SPAWNER-RECRUIT ANALYSIS AND EVALUATION OF ESCAPEMENT GOALS

By

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FOREWORD

This report was written at the request of U.S. members of the Pacific Salmon Commission (PSC) Northern Panel to review the U.S. CTC Technical Note 9501, Evaluation of indicator stock escapement goals, January 27, 1995. It was distributed in draft form to the U.S. Northern Panel at the PSC annual meeting, February 1995.

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INTRODUCTION

A goal of the Pacific Salmon Treaty (PST) chinook rebuilding program is to "attain by 1998, escapement goals established in order to restore production of naturally spawning chinook stocks." As 1998 approaches, not only do we need to evaluate whether our indicator stocks have reached their goals, but whether the interim goals specified at the beginning of the rebuilding period are valid maximum sustainable yield (MSY) goals and whether the indicator stocks are indicative of the PST rebuilding program (i.e., are they affected by PST harvest management regimes). Due to different productivities of different stocks, not all stocks in a mixed stock fishery can be maintained at MSY goals (unless effective terminal fisheries exist for each stock); however, lacking multi-stock management goals, MSY goals give us the best measure of stock-specific escapements needed for average maximum production over time. Not all stocks will have enough data to estimate MSY goals from spawner-recruit data, but the process of conducting the analysis and reviewing the data used will provide us with important information on the reliability of the data and the validity of the stock as an indicator stock. With 10 to 13 years of data collection since the beginning of the rebuilding program, additional data does exist to help evaluate both the existing goals and stock specific parameters (e.g., escapement expansion factors, age composition) used in Chinook Technical Committee (CTC) assessments and analyses.

USING THE RICKER FUNCTION

For salmon stocks which spawn once and then die, recruitment has been shown to be a function of the spawning population size and is best modelled using the Ricker relationship of density dependence (Ricker 1954, Hilborn & Walters 1992, see also appendix 1). However, in order to determine this relationship for a given stock, one must have a wide range of spawning population sizes. For a stock that is overexploited or managed for a fixed escapement level, only a limited range of spawning sizes is experienced and the S-R relationship will appear to be scattered and density independent. This does not mean that a Ricker function can't be fitted to the data, but the resulting relationship will have little meaning.

Experience has shown that practical realities of the management and data collecting processes and of natural variability in salmon returns coupled with a blind faith in the MSY S-R relationship can lead to erroneous decisions about fish management (Larkin 1977, Hilborn 1985a, Deriso 1987, Thompson 1992). Walters and Ludwig (1981) have shown that "if density dependence is weak, the effect of observation errors is to overestimate the amount of density dependence. This leads to overexploitation. On the other hand, if density dependence is strong (β is large), then observation errors lead to underexploitation."

However, given sufficient data, the S-R analysis provides us with more productive escapement goals than otherwise might be obtained. And assessing the data for sufficiency provides us with useful information about the stock and our measurement techniques. Some potential problems in fitting Ricker curves addressed by the CTC technical note (US CTC Technical Note 9501) are further addressed here.

Total Escapement: For many of the CTC escapement indicator stocks, index values are used rather than total escapement; this does not affect the rebuilding assessment since it just compares escapement trends over time. However, for use in spawner-recruit relationships, total escapement is needed to relate to total adult recruitment. Total escapement is also needed and used in the CTC model; thus expansion factors, whether valid or not, do exist. These should be identified, reviewed, and either discarded or used in the S-R analyses. It should be noted, however, that by using index escapements coupled with total catches, S-R analysis generates a higher escapement goal (resulting in more conservative management actions) than if the total escapements were used (see Upper Georgia Strait example below).

Age Specific Escapement: Age composition data is important for chinook stocks for which annual returns are composed of several age classes. When age specific data is not available for a wild stock, estimates of age composition from a nearby or associated hatchery stock is often used. How good these estimates are depends on how well the hatchery stock represents the behavior of the wild stock.

Cohort Size: The cohort size of a stock can be determined by estimating stock specific catch of the stock and adding it to the escapement or by estimating the exploitation rate and dividing the escapement by one minus the rate. In either case, the parameters for the wild stock are usually estimated from a tagged associated hatchery stock. Again, how good these estimates are depends on how well the hatchery stock represents the wild stock. The estimates used in the CTC model should be reviewed and, if deemed adequate for the model, used in the S-R analyses.

A Narrow Range of Escapements: As mentioned above, this is a serious problem in trying to determine if a density dependency exists. Management efforts should be made to get a range of escapements. However, some simulations may be run adding some theoretical points to see what the resulting range of S-R parameters might be. This is done for the four example stocks below. In general, the Ricker a parameter (productivity parameter) does not change much and is all that is needed to determine what the MSY exploitation rate is. This is the exploitation rate that sustains the population when it is as MSY levels. If the stock is currently overexploited, a lower rate is needed to bring the population up to MSY levels.

A Limited Number of Observations: For most of our CTC indicator stocks we should have at least 15 years of data (escapement data is reported from 1975). Efforts should be made to determine if agencies have a longer time series of data for their stocks.

Autocorrelation: The autocorrelation bias of spawner-recruit linear regression analysis is recognized, but is minimized if the number of observations is large over the whole range of escapement levels. With our limited amount of data, residuals should be tested for autocorrelation and time-bias.

Measurement Error: Large measurement error in the data can result in either spurious fitted relationships or no fitted relationships where a relationship does exist. This usually results in underestimating the MSY level and has led to depletion of stocks more than once Hilborn and Walters (1992) warn us.

Ludwig and Walters (1981) present a method for accurately estimating average S-R parameters and spawning stock sizes in the presence of substantial measurement error. To conduct the analysis, a correction term must be estimated; the correction term is based on the ratio of the error in measuring spawners (escapement) and/or recruits to the noise (μ) in the Ricker equation. Here, the authors assume that the measurement error for recruits and spawners are the same since recruitment is estimated as catch plus escapement and catch is measured with little or no error. In cases of mixed stock fisheries where one must determine stock-specific catches[2], error in estimating the number of recruits is often much larger than that for estimating spawners. Since it is difficult in practice to make a priori estimate of how biased an analysis will be, one should appraise the reliability of escapement and catch measurements prior to conducting a S-R analysis (Hilborn and Walters 1992, p288).

In general, S-R analyses, especially for those with potentially overexploited populations, should not be relied on unless the spawning stocks have been measured "accurately". Walters and Ludwig (1981) suggest measurement errors be less than ± 30%; they also suggest that, at least for salmon stocks in British Columbia, escapements are seldom measured with such accuracy. If the escapement estimates are not adequate for S-R analysis, then they are probably not adequate for measuring rebuilding either and efforts should be made to improve the escapement estimates.

EVALUATING ESCAPEMENT GOALS, FOUR EXAMPLES

The four examples that ADF&G put forth to the Chinook Work Group were initial analyses that demonstrate the usefulness of conducting such reviews in helping to understand the response of the stocks to the rebuilding program. When conducting the polished or final analyses, the best information available from the agency responsible for the stock must be used to reduce errors in escapement and catch estimates, such as inclusion of hatchery strays or use of index rather than total abundance estimates. As such errors are found, they should be corrected in the CTC escapement assessment and model analysis (the model uses expansion factors for all index escapements).

