1993. Obviously, something is missing from the simulation model.

It was shown that fishing mortality on pre-recruit flounder cannot explain the model deficiencies as argued by company scientists. Pre-recruit fishing mortality has been falling since the 1989 year class, consistent with the management history of regulations. Plant condenser coolant flow however did explain more variation and reduced uncertainty in other S-R parameters when added to the model. The estimated coolant flow parameter is negative, consistent with a negative plant impact associated with increased power output. The enhanced S-R model indicates that power generation activities can remove up to 63% of potential recruitment to the spawning stock. The deterioration in the Niantic population is synchronous with unit 3 activation suggesting that this action overwhelmed the stocks remaining compensatory reserve. Other candidate explanations either lack a local basis or cannot be fully evaluated. The available data for the Niantic population suggest the possibility of a depensatory stock-recruitment relationship possibly mediated by a type III predator. The working hypothesis is that the combined effect of fishing mortality, power generation, and environmental forcing has reduced the stock to a critical threshold below which recovery is unlikely at current levels of F and plant impact. The company should consider this possibility in future population projections. Under the "predator pit" scenario, it could be necessary to reduce fishing mortality and plant impact to unusually low levels to initiate recovery. The models indicate that the magnitude of larval entrainment and recruitment loss are directly related to condenser coolant flow at

Table 7- SUMMARY OUTPUT FOR NUSCO S-R RESIDUAL-COOLANT FLOW CORRELATION

Regression Statistics	
Multiple R	0.475827
R Square	0.226411
Adjusted	0.178062
Standard	6986.74
Observati	18

ANOVA

	df	*SS*	*MS*	*F*	*gnificance F*
Regressio	1	2.29E+08	2.29E+08	4.6828166	0.045938
Residual	16	7.81E+08	48814529		
Total	17	1.01E+09			

	Coefficient	*andard Err*	*t Stat*	*P-value*	*ower 95%*	*Upper 95%*
Intercept	8771.61	4455.021	1.968927	0.0665329	-672.611	18215.8315
X Variable	-9.9586	4.601979	-2.16398	0.0459377	-19.7144	-0.2028407

Table 8- Sensitivity of Alpha Parameter in NUSCo S-R Model to Terminal Data Year Used in Estimation.

Terminal Data Year	Alpha	Beta	Temp
1984	2.182	0.000028	0.212
1985	1.971	0.000026	0.236
1986	1.951	0.000026	0.239
1987	1.840	0.000025	0.259
1988	1.720	0.000026	0.295
1989	1.570	0.000025	0.335
1990	1.530	0.000025	0.344
1991	1.486	0.000025	0.358
1992	1.405	0.000024	0.375
1993	1.339	0.000023	0.385
1994	1.153	0.000020	0.382

Table 9- Niantic River Stock-Recruit Data and Gibson S-R Fit w/ Unit 3 flow.

	Spawners	Recruits	Temp	Flow	Pred Rec	Resid	Resid^2
1976							
1977	22838	50680	-2.40	0	43700.9	6979.1	48707656.0
1978	39236	39197	-1.67	0	41575.5	-2378.5	5657424.4
1979	26952	32221	-1.28	0	36012.3	-3791.3	14373901.5
1980	22363	25671	-0.38	0	27496.6	-1825.6	3332894.0
1981	59543	23821	-0.13	0	26299.7	-2478.7	6143894.7
1982	70335	30197	-1.20	0	29848.0	349.0	121790.9
1983	46815	29159	0.98	0	22431.1	6727.9	45264512.6
1984	22558	22247	1.26	0	19078.3	3168.7	10040855.6
1985	24498	22075	-0.40	0	28622.4	-6547.4	42868421.6
1986	19136	19247	0.62	49.8	8933.1	10313.9	106376881.9
1987	23077	16140	0.51	47.2	10406.4	5733.6	32873729.6
1988	37673	13620	-0.09	55.6	11567.4	2052.6	4213156.8
1989	30779	8680	0.48	51.3	10682.7	-2002.7	4010940.1
1990	14955	6481	1.52	48.7	6473.7	7.3	53.4
1991	27472	6241	2.00	38.7	9099.7	-2858.7	8172238.4
1992	16848	4256	0.92	51.1	7635.8	-3379.8	11422772.0
1993	9600	1766	0.34	58.8	5267.8	-3501.8	12262255.0
1994	14102	2341	-1.17	58.2	9765.3	-7424.3	55119693.3
						SSQ	410963071.8

Estimated S-R Parameters

alpha	2.019956
Beta	0.000026
Temp	0.225074
Flow	0.016614

Table 10- Comparison of Stock-Recruit Parameters Between NUSCo. Configuration and Enhanced Model Including Unit 3 Flow Variable.

Model	Parameter	Estimate	Bootstrap Std Error	CV
NUSCo	alpha	1.185	0.231	0.195
	Beta	0.000020	0.000004	0.219
	Temp	0.352	0.091	0.257
	Flow			
Enhanced	alpha	2.020	0.268	0.133
	Beta	0.000026	0.000003	0.116
	Temp	0.225	0.054	0.240
	Flow	0.017	0.004	0.241

Boostrap Parameter Correlation Matrix for Enhanced S-R Model.

	Alpha	Beta	Temp	Flow
Alpha	1.00	0.81	-0.56	0.47
Beta		1.00	-0.13	-0.27
Temp			1.00	-0.34
Flow				1.00

Fig.1- Abundance of Winter Flounder in the NUSCo. Trawl Survey in the Niantic River

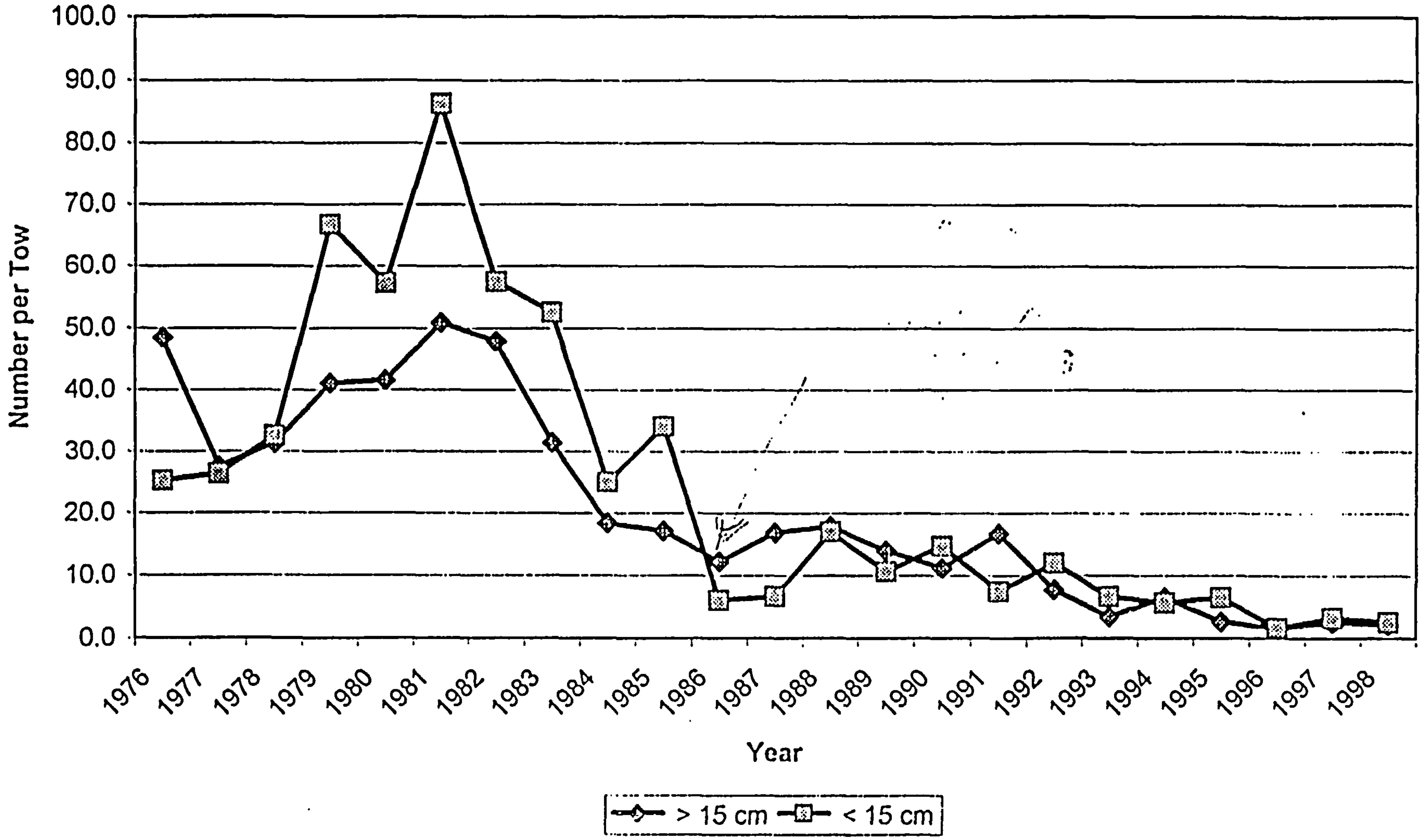


Fig.2- Winter Flounder Abundance in the Niantic River from NUSCo Mark Recapture Study

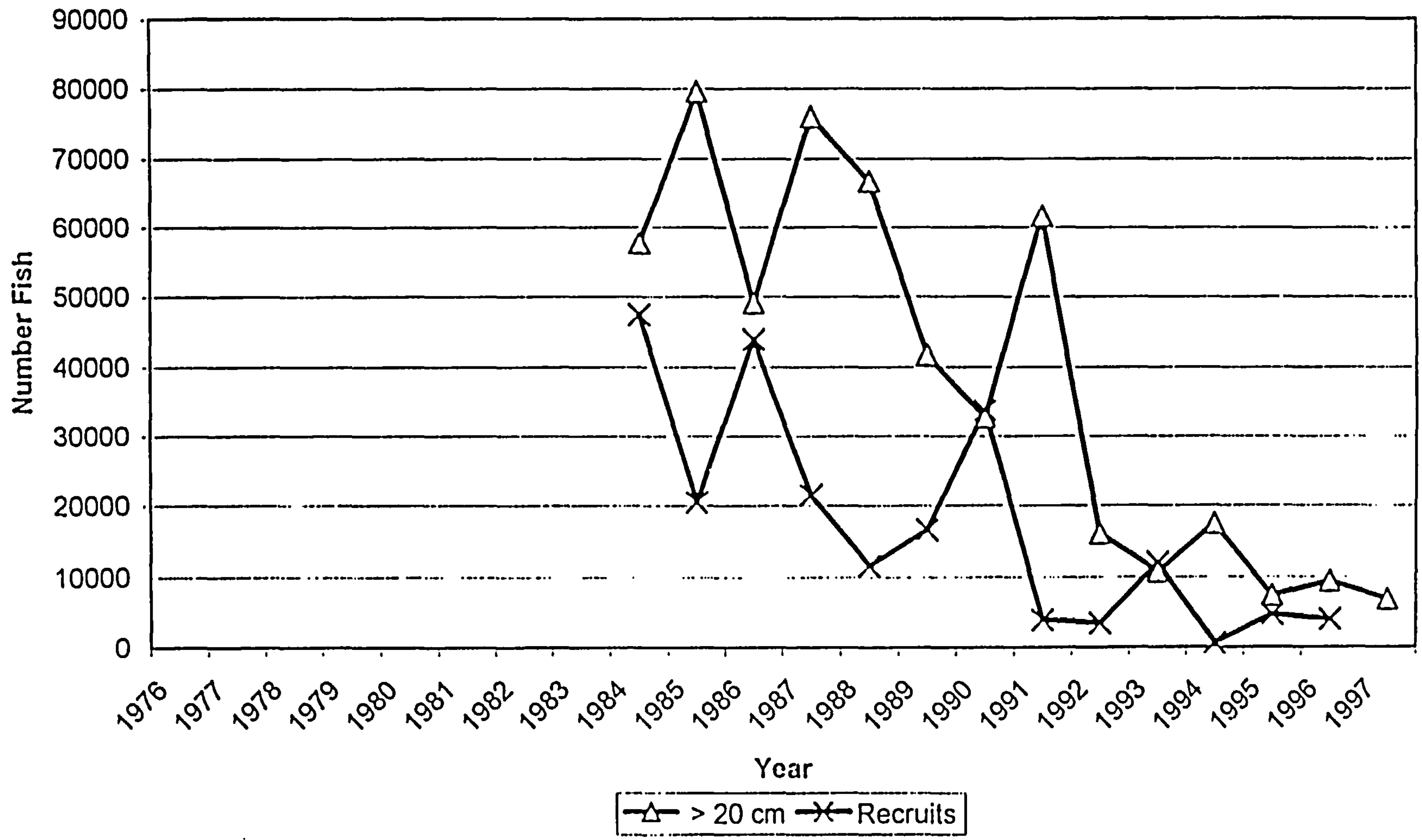


Fig.3- Trends in Spawning Stock and Recruitment for the Niantic River Winter Flounder Population

