Evaluation of Stock Assessment Methods for Commercial Walleye (*Sander vitreum*) Fishery of Red Lakes, MN

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Dedication

This dissertation is dedicated to my grandparents, William and Evelyn Grotheer and Kazuo and Martha Takade.

Abstract

In 1997, the Red Lakes walleye (*Sander vitreus*) fishery was closed due to extremely low population numbers and a massive rehabilitation program was started for the walleye in 1998, by tribal, state and federal authorities, because of the ecological, economic, and cultural importance of the walleye fisheries. Management authorities recognized that a stock assessment of some manner would be necessary to monitor the reopened fishery if it were to be maintained on a sustainable basis. However, it would be necessary to choose from a variety of methods, ranging in complexity from an index of abundance to an age-structured method such as a statistical catch-at-age model. The primary goal of this research is to examine different types of models that may be appropriate for use in the fishery and determine how they may perform when used for the Red Lakes fishery. A secondary goal was to determine if a simulation of potential unaccounted for catch or if previous research into annual growth factors might improve the predictive capability of the delay-difference model. This research found that generally, the age-structured models performed better than the delay-difference model, the inclusion of the walleye environmental coefficients improved the fit of the delay-difference model, the assumed black market catch resulted in only limited improved fit of the delay-difference model with general increases in fishing effort, and the environmental coefficients had limited explanatory power in changes in population abundance.

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Introduction

In 1997, the Red Lakes walleye (*Sander vitreus*) fishery was closed due to extremely low population numbers (Ostazeski 1998). The collapse and closure abruptly prevented the take of a species of prime economic importance to the communities of the area. Fisheries on the Red Lakes had been prosecuted in two parts, one was the commercial and subsistence fishery of the Red Lakes Band and the other was a recreational fishery on the eastern one-half of the Upper Red Lake. The Red Lakes Band of Chippewa Indians had conducted a commercial walleye fishery since World War I (Van Oosten and Deason 1957). Walleye and other fishes of Red Lakes comprised a subsistence fishery for the Band that pre-dated the commercial fishery. No commercial fishing had occurred in state-controlled waters of Upper Red Lake since the Great Depression, though it supported a popular recreational fishery that, in turn, supported small resorts along the lakeshore (Van Oosten and Deason 1957). The significant loss of income for those in the area would endure for nearly a decade before the limited re-opening of the fishery in the spring of 2006.

A massive rehabilitation program was started for the walleye in 1998, by tribal, state and federal authorities, because of the ecological, economic, and cultural importance of the walleye fisheries. The program included a stocking regime and monitoring using multiple methods. Management authorities also recognized that a stock assessment of some manner would be necessary to monitor the reopened fishery if it were to be maintained on a sustainable basis. However, it would be necessary to choose from a variety of methods, ranging in complexity from an index of abundance to an age-structured method such as a statistical catch-at-age model. The primary goal of this research is to examine different types of models that may be appropriate for use in the fishery and determine how they may perform when used for the Red Lakes fishery.

Overall, the goal is to determine the models and methodology that most accurately reflect the known behavior of the commercial fishery prior to the collapse of the stock, and to tune the biological and environmental parameters of those models so they will be better able to predict future behavior of the stock in a rehabilitated fishery. The objectives of this dissertation are: 1, to compare different stock assessment models (delay-difference, ADAPT, separable VPA, and a forward projecting age structured model) and computational methods to determine those which are most appropriate for this fishery, especially by comparison of predicted and actual catches; 2, to improve the verisimilitude of stock assessment models that include growth information by including high-resolution estimates of yearly growth; 3, to estimate the effect of black market catch on the predictive value of the catch estimates and estimates of fishing effort; and 4, to examine the relationship between estimates of population abundance and the previously reported commercial catch-per-unit-effort (CPUE).

Stock assessment background

Stock assessment has been an important tool of fishery management. Stock assessment can be defined, in its most narrow manner, as the collection and interpretation of data to determine stock status and predict future stocks based on patterns (NRC 1998b). As generally defined, stock assessment includes the quantitative estimation procedures and management decisions that must be determined through the use of methods that evaluate stock status and predict future stocks (Hilborn and Walters 1992).

Stock assessments are done in line with the most commonly viewed purpose of fisheries management, ensuring sustainable production of a fishery.

Three general classes of yield models historically have been used for commercial fisheries. The classes are surplus production models, age-structured models, and dynamic pool models. Surplus production models predict fishery yield through the use of stock abundance and fishing effort data. Dynamic pool models determine the yield per new recruits to a fishery. Age-structured models predict the population size and predict fishery yield using the estimated age-structure of the catch and available auxiliary information. Surplus production and dynamic pool models have become generally popular because they do not require catchability, or selectivity information, thus freeing these models from problems that can occur from using catch per unit effort estimates (Megrey 1989). However, surplus production models historically have assumed that the populations being assessed were in equilibrium with the fishery, frequently resulting in inaccurate conclusions (Haddon 2001).

Surplus production models are the least mathematically complex and least data intensive of the models typically used for stock assessments. The model basis is a straightforward concept that the new fishable biomass is comprised of four components: old biomass, its growth, new recruits, minus the fish lost to mortality (both fishing and natural) (Hilborn and Walters 1992). Surplus production models do not deal with many fisheries complexities, such as age effects, but describe the fishery simply as a population biomass (Hilborn and Walters 1992). Though heavily maligned for problems related to precision and accuracy, these models are often used in situations where catch-at-age information cannot be found (Ludwig and Walters 1985).

Delay-difference is another class of models that have been used in stock assessment and fall between the surplus production models and age-structured models in complexity. Delay-difference models split the known population into recruits and post recruits, which uses minimal age structure. Simply put, the model can be represented as:

Biomass this year = Biomass surviving last year + growth of individuals from last year + new recruit biomass,

or, that by subtracting the amount of biomass lost to catch or natural mortality and adding the recruited biomass from the current population reproduction estimates, the next year's biomass can be estimated.

A delay-difference type model has a number of advantages in simulating fishery yield. One advantage is that when auxiliary information is available, it can be fitted directly to relatively simple time-series data. Keeping track of numbers and sizes of animals in many age groups, a characteristic of more data-intensive age-structured models, is not necessary (Hilborn and Walters 1992). Delay-difference models have been known to accurately track the biomass history of some stocks, including Pacific halibut (*Hippoglossus stenolepis*) (Deriso 1980) and Pacific cod (*Gadus macrocephalus*), (Hilborn and Walters 1992). Thus, departures of the observed stock status from that predicted by the model should raise concern with management agencies. Perhaps the most appealing feature of the delay-difference model is that any reasonable growth or recruitment functions can be inserted. Then the model can be modified when additional information becomes available as to the reproductive success of individual cohorts of fish, or, as I will demonstrate later, the verisimilitude of the model may be enhanced by incorporating high-resolution growth functions that may be responsive to biotic or abiotic factors in the environment of the modeled population.

Using delay-difference models also has some disadvantages. One disadvantage is that when using simple time-series data, models can be explained equally well by a variety of (different) parameters (Hilborn and Walters 1992). Different suites of parameters may imply different responses to policy changes. Another risk is favoring parameters that can achieve a strong fit with almost any data set, possibly leading to parameter sets that are biologically meaningless or misleading (Hilborn and Walters 1992). Delay-difference models can appear to track changes in biomass quite accurately and still mask substantial changes occurring within a stock (Hilborn and Walters 1992). A more detailed analytical model should be used in parallel with a delay-difference model to provide an opportunity for changes masked by one model to be revealed by the other. Another important note is that it may be necessary to estimate certain parameters for which no historical data exist.

Finally there are age-structured models, including general catch-at-age models. The abundance of fish of a particular age in a given year is the result of the abundance of the cohort in the previous year, multiplied by the exponentials of both natural and fishing mortality. The formulation allows the tracking of a year-class as it moves through a fishery over time, thus exhibiting the overall composition of the standing stock in year-classes available to a fishery.

Age-structured models can be generally classified as backward or forward projecting, also called virtual population analysis (VPA) and statistical catch-at-age, respectively (Hilborn and Walters 1992). The first VPA was created by Fry (1949), using annual catch values and annual age composition values to compute estimates. The backwards calculating method estimates first the last age class in all the years in the stock assessment period and the terminal year's ages, and then projects the cohort backwards through time and ages (Gulland 1965 cited in Megrey 1989, Pope 1972). Forward-calculating methods assume knowledge of all ages in the first year of analysis and the first age class of all years included in the stock assessment period and then project cohorts forward through time (Deriso et al. 1985, Doubleday 1976, Fournier and Archibald 1982, Methot 1989, Paloheimo 1980). Statistical catch-at-age models typically require a measure of effort that is not a requirement of VPA models.

One advantage of age-structured models is the ability to follow each year-class as it moves through the fishery. Information of that kind allows managers to adjust harvest regulations for weak or strong year-classes. Age-structured models are, generally speaking, quite flexible mathematically. That flexibility allows the incorporation of different kinds of auxiliary information (Hilborn and Walters 1992). Examples of auxiliary information include effort data, stock-recruitment relationships, or recruitment estimates.

The main disadvantage is that changes in the fishery may not be captured as a result of estimating incomplete cohorts, where members of a cohort are not fully recruited to the fishery (Hilborn and Walters 1992). The main concern is that the catchability coefficient or fishing rate may rapidly increase in the most recent years if a stock is in decline, problems that may not be detected in younger cohorts through regression (Hilborn and Walters, 1992). Also, age determination involves a certain amount of error, though there should be no difficulty in obtaining the catch-at-age data in the Red Lakes.

In fact, all sources of variation and error that could affect the model's results should be considered (Hilborn and Walters, 1992).

In comparison with delay-difference models, age-structured models have different and a greater number of data inputs and parameters when compared to the delay-difference model. Whereas the delay-difference models presented above seek to describe the population according to annual changes in biomass, the age-structured models attempt to track the numeric abundance of each year-class through the years in which it contributes to the fishery.

Red Lakes Background

History of the Commercial Fishery

The Red Lakes are located in north central Minnesota approximately 44 km north of Bemidji and comprise two relatively oval basins (the Upper and Lower Lakes) that are joined by a 1.2 km channel. The Lakes encompass a total area of 116,876 hectares. The Lakes are shallow with a maximum depth of 6.1 m in the Upper Lake and 10.7 m in the Lower Lake (Smith et al. 1952). The entire Lower Lake and all but 24,800 hectares of the Upper Lakes are contained within the reservation boundaries of the Red Lakes Band of Chippewa Indians. The fisheries of the Upper Lake area outside of the reservation boundary are under the jurisdiction of the State of Minnesota. The early history of fishing in the Red Lakes is described in great detail by Van Oosten and Deason (1957), and is the source of much of the following information.

The Band determines how their resources may be utilized within the boundaries of the reservation. Band members have been allowed subsistence and commercial fishing in the case of the walleye and other fishes. The Band's commercial fishery focused primarily on walleye that were caught using gillnets with 7.62 cm (3 inch) stretch measure mesh that were 91.44 meters (300 feet) in length and were generally in the water between 12 and 18 hours (Smith and Krefting 1953). The walleye fishery traditionally opened in June and closed in early October (Smith 1977). Peak catches occurred in late July or early August (Smith 1977). Walleye were the target species of the fishery, with lesser interest in yellow perch, *Perca flavescens*, and freshwater drum, *Aplodinotus grunniens*, (generally sold as animal feed) (Ostazeski 1998). Walleye catches were separated into

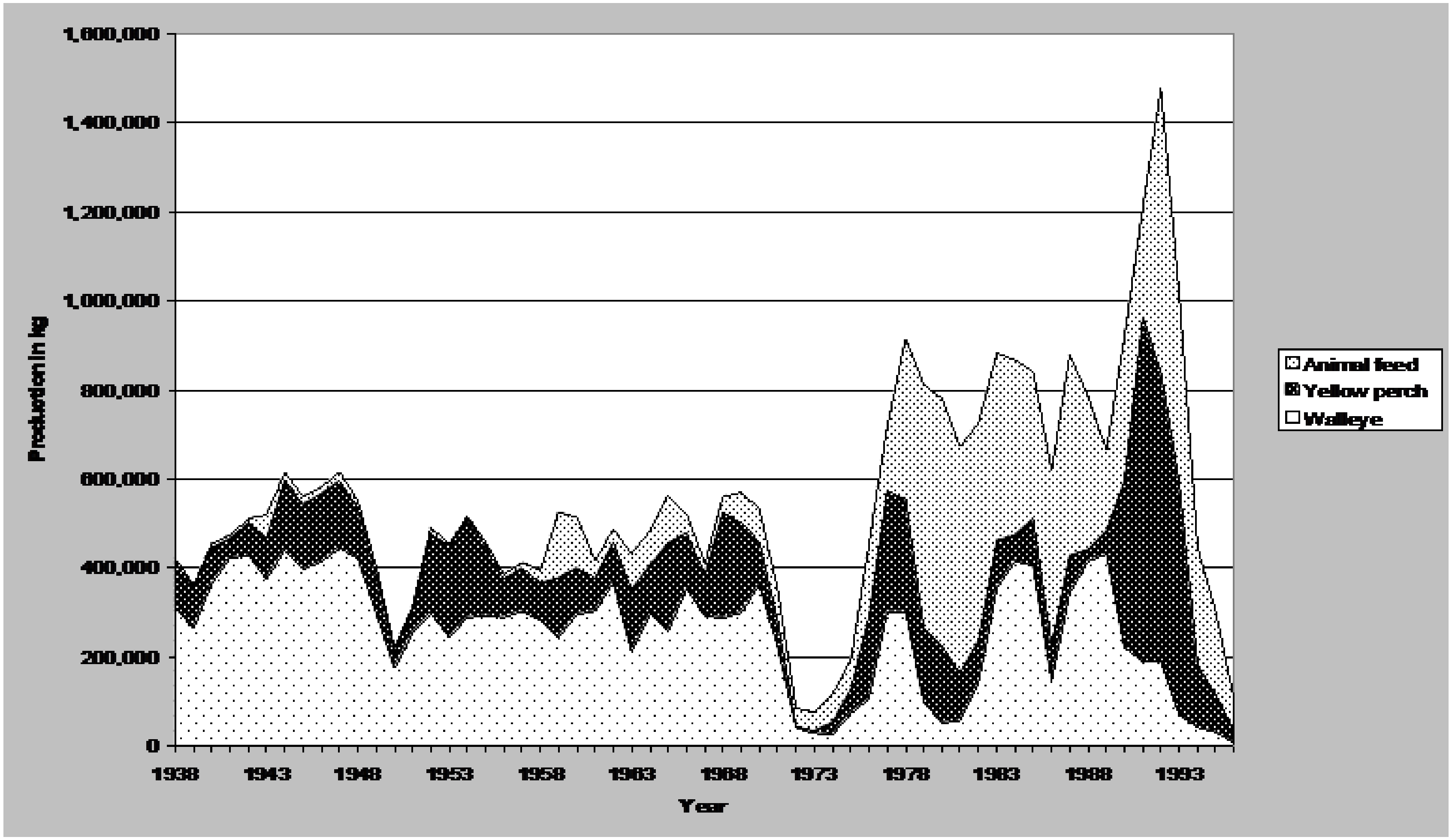

Figure 1: Commercial fishing production for the Red Lakes over the period 1938-1996, including walleye, yellow perch, and animal feed (primarily freshwater drum).

regulation and cull walleye, with cull fish defined as those weighing less than 0.45 kg. The annual commercial fishery yields can be seen in Figure 1, which shows the total catch and proportions belonging to the three primary species, and indicates the importance of walleye to the fishery historically. Minnesota laws prevented commercial fishing in the state's inland waters prior to 1917, defining inland waters as those waters contained entirely within state borders. The only fishing that was conducted during that time period on the Red Lakes was a subsistence fishery by the members of the Red Lakes Band of Chippewa Indians. Difficult economic conditions occurred during World War I that resulted in price increases for meat and the need to conserve the country's food supply. This resulted in a change in state law, though little commercial fishing occurred until 1918.