The following analyses use the same spawner-recruit data in the original ADF&G analysis, but explores the behavior of the relationships with the intent of demonstrating sensitivity of the estimates. The escapement goals presented here are not meant to be the suggested new escapement goals for the stocks but are rather the first step in analyzing the data and examining potential problems with the data and/or analyses. A standard Ricker analysis was conducted and compared to an analysis incorporating the error

[2] This is usually estimated as the product of a stock composition estimate and total catch. In the case of chinook salmon, stock composition estimates are usually based on coded-wire-tag data.

term (see Appendix 1) of R on S. This adjusts the Ricker parameters for the bias inherent in the wide range of returns observed for given S levels due to marine survival. Additional analyses were conducted introducing a fabricated data point at the far range of escapements (near the replacement level, where R=S, in the original analysis) to test the sensitivity of the MSY goal and exploitation rate estimates.

Columbia Upriver Bright (Figures 1 and 2): This stock is classified as above goal and has had a wide range of spawning levels over the years included in the S-R analysis. The escapement estimates are probably fairly reliable. The resulting MSY escapement goal (46,589 from standard fit and 51,541 incorporating the error bias) is close to the current escapement goal (40,000) for this stock. The recruits resulting from approximately 25,000 to 50,000 spawners varies greatly, indicating, perhaps, widely fluctuating marine survival. A time-bias is apparent when years are attached to the data points. The three highest returns correspond the brood years with the highest survival (1982-1984) (see survival graph appendix I of CTC 1993 annual report). However, there is also evidence of nonstationarity: the clump of points in the lower left hand corner represent the years 1975-1979 when survival was "average", and the points to the right of 90,000 spawners (which describe the overcompensation or decrease in returns with larger spawning population) all occurred from brood years experiencing very low survival. The shape of the curve might have been quite different if marine survival had been higher during the years following the 1985-1989 broods. Since there are several observations for large spawning sizes, adding an additional point does not change the goal a lot.

Columbia Upriver Bright	Standard Analysis		Adjusted for Error Term	
Analysis	Goal	Expl.Rate	Goal	Expl.Rate
Observed Data	46,589	73%	51,832	82%
Added S= 120,000 R= 100,000	44,771	74%	49,429	82%
Added S= 120,000 R= 400,000	52,999	80%	59,449	80%

Upper Strait of Georgia (Figures 3 and 4): This stock is classified as Indeterminate due to the widely fluctuating returns during the rebuilding period. While this stock has a wide range of spawner levels, only two points describe the overcompensation in the relationship. The returns off spawning levels of 4,000 to 6,000 chinook vary greatly. The data points that describe the overcompensation for this stock occurred for brood years whose survival rates were both low (1975) and high (1976). The analysis shows that the productivity of both the Columbia Upriver bright and Upper Strait of Georgia stocks should support, on average, around 73-74% exploitation rate. The MSY goals determined from the S-R analyses for both these stocks are similar to existing goals. Since the escapements for this stock are known to be index estimates rather than total estimates, an additional analysis was done doubling the escapement (and increasing recruits by same increment assuming the catch estimate is correct) to test the difference in the resultant goal and exploitation rate (the true expansion should be discovered and used). Changing to total escapement actually allowed us to reduce the escapement goal from the original 5,816*2 = 11,632 to 9,242 in the standard analysis; however the exploitation rate decreases from 74% to 63%.

Upper Strait of Georgia	Standard Analysis		Adjusted for Error Term	
Analysis	Goal	Expl.Rate	Goal	Expl.Rate
Observed Data	5,816	74%	6,003	77%
Added S= 20,000 R= 15,000	6,040	74%	6,225	76%
Added S= 20,000 R= 60,000	9,339	69%	9,797	73%
Doubling escapement	9,242	63%	9,660	66%

West Coast of Vancouver Island (Figures 5-8): This stock is classified as Not Rebuilding. Basically, the stock has shown no response to the rebuilding program. The range of spawning escapements for this stock is not as great as desired for the S-R analyses; there are few points at the high end of the range suggesting that it could be overexploited. The presence of just one point at the high range of the spawning escapements could change the estimated MSY goal significantly depending on the return size (see table). The 1983 brood year experienced an near complete failure in returns. It could be argued that this was a rare event and should not be included in determination of the Ricker curve. An analysis omitting this point results in a low escapement goal that is almost certainly an underestimate due to the limited range of data. For this stock, one must decide what can be done to get some high spawning levels so that a MSY goal can be determined in the future. At the moment, it would not be wise to depend on S-R analysis to determine the goal or exploitation rate.

West Coast of Vancouver Is.	Standard Analysis		Adjusted for Error Term	
Analysis	Goal	Expl.Rate	Goal	Expl.Rate
Observed Data	6,941	86%	7,118	88%
Added S= 20,000 R= 15,000	5,427	88%	5,516	89%
Added S= 20,000 R= 60,000	9,528	84%	9,839	87%
Observed Data minus '83 death brood	5,308	89%	5,329	89%

Big Qualicum (Lower Strait of Georgia) (Figures 9-10): This stock is classified as Not Rebuilding and has also showed no response to the rebuilding program. The range of spawning escapements for this stock is not as great as desired for the S-R analyses; again, there are few points at the high end of the range, suggesting overexploitation. The presence of just one point at the high range of the spawning escapements could change the estimated MSY goal significantly depending on the return size (see table). For this stock, one must decide what can be done to get some high spawning levels so that a MSY goal can be determined in the future. At the moment, it would not be wise to depend on S-R analysis to determine the goal or exploitation rate.

Big Qualicum	Standard Analysis		Adjusted for Error Term	
Analysis	Goal	Expl.Rate	Goal	Expl.Rate
Observed Data	6,266	83%	6,384	85%
Added S= 20,000 R= 15,000	5,823	84%	5,914	86%
Added S= 20,000 R= 60,000	9,145	78%	9,429	80%

CONCLUSIONS

Care must be taken in employing S-R analysis with stocks with limited data; the tendency is to underestimate the escapement goal and overexploit the stock. On the other hand, Hilborn and Walters (1992) also recount the incident when the spawner-recruit analysis was discarded in favor of one high return observed from one high spawner level in determining the escapement goal for Rivers Inlet sockeye salmon which resulted in deprived catch levels over what now appear to be sustainable. As many of the existing chinook escapement goals were derived from the highest return observed in some past record of data, we could be causing ourselves the same problem if we continue to use these goals as target goals rather than the upper limit of a range of levels to obtain in order to improve our database for the spawner-recruit analysis.

In the face of large uncertainty in the spawning data, it is generally accepted that managers should either allow great flexibility in escapements in order to gain more knowledge of resulting returns or, perhaps better yet, employ more accurate counting procedures to reduce measurement error and noise in the model fit (Ludwig and Walters 1981, Walters 1986, Hilborn and Walters 1992).