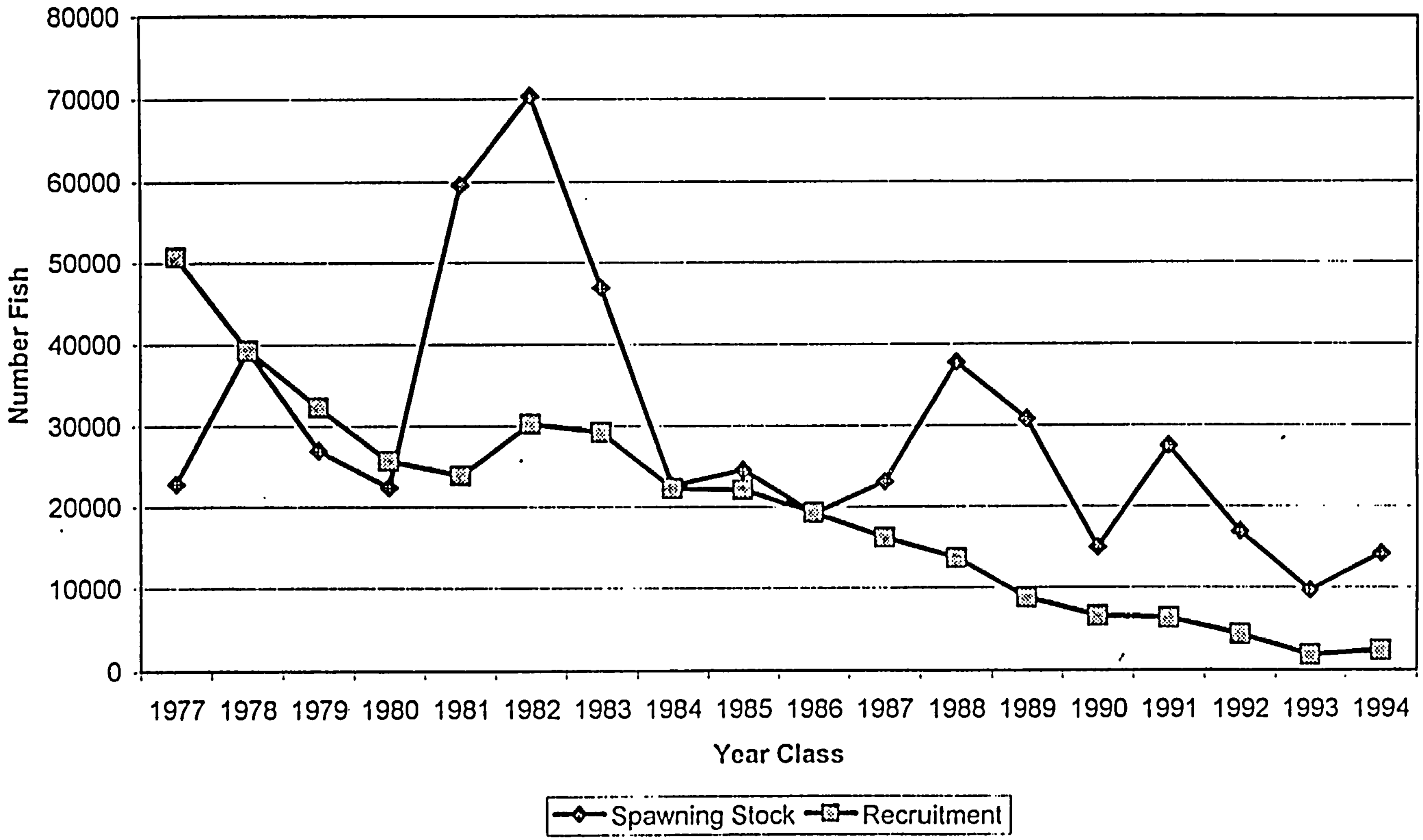


Fig.4- February Water Temperature Deviations from Long Term Mean Near Millstone Station

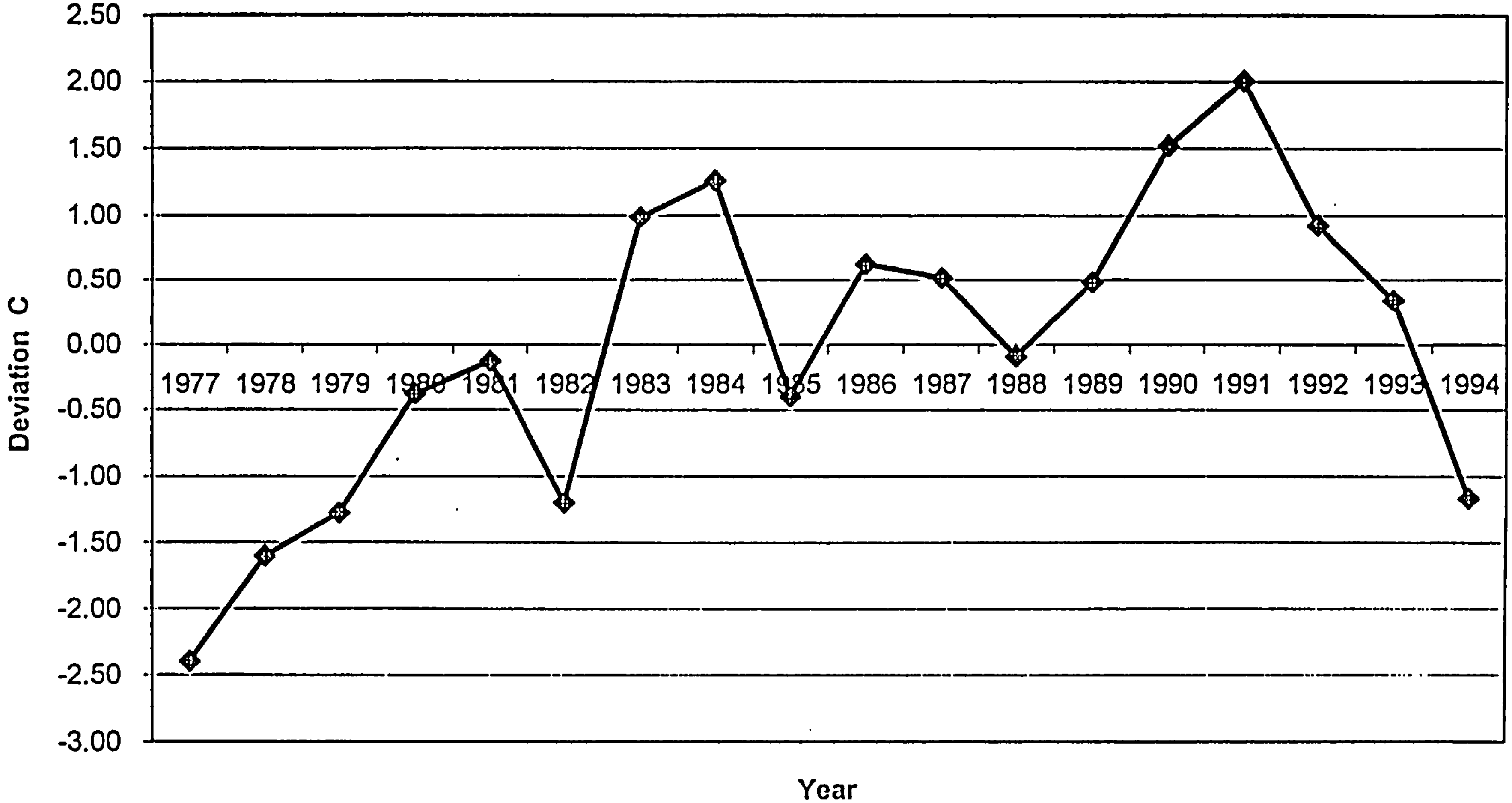


Fig.5- Trend in Total Condenser Coolant Flow at Millstone Station

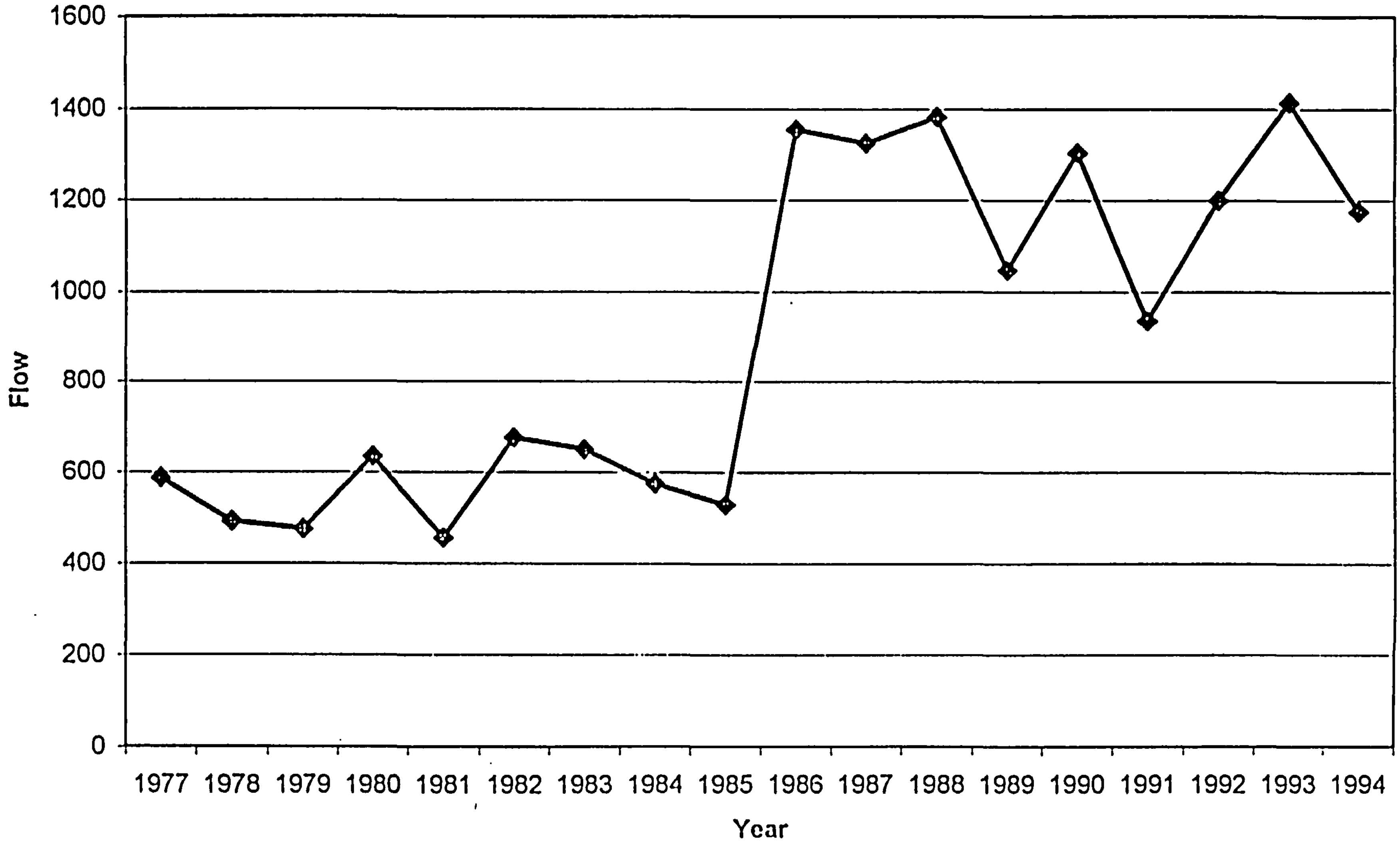
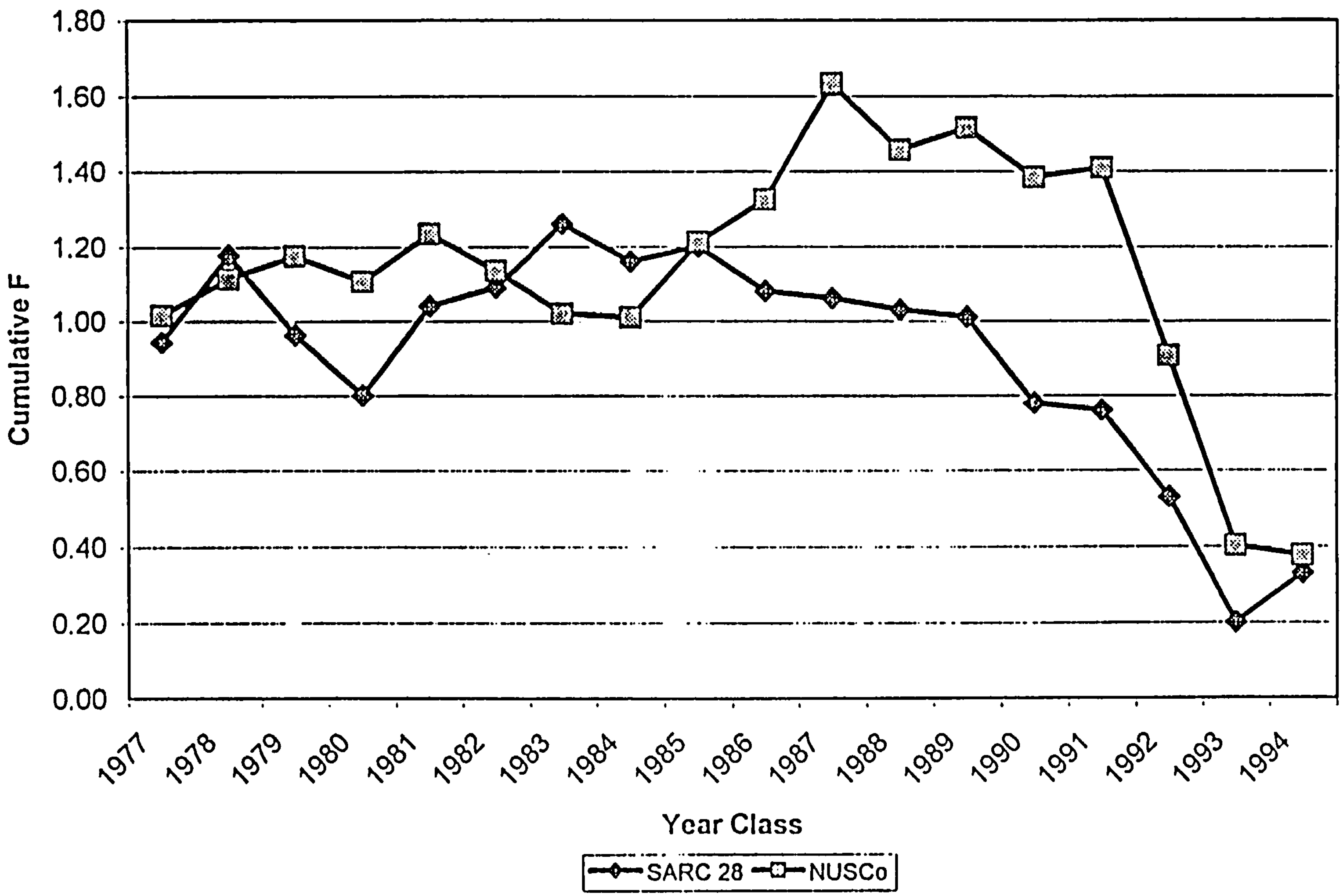


Fig. 6- Cumulative Age 1 to Age 3 Fishing Mortality Rates from SARC 28 VPA on the 1977 to 1994 Year Classes of Winter Flounder



the station. Every effort should be made to minimize coolant flow especially during periods of larval abundance.