Multiple types of gear were used during the period of lake-wide fishing. The tribal fishermen used hook and line and gillnets, whereas licensed state fishermen fished using pound-nets. The tribal fishery had been shifted almost entirely to 8.89 cm (3.5 inches) mesh gillnets by 1919; eventually the mesh size was increased to 9.525 cm (3.75 inches) (Van Oosten and Deason 1957).

The original call to abandon the Red Lakes as a commercial fishery came in 1919, though commercial fishing continued with the justification that it was a continuing source of employment (Klancke 1929). Competition between the state and tribal fishing crews was already an ongoing source of controversy. The tribal fishery was conducted under contract between the Department of the Interior, the Commissioner of Indian Affairs, and the State of Minnesota. Regulations limited the type and numbers of nets, as well as an annual allowable catch. The fishing contract became a central aspect of the dispute.

Tribal members had already objected to the state competition, and over the state-appointed manager's handling of the wholesaling operation. The tribe, by resolution, accused the manager of wasting resources, inaccurate weighing, and failing to pay a fair price. To remedy the situation a check-weigher was appointed and a cold storage and smoking house were completed to prevent fish waste. An investigation showed that the state was underpaying tribal members compared to private sellers.

The next major controversy arose in 1926, when tribal fishermen were accused of the use of illegal mesh sizes and destroying undersized fish. Fishermen were found with nets with mesh less than 10.15 cm (four inches), the size stipulated in the contract. The state refused to purchase fish from fishermen known to be in possession of illegal mesh sizes.

The right of the state to conduct a wholesale business for private profit in competition with private industry was challenged in 1927. Appeals were exhausted by 1929 and the state was prevented from the commercial purchase of fish in competition with private buyers. The state Commissioner of Game and Fish was authorized by the Minnesota Legislature to lease the fishery plant to the United States or an authorized agency after 1929, forming the basis for the operation into recent times of the Red Lakes Fishery Association. The Association entered into a five year lease of the plant beginning in 1929 and fishing began in July.

The state fishery was incorporated into the Red Lakes Fishery Association when it was created in 1929. Estimates were that there were no more than 18 to 20 state licensed fishermen in any one season that continued to operate in state waters, typically contributing 4.8% of the total commercial catch. The commercial fishery in the

Minnesota waters of Red Lakes was discontinued in 1937. The economic interests of the state waters shifted from commercial to recreational walleye fishing after commercial fishing was terminated.

Primary access for recreational anglers was along the Tamarack River, an inlet at the east end of Upper Red Lake, with three public access areas. Multiple resorts and campgrounds were located in the area of the Tamarack River (Boe 1998). Private homes and cottages are also scattered along the shore of the Upper Red Lake. Fees are paid during the winter by anglers to cross private property for lake access (Boe 1998). The majority of recreational angling has taken place within 0.8 km (0.5 miles) of shore during all seasons.

Reservation waters within the two basins were open to any band member granted a commercial fishing license during most of the existence of the Red Lakes commercial fishery (Smith and Krefting 1953). Commercial fishery regulation fell primarily to the Red Lake Fishery Association, the cooperative responsible for marketing of walleye caught from the Lakes (Smith and Krefting 1953). Until the Red Lakes Department of Natural Resources created a fishery assessment unit under the control of the tribal council in 1987, the fishery association was the entity that conducted monitoring and controlled the opening and closing of the harvest seasons (Smith et al. 1951). The original regulations were created by the Commissioner of Indian Affairs, who set general quotas for the fishery (Smith and Krefting 1953).

The fishery produced up to 727,300 kilograms of fish (Figure 1) at the peak of the commercial fishery in the 1950's, of which walleye was dominant (Smith 1977). Annual landings in the tribal fishery, processed exclusively through the fishery association plant at Redby, Minnesota, fluctuated moderately, largely between 300,000 and 400,000 kg, from 1938-1968. Landings then declined precipitously after a 1970 year-class failure, and fluctuated wildly until the collapse of the fishery in the middle 1990s. During this time, the reported proportions of walleye in the total catch also fluctuated greatly, with animal feed alternating with walleye as the most abundant component of the catch from 1978 to 1988. Animal feed includes a mix of species, including walleye, which are not marketable as human food, with freshwater drum the largest component species. After 1988, yellow perch alternated with walleye as the most abundant component. However, the Minnesota Department of Natural Resources estimated by the late 1990's that the potential harvest of 68,492 kilograms in the recreational fishing waters of Upper Red Lake was not being realized, because of the depressed nature of the population (MDNR 1997). The entire lake system was closed to walleye fishing in 1997 (Ostazeski and Spangler 2001), a practice that has been followed in other depleted fish stocks such as cod (*Gadus morhua*) in Canada (Haedrich and Hamilton 2000).

Previous Findings on Red Lakes

The Red Lakes commercial fishery has been extensively studied. The large historical core of research (and the creation of the large physical collection) was assembled by Dr. Lloyd L. Smith, Jr. and his colleagues. Previous findings have indicated that the two basins do not have separate walleye populations (Smith et al. 1951). Fluctuations of the commercial fishery and the reasons behind those fluctuations have been examined (Smith and Krefting 1953, Smith and Pycha 1960, Smith 1977). Attempts to understand the dynamics of young of the year (YOY) walleye pointed to different influences between the factors that influence growth between young and older walleye (Smith and Pycha 1960). Some studies have focused on yellow perch as a secondary species of interest, with evidence indicating the importance of yellow perch as a food source for young walleye (Smith 1977).

More recent research has focused on creating biochronologies, or characterizing aspects of growth, for walleye and other key species from the fishery (Pereira et al. 1992, Shroyer 1991, Cyterski 1995, Ostazeski 1998). Studies have shed light on the relationships between growth factors and ages (Shroyer 1991). The relationship between growth and other factors such as temperature and the growth or abundance of other species such as yellow perch and freshwater drum have also been examined (Cyterski 1995, Ostazeski 1998).

The work elucidating the relationship between walleye and yellow perch in particular was suggested by previous research in other systems that indicated a predator-prey relationship between the two species. Oneida Lake age-3 walleye had higher mean weights when there were large year classes of young-of-year yellow perch (Forney 1977). In Lake Erie, large year classes of walleye and yellow perch coincided, suggesting that factors influencing walleye and yellow perch year class success were similar (Nepszy 1977). Walleye in Lake of the Woods, Minnesota, and Shagawa Lake were found to consume primarily age-0 yellow perch during summer months, when age-0 yellow perch are active during walleye feeding periods (Swenson 1977). Lake of the Woods yellow perch were also described as having survival most limited by walleye predation (Swenson and Smith 1976). Cyterski (1995) found a relationship between annual walleye environmental growth coefficients and the CPUE from the fishery. Ostazeski (1998) reaffirmed the importance of temperature and yellow perch to walleye growth. Freshwater drum appear to have little direct influence on walleye, although freshwater drum are a major biomass component of the fish community (Ostazeski 1998). These relationships may be useful in predicting the population status of the walleye of the Red Lakes.

Methods

Two models will be examined in order to determine the most appropriate model for the stock and the available data, a Deriso-Schnute delay-difference model and a general catch-at-age model (Deriso 1980, Schnute 1985). More than one model is often used in stock assessments when a variety of information is available. Not all models will reflect population estimates in the same way, and there is no assurance that the most complex model will be the most appropriate to either the data available or the system being examined (Ludwig and Walters 1985). Catch-at-age models were chosen for this research because they are adaptable to local conditions, have proven useful in modeling other fisheries, and, with the advent of modern computing technology, there is no reason not to use the most versatile models that can be used with the data, even if they are analytically complex (Hilborn and Walters 1992). The delay-difference model was also examined because it has been useful in other fisheries (such as some tuna fisheries) to generate supplemental information for the catch-at-age models (Quinn and Deriso 1999, NRC 1998a). Different computational methods for estimating the parameters of age-structured models are also examined as are methods for improving the estimates generated by the delay-difference model.

I present three different methods for computing the catch-at-age model. Multiple computing methods are in use in fishery stock assessment, each with slightly different capabilities and their use by any given agency appears to be based on regional consensus (NRC 1998a). Few studies exist on the relative abilities of different computational programs and those that do find few differences, but using different computational methods remains an area of exploration for determining the most appropriate means for managing stocks (NRC 1998a, Patterson and Kirkwood 1993). The three methods explored here are all readily available. The VPA/ADAPT is a program that is available from the Canadian Department of Fisheries and Oceans (Anon. 2003). The VPA (virtual population analysis) program was created by a workgroup out of the Lowestoft laboratory in England (Darby and Flatman 1994). Finally, there is a method wherein results are calculated in an Excel©[1] spreadsheet (Ianelli 2003).

The results of the various analyses will be compared against levels of observed historical catches through the use of correlation analysis and a concordance sum of squares criterion described below. The three age-structured methods and the delay-difference model will be compared with the Akaike information criterion (AIC) that permits analysis not only of the precision of the estimate but also the number of parameters required to achieve that estimate (Akaike 1973, Buckland et al. 1993). Examining the historical data can identify whether previous data collection methods were sufficient for the models being used in this dissertation and to determine how data collection may be altered in the future to enhance applicability of the models.

The second aspect of my analysis is an attempt to improve the verisimilitude of the catch estimates generated by the delay-difference model. An initial version of this model assumes that growth is constant over time, an assumption that may not reflect the growth exhibited by walleye where growth in any given year may be influenced by a collection of yearly and non-constant environmental factors. In fitting a model of this kind, only the most general characterization of body growth is taken into account, frequently by fitting a Von Bertalanffy growth function, or any of the common fish growth models that fit the stock reasonably well, to obtain estimates of size-at-age. At the

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[1] Microsoft Corporation, Redmond, WA, Excel version 2002 (10.2614.2625)

cost of only a small increase in model complexity, Weisberg growth coefficients (described below), reflecting yearly growth that is influenced by external factors, can be incorporated to allow the model to accommodate a broader range of biological or environmental variability.

Two components compromise fish growth, the amount that a fish will grow because of its age or size already attained and the amount of growth that is influenced by factors found in the external environment. These two factors can be separated through growth coefficients that will be used to reflect year-to-year (Weisberg 1993). These two influences can be teased apart analytically and the coefficients then applied in models where growth is a factor. Age effect coefficients are integrated as a part of growth for all fish through the von Bertalanffy equation and are described in further detail in the modified delay-difference model section below. The year effect for walleye will be included into the growth functions of the delay-difference equation, as well as regressions reflecting the relationship between the coefficients and yellow perch growth measures (year-class strength and year effect coefficients). The full equation for the year effect modifications can be found in the modified delay-difference model section and equation 7. Yellow perch were included because Ostazeski (1998) found a correlation between walleye and yellow perch environmental coefficients. The altered model estimates will be compared to the observed catch estimates using correlation analysis and a concordance sum of squares.

The walleye year coefficients will be correlated to population estimates generated by the catch-at-age methods. This will examine the relationship of these coefficients to the entire simulated population. Previously, catch per unit effort (CPUE) had been correlated with the walleye year coefficients (Cyterski 1995). The CPUE has been, and continues to be, used as a measure of population abundance even though it may not reflect the actual abundance (Hilborn and Walters 1992). The CPUE may exhibit hyperstability in situations where fish are prone to congregating and where the search for fish is highly efficient, which will result in the CPUE remaining high even when the actual abundance is declining (Hilborn and Walters 1992). It is unlikely that this was the situation in the Red Lakes. However, given situations where CPUE may not accurately reflect the stock condition, it would be informative to use the simulated results as another means to determine the usefulness of the walleye growth coefficients as a measure of stock condition.

Coefficients of environmental effect for walleye and the estimates of population abundance were split into three groups using the 1949-1957, 1959-1969, and 1949-1969 time series to determine if there were differences between shorter and longer time series. Generally, longer time series give models a greater ability to track trends. To examine this fully, all three data sets were separated into slightly different time lengths. Also, different data sets, even when only different with connecting two data sets, may behave differently when modeled. It is important to investigate any possible differences that could be driven by differences in the length of the data sets.

Part of the rationale for this simulation study is to characterize the amount of fishing effort that may have resulted in the collapse of the population. Unknown or unreported catch would create a significant problem with estimating the status of the population or in devising a model structure for the population. There is evidence that during the 1960’s, tribal members were selling walleye on a black market in numbers that would not be reflected in the commercial catch statistics. Since the database for the historical analysis relies upon a reported catch, coupled with a reported effort, it was necessary to develop simulations that could arbitrarily accommodate a range of unreported catches that may have arisen in a black market fishery. To address this possibility of a significant black market (BM) catch, the delay-difference model was run using several different assumed levels of BM catch. The basic concept is to vary the simulation of the BM catch until the greatest possible degree of concordance occurs between reported catch and the simulated total catch. In the initial simulation, the base-line model used only catches and corresponding effort (CPUE) reported through the 'official fishery' at the Redby plant. Then, in successive simulations, catch and effort inputs to the delay-difference model were increased by 5, 10, 15 and 20 percent, respectively, in order to simulate the effect of a BM fishery that was removing an unreported (5, 10, 15, or 20 percent relative to the reported catch) quantity of fish from the population. At the level of BM catch resulting in the greatest concordance between observed and simulated catch, the "new" catch and effort levels (which now include the estimated BM catch) would be used to generate a new catch-at-age matrix, assuming that the age proportions of the catch would be the same. In this way, the two population models, catch-at-age and delay-difference, would interact with each other to produce the greatest possible agreement between the age structure of the population and the historical record of catch. Then the spreadsheet catch-at-age method will be used to determine annual fishing mortality rates (F) that include the black market catch. From these estimates, the unknown fishing effort can be estimated. There may also have been underreporting or inaccurate reporting of catch and possibly effort by the fish plant in

Redby. Currently, this is hypothetical and there is very little anecdotal evidence with which to base estimates of mis-reporting by the plant on top of black market catch. Therefore, only black market catch adjustments were made for this dissertation.