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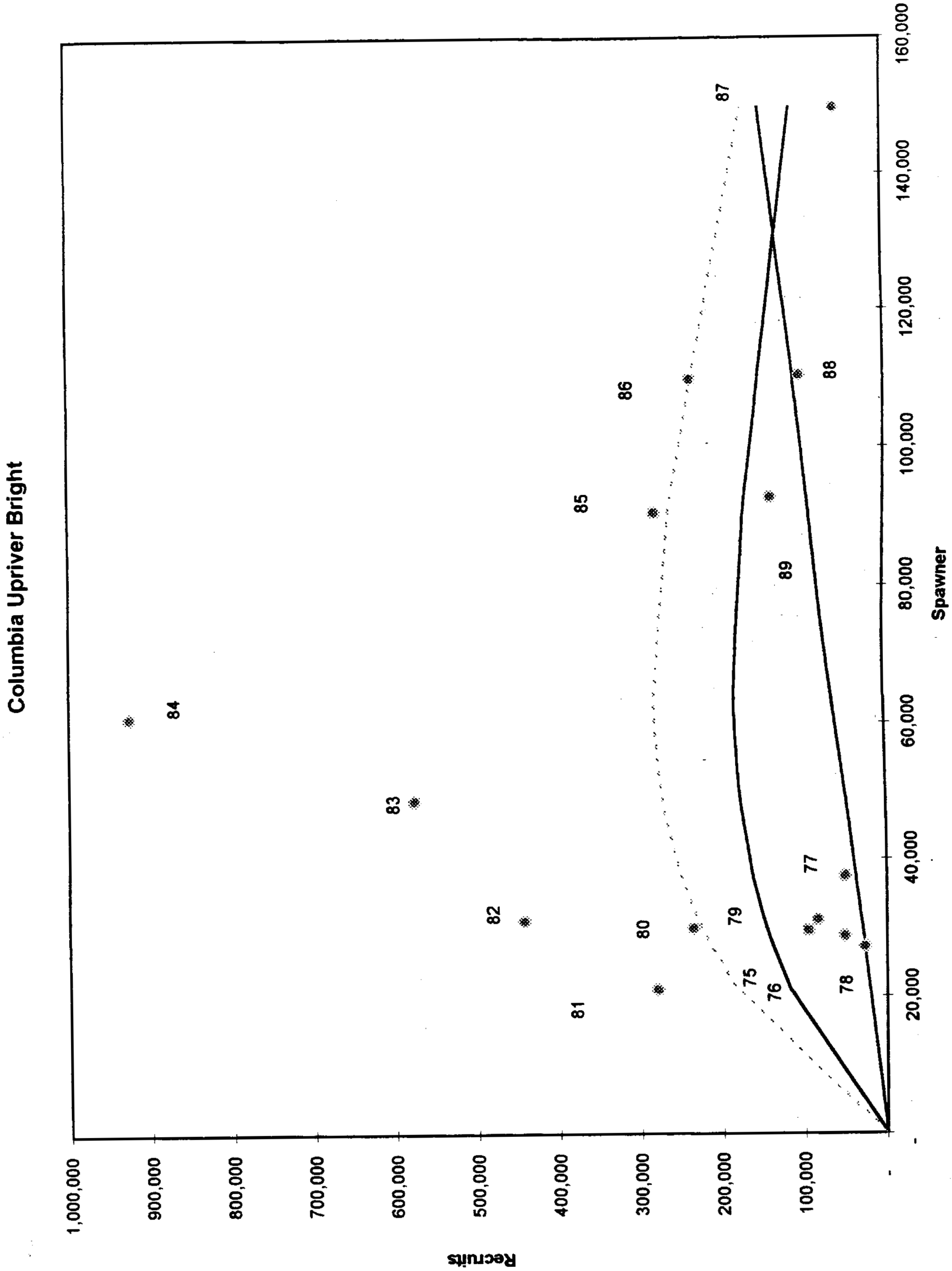

Figure 1. Spawner-recruit relationship for the Columbia Upriver Bright chinook stock. Solid line is recruits = spawners. Dots are observed number of recruits and year of return for given spawning level. Heavy doted line is the predicted number of recruits per spawning level for the normal Ricker function; light dotted line is correct for variation (error) in the number of recruits returning.

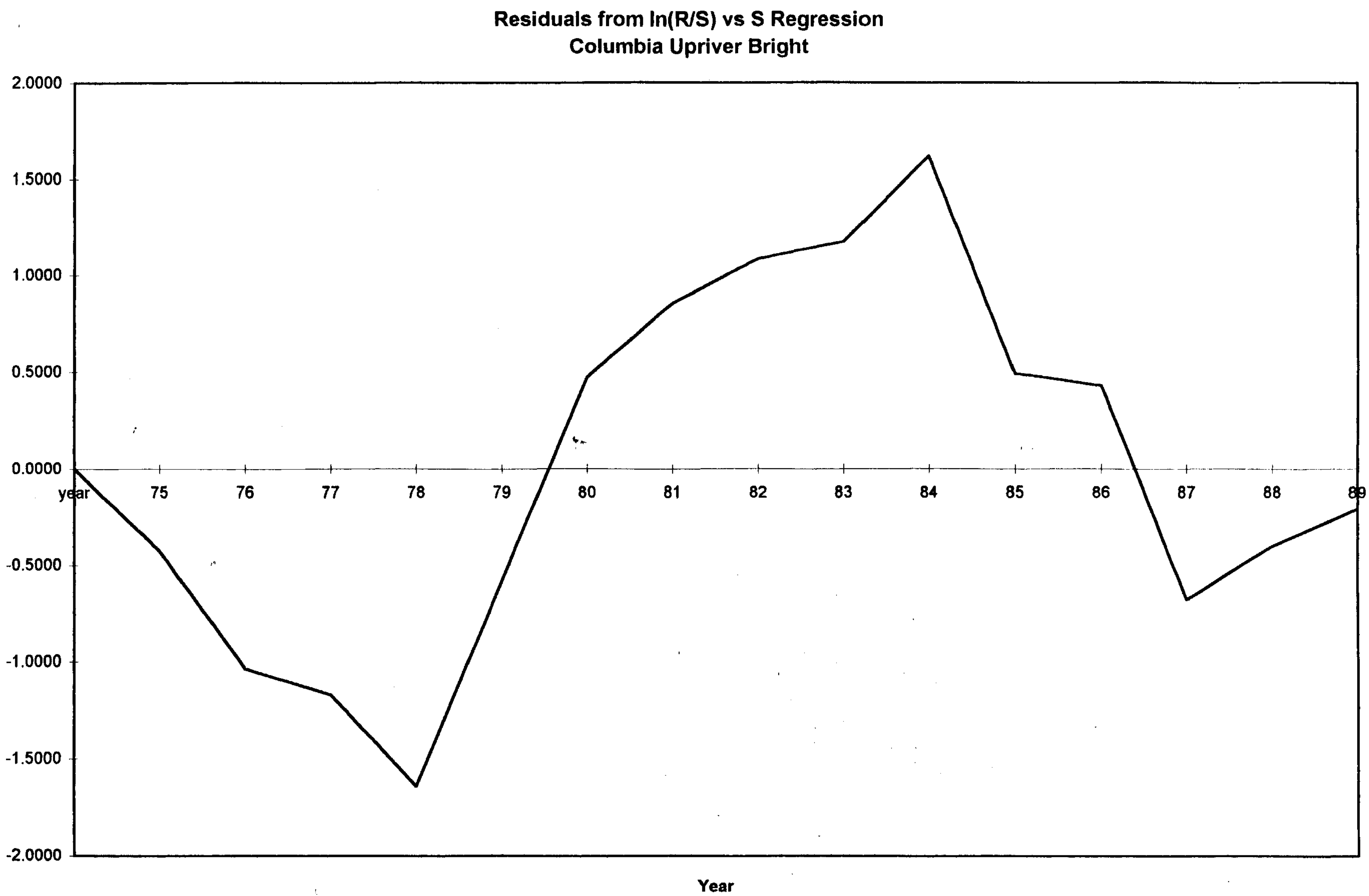

Figure 2. Residuals from the ln(R/S) vs S regression analysis for the Columbia Upriver Bright chinook stock.