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Table 1- Winter Flounder Indices of Abundance in Niantic River from NUSCo. (1999).

Year	Trawl CPUE > 15 cm	Trawl CPUE < 15 cm	Total CPUE	Female Stock	Jolly-Seber > 20 cm	Jolly-Seber Recruits
1976	48.4	25.2	73.6			
1977	27.5	26.3	53.8	28638		
1978	31.2	32.5	63.7	43819		
1979	41.0	66.7	107.7	32306		
1980	41.5	57.2	98.7	27229		
1981	50.8	86.2	137.0	64660		
1982	47.8	57.4	105.2	68210		
1983	31.3	52.5	83.8	45493		
1984	18.4	25.0	43.4	21947	57706	47428
1985	17.1	34.0	51.1	22660	79607	20454
1986	12.2	6.0	18.2	16112	49057	43850
1987	16.9	6.6	23.5	20774	75909	21472
1988	17.9	17.0	34.9	31196	66688	11524
1989	13.9	10.6	24.5	23723	41744	16544
1990	11.2	14.7	25.9	13322	32691	33691
1991	16.7	7.4	24.1	25632	61611	3837
1992	7.7	11.9	19.6	12905	15995	3367
1993	3.4	6.6	10.0	6593	10695	11916
1994	6.4	5.6	12.0	12177	17375	589
1995	2.6	6.4	9.0	5097	7302	4661
1996	1.6	1.6	3.2	2349	9324	3903
1997	2.4	3.2	5.6	4405	6829	
1998	2.1	2.5	4.6	3141.		
Mean	20.4	24.5	44.9	24199	38038	17172
STD	16.3	23.9	39.0	18284	27023	15719
CV	0.797	0.978	0.867	0.756	0.710	0.915

Table 2- Niantic River Winter Flounder Stock-Recruit and Winter Temperature Data. From NUSCo. (1999) Monitoring Programs at Millstone Station.

	Spawners	Recruits	Recs/Spawn	Feb. Temp	Temp
1976					
1977	22838	50680	2.22	0.36	-2.40
1978	39236	39197	1.00	1.09	-1.60
1979	26952	32221	1.20	1.48	-1.28
1980	22363	25671	1.15	2.38	-0.38
1981	59543	23821	0.40	2.63	-0.13
1982	70335	30197	0.43	1.56	-1.20
1983	46815	29159	0.62	3.74	0.98
1984	22558	22247	0.99	4.02	1.26
1985	24498	22075	0.90	2.36	-0.40
1986	19136	19247	1.01	3.38	0.62
1987	23077	16140	0.70	3.27	0.51
1988	37673	13620	0.36	2.67	-0.09
1989	30779	8680	0.28	3.24	0.48
1990	14955	6481	0.43	4.28	1.52
1991	27472	6241	0.23	4.76	2.00
1992	16848	4256	0.25	3.68	0.92
1993	9600	1766	0.18	3.10	0.34
1994	14102	2341	0.17	1.59	-1.17
Mean	29377	19669	0.70	2.76	
STD	16025	13612	0.52	1.19	
CV	0.545	0.692	0.745	0.431	

Table 3- Millstone Station Flow Data for March-May by Unit

	Mean m3 per sec				m3 x 10^6 Feb.15 to June 30
	Unit 1	Unit 2	Unit 3	Total	
1971	19.7	0.0	0.0	19.7	
1972	29.1	0.0	0.0	29.1	
1973	9.9	0.0	0.0	9.9	
1974	24.4	0.0	0.0	24.4	
1975	29.1	0.0	0.0	29.1	
1976	25.4	29.2	0.0	54.6	662.8
1977	27.6	24.6	0.0	52.2	585.6
1978	17.5	18.9	0.0	36.4	490.9
1979	17.2	21.5	0.0	38.7	474.1
1980	27.6	31.8	0.0	59.4	633.3
1981	1.5	34.0	0.0	35.5	455.2
1982	27.6	32.3	0.0	59.9	674.1
1983	26.8	30.9	0.0	57.7	648.0
1984	13.9	35.8	0.0	49.7	573.8
1985	27.9	16.4	0.0	44.3	528.1
1986	27.2	36.9	49.8	113.9	1353.4
1987	29.0	37.0	47.2	113.2	1323.6
1988	28.8	32.8	55.6	117.2	1381.0
1989	13.9	24.7	51.3	89.9	1045.9
1990	27.6	33.3	48.7	109.6	1302.7
1991	10.8	32.3	38.7	81.8	934.4
1992	25.1	28.5	51.1	104.7	1199.3
1993	27.8	33.5	58.8	120.1	1412.3
1994	4.3	31.4	58.2	93.9	1174.6
1995	29.0	21.6	37.4	88.0	1133.8
1996	0.7	14.4	31.1	46.3	544.7
1997	0.2	9.7	7.6	17.5	185.1
1998					337.3
Mean	20.4	22.6	19.8	62.8	850.8
STD	9.9	13.0	24.5	34.8	377.9
CV	0.487	0.575	1.233	0.554	0.444

Table 4- Cumulative Cohort Fishing Mortality Rates for SNE Winter Flounder from SARC 28 VPA

Year Clas	Cohort F by Age Age 1	Age 2	Age 3	Total F	Total Z	Surv
1977	0.013	0.313	0.617	0.943	1.543	0.214
1978	0.013	0.313	0.850	1.177	1.777	0.169
1979	0.013	0.350	0.600	0.963	1.563	0.209
1980	0.020	0.380	0.400	0.800	1.400	0.247
1981	0.010	0.210	0.820	1.040	1.640	0.194
1982	0.010	0.330	0.750	1.090	1.690	0.185
1983	0.020	0.330	0.910	1.260	1.860	0.156
1984	0.010	0.290	0.860	1.160	1.760	0.172
1985	0.010	0.250	0.940	1.200	1.800	0.165
1986	0.000	0.230	0.850	1.080	1.680	0.186
1987	0.000	0.310	0.750	1.060	1.660	0.190
1988	0.020	0.130	0.880	1.030	1.630	0.196
1989	0.000	0.260	0.750	1.010	1.610	0.200
1990	0.000	0.180	0.600	0.780	1.380	0.252
1991	0.000	0.380	0.380	0.760	1.360	0.257
1992	0.030	0.140	0.360	0.530	1.130	0.323
1993	0.000	0.020	0.180	0.200	0.800	0.449
1994	0.000	0.050	0.280	0.330	0.930	0.395
Mean	0.009	0.248	0.654	0.912	1.512	0.231
STD	0.009	0.107	0.239	0.298	0.298	0.081
CV	0.970	0.433	0.365	0.326	0.197	0.351

Table 5- Niantic River Stock-Recruit Data and Replicated NUSCo S-R Fit.

	Spawners	Recruits	Temp	Flow	Pred Rec	Resid	Resid^2
1976							
1977	22838	50680	-2.40	0	43639.5	7040.5	49568163.2
1978	39236	39197	-1.60	0	39981.9	-784.9	616127.2
1979	26952	32221	-1.28	0	30868.5	1352.5	1829339.2
1980	22363	25671	-0.38	0	19808.1	5862.9	34373730.5
1981	59543	23821	-0.13	0	23157.6	663.4	440116.3
1982	70335	30197	-1.20	0	33452.5	-3255.5	10598157.0
1983	46815	29159	0.98	0	15226.4	13932.6	194118158.8
1984	22558	22247	1.26	0	10582.5	11664.5	136060103.7
1985	24498	22075	-0.40	0	20973.2	1101.8	1213949.5
1986	19136	19247	0.62	49.8	12281.7	6965.3	48514767.2
1987	23077	16140	0.51	47.2	14306.6	1833.4	3361474.7
1988	37673	13620	-0.09	55.6	22123.7	-8503.7	72313037.8
1989	30779	8680	0.48	51.3	16605.3	-7925.3	62810154.3
1990	14955	6481	1.52	48.7	7364.1	-883.1	779881.4
1991	27472	6241	2.00	38.7	8803.6	-2562.6	6567173.6
1992	16848	4256	0.92	51.1	10073.7	-5817.7	33846172.4
1993	9600	1766	0.34	58.8	8269.4	-6503.4	42294665.0
1994	14102	2341	-1.17	58.2	19901.6	-17560.6	308373400.6
						SSQ	1007678572

Estimated S-R Parameters

alpha	1.184626
Beta	0.000020
Temp	0.385218

TABLE 6- SUMMARY OUTPUT FOR NUSCO S-R RESIDUALS VS. CUMULATIVE F REGRESSION

Regression Statistics	
Multiple R	0.61752
R Square	0.381331
Adjusted	0.342664
Standard	6248.109
Observati	18

ANOVA

	df	*SS*	*MS*	*F*	*gnificance F*
Regressio	1	3.85E+08	3.85E+08	9.861971	0.006322
Residual	16	6.25E+08	39038864		
Total	17	1.01E+09			

	Coefficient	*andard Err*	*t Stat*	*P-value*	*ower 95*	*pper 95*	*ower 95.0*	*pper 95.0%*
Intercept	-14767.5	4871.153	-3.03163	0.007938	-25093.9	-4441.17	-25093.9	-4441.17
X Variable	15990.97	5092.055	3.140377	0.006322	5196.303	26785.65	5196.303	26785.65

Fig.7- Stock and Recruitment Relationship in Niantic River Winter Flounder, 1977-1994 Year Classes

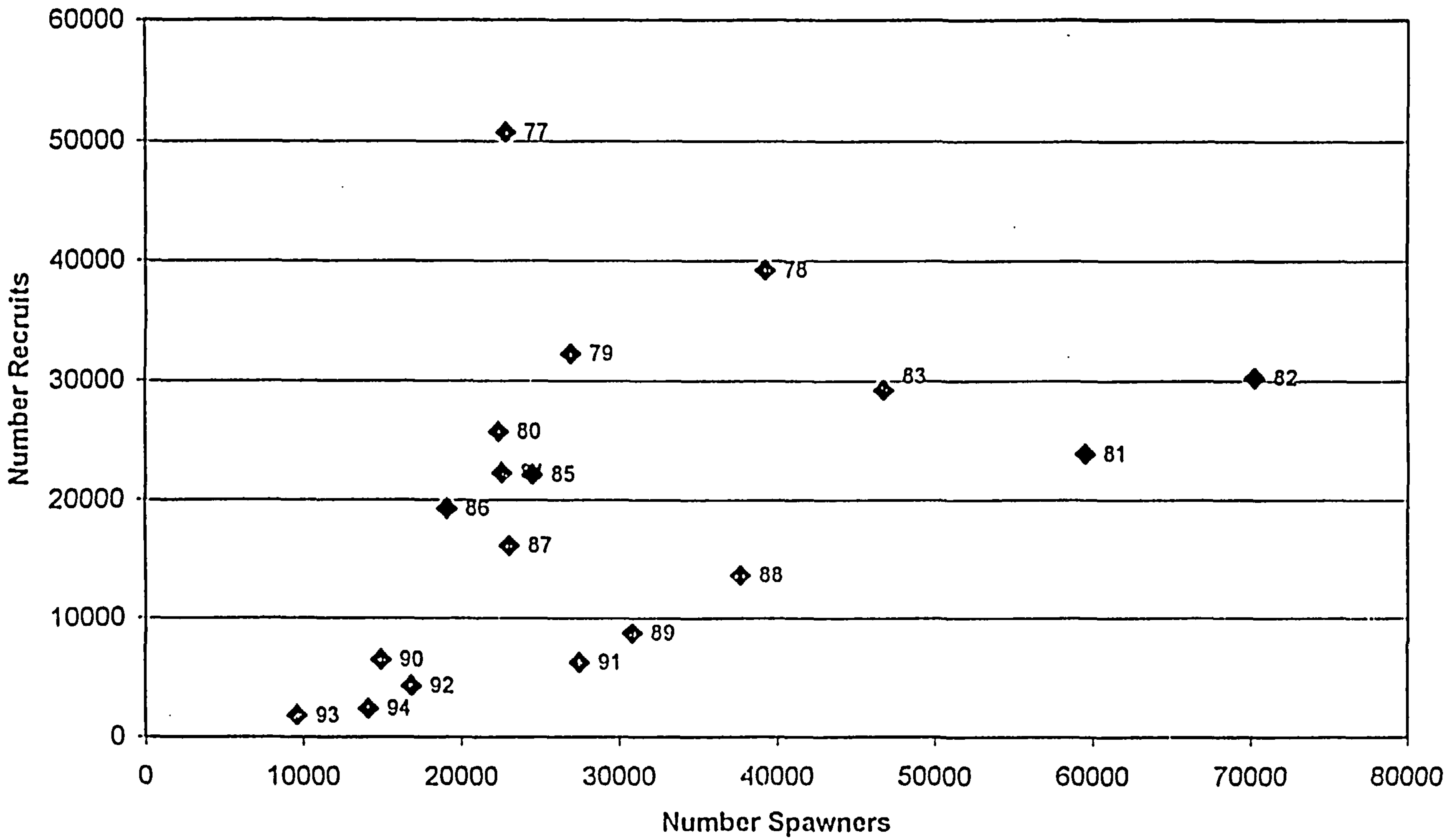

Fig.8- Stock and Recruitment in the Southern New England Winter Flounder Stock from SARC 28 VPA and Survey Data