Delay-Difference model

Model

The delay-difference model (Deriso 1980, Schnute 1985) is based on several equations that break the total fishable biomass into component parts. The equation for the delay-difference model is (Hilborn and Walters, 1992):

$$B_t = s_{t-1}B_{t-1} + \rho s_{t-1}B_{t-1} - \rho s_{t-1}s_{t-2}B_{t-2} - s_{t-1}\rho w_{k-1}R_{t-1} + w_k R_t \quad \text{(eq. 1)}$$

where B_t is the fishable biomass at time t, s_t is the survival rate at time t, w_k is weight at age k (age k fish are at the age of full recruitment), R_t is the number of recruits at time t, and ρ is a growth parameter. The first term of the equation is an estimate of the surviving fishable biomass. The second term estimates the amount of growth that has occurred for that existing biomass. The third and fourth terms remove growth attributed to previous years or ages. The final term adds the biomass that will recruit into the fishery that year.

A mathematical simulation to calculate the fishable biomass was created using Microsoft Excel©. Procedures for running the model are detailed in Appendix 1. The spreadsheet simulation requires some estimation of initial parameters, including fishable biomass and number of recruits prior to the beginning of the time series, the catchability coefficient (q), and ρ. The catchability coefficient is used to calculate the predicted catch biomass from the estimated fishable biomass, and the subsequently calculated predicted CPUE. Note that rho, ρ, is an individual body growth parameter used here to index the fish populations' growth response (see Growth section, below).

The simulation is tuned using the Solver function of Excel©, which utilizes a non-linear optimization algorithm to minimize the residual sum of squares for the catch-per-unit-effort (CPUE) by altering four values; *q*, estimated fishable biomass for the two years prior to the first year of analysis, and the number of recruits for the year previous to the first year of analysis[2]. The Solver function iteratively alters the adjustable cells to arrive at a specified optimum to minimize the likelihood error function; the closest agreement between the predicted and actual values. The Solver was set for 100 iterations, time stop at 100 seconds, 0.000001 precision, 5% tolerance (the percentage of allowable error), and 0.0001 convergence[3]. The estimated fishable biomass and *q* are used to compute the predicted catch biomass for each year. Then a predicted CPUE is computed, with residuals found by subtracting the predicted and actual CPUEs.

Input data

Catch biomass

The input data for the model are taken from the catch statistics from the commercial fishery. The catch is measured in kilograms of walleye (Appendix 2, Table A.2.1). There are two commercial grades of walleye, with the cull walleye consisting of walleye less than 0.45 kilograms (one pound) that were sold for animal feed. These records were kept as a standard part of the commercial records at the Redby, Minnesota, fish processing plant.

Catch, effort and CPUE

The fishing effort was recorded from the commercial walleye fishery. Gear type was relatively well-standardized in recent decades by having the Fishery Association

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[2] Article by Wittwer, J. at: http://www.vertex42.com/ExcelArticles/excel-solver-examples.html
[3] Article by Microsoft at: http://support.microsoft.com/default.aspx?scid=kb;en-us;q82890

plant at Redby supplying the nets to the fishermen. The commercial gear throughout the time series consisted of bottom-set gill nets of 8.89 cm (3 inch) mesh, stretched measure, approximately 91.44 m (300 feet) in length, soaked overnight. The unit measure for the effort statistics was 5 net lifts. The numbers of 5-net lifts are collected as part of the standard commercial statistics. The commercial catch per unit effort (CPUE) is computed from the catch biomass and the fishing effort statistics (Appendix 2, Table A.2.1).

Weight at age

Weight at age k (w_k) from equation 1 was estimated to be the average weight at age 4, chosen because of the result of a previous catch-curve analysis that found the minimum age at full recruitment to be ages 4 or 5 (Smith and Pycha 1960). Following this logic, w_{k-1}, or the weight for the age before full recruitment, was determined by the average weight of walleye at age three.

Survival

There are no existing estimates of the survival rate for walleye from Red Lakes. As it is unlikely that survival is constant over extended periods of time, an annual survival rate was determined for each year (Quinn and Deriso 1999):

$$s_t = exp(-M - q\,E_t) \qquad \text{(eq. 2)}$$

where M is the natural mortality, q is the catchability, and E_t is the fishing effort at time t. Both natural mortality and catchability are held constant through time at 0.20 and 3.42E-02, respectively, and fishing effort is in five-net lifts divided by 1000.

Recruitment

The delay-difference model is dependent on the recruitment relationship with the previous stock size. The two most commonly used stock-recruitment functions are Beverton-Holt curves or Ricker curves. Which relationship is used depends on the level of density dependent recruitment response exhibited by the population. Beverton-Holt recruitment relationships incorporate density-dependent survival rates. These survival rates incorporate intraspecific competition between cohorts (Hilborn and Walters 1992). The relationship is based on the idea that the larger the spawning stock, the faster the juveniles will die, resulting in the overall appearance of these functions, approaching asymptotic recruitment at high parental population densities. The Ricker model differs by having a relationship that does not reach an asymptote but instead peaks at mid-level parental abundance and declines regularly in recruitment at very high levels of parental stock (Ricker 1954).

To determine the best stock-recruitment relationship, the estimated CPUE was used as an index of (parental) abundance and the estimated numbers at age 2 were an index of the number of recruits. A comparison method (Haddon, 2001) was used to determine which relationship is most appropriate for the Red Lakes walleye (Figure 2). The parameters required for the recruit estimation are *a* and *b*, the intercept and slope of the regression for the stock-recruitment relationship; from Ricker (1954):

$$R = aSe^{-bS} \qquad \text{(eq. 3)}$$

where R is the recruitment, S is the spawning stock, a is the recruits-per-spawner at low stock levels, and b is the decreasing rate of recruits per spawner as S increases.

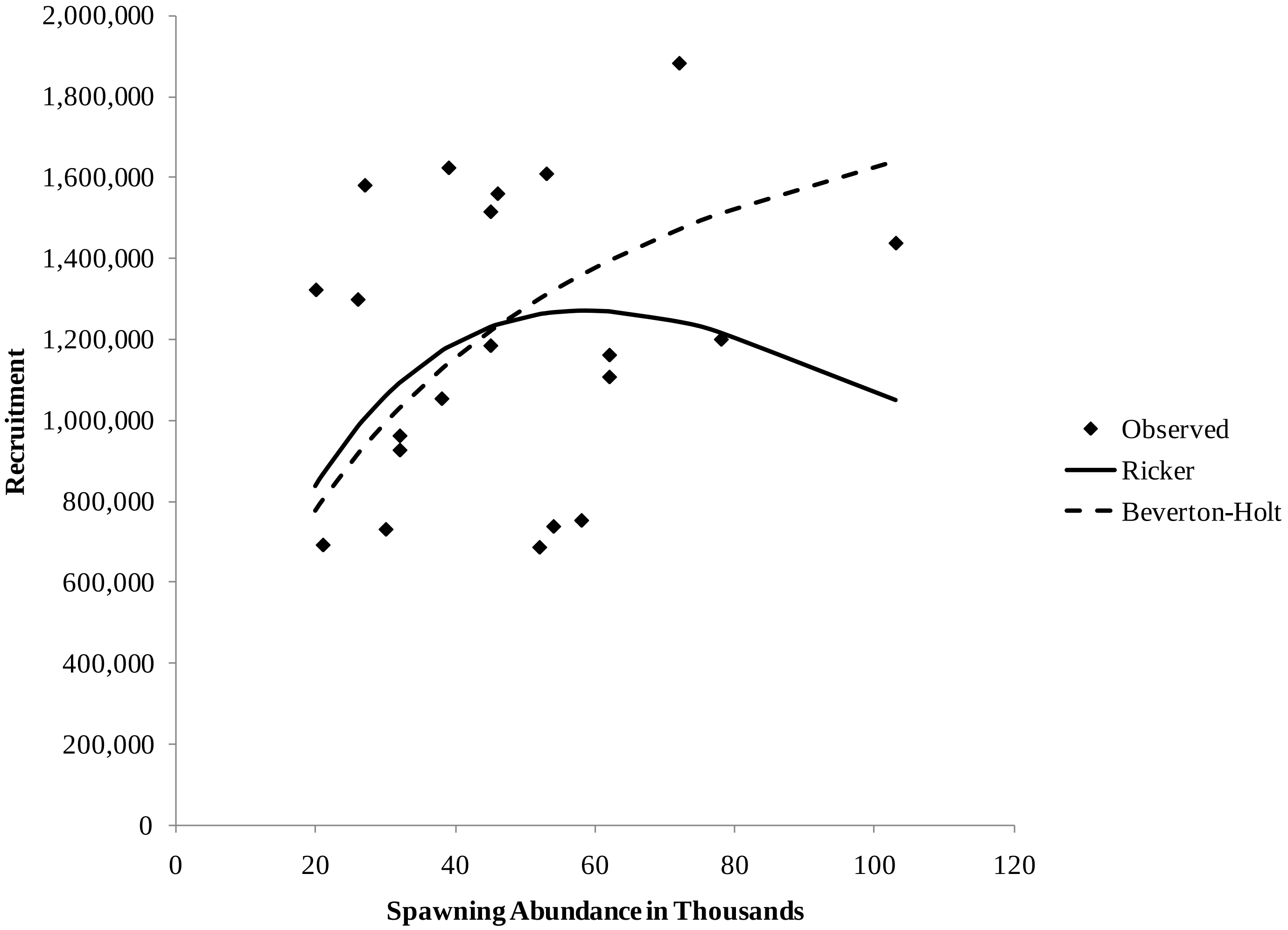

Figure 2: Ricker and Beverton-Holt stock-recruitment relationship for Red Lakes walleye.

The means for determining the number of recruits depends on whether or not the gear recruitment is knife-edged, where virtually all the recruitment happens within a short time period, for example, within a single age. If recruitment is not knife-edge, it will involve different age-classes comprising different percentages of the total recruitment class for that year. The Red Lakes walleye fishery does not experience knife-edge recruitment to the gear, rather, annual recruitment includes portions of ages 2, 3, and 4. The relationship is shown in the equation (Hilborn and Walters, 1992):

$$R_t = \sum_{j=k_1}^{k_2} p_j R'_{t-j} \qquad \text{(eq. 4)}$$

where p_j is the proportion of the total recruitment comprised of fish that will recruit at weight w_k after year j. The proportion of total recruitment was based on estimated from the age structured models at age, converted using average weight at age. Summing the relationship yields total recruitment in numbers at time t (R_t). The method yields a value of R_t (annual recruitment) that is a running average of more variable past recruitment rates, and the result will be generally less variable over time (Hilborn and Walters, 1992).

Growth

The delay-difference model includes the surviving population from the previous year and the increase in population biomass resulting from individual body growth that occurred during the year. The von Bertalanffy growth curve is one standard method for determining individual fish growth. It expresses growth as a sigmoid function where the increase in annual growth decreases as the fish reaches successively greater ages. The general equation for these plots is:

$$l_{t+T} = L_{\infty}(1 - e^{-KT}) + l_t e^{-KT} \quad \text{(eq. 5)}$$

where *l* is the length, *t* is time, *T* is the increase in time, κ is a growth parameter with units t^{-1} and L_{∞} is the length at which the fish reaches an asymptote of growth. The required data to construct the von Bertalanffy growth model denoted in equation 5 is fish lengths at time t and t+1, i. e. L_t and L_{t+1} (Gulland 1983). Fitting a linear model to the variables in eq. 5 results in the Ford-Walford plot where T=1 (corresponding to one years' growth), with slope, Rho:

$$\rho = -(1 - e^{-K}) \quad \text{(eq. 6)}$$

The factor that is used in the delay-difference equation is ρ, the rate at which growth to maximum size occurs (Gulland 1983).

Weisberg Coefficients and Model Variants

The basic Weisberg growth model postulates the annual growth increment as a linear combination of age-related growth and year-related growth. Conceptually, the model can be expressed as (Weisberg 1993):

Expected annual growth increment = age effect + year effect

The annual growth can be determined through the examination of hard part aging structures, such as scales, spines, or otoliths from fish of known ages. Ostazeski (1998) used scales for the aging and increment data. The walleye and yellow perch scale samples were a subset of the archived hard parts collection at the University of Minnesota, the Red Lakes Band of Chippewa Indians' Department of Natural Resources and the Minnesota Department of Natural Resources. The year effect coefficients are values that are relative to the aliased year used in the original analysis. Therefore, the aliased year is the baseline for all other years. For the analysis done by Ostazeski (1998), the year chosen for the aliased year was the last year in the analysis, 1996. There is no evidence that the aliased year was an inappropriate choice in any of the previous work. The current aliasing approach to obtaining year effect coefficients is a particularly powerful framework in the simulation, as an alternative alias can be chosen as necessary if additional information becomes available on significant growth factors in the future. Greater detail on the aging techniques and protocol can be found in Shroyer (1991), Cyterski (1995), and Ostazeski (1998).

It should be noted that the age effect coefficients only cover ages one through six, which is less than the assumed maximum age of the fish, because of previously reported unreliability in aging past age six from scale samples.

Delay-Difference Modifications

The delay-difference model (equation 1) was modified to include greater response latitude in the year effect coefficients, as follows:

$$B_t = s_{t-1}B_{t-1} + \rho s_{t-1}c_{t-1}B_{t-1} - \rho s_{t-1}s_{t-2}c_{t-2}B_{t-2} - s_{t-1}c_{t-1}\rho w_{k-1}R_{t-1} + w_k R_t \quad \text{(eq. 7)}$$

with c representing the walleye year effect coefficient. For the reasons described above, a method was devised to use the walleye year effect coefficients to accommodate year-to-year variations in growth rather than assuming a von Bertalanffy growth factor that remains constant through time. It was expected that including a year effect would more accurately reflect the variation in fishable biomass and the subsequent estimates of predicted catch. Year effect coefficients (c) in equation 7 thus modify the von Bertalanffy growth factor to allow for a greater expression of year-to-year growth variation.

I constructed six variants of the delay-difference model (Table 1) to examine four different values of the year-effect coefficient, *c*, along with two treatments without a value of *c* included. Each of the delay-difference model variants were fitted to four time periods (1949-1957, 1959-1969, 1949-1969, and 1949-1996). The first three time periods were chosen to be comparable with age-structured model runs (see the Age-Structured" section for further explanation for those time periods) and the final time period was the longest available continuous data series. Inputs to each of the variants described in Table 1 are presented in greater detail below.

Table 1: Labeling conventions for different growth variable combinations examined in the delay-difference models.