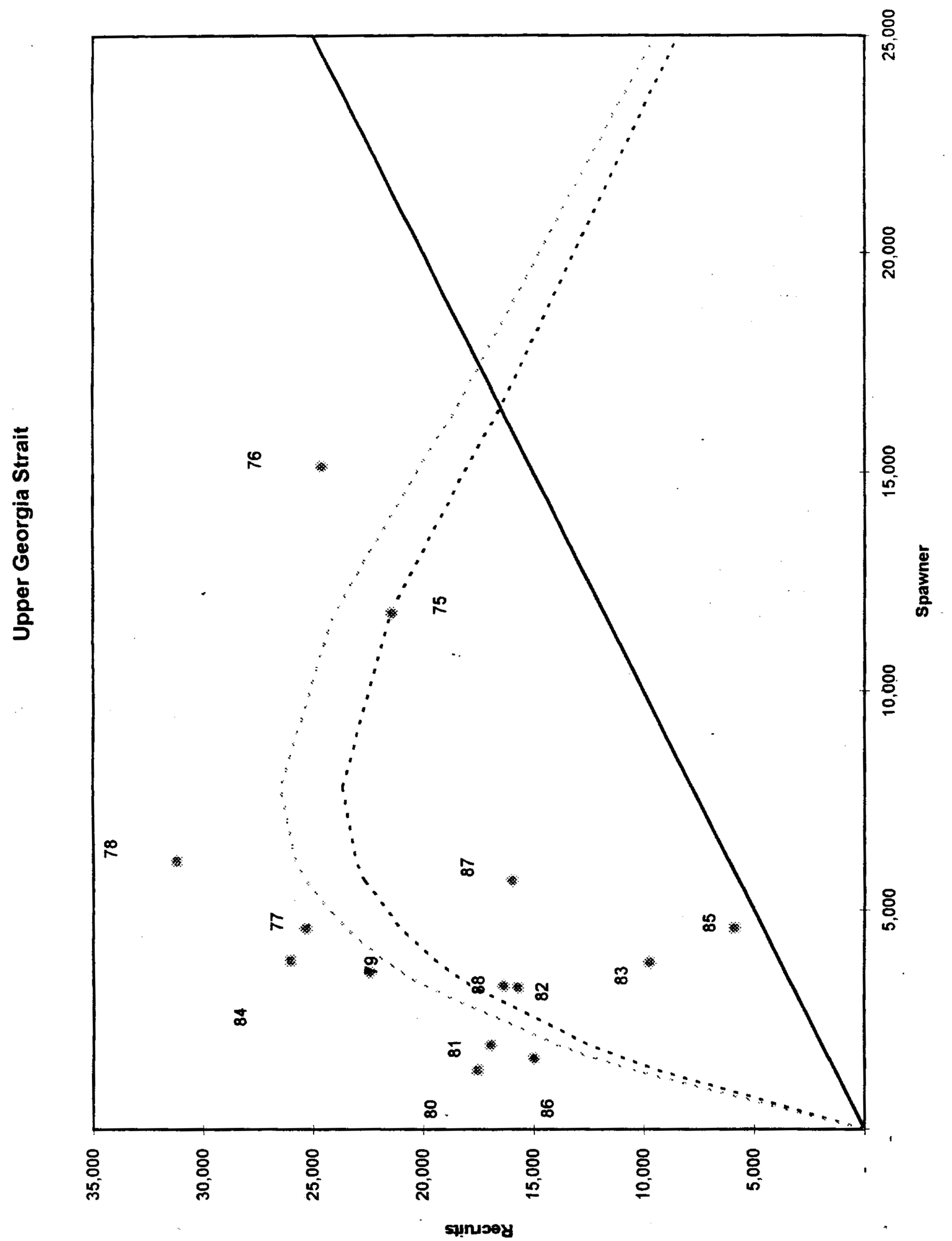

Figure 3. Spawner-recruit relationship for the Upper Strait of Georgia chinook stock. Solid line is recruits = spawners. Dots are observed number of recruits and year of return for given spawning level. Heavy doted line is the predicted number of recruits per spawning level for the normal Ricker function; light dotted line is correct for variation (error) in the number of recruits returning.

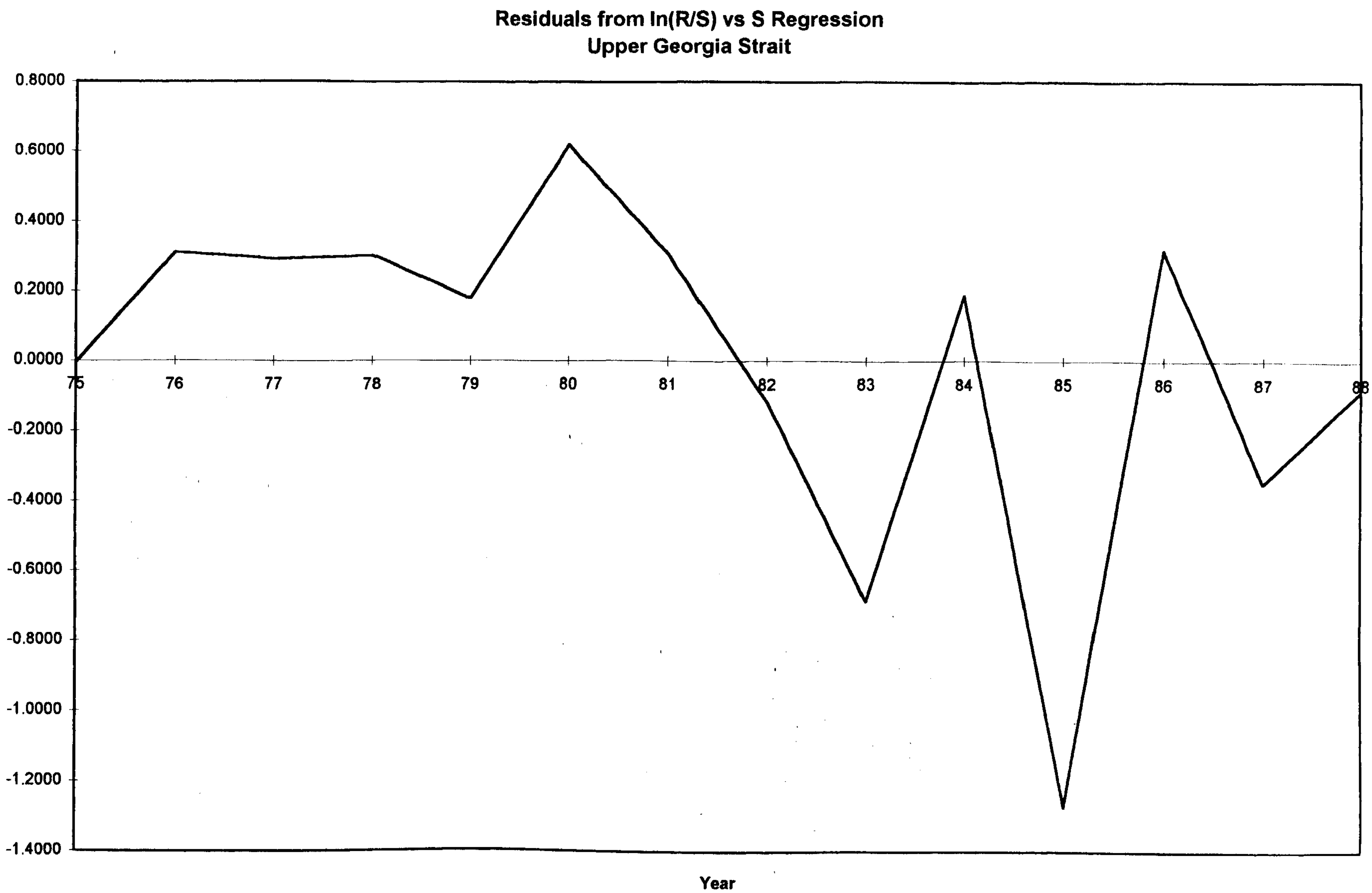

Figure 4. Residuals from the ln(R/S) vs S regression analysis for the Upper Strait of Georgia chinook stock.