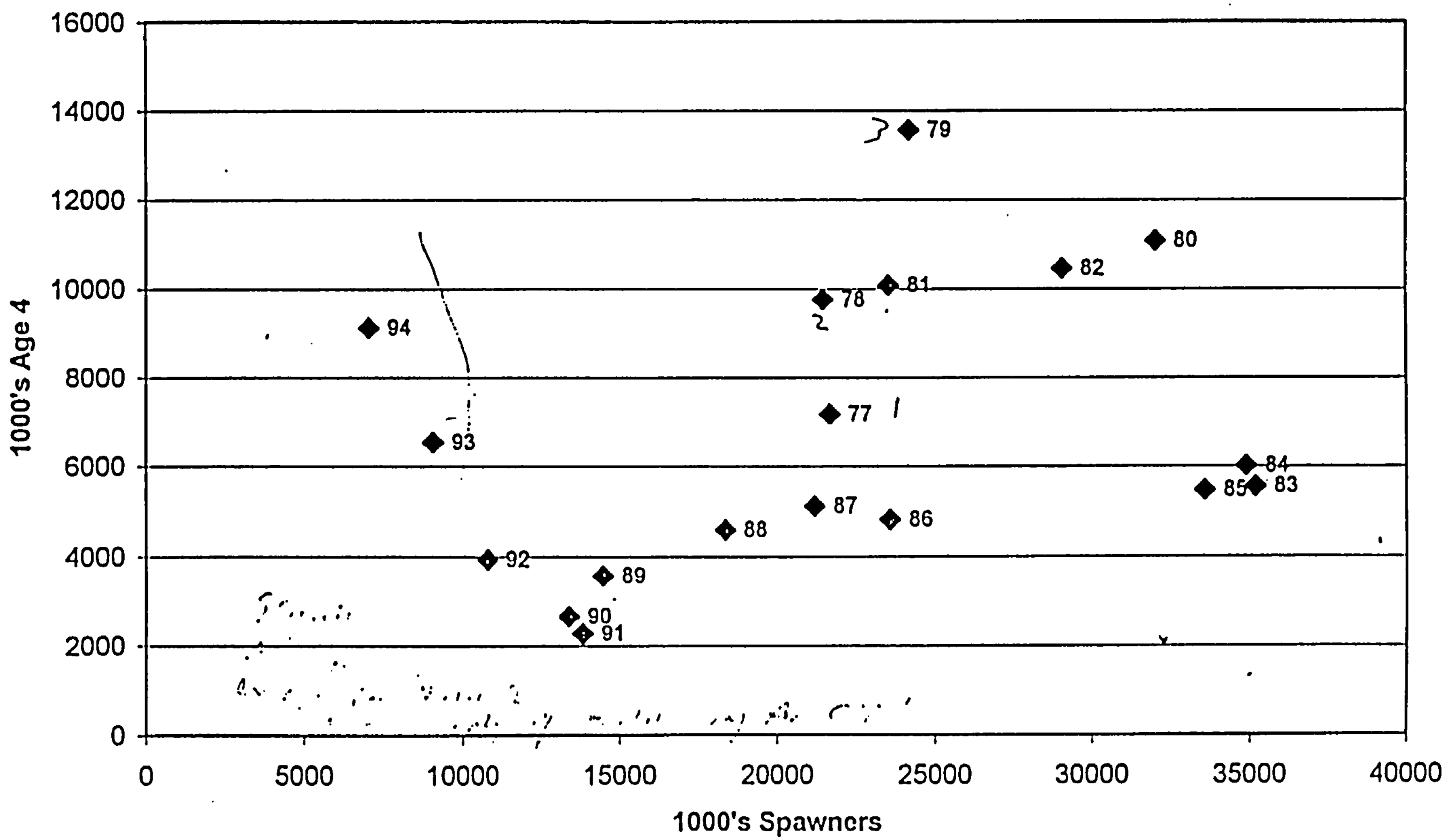

Fig.9- Stock and Recruitment in the Georges Bank Winter Flounder Stock from SARC 28 VPA and Survey Data

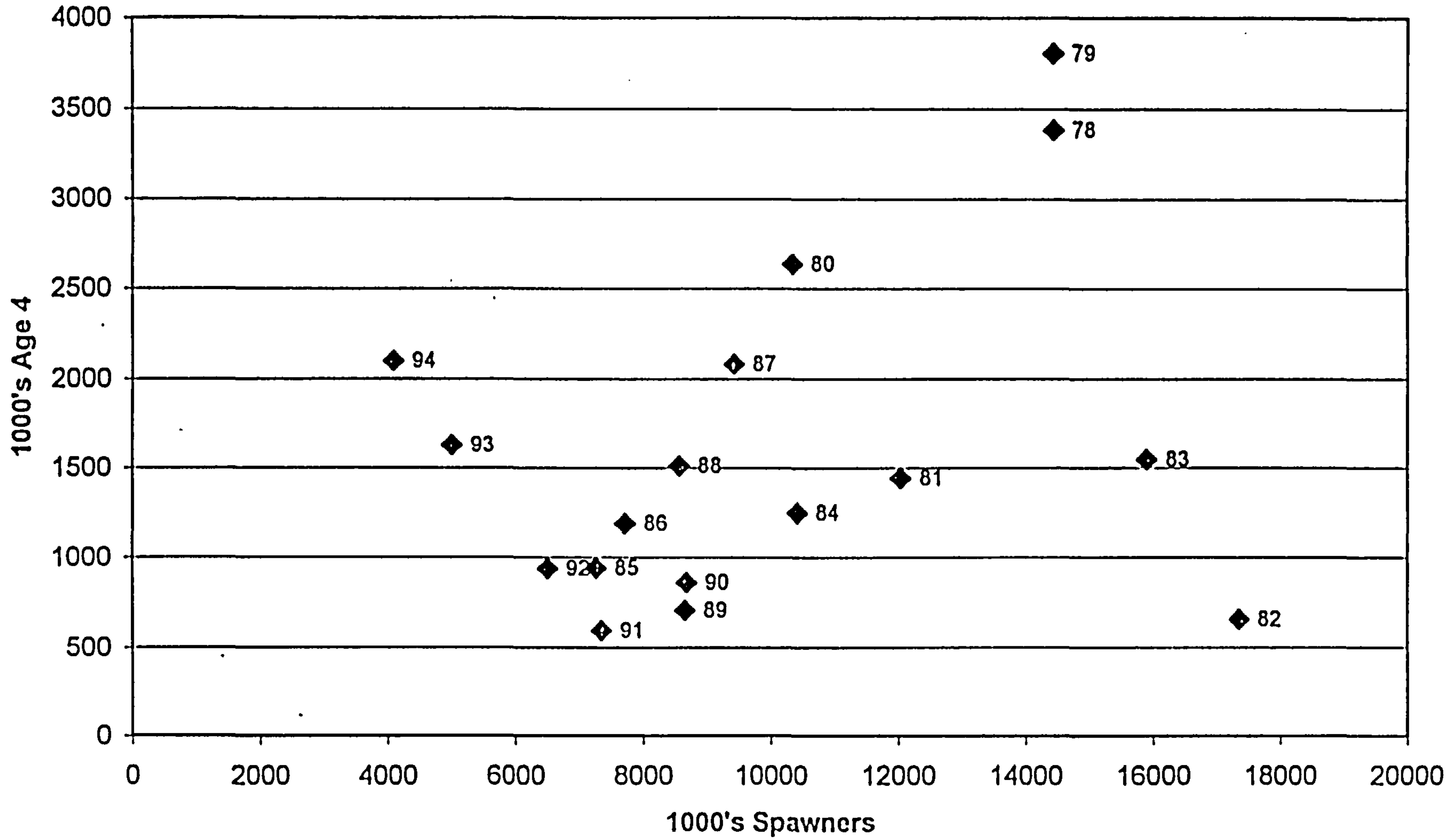

Fig.10- Standardized Recruitment Rates in Several Winter Flounder Populations

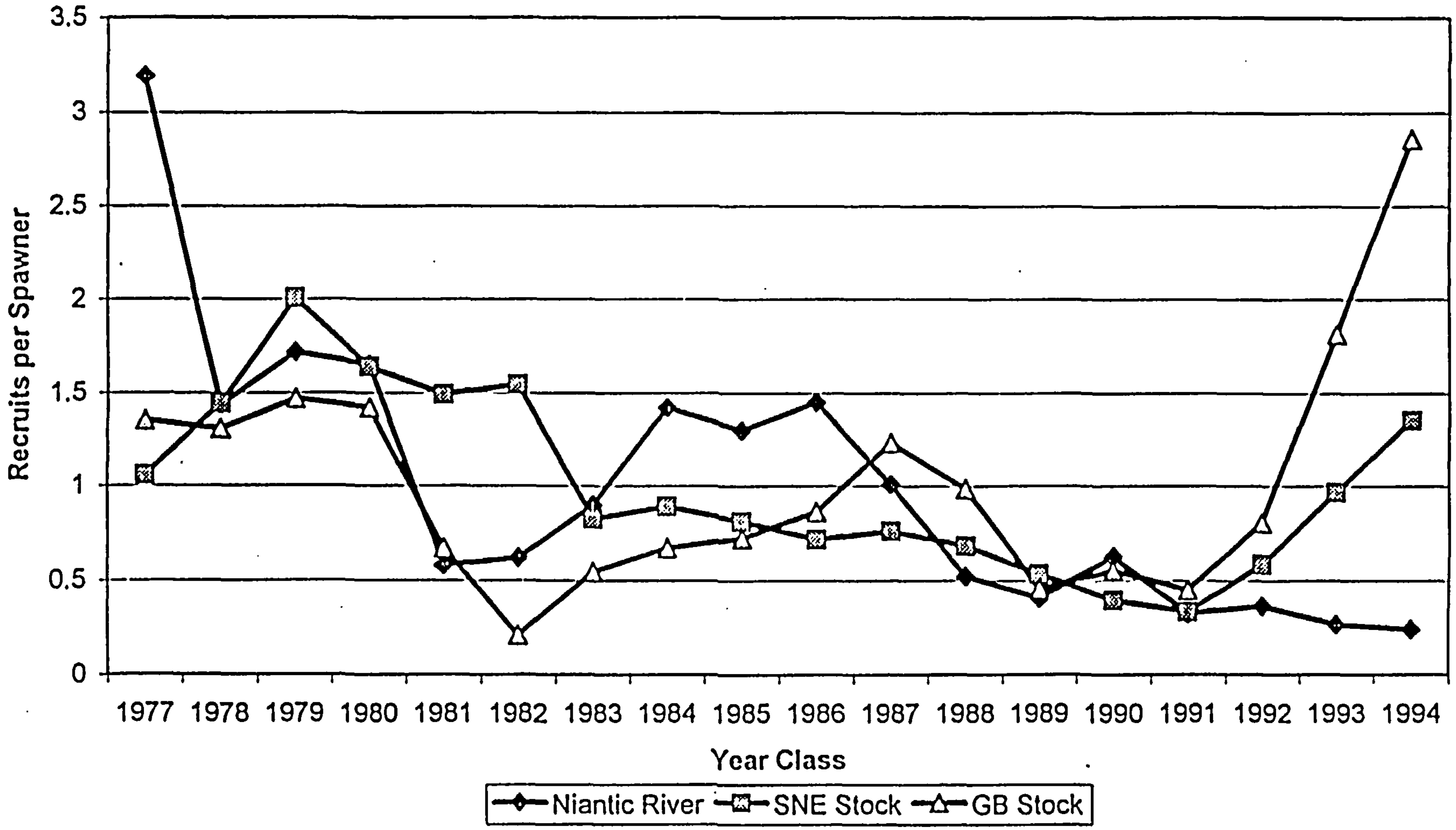

Fig.11- Recruitment Rates of Winter Flounder in SNE Area from State Agency Trawl Surveys

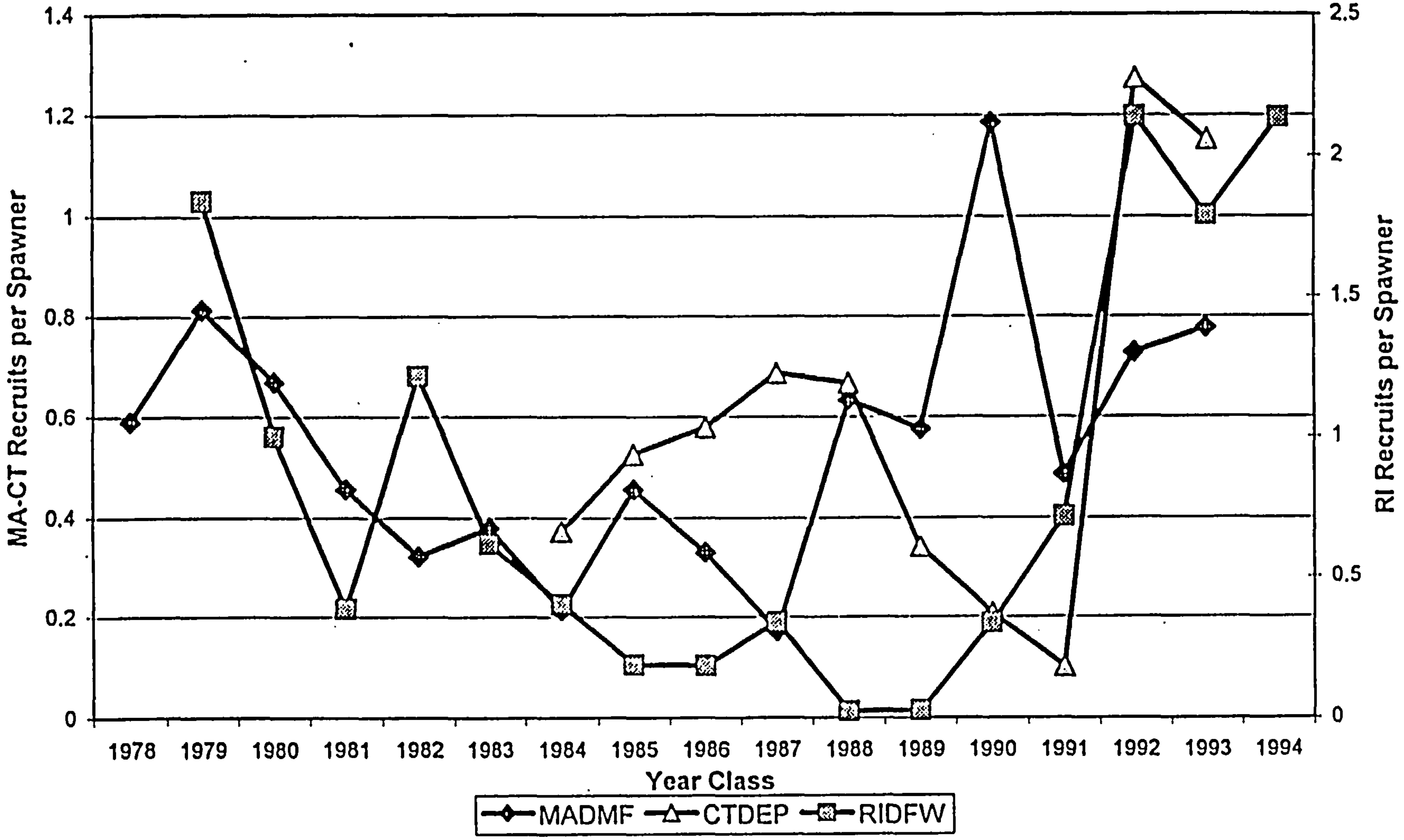

Fig. 12- Bootstrap Frequency Distribution for NUSCo Stock-Recruit Slope Parameter