Label	Model	Description
DDM1	Equation 1	Growth factor ρ only, calculated using the average total walleye lengths at time t and time t+1 (traditional calculation of ρ from Walford plot--Equations 4 and 5)
DDM2	Equation 1	Growth factor ρ only, calculated using the Weisberg age effect coefficients for walleye from ages 2 to 6--See text and Table 2
DDM3	Equation 7	Growth factor ρ and factor *c*, with *c* values from the Weisberg year effect coefficients for walleye-- See text and Table 2
DDM4	Equation 7	Growth factor ρ and factor *c*, with *c* values from the regression of walleye year effect coefficients and yellow perch year effect coefficients-- See text and Table 2
DDM5	Equation 7	Growth factor ρ and factor *c*, with *c* values from the regression of walleye year coefficients and yellow perch year coefficients from two eras, 1949-1982 and from 1983-1996-- See text and Table 2
DDM6	Equation 7	Growth factor ρ and factor *c*, with *c* values from the regression of walleye year effect coefficients and yellow perch year-class strength from the same year-- See text and Table 2

The different *c*-values for input to models using equation 7 were derived from previously published (Ostazeski 1998) Weisberg coefficients that express year to year growth variation in walleye and perch in the Red Lakes. The base model, DDM1, adheres strictly to the general delay-difference model described by equation 1. It does not include a value of *c* and uses a value for ρ computed from a Ford-Walford plot according to equations 4 and 5. The DDM1 also corresponds with equation 7 where all *c*-values are set to 1.0.

DDM2 also does not include *c*, but Rho (ρ) is calculated using the age coefficients determined by Ostazeski (1998). The age coefficients were used to fit a Walford plot, which resulted in a rho of 0.7389 rather than the traditionally calculated value of 0.6573. The age coefficients were substituted for the previously calculated size at age for fitting the Walford plot. It was anticipated that the change in size-at-age estimates used would change the slope of the Walford line (ρ). DDM2 calculations include ages 2-6 to be consistent with the age range available for the DDM1 calculation of the Walford plot. Attempts to understand the dynamics of young-of-year (YOY) walleye pointed to different influences between the factors that influence growth between young and older walleye (Smith and Pycha 1960).

DDM3 used the estimated walleye year effect coefficient for each of the calendar years in the model, respectively. Including the walleye year coefficients as multipliers to growth would allow for the amount of growth that occurred that year to vary. Currently, population growth will be the same every year, only varied by the numbers of fish in the population to grow. It does not take into account natural variations in weather and other environmental conditions that may improve or impede growth. Also it cannot take into account population-driven changes in growth.

The remaining delay-difference models, DDM4-DDM6, used estimates of the growth coefficients for Red Lakes yellow perch and walleye in various combinations, and the index of yellow perch year-class strength, to compute *c*-values for modeling with equation 7. Previous research has shown a predator-prey relationship between walleye and yellow perch, therefore modeling the relationship between walleye and yellow perch year coefficients was thought likely to be instructive in understanding the dynamics of the walleye fishery. As noted earlier, strong ecological linkages, specifically an inverse relationship with respect to growth, have been shown between walleye and yellow perch (Ostazeski 1998). This idea was incorporated in the historical modeling of the Red Lakes fishery by using two approaches. The first approach is a general regression model, and the second divides the yellow perch time series into two periods of several years, each of which had markedly different relationships to walleye growth. Table 2 summarizes all the *c*-value coefficients and the models to which they apply. DDM4 used a *c* value from a regression between the walleye year coefficients and the yellow perch year coefficients in each of the years for 1949-1996 (Table 2, column 5). A linear regression was selected as Ostazeski (1998) had previously determined an inverse relationship through the use of a linear-based method, a Pearson's correlation analysis. The yellow perch year coefficients were regressed against the walleye year coefficients (Table 2, column 6), according to:

$$y = -0.4566x + 1.4289 \qquad \text{(eq. 8)}$$

Table 2. DDM values for the c conversion factor for each run. Asterisks indicate years not included in those analyses. DDM1 and DDM2 have c conversions factors of one as they lack the environmental growth component.

Year	DDM1	DDM2	DDM3	DDM4	DDM5	DDM6
1947	*	*	*	*	*	1.0374
1948	*	*	*	*	*	1.0304
1949	1.00	1.00	0.99	1.13	0.97	1.03
1950	1.00	1.00	0.81	1.25	0.84	1.17
1951	1.00	1.00	1.85	1.10	1.00	1.22
1952	1.00	1.00	1.03	1.10	1.00	1.04
1953	1.00	1.00	0.90	1.06	1.05	1.04
1954	1.00	1.00	1.01	1.09	1.01	1.02
1955	1.00	1.00	1.06	1.02	1.09	1.03
1956	1.00	1.00	0.97	1.07	1.03	1.02
1957	1.00	1.00	1.07	1.11	1.00	1.02
1958	1.00	1.00	0.81	1.07	1.04	1.06
1959	1.00	1.00	0.91	1.08	1.03	1.07
1960	1.00	1.00	1.29	0.98	1.13	1.09
1961	1.00	1.00	1.23	1.09	1.01	1.03
1962	1.00	1.00	0.83	1.07	1.04	1.02
1963	1.00	1.00	0.79	0.99	1.12	1.03
1964	1.00	1.00	1.21	1.08	1.03	1.20
1965	1.00	1.00	0.79	1.10	1.00	*
1966	1.00	1.00	1.36	1.04	1.07	*
1967	1.00	1.00	0.86	1.04	1.07	*
1968	1.00	1.00	0.77	1.11	1.00	*
1969	1.00	1.00	1.18	1.11	1.00	*
1970	1.00	1.00	1.24	1.03	1.07	*
1971	1.00	1.00	0.82	1.05	1.06	*
1972	1.00	1.00	0.64	1.23	0.86	*
1973	1.00	1.00	0.66	1.16	0.94	*
1974	1.00	1.00	1.15	1.00	1.11	*
1975	1.00	1.00	0.99	1.08	1.02	*
1976	1.00	1.00	1.02	1.11	0.99	*
1977	1.00	1.00	1.09	1.53	0.53	*
1978	1.00	1.00	1.05	1.53	0.53	*
1979	1.00	1.00	1.10	1.08	1.03	*
1980	1.00	1.00	0.90	1.11	0.99	*
1981	1.00	1.00	0.94	1.09	1.01	*
1982	1.00	1.00	0.94	1.10	1.01	*
1983	1.00	1.00	1.24	1.03	1.19	*
1984	1.00	1.00	1.19	1.06	1.22	*
1985	1.00	1.00	1.02	1.12	1.29	*
1986	1.00	1.00	1.30	1.18	1.36	*
1987	1.00	1.00	1.38	1.19	1.38	*
1988	1.00	1.00	1.30	1.13	1.30	*
1989	1.00	1.00	1.33	1.24	1.43	*
1990	1.00	1.00	1.55	1.19	1.37	*
1991	1.00	1.00	1.70	1.12	1.29	*
1992	1.00	1.00	1.04	1.20	1.38	*
1993	1.00	1.00	1.13	1.22	1.41	*
1994	1.00	1.00	1.47	1.18	1.36	*
1995	1.00	1.00	1.55	1.25	1.44	*
1996	1.00	1.00	1.72	1.33	1.53	*

where y is the walleye year coefficient and x is the yellow perch year coefficient without a time lag incorporated, which assumes that the yellow perch environmental growth could predict that year's walleye environmental growth from the linear regression (Figure 3). These values were then used to define c as the dependent variable of a linear regression through the equation:

$$c=\alpha*(\text{yellow perch year coefficient})+\beta \qquad \text{(eq. 9)}$$

As Ostazeski (1998) found that the relationship between walleye and yellow perch coefficients improved when separated into two time periods, DDM5 used two regressions of the walleye and yellow perch year coefficients as the basis for the c conversion factor. Regression determined values were $\alpha = 0.5279$ and $\beta = 0.5322$ for the 1949-1982 time period and $\alpha = -0.5706$ and $\beta = 1.7758$ for the 1983-1996 time period.

The final variant of the delay-difference model, DDM6, used Ostazeski's (1998) relationship between the walleye year effect coefficients and previously calculated yellow perch year-class strengths (Table 2, column 7). Ostazeski (1998) found a relationship between walleye and yellow perch year-class strength. Regression values were $\alpha = 0.0005$ and $\beta = 1.0129$.

Age-Structured Model

Inputs and Parameters

As mentioned previously, age-structured models have different and a greater number of data inputs and parameters when compared to the delay-difference model.

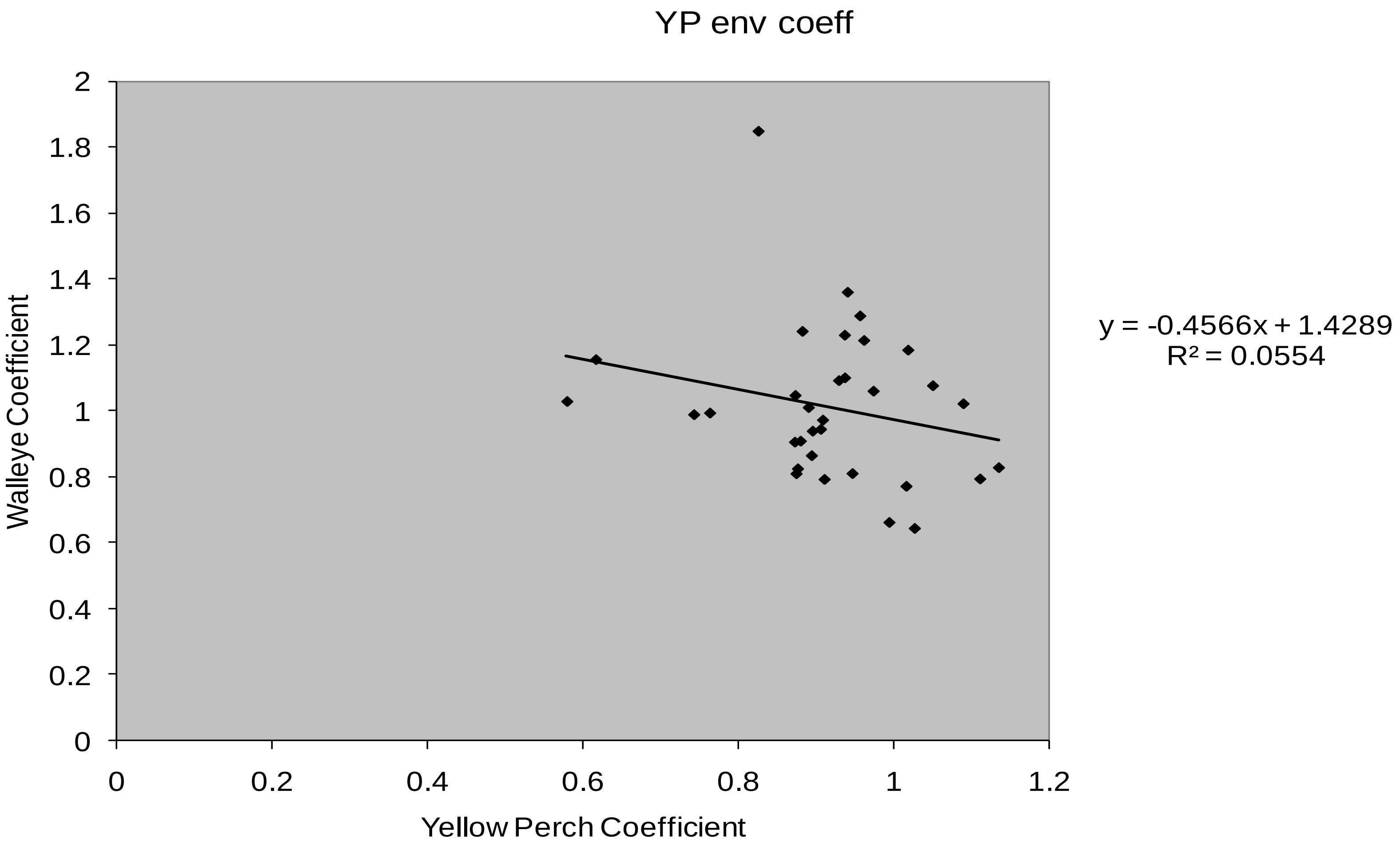

Figure 3: Regression of yellow perch and walleye coefficients as described by DDM4.

The central focus of the age-structured models applied here, ADAPT, VPA, and the Ianelli spreadsheet, is the catch-at-age matrix.

Catch-at-age

The typical procedure for catch-at-age analysis is to have ages for a portion of the commercial catch, then extrapolate those data to the entire catch. Catch-at-age data were not kept for the total numbers of fish caught for the Red Lakes walleye fishery. Instead, total biomass was recorded. The recommended procedure is to determine the proportion of numbers to biomass following Quinn and Deriso, 1999:

$$\hat{C} = {}^{Y}\!/_{W} \qquad \text{(eq. 10)}$$

where C is the catch, Y is the fishery yield in biomass, and W is the mean weight of the fish in the catch. Equation 9 can be modified to incorporate fish at a particular age and weight at that age. A modified equation would be denoted as:

$$C_{a,t} = Y_{a,t}/W_{a,t} \qquad \text{(eq. 11)}$$

where $C_{\mathrm{a,t}}$ is the catch at age a in year t, Y is fishery yield at age a in year t, and W is the mean weight of age a in year t.

Numbers of fish were not part of the recorded catch statistics, as is common when dealing with commercial catches. Instead, the total catch is recorded in biomass, thus the need for a conversion to create the catch-at-age. Samples taken from the commercial gillnet fishery (mesh size was 8.89 cm (3-in) stretch mesh) were the primary basis for determining the age- and size-composition for the index. For the years 1949-1957, the catch-at-age was taken from baseline data used for analysis by Smith and Pycha (unpublished, Table A.2.1), though not published in this form. For the years 1959-1969, the catch-at-age was generated using the conversion described by Smith and Pycha

(1960), which is the more detailed procedure they used to create the relatively simple relationship described in equation 10, as follows. A sample of the catch was aged and, for 1959-1969, the samples for all years were combined to create a single age-length key (Table A.2.2 and A.2.3). Then the larger sample of length only records was applied by year to the age-length key. The age-length key was separated into 0.3 inch intervals. The total weight for each interval was calculated by multiplying the number of fish per interval by the average weight of that interval, and then totaled to create the total weight of the sample. Then, the total biomass of the catch was divided by the computed total biomass for the sample. These values were used to create the proportional difference between the catch and sample, with the assumption that the biomass proportion would have been the same as that for the numbers of fish. The numbers of fish at age in the catch for that length interval were estimated by multiplying the numbers of fish at age in each length interval by the proportion. Then the numbers per age were summed to create the catch-at-age for that year. I excluded any length frequency data outside the available length-at-age series. The generation of the catch-at-age is illustrated in appendix 3 with examples of the spreadsheets inserted.

No scale samples were aged in 1958, therefore the cohorts are averaged forward from 1957 and backward from 1959 to create an estimate for that year for each cohort. A separate calculation was made for cull and commercial grade walleye. The commercial grade required a particular age-length key, incorporation of length-only data, estimation of average weights per length bin, and the total weights per bin (Table A.2.2). The culled sample was calculated using the same methodology as the commercial grade, but also had a separate age-length key, length frequency, and average and total weights per bin (Table A.3.3).

Indices

Each of the models may use different indices to estimate the actual abundance of the population. In the ADAPT model, the CPUE at age is the tuning index, as the catch and effort both come from the commercial walleye fishery and are known. The same catch-at-age matrix (Table A.2.1) computed with the commercial information is divided by the measured effort from the commercial fishery in number of 5-net lifts.