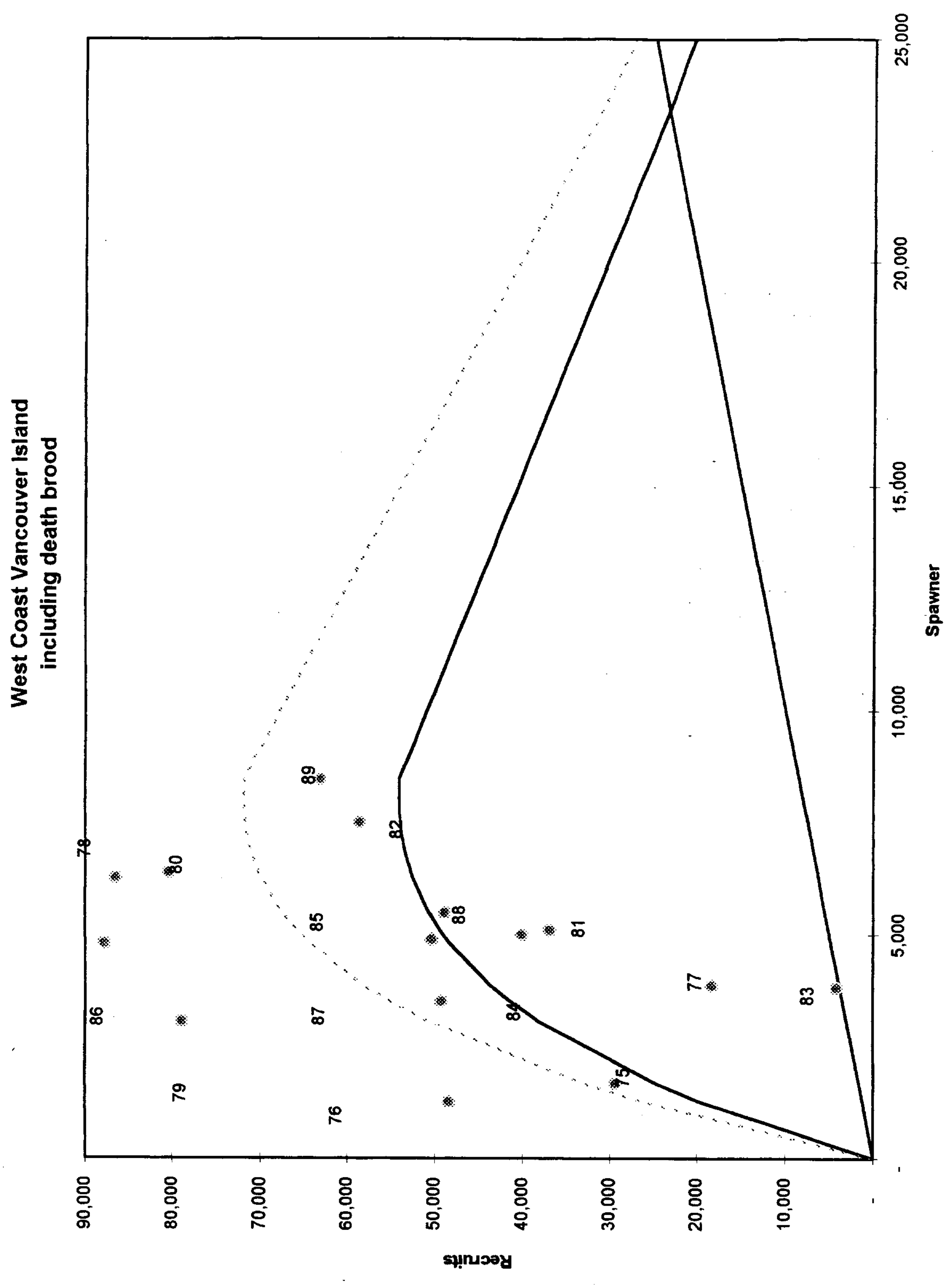

Figure 5. Spawner-recruit relationship for the West Coast Vancouver Island chinook stock including all years. Solid line is recruits = spawners. Dots are observed number of recruits and year of return for given spawning level. Heavy doted line is the predicted number of recruits per spawning level for the normal Ricker function; light dotted line is correct for variation (error) in the number of recruits returning.