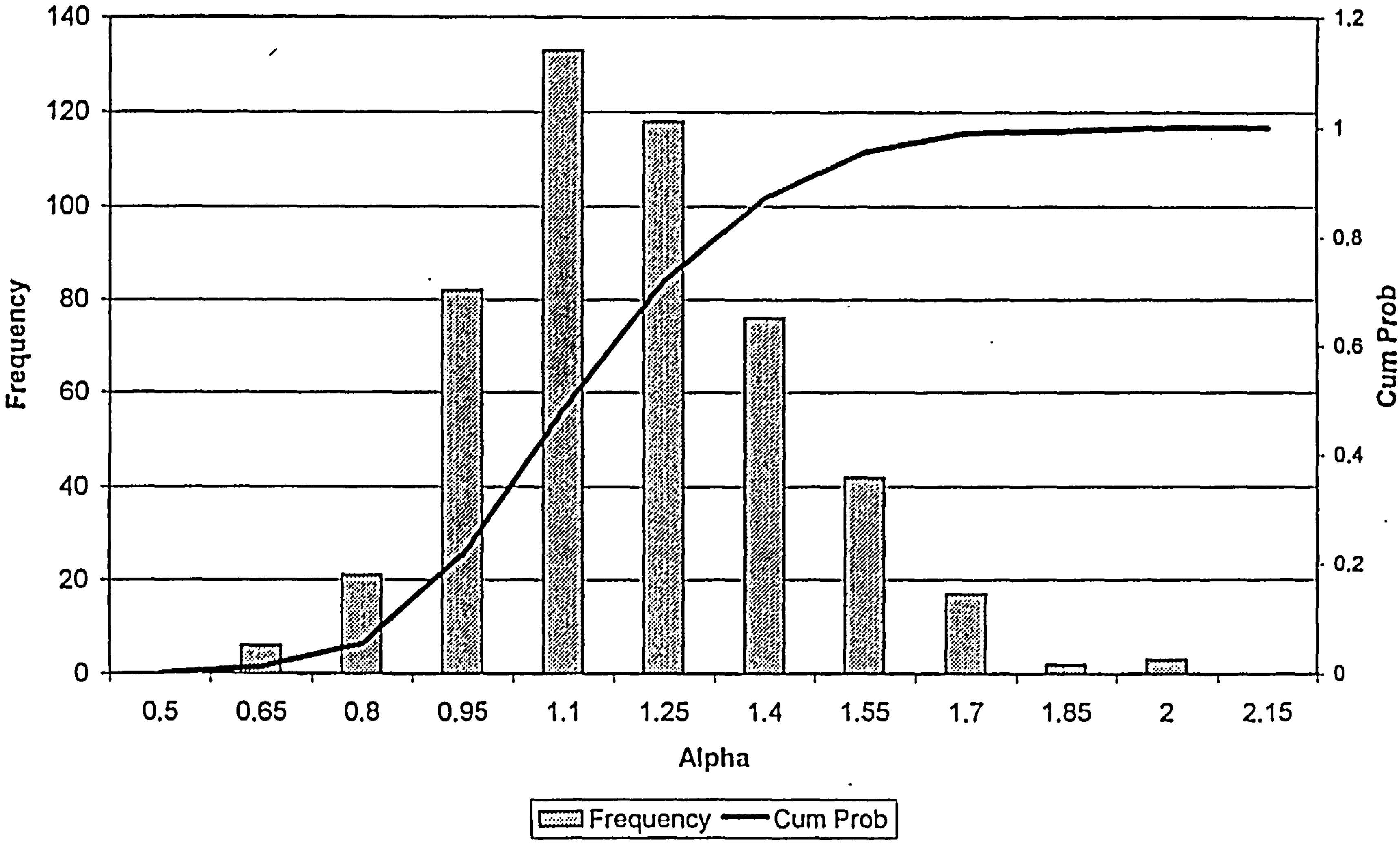

Fig. 13- Bootstrap Distribution for NUSCo Stock-Recruit Compensatory Rate Parameter

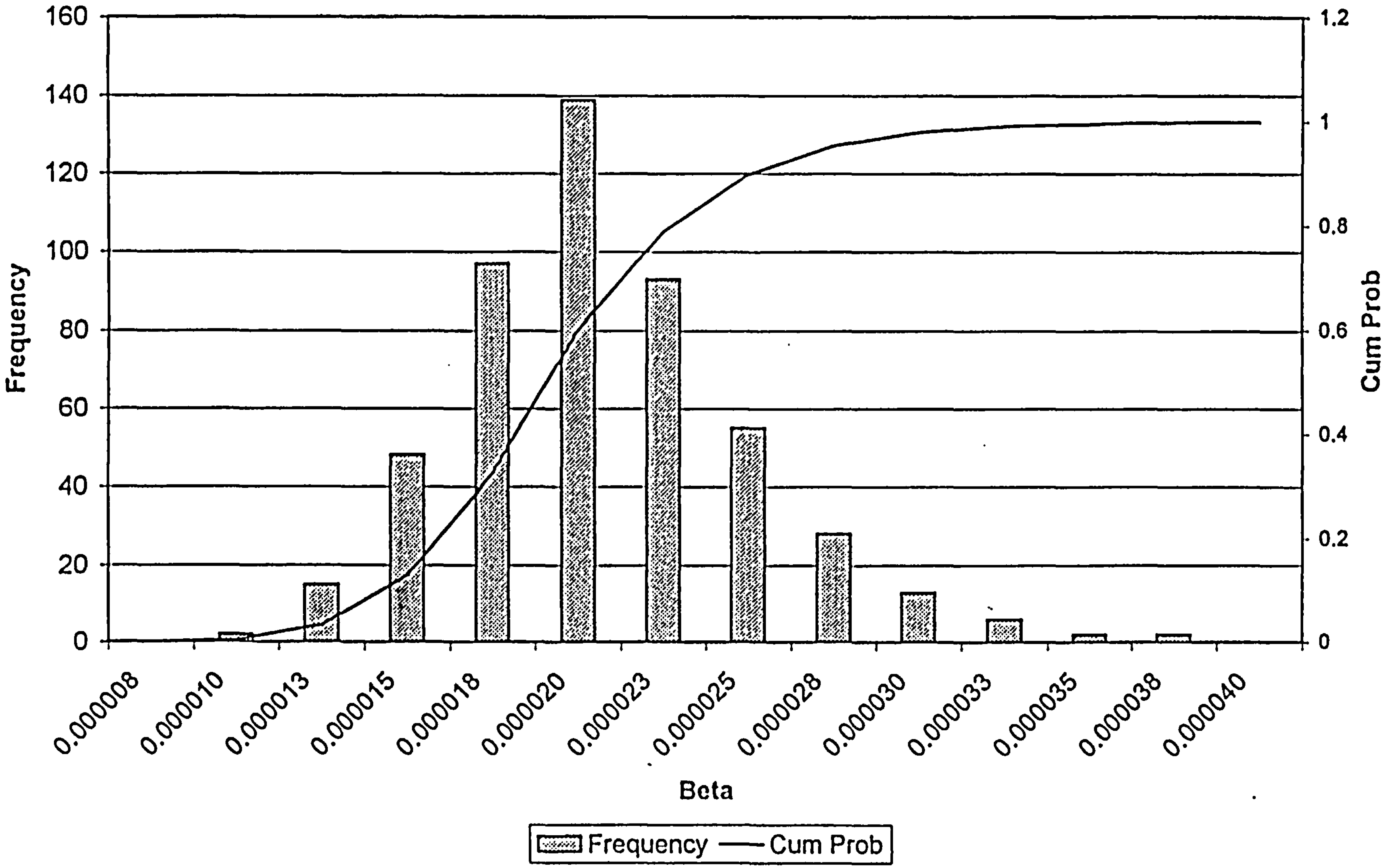

Fig. 14- Bootstrap Distribution for NUSCo Stock-Recruit Water Temperature Effect Parameter

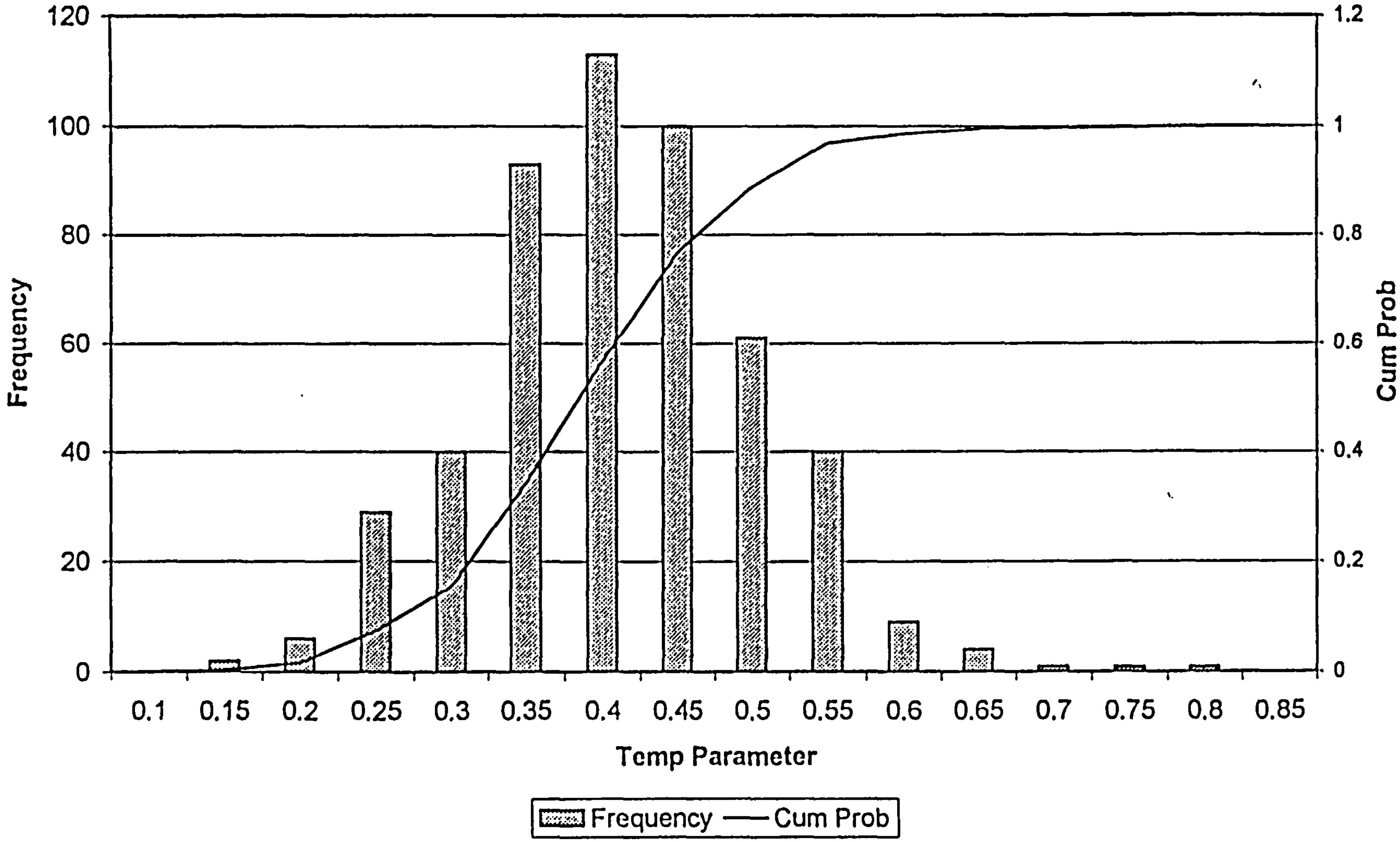

Fig. 15- Observed Winter Flounder Recruitment in Niantic River and Predicted from NUSCo Stock-Recruit Model