A fishery independent index is one that is not collected as a part of an active fishery. Typically, independent indices are better at reflecting population changes if index sampling is sufficiently intense and well-designed. Eight years of fishery independent data were usable over a 9-year span from 1949-1957. The comparison of 1949-1957 results are the only ones that contain the fishery independent index as the following method, the Lowestoft VPA, cannot utilize the index unless it shares the same terminal year as the entire data set analyzed.

The Lowestoft VPA uses catch-at-age and CPUE by year for the fishery dependent and independent indices. These analyses were conducted using the Ad Hoc calculation method rather than the separable VPA. A separable VPA separately estimates the fishing mortality by age and year and the selectivity by age and year. The Ad Hoc method involves the estimation of many more parameters than non-separable calculation methods, which will typically hold the selectivity at age constant over time. The term non-separable means that the calculation method does not separate exploitation fraction into time-dependent exploitation for fully recruited fish and age-dependent gear selectivity (Quinn and Deriso 1999). The spreadsheet method does not include the catch-at-age but uses an independent index to estimate a survey biomass (Table A.2.2.) based on the relationship:

$$n = CPUE/q \qquad \text{(eq. 12)}$$

where n is the estimated survey biomass, CPUE is the survey index catch-per-unit effort, and q is the estimated catchability of that index. Catchability was estimated internally for both these models using both DeLury (1947) and Leslie (Leslie and Davis 1939) methods rather than estimated externally using alternate data.

Biomass Measures

The estimated biomass of the fishery depended upon the computational method used. One means is to include the total catch biomass for the year as a separate data input. This measure of biomass is used as a part of the separable VPA and the spreadsheet catch-at-age method. The ADAPT model does not explicitly use biomass. The two other methods use an estimated catch biomass that can be compared to the observed catch biomass to determine the fit of the model, or be included in the minimizing calculations to fit the model.

The separable VPA and the spreadsheet catch-at-age were measures of average individual fish weight-at-age. The spreadsheet method used the same weight-at-age through the entire time series, which implicitly assumes that there were minimal differences in weight-at-age from year to year. The separable VPA used two measures for fish weight-at-age. One was the weight-at-age for the catch. The other was the stock weight-at-age, a measure that reflected the weights of fish at age in the total population. The stock weight-at-age may be observable by fishery independent sampling. Catch weight-at-age may be used in the absence of a good measure of stock weight-at-age (Darby and Flatman 1994). Weight-at-age was computed from the length-weight equation determined by Smith and Pycha (1960) then converted into weight-at-age from the numbers of lengths at age for all these inputs (see Appendix 3, steps 6-8 for relevant computation techniques). For the spreadsheet model only, the weight-at-age was averaged over the entire time period, thus the weight-at-age was assumed constant over the time period analyzed. Weight-at-age was kept constant to determine true differences in the model and computation rather than differences in the data inputs. Catch weight-at-age was used instead of stock weight-at-age for all years in the separable VPA.

Natural Mortality

There were no previously published measures of natural mortality for Red Lakes walleye. All of the computational methods for the catch-at-age analyses require the input of a level of natural mortality. Using the Hoenig (1983) formulation, M estimated at approximately 0.27 with a maximum age of 16, the oldest age in the collection. The Hoenig method assumes that the maximum age of a species is necessary to know the average natural mortality for all ages of the species. The M estimate was 0.27, which was considered high for the productivity of the system. The oldest reported age for walleye was 29, though the original reference for that source could not be determined. The Lake Erie Walleye Task Group for the Great Lakes Fishery Commission has used natural mortality levels ranging from 0.218 historically to more recent values of 0.18 for the eastern basin (GLFC 2005). The western and central basins had higher values of 0.32. Recent values were determined through mark-recapture studies. Given this range of values, the 0.2 value is in line with other estimations of walleye M in other systems. Natural mortality was assumed constant over time and for all ages that were vulnerable to the fishery.

Catchability

All the computational methods require some measure of catchability or vulnerability to the fishing gear. The separable VPA has the catchability levels set by the user. Previous Red Lakes research indicated that walleye are fully vulnerable to gillnets used at the Red Lakes by age 4 (Smith and Pycha 1960, Smith 1977), therefore vulnerability for age 4 was set at 1.0, and ages 2 and 3 were set proportions of catchability at less than one to reflect the gradual recruitment to the gear across younger ages, with ages older than 4 allowed to estimate a selectivity at some number below 1.0.

ADAPT determines the relationship between the numbers caught in the fishery gear and the proportional population relationship. This means that the numbers caught in the gillnet fishery are proportional to the estimated population by a determined proportional value, which is the catchability. This is the relationship only for the fully selected ages. Ages 5 and older, except for age 10+, had a proportional relationship with the population abundance, in accordance with the assumption that after age-5 all fish were fully available to be caught. Ages 2 through 4 and age 10+ were set as a trend relationship with the abundance. The trend relationship means that the model calculates the catchability values based on existing trends estimated for the proportional ages (5 through 9). The plus group, which is all fish age-1 and older, was found to require a different abundance relationship than was used for any of the other ages (2-9) through tuning runs. Tuning runs were conducted in this situation by beginning the runs at the same "reasonable value guesses", then adjusting the different assumed calculated relationship for age-10 and older. There were four different calculation methods and each was run and the model was examined for the best overall fit by examining the residual sum of squares.

Computational Methods

The ADAPT method, the separable VPA, and the spreadsheet catch-at-age models that were applied to the historic Red Lakes data are all variations of age-structured models. The three methods analyze fishery data in slightly different ways. Conceptually, they track the numbers of fish in each age group as they move through the fishery. Summed age groups comprise the total fishable population. Catch-at-age models can be generally formulated:

$$N_{a+1,y+1} = N_{a,y} e^{-M} e^{-s_a \hat{F}_y} \quad \text{(eq. 13)}$$

where $N_{a,y}$ is the fish abundance of age a in year y, M is natural mortality, s_a is the selectivity of age a, $\hat{F}_y$ is the fitted fishing mortality rate in year y (Haddon 2001). In other words, the abundance of fish of a particular age in a given year is the result of the abundance of the cohort in the previous year, times the exponentials of both natural and fishing mortality. This formulation allows for tracking a year-class as it moves through the fishery, thus exhibiting the overall composition of the standing stock in year-classes available to the fishery.

ADAPT model

ADAPT is a backward-calculating method that is also non-separable and minimizes a weighted sum of squares to calculate parameter estimates (Gavaris 1988). The standard backward-calculation equation follows (Pope 1972):

$$N_a = N_{a+1}\, e^{M} + C_a\, e^{M/2} \qquad \text{(eq. 14)}$$

where N_a is the population in numbers at age a, N_{a+1} is the population numbers at age $a+1$, M is natural mortality, and C_a is the catch at age a.

As before, the term non-separable means that the calculation method does not separate exploitation fraction into time-dependent exploitation for fully recruited fish and age-dependent gear selectivity (Quinn and Deriso 1999). Terminal abundance is estimated for each age, fishing mortality at age and year, and catchability at age (Gavaris 1988).

ADAPT incorporates external data sources, like the fishery dependent index, for tuning the VPA (Gavaris, 1988):

$$I'_{i,a,x} = q_{0,i,a} + q_{1,i,a} N_{a,x} + \varepsilon = I_{i,a,x} + \varepsilon \qquad \text{(eq. 15)}$$

where q_0 and q_1 are calibration coefficients for the indices and age, which are estimated internally by the model for each external data source and are not input. Model estimates of population numbers at age and year ($N_{a,x}$) are calibrated to estimate index values with error. These estimated indices are compared to and minimized against the observed index values. The minimization process using the indices iteratively solves for the population numbers at age. The procedure for running ADAPT is located in the help guide associated with the program (Anon 2003) and the data and parameter settings for all three time periods analyzed (1949-1957, 1959-1969, 1949-1969) can be found in Appendix 4.

ADAPT also requires that the catch-rate be incorporated as input data and that some parameters must be set, the catch-rate and the fishing mortality ratios. Catch-rate, defined as CPUE at age, was determined by dividing the elements of the catch-at-age matrix by the fishing effort for that year. The F ratio for the plus group must be set in relation to the last non-plus age group (age 9) when the final age group is a plus age group. The Red Lakes catch-at-age ended in a 10+ age group, which means that the F ratio must be set in relation to the age 9 group. The 10+ age group was set at a ratio of 1 to the age 9 group.

VPA analysis

A separable VPA calculates fishing mortality assuming that the exploitation pattern is constant over time, reducing the number of parameters to be estimated when compared to the ADAPT method (Pope and Shepherd 1982). The separability assumption accounts for factors that may cause fishing mortality (F) to vary by age, year or both (Doubleday 1976, Pope 1977). The separable VPA option in the Lowestoft VPA suite of VPA calculation methods was chosen as it is a particularly useful method when tuning indices are variable. Commercial CPUE at age indices that were used as tuning indices could vary greatly, ranging from over 300 fish per trip at age to 2 fish per trip. Catch and effort both vary greatly year to year, depending on the amount of estimated culled catch. The Lowestoft VPA, like ADAPT, is also a backward calculating method that follows equation 13. The inputs for this method are catch-at-age, catch biomass, stock and catch weights-at-age, and the proportions mature at the start of the year, population experiencing fishing mortality before spawning and population experiencing natural mortality before spawning. It is also necessary to input the catch biomass for each year being computed in addition to a catch-at-age matrix. Methods for calculating the mean weight of the catch and the mean weight of the stock at age per year were described previously. The mean weights-at-age were taken from catch-at-age estimates.

Three additional proportional matrices need to be estimated for the separable VPA. The matrix of the proportion mature at the start of the year was estimated from the age when the fish enter the fishery (age two) until fully mature at age five (Table 3). Only the vector of maturity is presented as estimated maturity is held constant for all years. The matrix contains the same data used to create the proportional recruitment in the delay-difference model. Two proportions experiencing either fishing or natural mortality before spawning also need to be set. These proportions were set at zero for all years and ages in the absence of reliable estimates and as they are matrices of zeroes for all ages and years, they are not replicated here.

Table 3: Vector for proportion mature at start of year, vector only for separable VPA.

Age	2	3	4	5	6	7	8+
Est. Maturity	0.00	0.50	0.50	1.00	1.00	1.00	1.00

It is also necessary to estimate the terminal F and terminal S (terminal selection value for oldest independent age). It is also necessary to estimate a reference age, the age at highest level of catch, which does not affect results but may cause unusual program behavior (Darby and Flatman 1994). If the reference age is chosen to be an age in the partial recruitment period, then selection values will be greater than one where fully selected ages should be one. If the reference age is chosen too close to the maximum age, then the program is prone to crashing. The reference age should be the first age when fish are fully recruited (Darby and Flatman 1994). Walleye were previously assumed fully recruited to the gillnet fishery at age 4.

A detailed description of running a separable analysis can be found in the user's guide (Darby and Flatman, 1994). The input data are listed in appendix 3.

Spreadsheet model

An Excel© spreadsheet (J. Ianelli, personal communication)[4] uses the Excel© solver function to minimize five arrays of residual sums-of-squares, including estimates of catch biomass, catch number, independent survey abundance (where applicable), yearly recruitment coefficients, and annual fishing mortality. These arrays can be weighted. The weighting structure assumes that the catch is a reflection of the population abundance and not simply a reflection of availability, but also assumes that the catch-at-age matrix was not generated without error. The catch-at-age was given a lower weighting value and the catch biomass given a higher weighting value. The catch biomass was given a higher weight because typically the weight of the actual catch is the best known statistic for a fishery (J. Ianelli, personal communication). The catch-at-age was weighted lower because the catch-at-age is not known exactly. This assumption is made because the catch-at-age is actually an extrapolation and that may have ageing error present. When the survey values were included for the 1949-1957 time span, the survey was given lower weighting values because of what appeared to be unusually low estimates.

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[4] Alaska Fisheries Science Center, NMFS/NOAA, 7600 Sand Point Way N.E., Building 4
Seattle, WA

The spreadsheet model is a forward calculating method, specifying numbers-at-age according to:

$$N_a = R\, e^{-\Sigma F - \Sigma M} \qquad \text{(eq. 16)}$$

where R is the initial cohort strength (Doubleday 1976, Paloheimo 1980, Methot 1989). Other inputs were the estimated catch-at-age, the observed catch biomass, and the average weight-at-age. The average weight-at-age estimates are constant over the time series unlike the specific weight-at-age estimates used in the separable VPA analysis. Therefore, estimates were generated by finding the total biomass at age over the time series divided by the total number of estimated fish at age for the entire time series. Detailed instructions on how to use the spreadsheet can be found in appendix 4. The catch-at-age and biomass data were gathered from tables A.2.1 and A.2.2.

Black Market Catch Estimation

The sale of black market fish was believed to begin in the early 1960's. Black market fishing effort was estimated with two of the model methods with a single method to augment catches. The delay-difference model, DDM2, was used to estimate the level of unknown catch required to increase the verisimilitude of the simulation results to more closely match the observed catches. Generating new total catch biomass levels was accomplished by adding 5, 10, 15 and 20 percent (each number, in turn, reflecting a simulation of black market catches) to the known commercial catch and known commercial effort. The new predicted catch and effort levels were estimated in order to examine the changes in catch behavior. The new effort estimates were used to also estimate overall commercial and black market F. Fishing mortality values were converted into fishing effort by:

$$F = q^*(f + b) \qquad \text{(eq. 17)}$$

where b is the black market fishing effort and f is the known commercial fishing effort.

The black market catch estimates were also applied in varying manners in the post-1970 time period. This was done to attempt to further simulate the high levels of variation between 1970 and 1987. Here the catch and effort were increased to a greater magnitude than the 1960-1969 period, 10% to 20% and 20% to 30%. A second simulation to incorporate varying catch and effort levels involved increasing the catch by a greater percentage than the effort, which did change the CPUE. A third set of simulations targeted higher levels of increase (50, 75, and 100 percent of the catch).

Correlation, Concordance Sum of Squares, AIC

Following the previously discussed analyses, different methods were needed to continue to compare the various time series for congruency. One method was to examine the modeled population estimates with previously estimated environmental coefficients. The second set of methods was to examine the different modeling methods for concordance and parsimony. These are methods to evaluate the performance of the different models to determine the “best” performing model of the available analyses.

Environmental Coefficients and Population Abundance Estimates

Because walleye year effect growth coefficients have been previously compared to a simpler measure of population abundance like CPUE (Cyterski 1995), correlation analysis was used to examine the relationship between estimated population abundances (numbers of fish from the catch-at-age methods) and the walleye year effect growth coefficients. This analysis was done using a Pearson correlation in SAS© software.[5]

Time lags were examined in correlation of the walleye year effect (growth) coefficients with the population abundance estimates from the catch-at-age models, because Cyterski (1995) found a statistically significant correlation between CPUE (as a supplement for population abundance) and walleye year effect coefficients at a positive one year lag. A two-year lag was also examined as walleye began to recruit to the gillnet fishery at age-2, though they do not recruit fully until age-4.