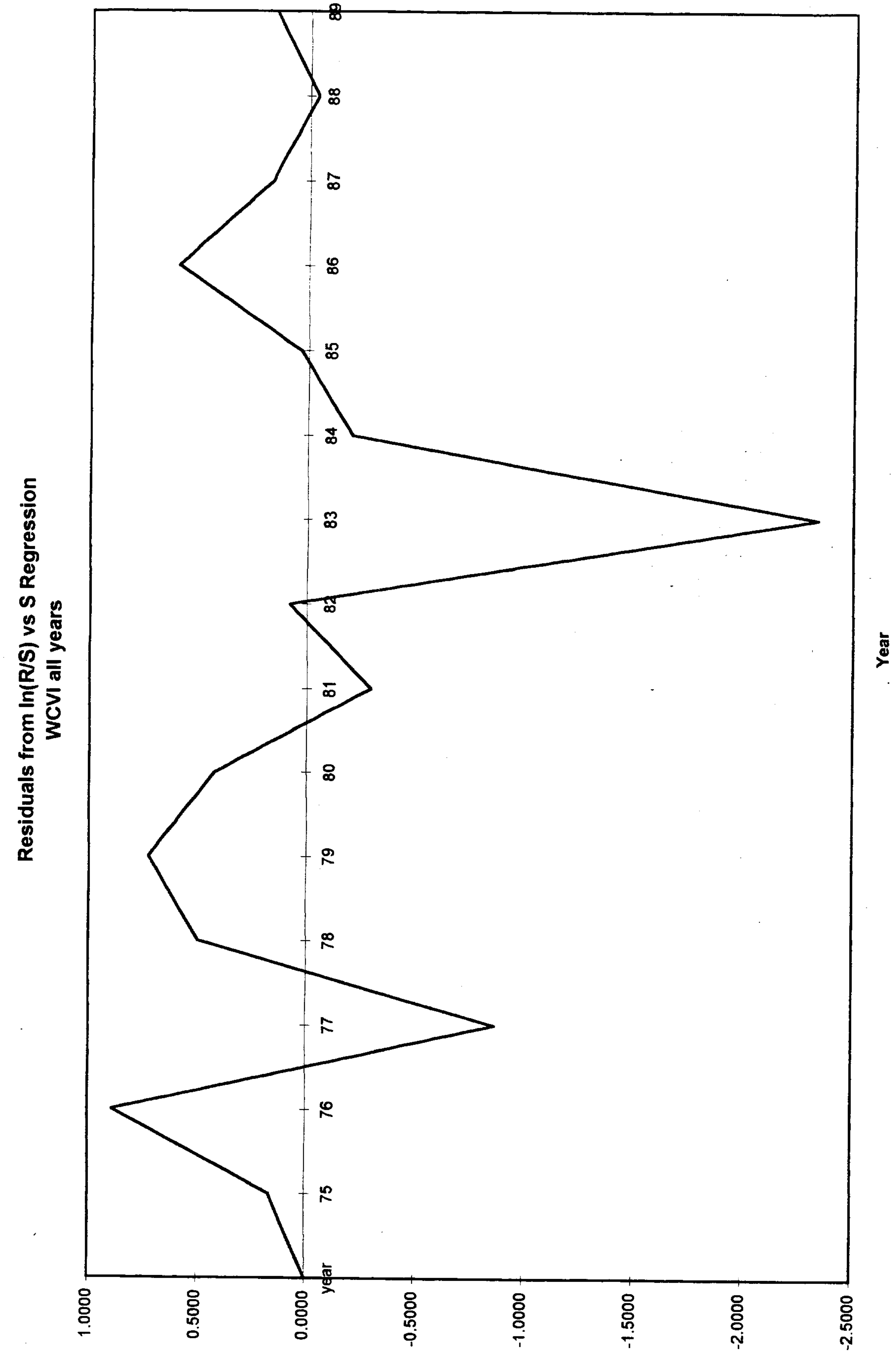

Figure 6. Residuals from the ln(R/S) vs S regression analysis for the West Coast Vancouver Island chinook stock including all years.

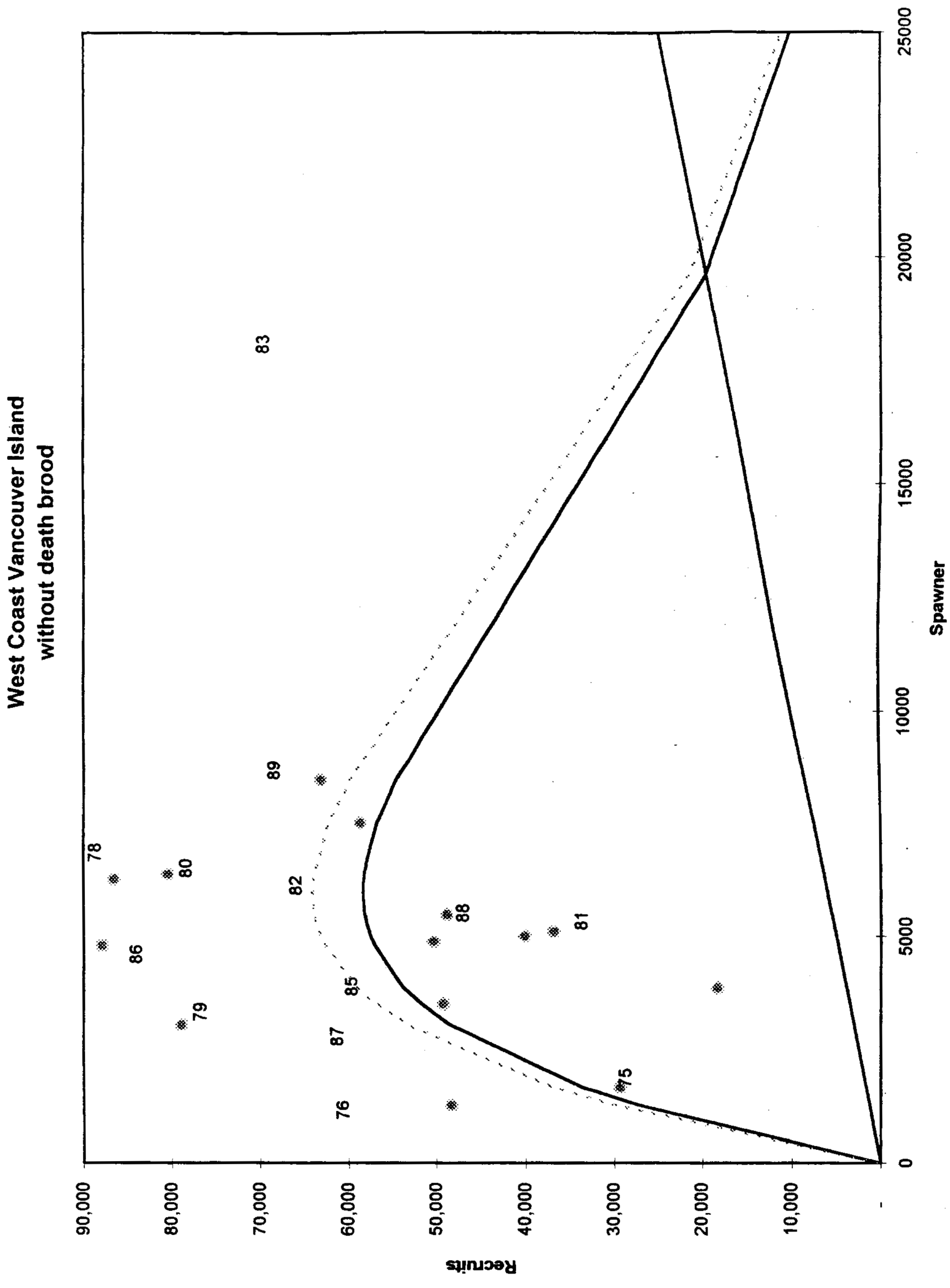

Figure 7. Spawner-recruit relationship for the West Coast of Vancouver Island chinook stock (with the death brood excluded from the analysis). Solid line is recruits = spawners. Dots are observed number of recruits and year of return for given spawning level. Heavy doted line is the predicted number of recruits per spawning level for the normal Ricker function; light dotted line is correct for variation (error) in the number of recruits returning.