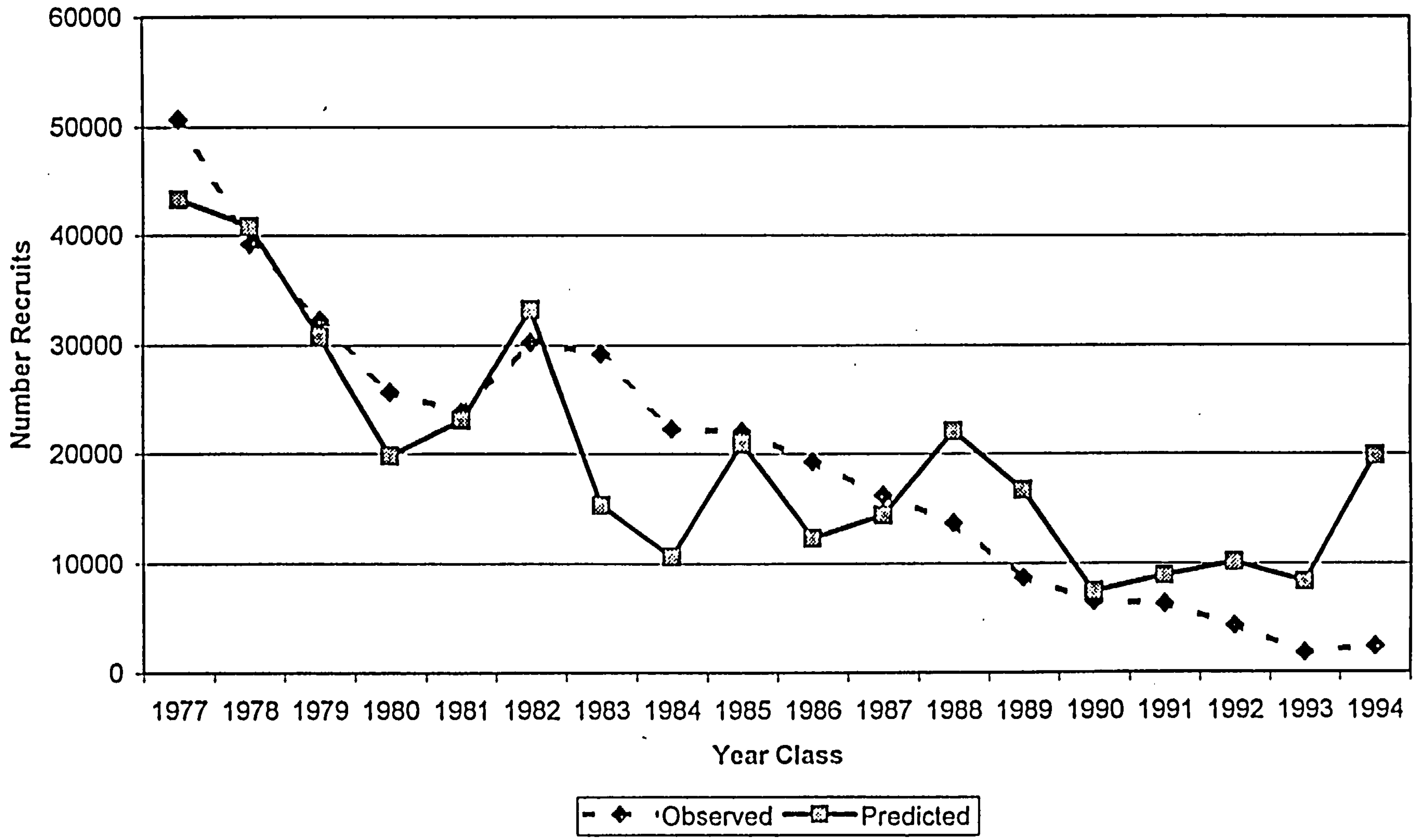

Fig. 16- Time Residual Plot for NUSCo Stock-Recruit Model

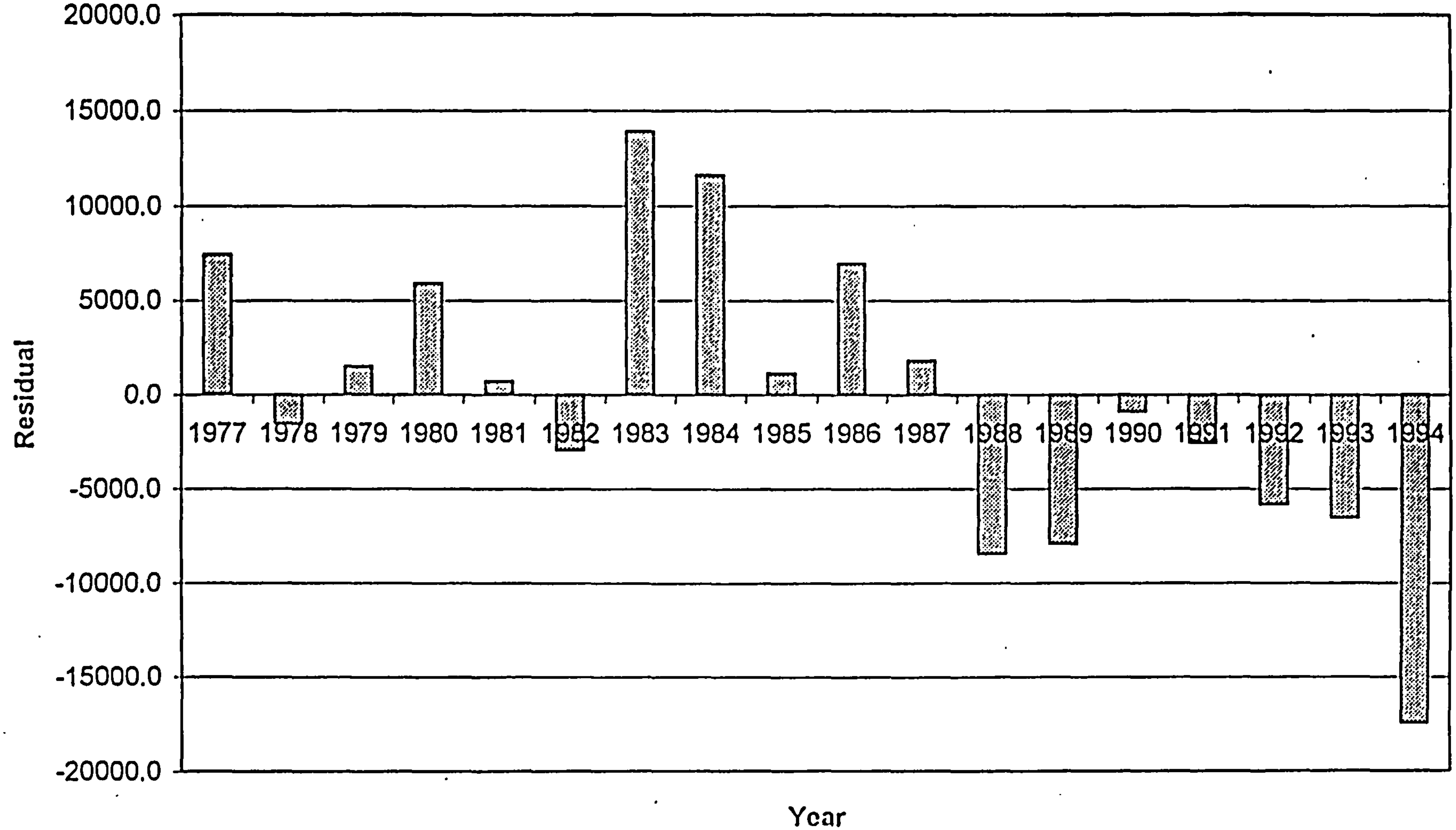

Fig. 17- NUSCo Stock-Recruit Model Residuals vs. Cumulative Cohort F Rate from Age 1 to Age 3

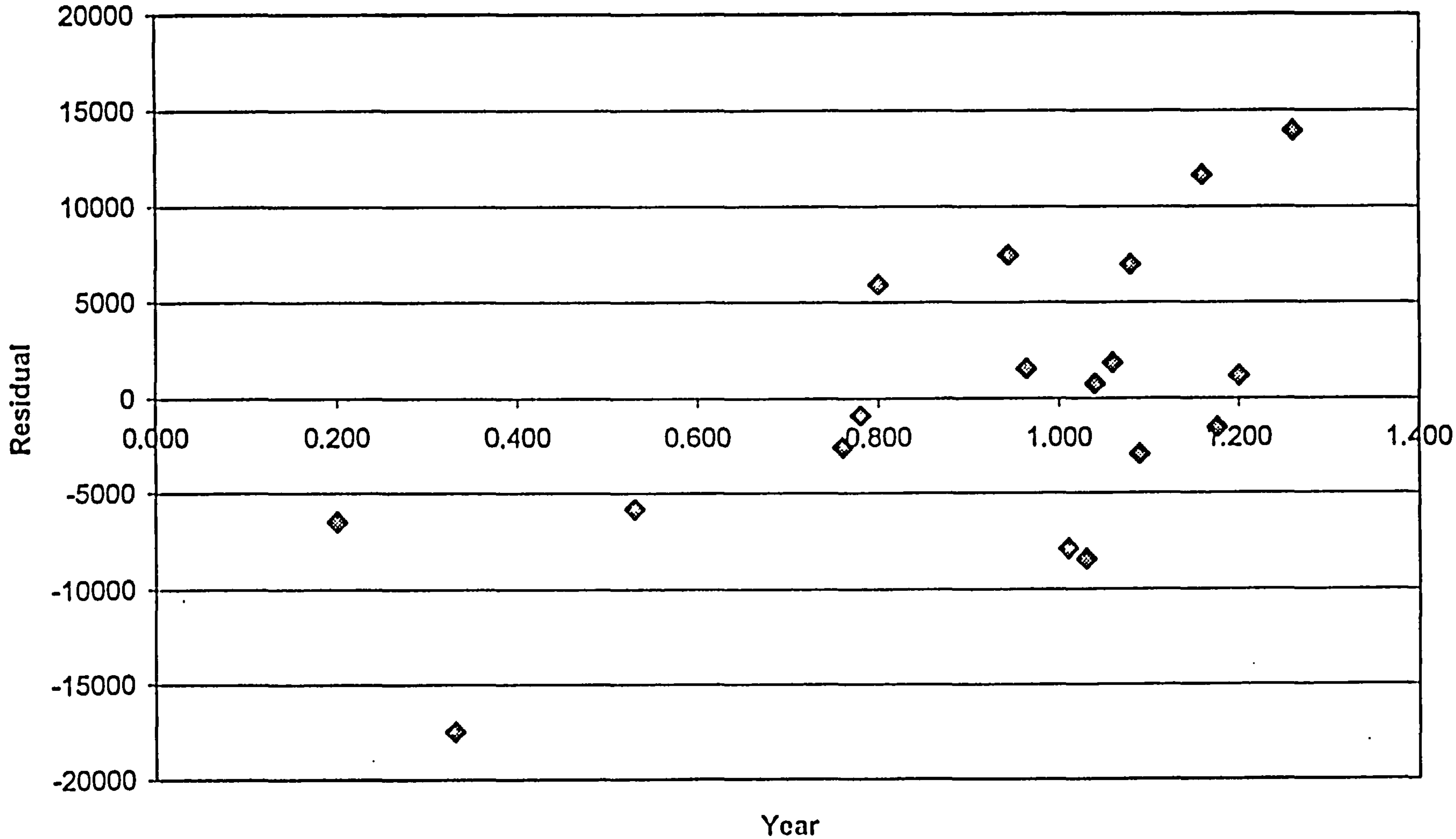

Fig. 18- NUSCo Stock-Recruit Model Residuals vs. Total Station Condenser Coolant Flow

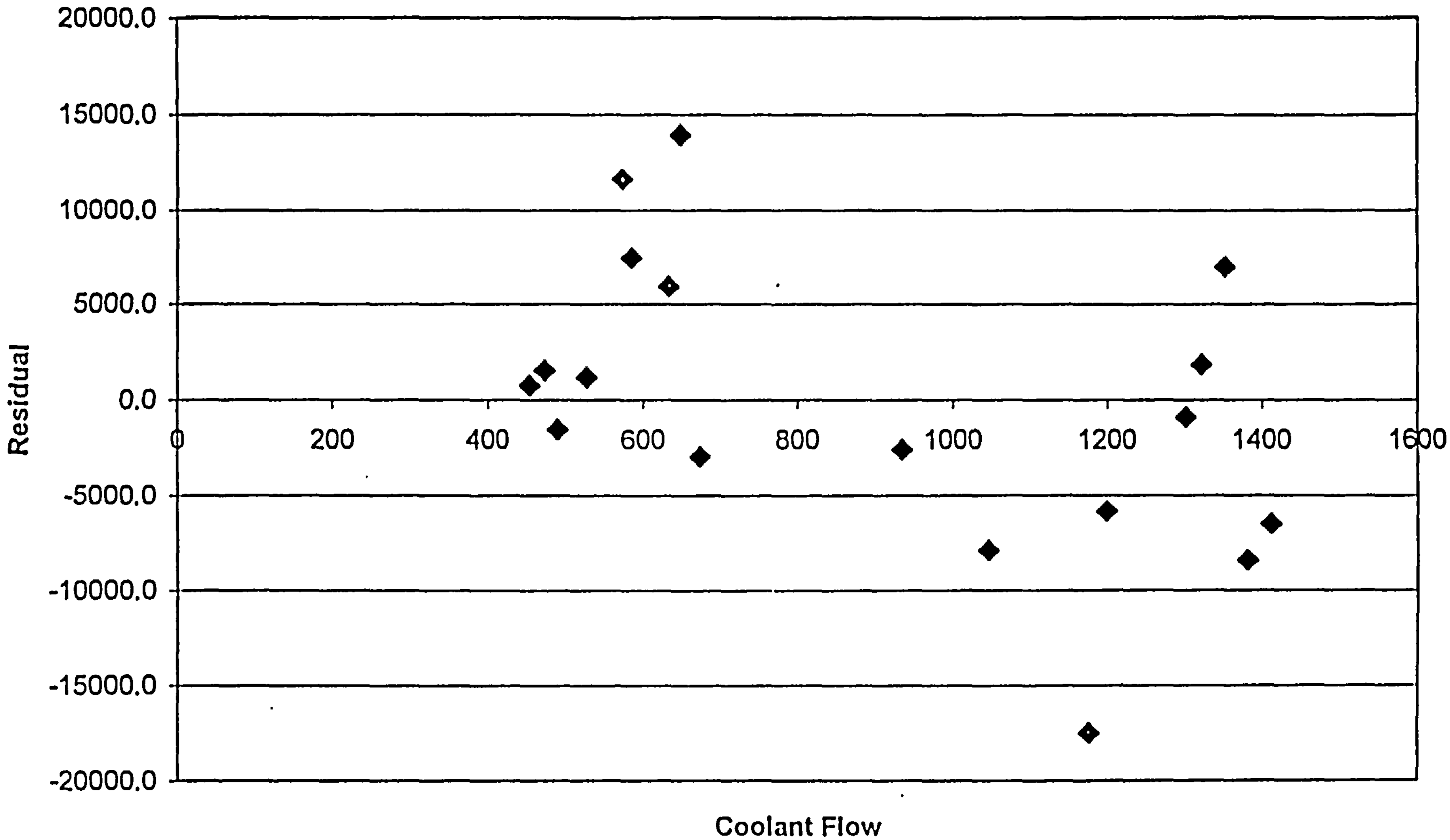

Fig. 19- Trends in NUSCo Stock Recruit Parameters with Respect to Terminal Data Year