Once population estimate correlations were completed, I sought to determine why lag may have occurred. Different amounts of lag were investigated, as different amounts of lag would have different interpretations. No lag might indicate that the walleye environmental coefficients most accurately described the walleye population that is recruited to the fishery. A one year lag could indicate that the environmental growth is realized in population increases in the following year. The two year lag could be explained through the previous discussion, where walleye began to recruit to the gillnet fishery at age two.

Percent change was used to determine “good” or “poor” growth. I assumed that “poor” growth was the result of individual body growth declining in direct proportion to increases with population abundance. The equation for the percent change in the year-effect coefficients was:

$$\textit{Percent change} = (\textit{Current Year}/\textit{Previous Year}) - 1 * 100$$

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[5] SAS, Cary, NC. SAS System for Windows V9.1

Positive and negative growth as a percent was correlated with the population abundance estimates within the same year. This analysis allowed for comparison between the population estimate and previously estimated results from the same stock.

Model Concordance and Parsimony

Pearson's correlation, using SAS© software, and a concordance sum of squares were used to compare levels of predicted catches to the observed fishery catch of that same year to examine the predictive ability of the delay-difference and age-structured models, including comparison of the three age-structured computational methods. The biomass of actual catch was assumed to be accurately reported in the catch records for these analyses. The actual biomass of the catch was tested for correlation to the predicted catch biomass from each delay-difference model and the three catch-at-age estimates.

Concordance sum of squares is an error sum of squares that can be denoted (Ogle et al. 1994):

$$CSS = \sum^{f} (y_i - Y_i)^2 \quad \text{(eq. 18)}$$

where *y* is the predicted catch in year *i* and *Y* is the actual catch in year *i*. The lower the CSS value, the greater the concordance exhibited in the relationship between predicted and actual catches. The actual catch biomass was taken from the commercial record and the predicted catch biomass estimates were from the delay-difference formulations and the three catch-at-age methods. This analysis would allow for examination between observed results and the predicted results of the models as a possible means to evaluate predictive performance.

A third method for comparing models is the Akaike information criterion (AIC) (Akaike 1973, Buckland et al. 1993). AIC includes the number of parameters used in the method rather than examining only the fit between the predicted and observed catches. The definition of the AIC is:

$$AIC = -2 \ln L + 2p \qquad \text{(eq. 19)}$$

where *ln L* is the log likelihood evaluated as the maximum likelihood estimates and p is the number of parameters. The lowest AIC score is exhibiting the best fit and may be the most parsimonious, given that the AIC is constructed to penalize models with a lack of parsimony. Therefore, models with slightly better fits but many more parameters may have higher AIC scores than models with fewer parameters, which would be considered more parsimonious models. This method goes a step beyond the concordance analysis because it takes into account the increasing complexity of the models.

Results

Delay-Difference Biomass Models

DDM1 models for 1949-1957 were fitted to two different measures, CPUE and catch. The predicted and observed CPUE values fit closely, with a residual sum of squares of 361.6 (Figure 4). The predicted catch did not vary to the same extent as the actual catch, both in the extent of highs and lows as well as some of the year to year variability, in 1950, for example (Figure 5). The standardized residuals for both catch and CPUE were very similar and appeared to lack pattern (Figure 6). More quantitative comparisons of these models using the criteria described above will be presented at the end of this section.

DDM1 models for 1959-1969 were also fitted with two measures, CPUE and catch. The predicted and observed CPUE values fit closely, showing a high level of correspondence with a residual sum of squares of 913.2 (Figure 7). The predicted catch biomass to the observed catch biomass did not fit as well, particularly in terms of year-to-year variation (Figure 8). The predicted catch did not correspond with some of the lows (1963) or highs (1966) of the actual catch. The standardized residuals were not the same between the catch and CPUE, but both appeared to lack pattern (Figure 9).

DDM1 models for 1949-1969 were also fitted to two measures, CPUE and catch. The predicted and observed CPUE values fit very closely, showing a high level of correspondence with a residual sum of squares of 1,934.9 (Figure 10). The predicted catch biomass to the observed catch biomass fit did not correspond as well (Figure 11). There was also limited correspondence in pattern between observed and predicted catch.

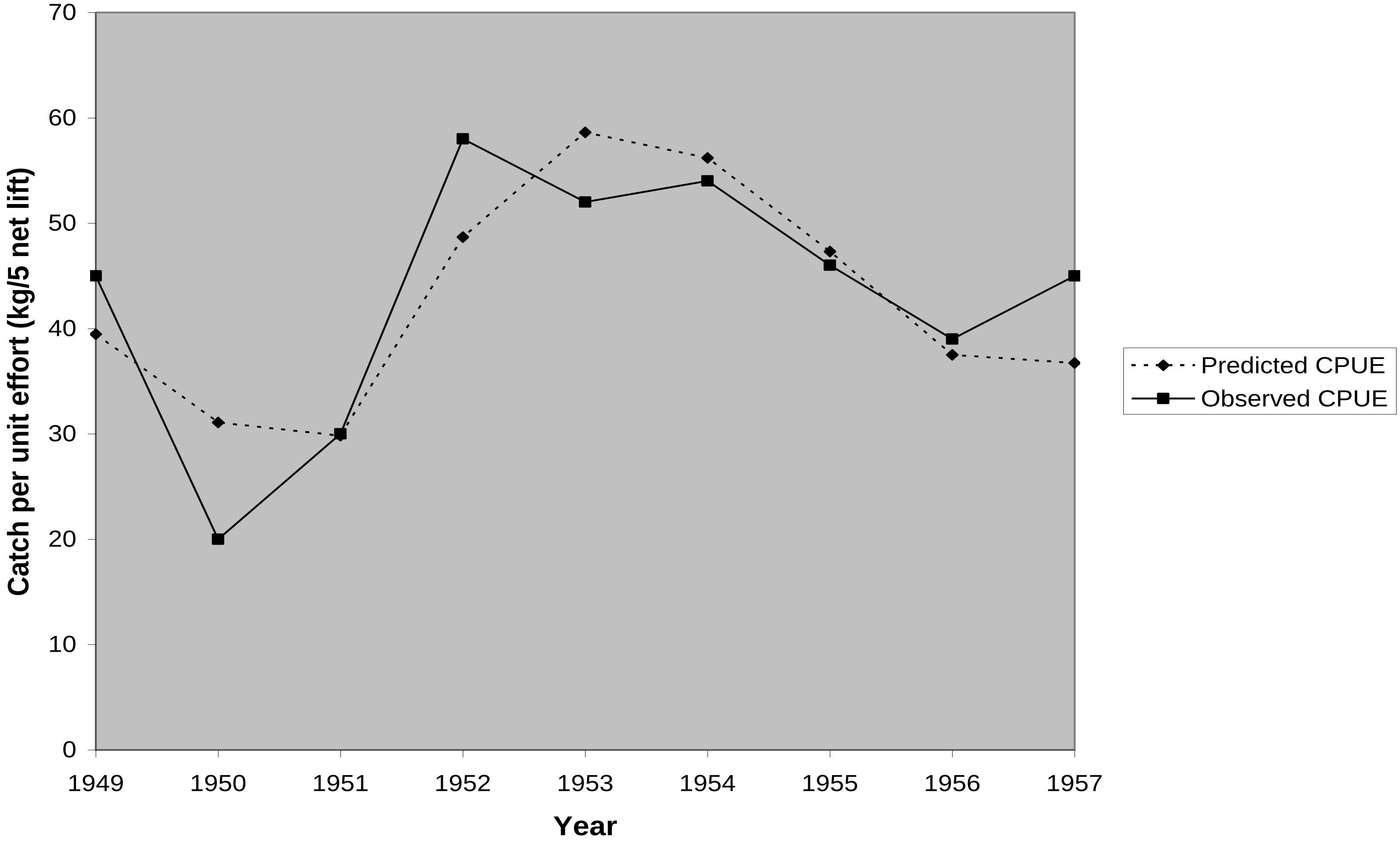

Figure 4. Predicted and observed CPUE for DDM1 from 1949 to 1957. CPUE measured in kilograms of walleye per 5 net lift.

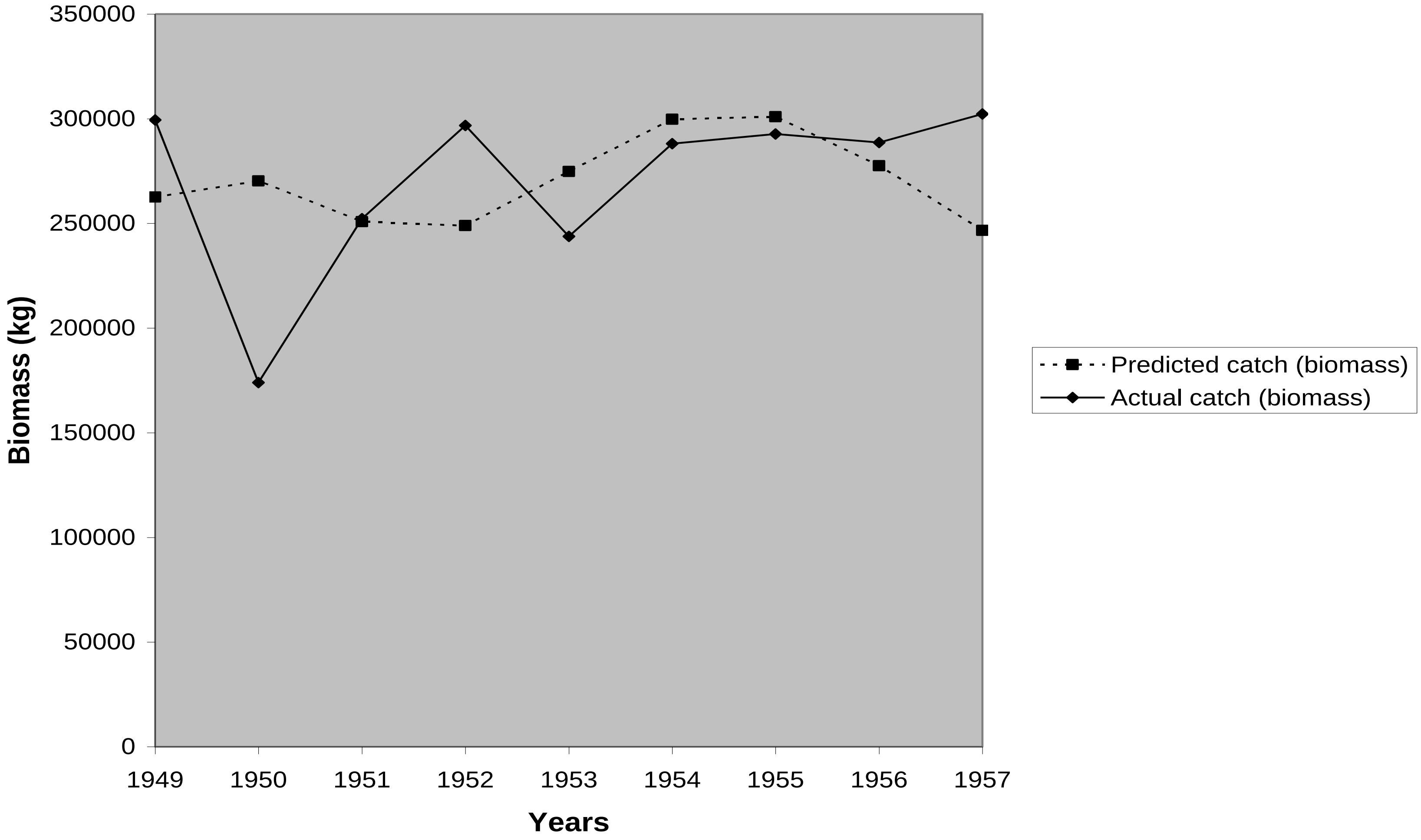

Figure 5. Comparison between predicted and actual catch per year for DDM1 from 1949-1957, catch measured in kilograms of walleye.

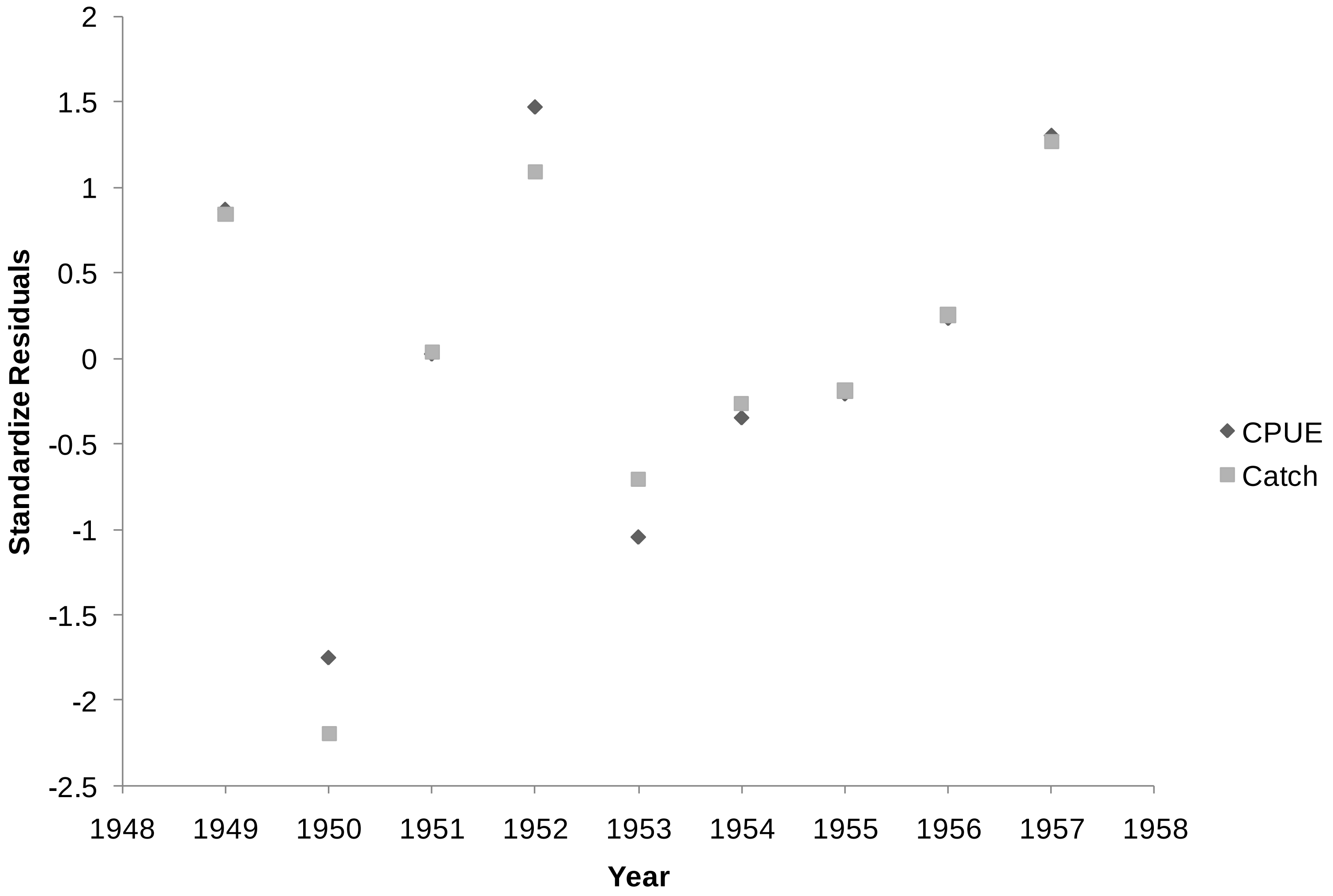

Figure 6. Standardized residuals for the CPUE and catch of the DDM1 for the years 1949-1957.