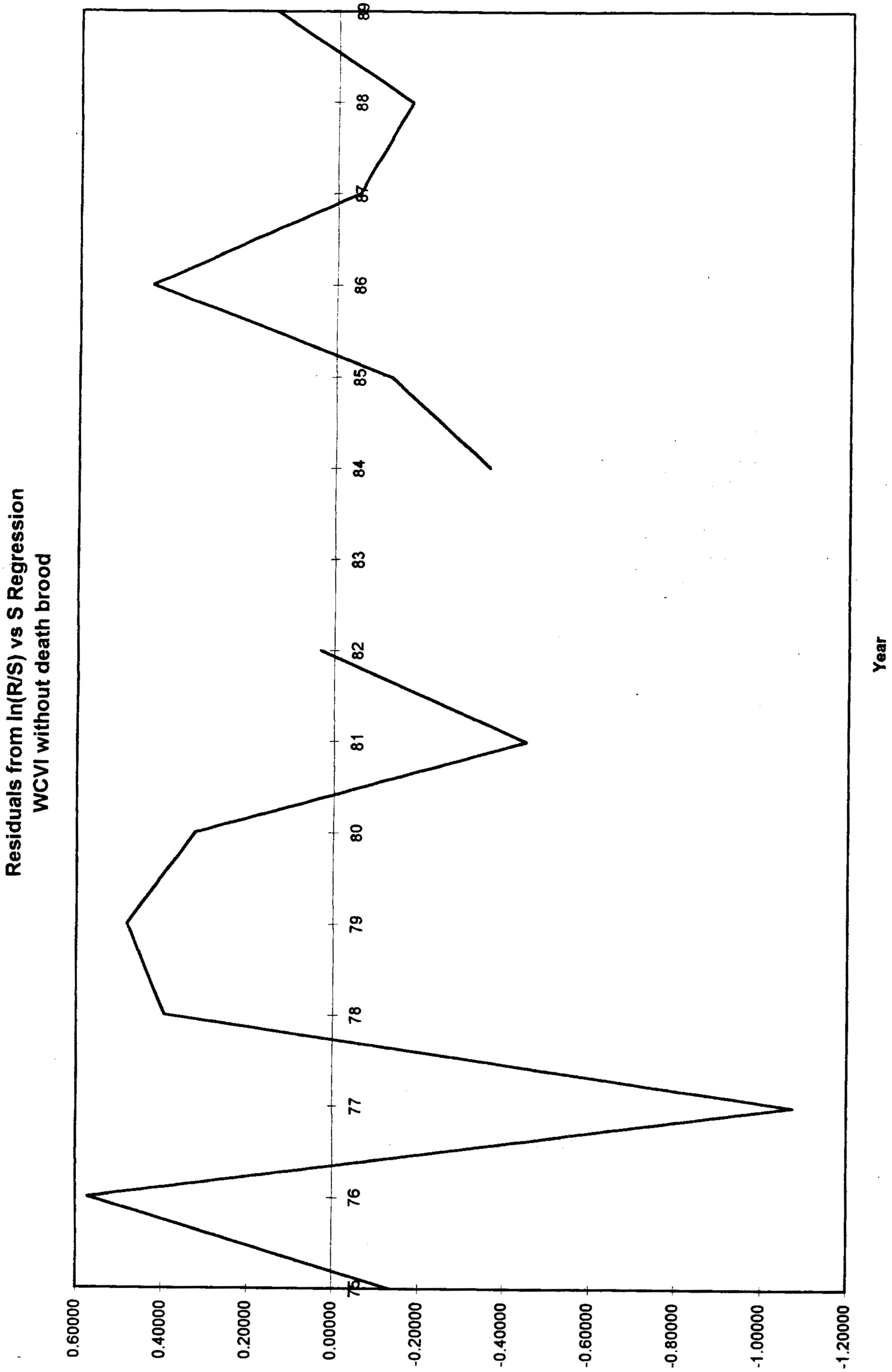

Figure 8. Residuals from the In(R/S) vs S regression analysis for the West Coast Vancouver Island chinook stock (with the death brood excluded from the analysis).

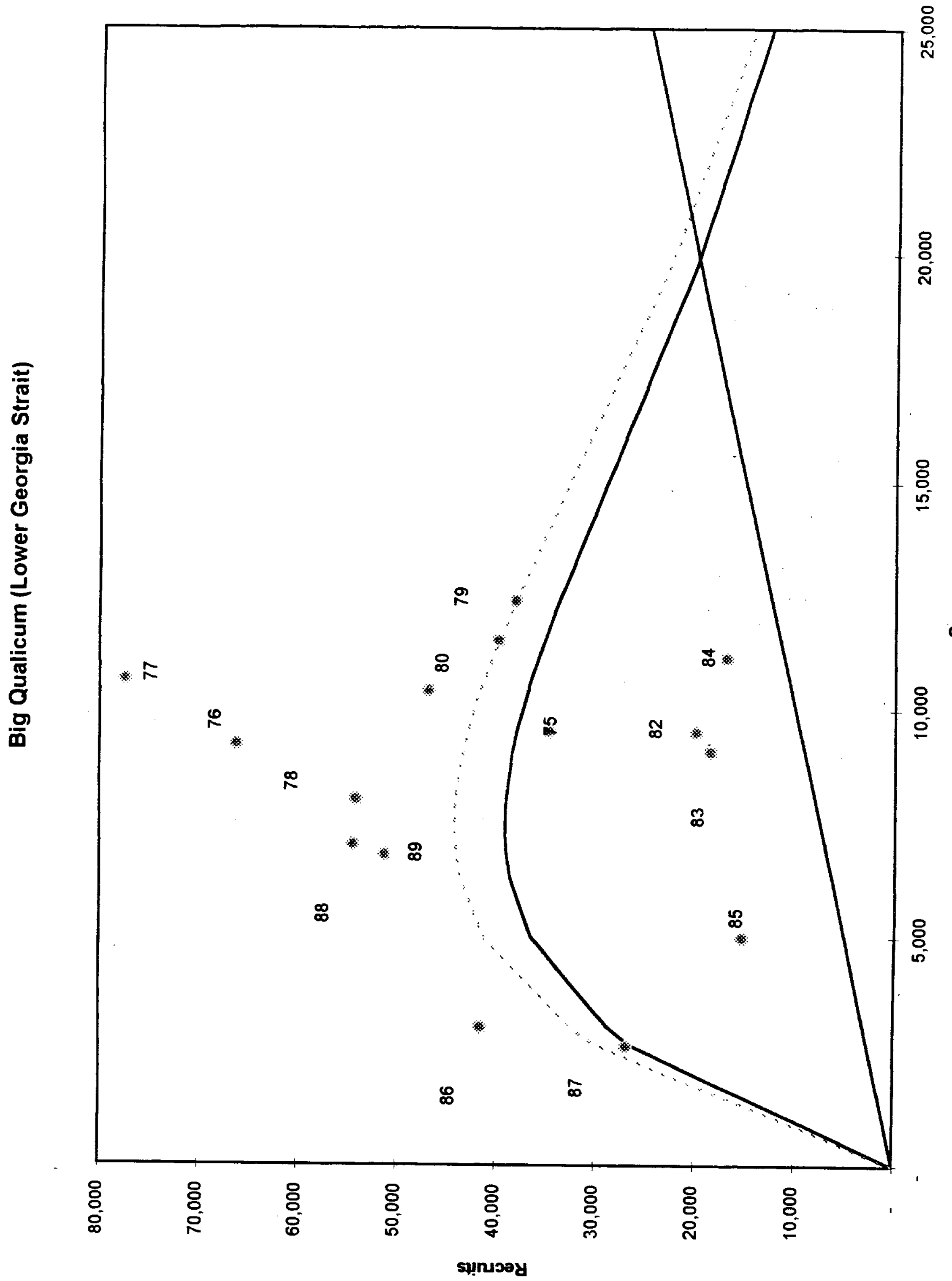

Figure 9. Spawner-recruit relationship for the Big Qualicum (Lower Georgia Strait) chinook stock. Solid line is recruits = spawners. Dots are observed number of recruits and year of return for given spawning level. Heavy doted line is the predicted number of recruits per spawning level for the normal Ricker function; light dotted line is correct for variation (error) in the number of recruits returning.