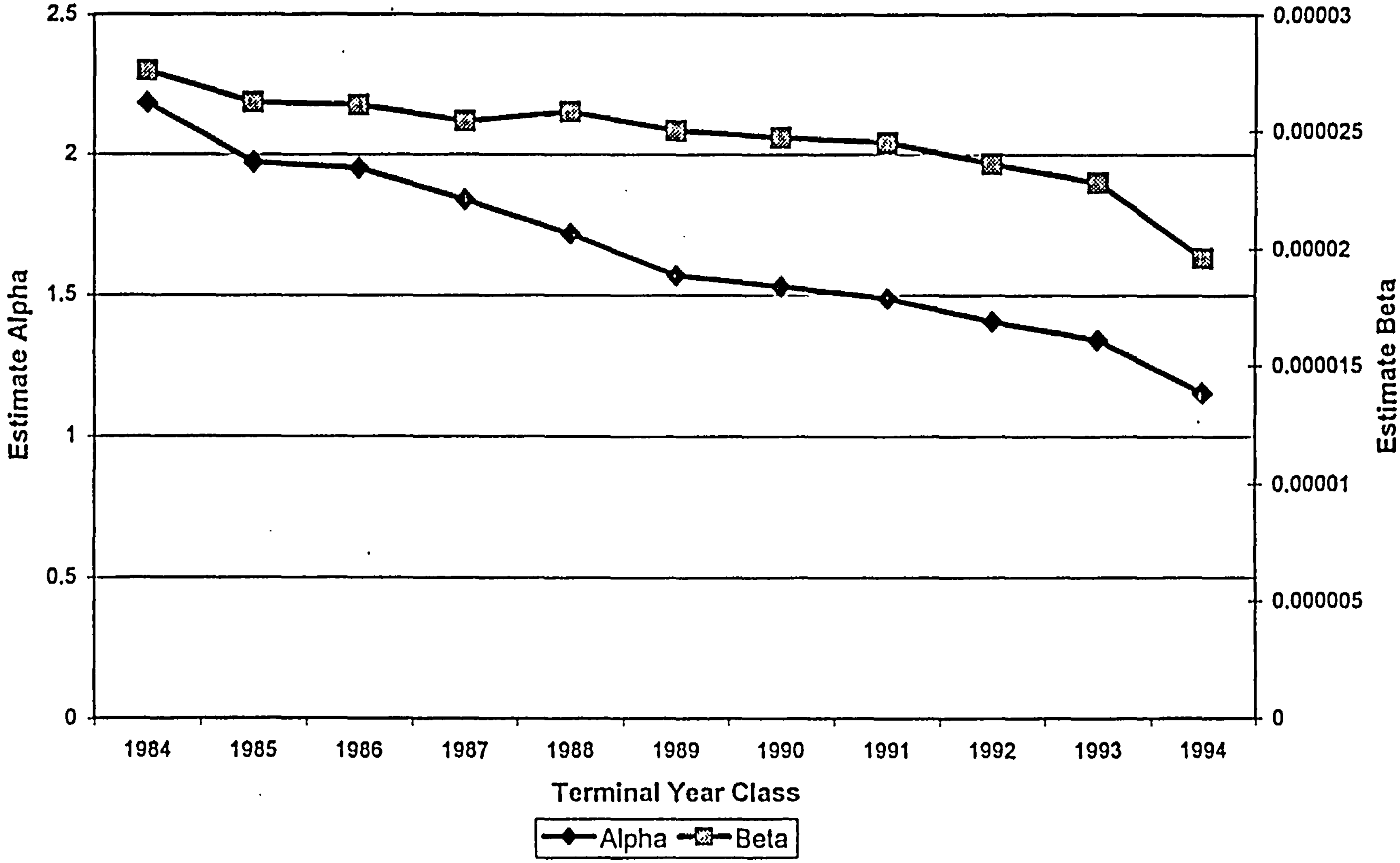

Fig. 20- Bootstrap Frequency Distribution for Gibson Stock-Recruit Model Slope Parameter

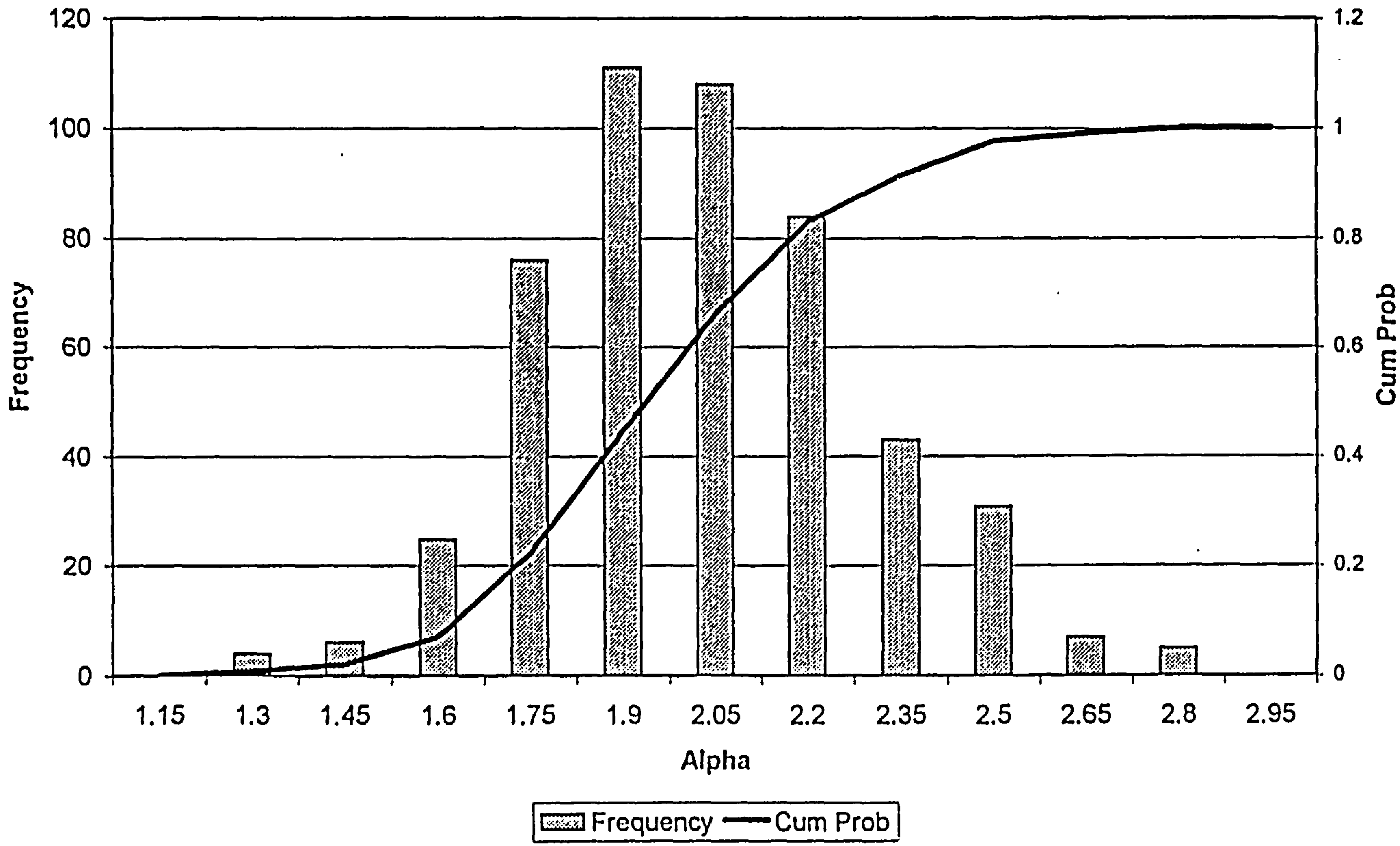

Fig. 21- Bootstrap Distribution for Gibson Stock-Recruit Model Compensatory Rate Parameter

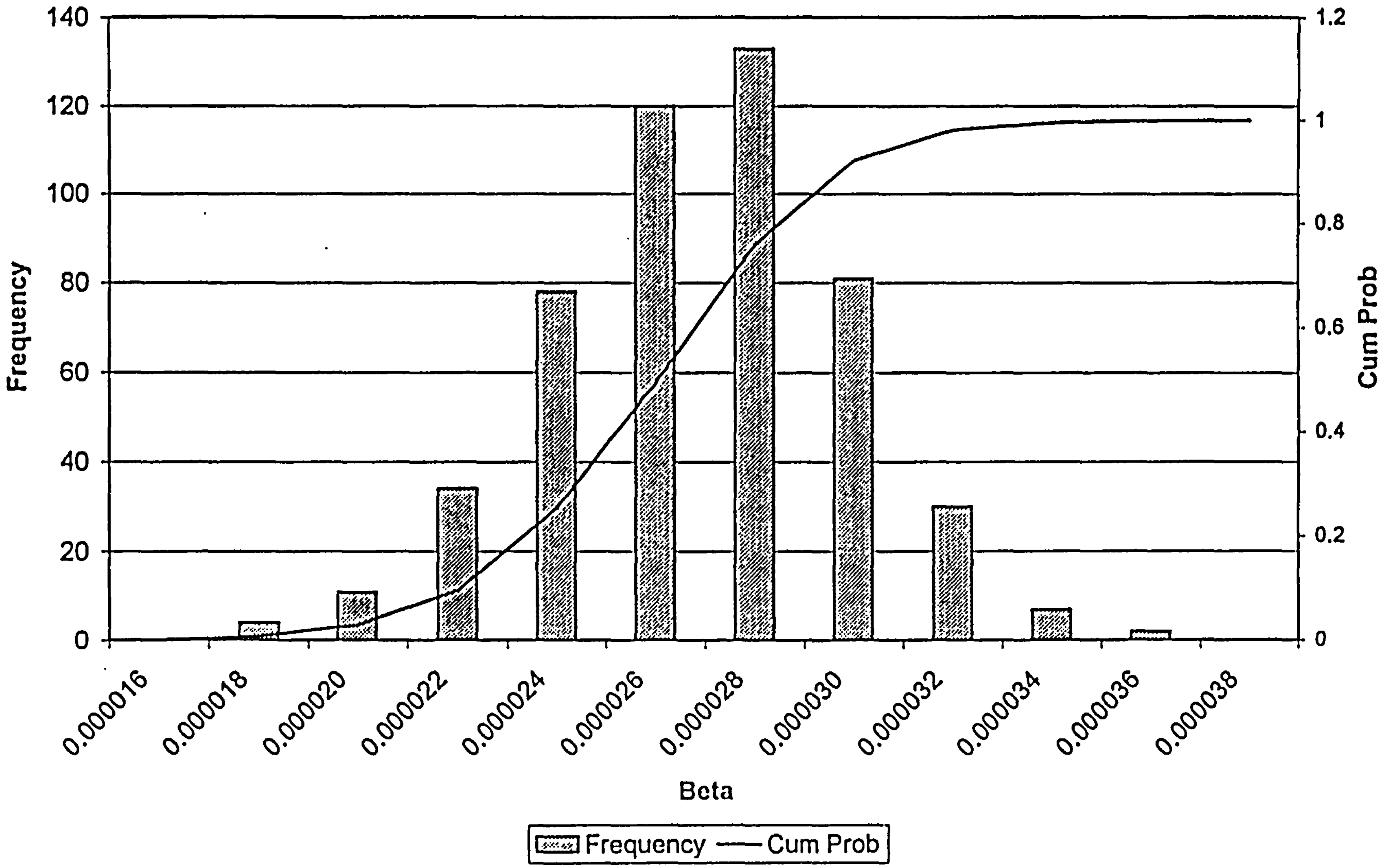

Fig. 22- Bootstrap Distribution for Gibson Stock-Recruit Model Water Temperature Effect Parameter