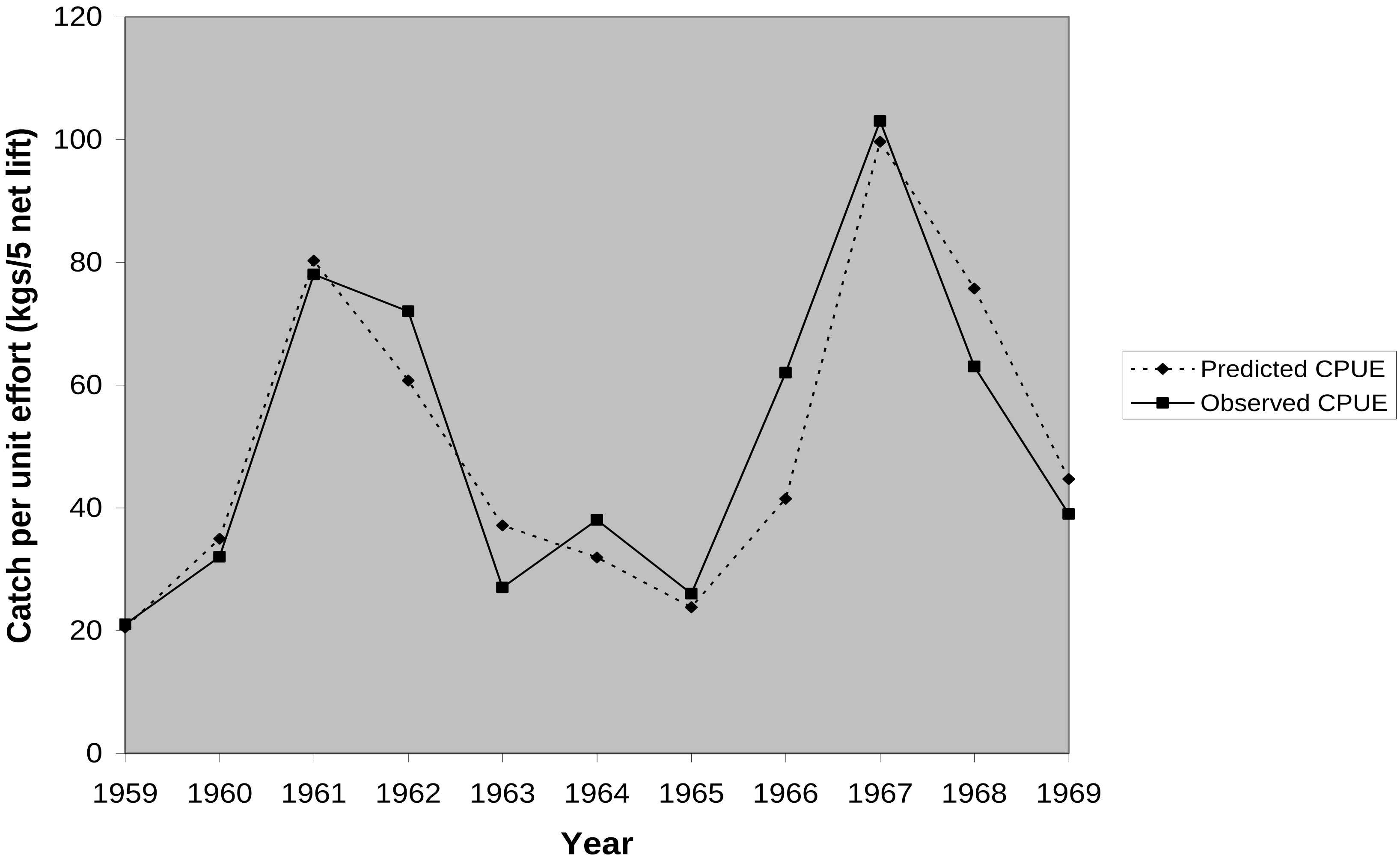

Figure 7. Predicted and observed CPUE for DDM 1 from 1959 to 1969. CPUE measured in kilograms of walleye per 5 net lift.

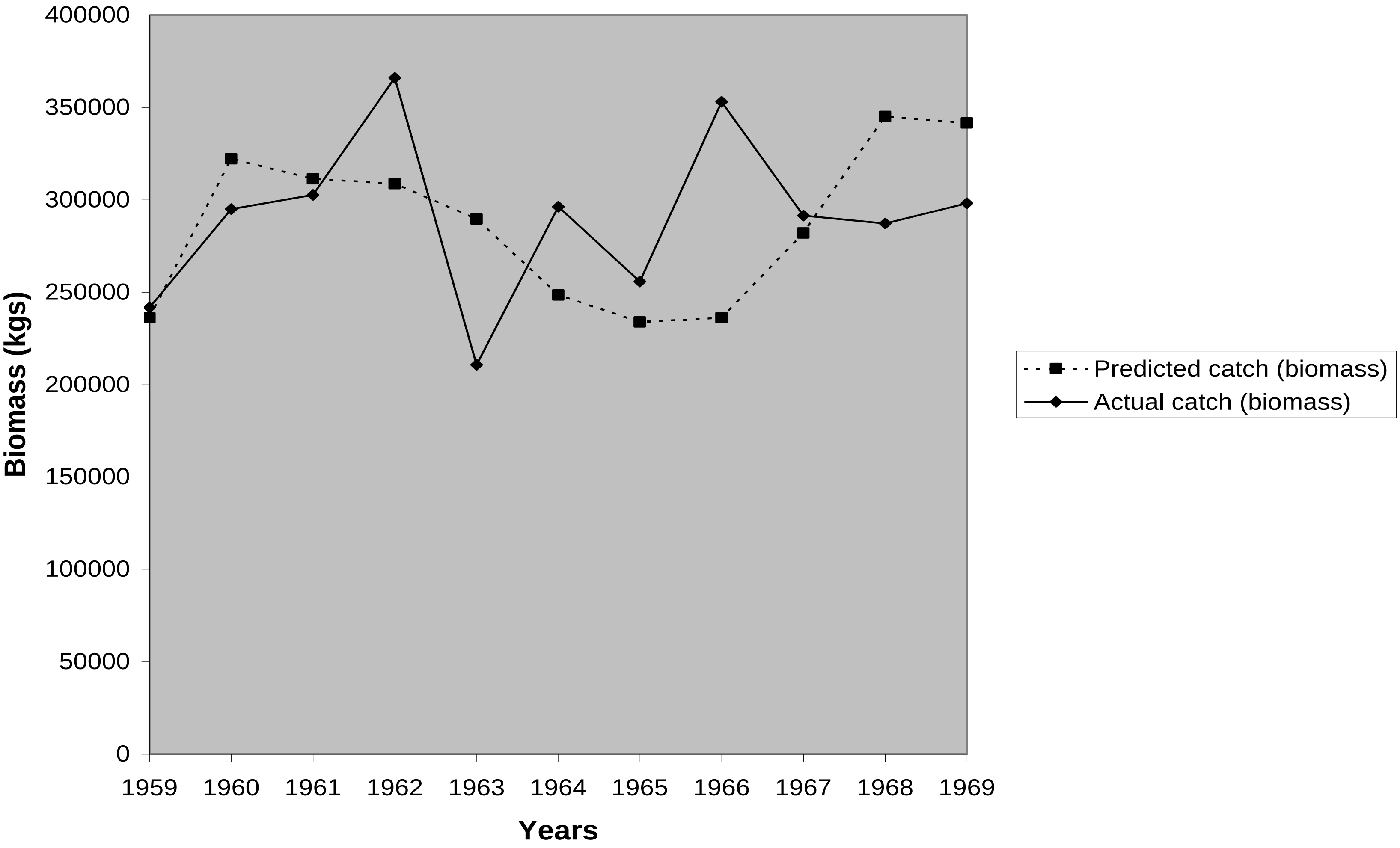

Figure 8. Predicted and actual catch per year for DDM1 from 1959 to 1969, catch measured in kilograms of walleye.

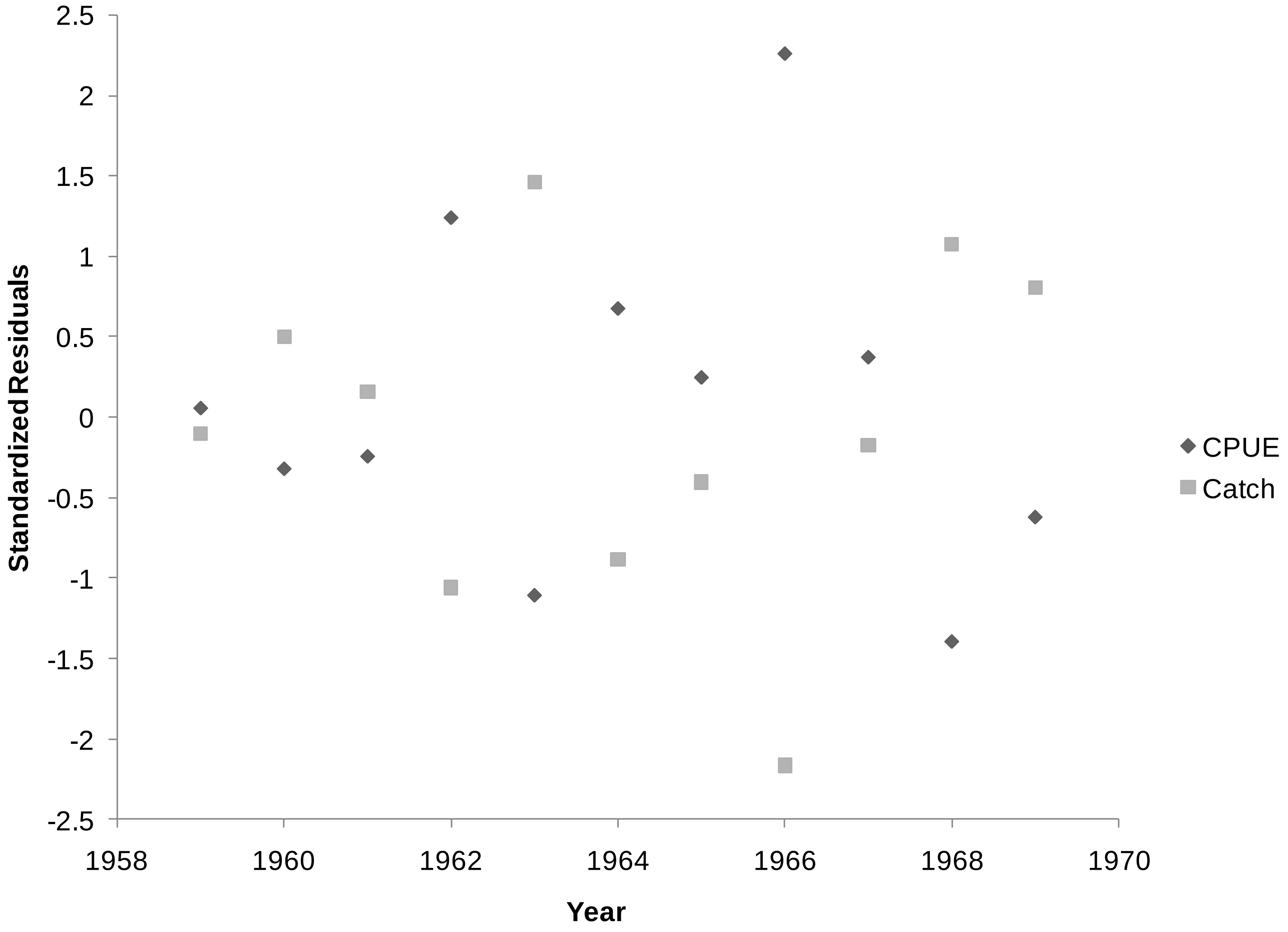

Figure 9. Standardized residuals for the CPUE and catch of DDM1 for the years 1959-1969.

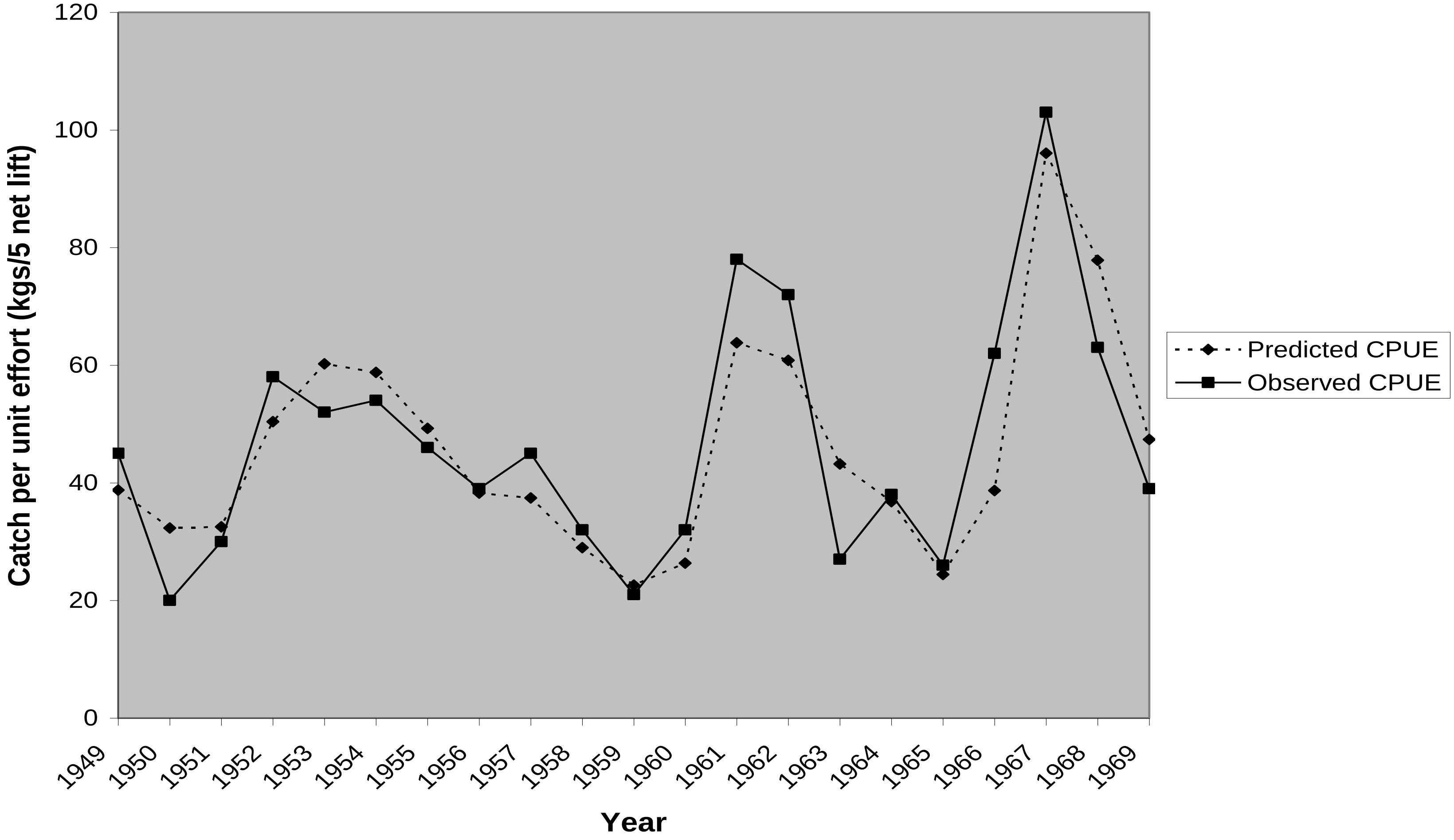

Figure 10. Predicted and observed CPUE for DDM1 from 1949 to 1969. CPUE measured in kilograms of walleye per 5 net lift.