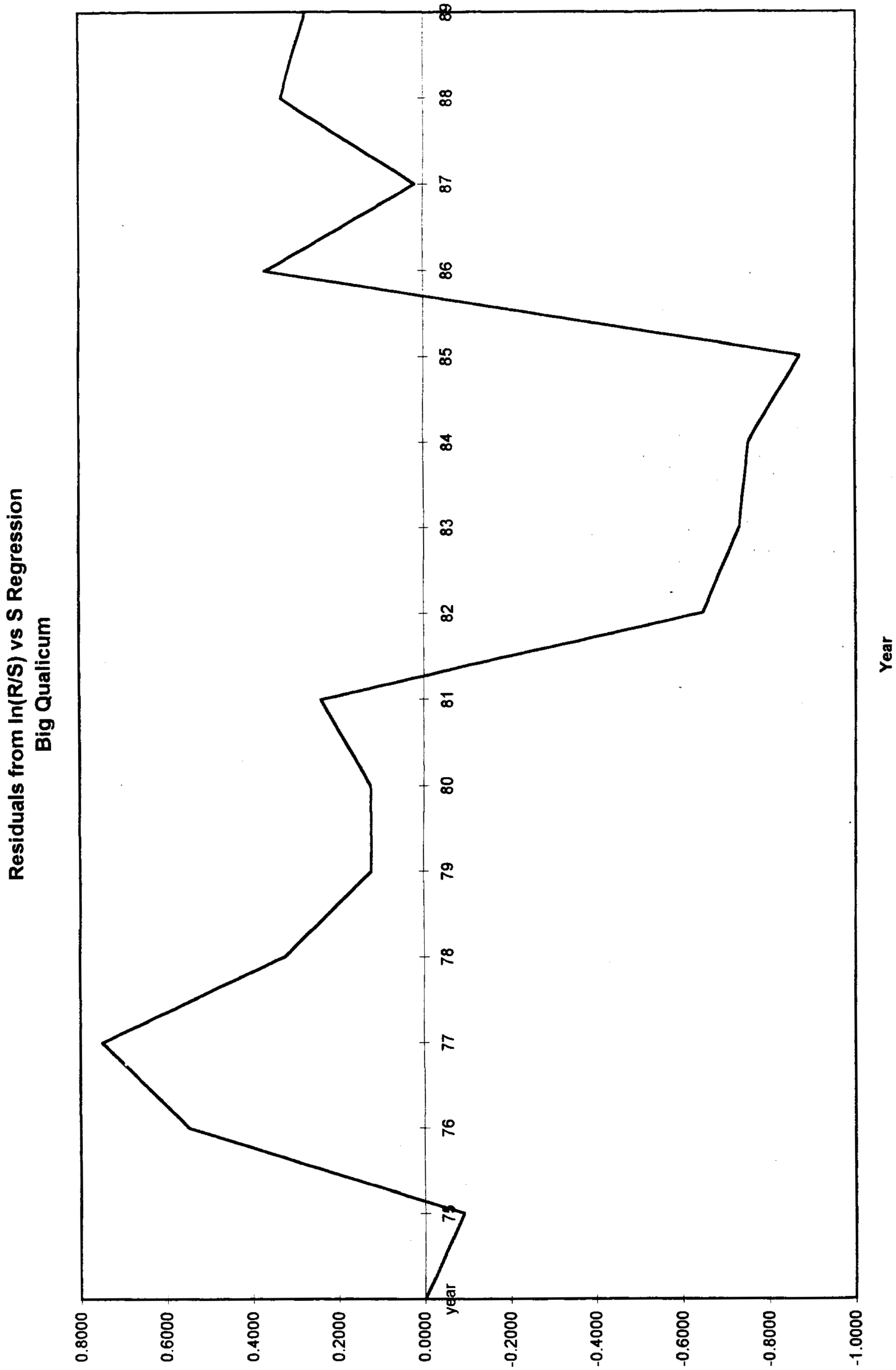

Figure 10. Residuals from the ln(R/S) vs S regression analysis for the Big Qualicum (Lower Georgia Strait) chinook stock.

APPENDIX: THE RICKER SPAWNER-RECRUIT ANALYSIS[1]

In analyzing spawner-recruitment (S-R) relationships for salmon stocks, the question that should first arise is whether the relationship shows density dependence or not. For a stock that is greatly over exploited, one would expect that the relationship is not density dependent and that an increase in spawners (S) should result in a proportional increase in the recruitment (R) some k years later:

$$R_{t+k} = \alpha\, S_t\, e^{\mu}$$

where α is a productivity parameter (recruits-per-spawner), and μ is an error term with a normal distribution as recommended by Peterman (1981) and Walters (1986).

If a salmon stock is not greatly over exploited, some density dependence might be apparent, especially if production is limited by spawning habitat and/or favorable nursery ground conditions. The density-dependent model usually used for salmon stocks is the Ricker equation (Ricker 1954, 1975):

$$R_{t+k} = \alpha\, S_t\, e^{-\beta S_t}\, e^{\mu} \qquad \textit{eq. 1}$$

where α is again the productivity parameter, β describes how quickly recruits-per-spawner decrease as S increases, and μ is the error term as above. Ricker (1975) shows that the number of spawners needed to obtain the maximum sustainable yield (MSY) is derived from the iterative solution of:

$$(1-\beta S_{MSY})\, \alpha\, e^{-\beta S_{MSY}} = 1.$$

Deriso (1985) and Hilborn (1985b) have shown that for a stock demonstrating a Ricker S-R relationship, the MSY goal is approximately equal to:

$$b(0.5 - 0.07a)$$

and the optimal exploitation rate (exploitation rate at MSY levels of catch and escapement) is approximately equal to:

$$0.5a - 0.07a^2$$

for a in the range $0 < a < 3$, where a is $\ln(\alpha)$ and b is $\ln(\alpha)/\beta$ and α and β are from equation 1.[2]

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[1] adapted from Sands and Marshall (1995).

[2] The Ricker equation can also be expressed as $R = Se^{a(1-S/b)}e^{\mu}$, in which case the a and b of the above two equations correspond to the a and b in this form of the Ricker. In this case a is the intercept of the linear-regression solution and a/b is the slope; b is the value of replacement where R=S.

The error term (e^{μ}) in equation 1 models lognormal errors in R. The expected value of e^{μ} is $e^{\sigma 2/2}$ where σ is the standard deviation of the residuals of ln(R/S) from the model predicted values. When S predicts R exactly, e^{μ} equals 1. However, if μ is normally distributed with a mean of zero, the expected value of e^{μ} is not 1 and the average S-R curve will not be that described by the parameters α (or a and b); β will remain the same. Hilborn (1985b) has shown that a and b may be redefined as a^{l} and b^{l} as follows:

$$a^{l} = a + (\sigma^2/2)$$

$$b^{l} = (a^{l}/a)\ b$$

with a and b defined as above. Utilization of this error correction helps correct the bias resulting from annual variation due to environmental factors. Natural or environmental factors attribute to variation in survival (e.g., water and temperature levels, prey abundance, competition, predation). Those variations that are random and unpredictable will be included in the random error term when fitting S-R curves. Predictable environmental influences can be included into the S-R model (Noakes, Welch, and Stocker 1987) but attempts to identify these factors may be frustrated when data collections are sparse or inappropriate and/or spawning stock is measured with significant error (Marshall 1992). Long-term environmental influences on production may be profound (Beamish and Bouillon 1993) and change the S-R model parameters α and β over time (Walters 1987). If this occurs, graphical and statistical procedures can be used to detect this nonstationarity in S-R data sets (Armstrong and Shelton 1988, Walters 1987).

Adding environmental or other factors to the Ricker model to improve the fit is not generally recommended as, although it may improve the fit of the data to the model, it generally worsens the predictive quality of the model unless you can predict or measure the environmental factor. Adding factors to the basic model also requires additional years of data in order to model the additional parameter(s) correctly.

Before applying the error correction procedure above, one should examine the residuals for patterns that may indicator an incorrect model fit to the data or a systematic change in the stock productivity (caused, for example, by environmental change). A strong autocorrelation pattern will indicate potentially badly biased S-R parameter estimation (Hilborn & Walters 1992).

Large variability in the annual returns of salmon due to marine survival often prevents the linear-regression statistic r-sq from being a good indicator of model fit even when an underlying density dependent relationship exists. Other methods of assessing the reliability of a model fitted R-S relationship are to examine the escapement data for a wide range of values, assure that measurement error in estimating spawners and recruits is low, examine the residuals for time-related patterns and autocorrelation, and simulate the estimation procedure using the estimated model parameters as true values and incorporating estimates of observation and process errors.

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