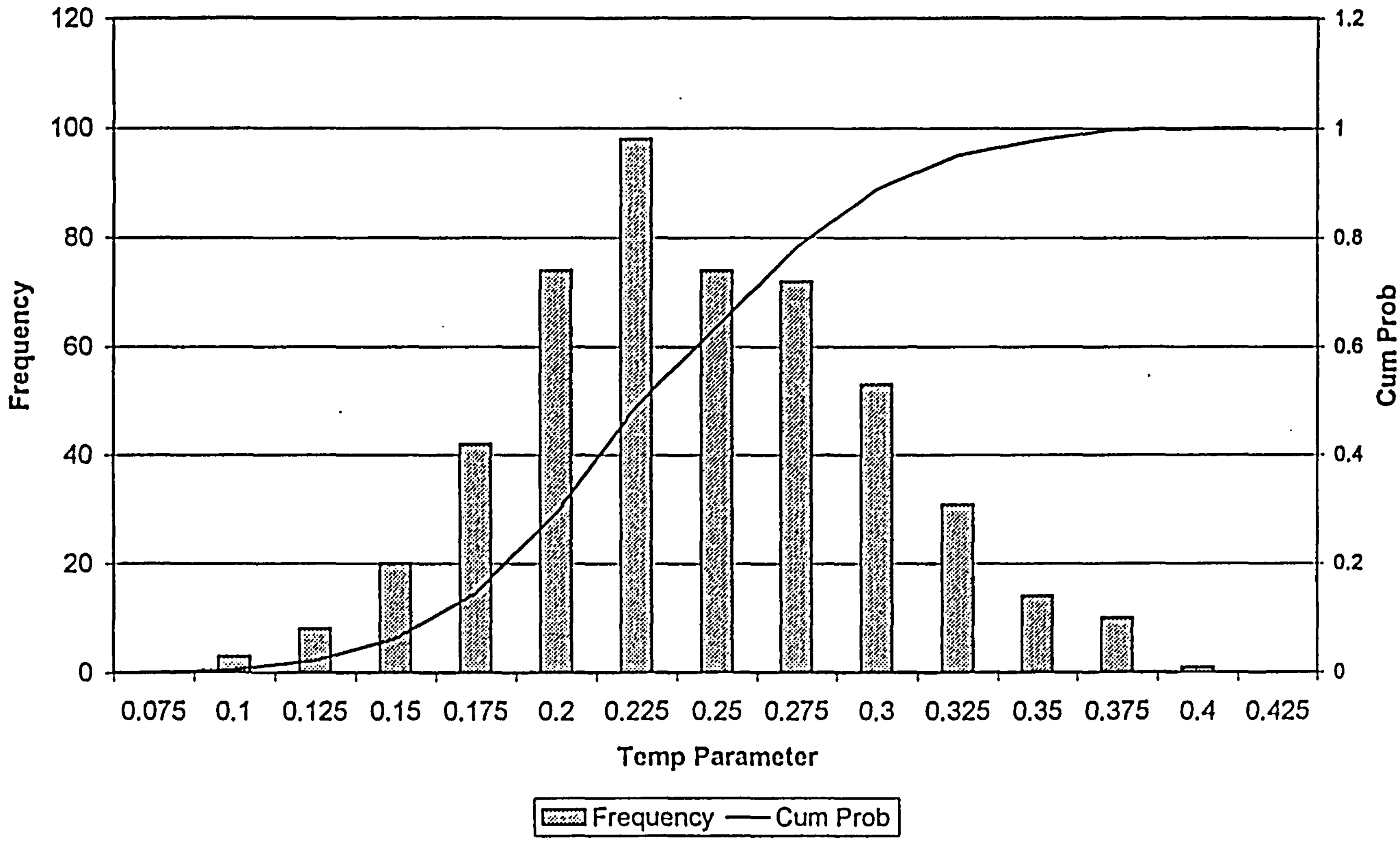

Fig. 23- Bootstrap Distribution for Gibson Stock-Recruit Model
Flow Effect Parameter

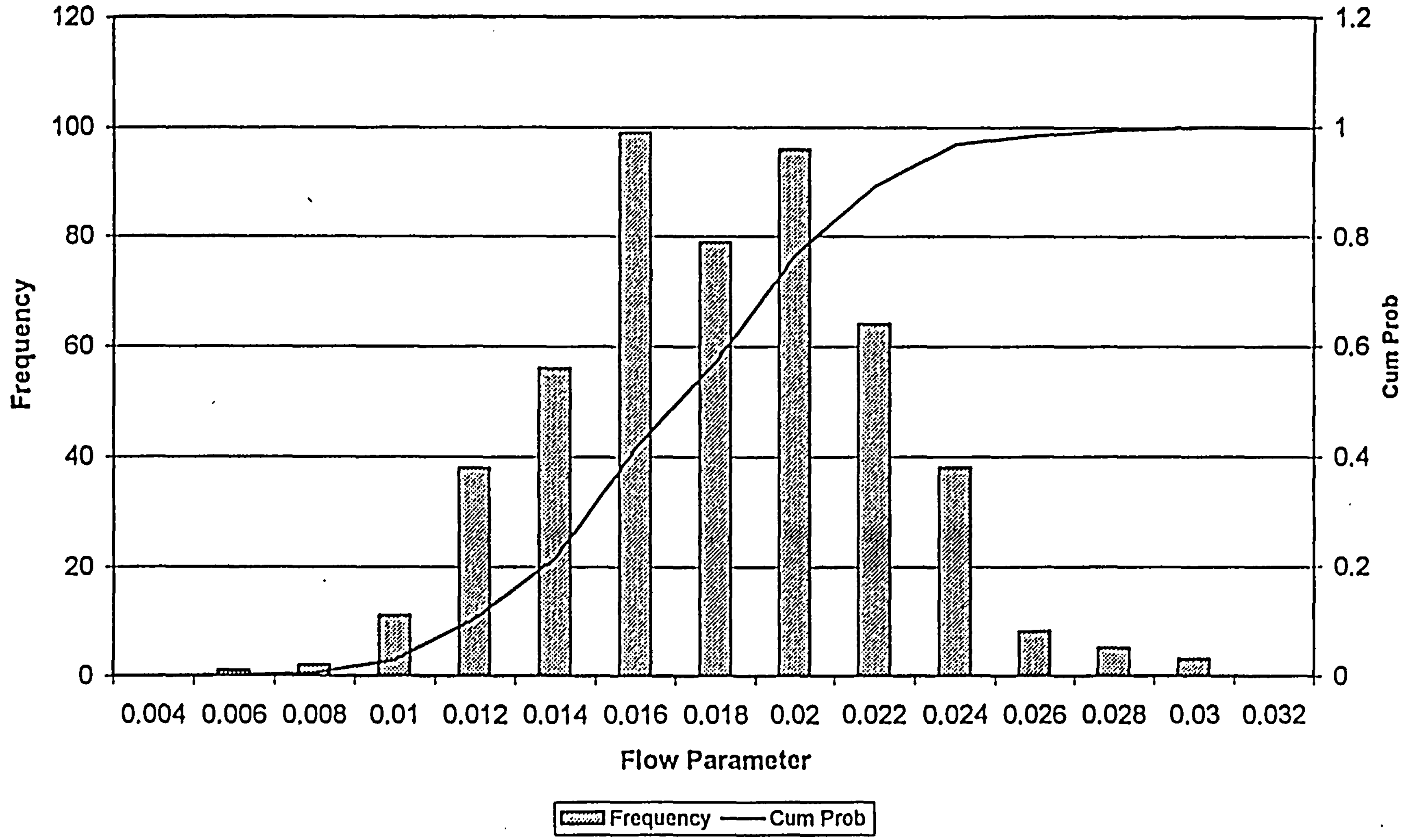

Fig.24- Observed Recruitment and Predicted from Gibson S-R Model

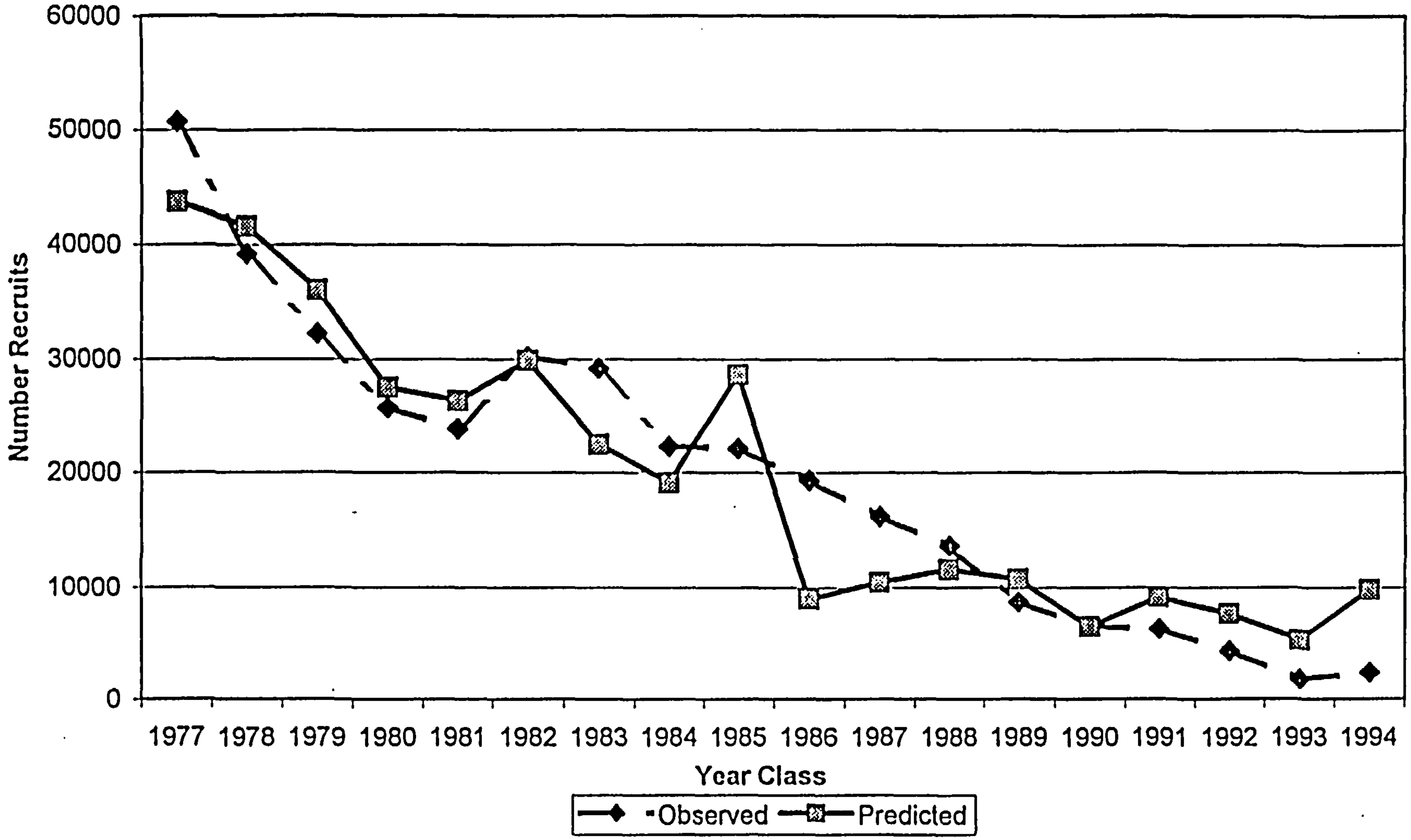

Fig. 25- Residual Plot for Stock-Recruit Model Incorporating Water Temperature and Unit 3 Coolant Flow

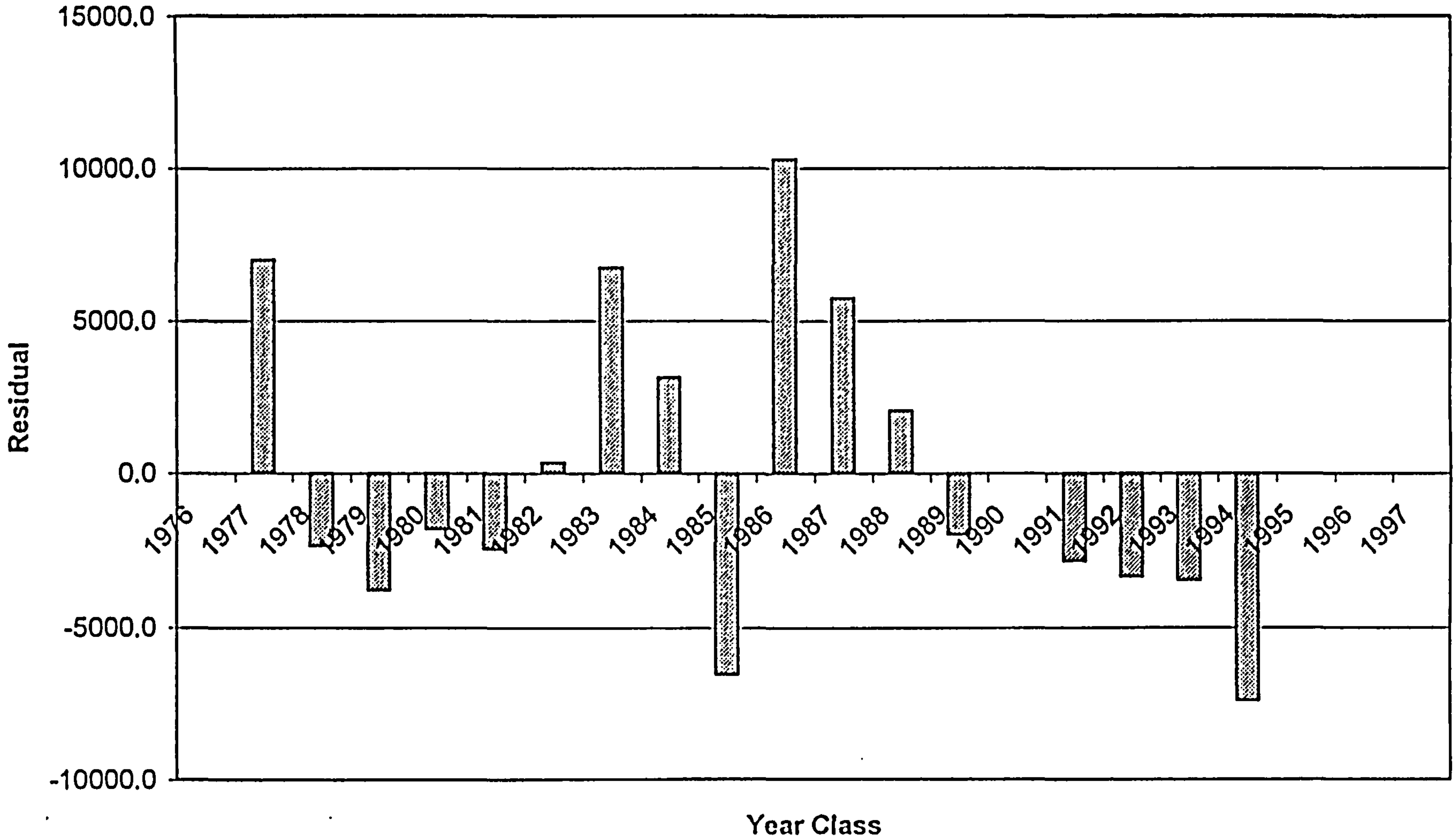

Fig.27- Niantic River Winter Flounder Stock-Recruitment with Extended Data