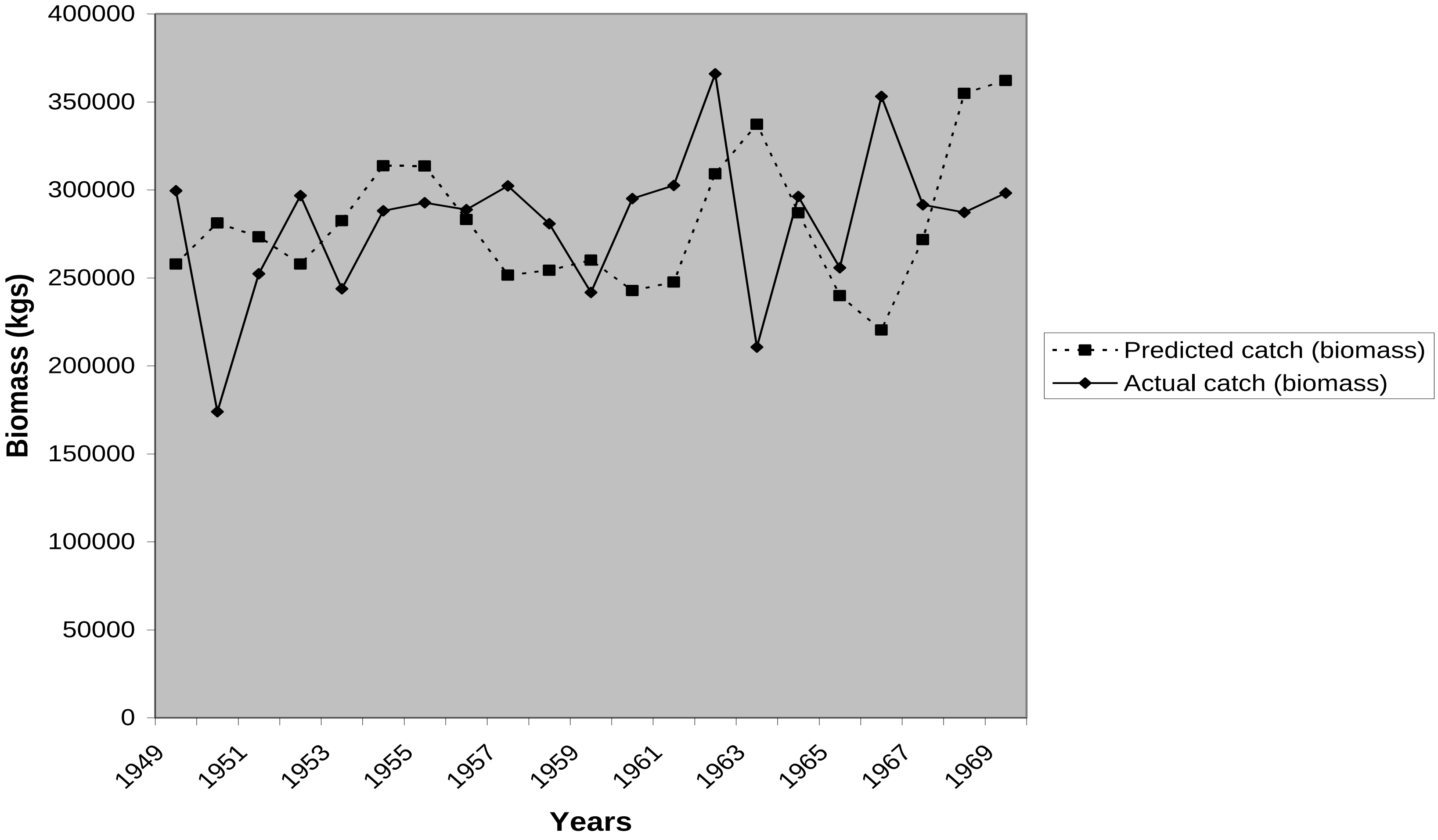

Figure 11. Comparison between predicted and actual catch per year for DDM1 from 1949 to 1969, catch measured in kilograms of walleye.

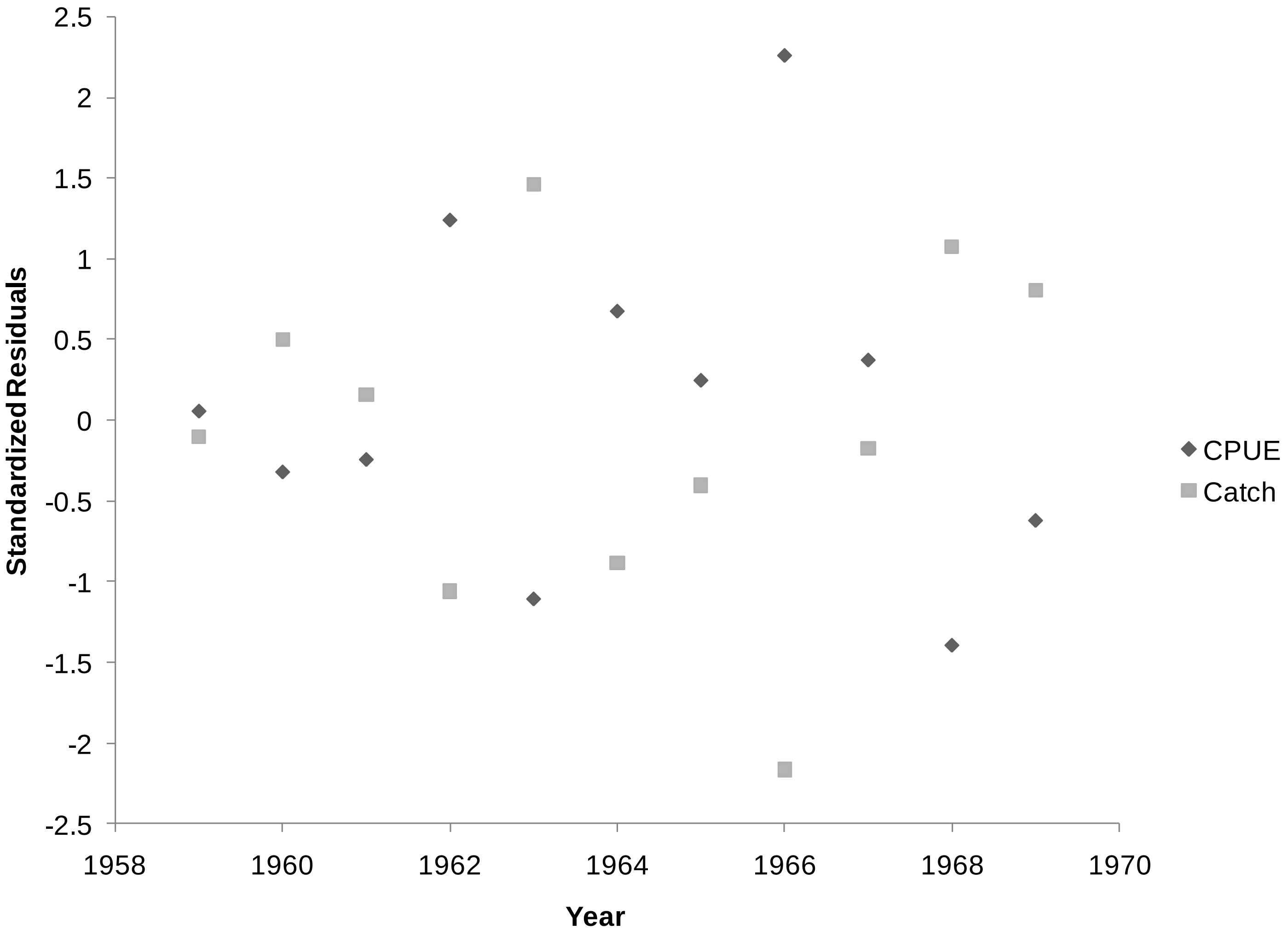

Figure 12. Standardized residuals for the CPUE and catch of DDM1 for the years 1949-1969.

The standardized residuals for both catch and CPUE were different patterns, but showed no pattern (Figure 12). Particularly, the predictions of increased or decreased catch appears lagged from observed increases and decreases.

DDM1 growth functions for 1949-1996 were also fitted to two measures, CPUE and catch. The predicted CPUE fit with the observed CPUE demonstrates a limited agreement of pattern, and very little matching of the CPUE values, especially through the period from 1972 to 1987 with a residual sum of squares of 41.1 (Figure 13). The predicted catch biomass estimates are initially higher than observed, then quickly drop to what appears to be the long-term mean and is largely flat and slightly variable (Figure 14). The standardized residuals for catch and CPUE show pattern in the final years of analysis, where the catch residuals increase and the CPUE residuals decrease (Figure 15).

Inclusion of Weisberg Coefficients in Delay-Difference Model

The inclusion of the Weisberg growth increment factors generated a slightly positive correlation between the predicted and observed catches when compared to the correlation found with the more traditional length-based method for determining ρ, the Ford growth coefficient. The two methods for estimating catch generated different values for ρ; a value of 0.6573 when estimated from the traditional length-based means (DDM1) and a value of 0.7389 when Weisberg values were substituted for fish lengths (DDM2). The Weisberg growth coefficients generated ρ value exhibits greater variation than the more conventional method for estimating ρ (Figure 16). The Weisberg-ρ produces model estimates that appear to follow the pattern of the actual catch better than DDM1 (Figure 14, Figure 17). The predicted catch behaved similarly as did the DDM1 predicted catch model (Figure 17). Like the previous, the standardized residuals for the

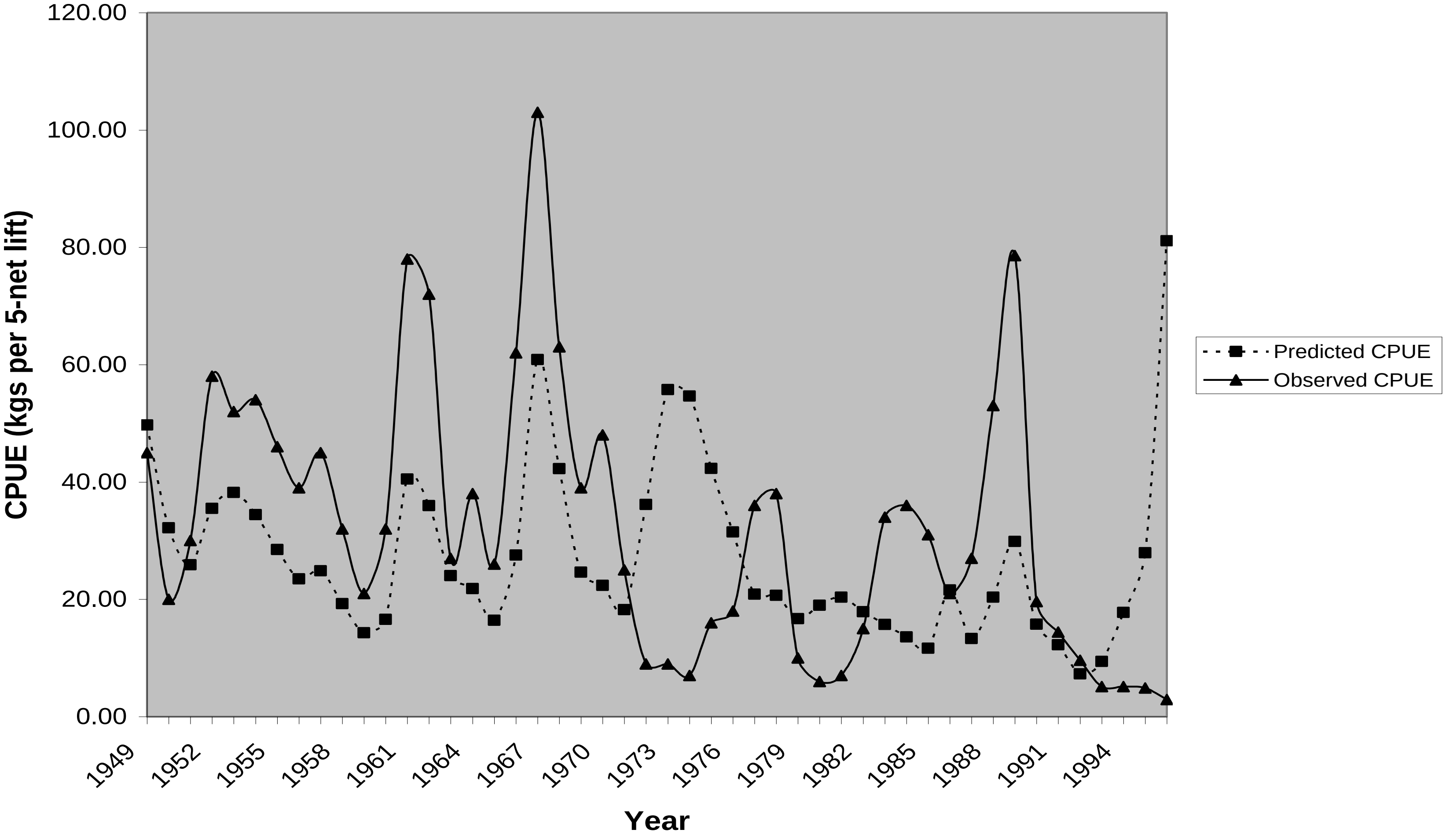

Figure 13. Predicted and observed CPUE for the years 1949-1996 using DDM1 settings. CPUE measured in kilograms of walleye per 5 net lift.

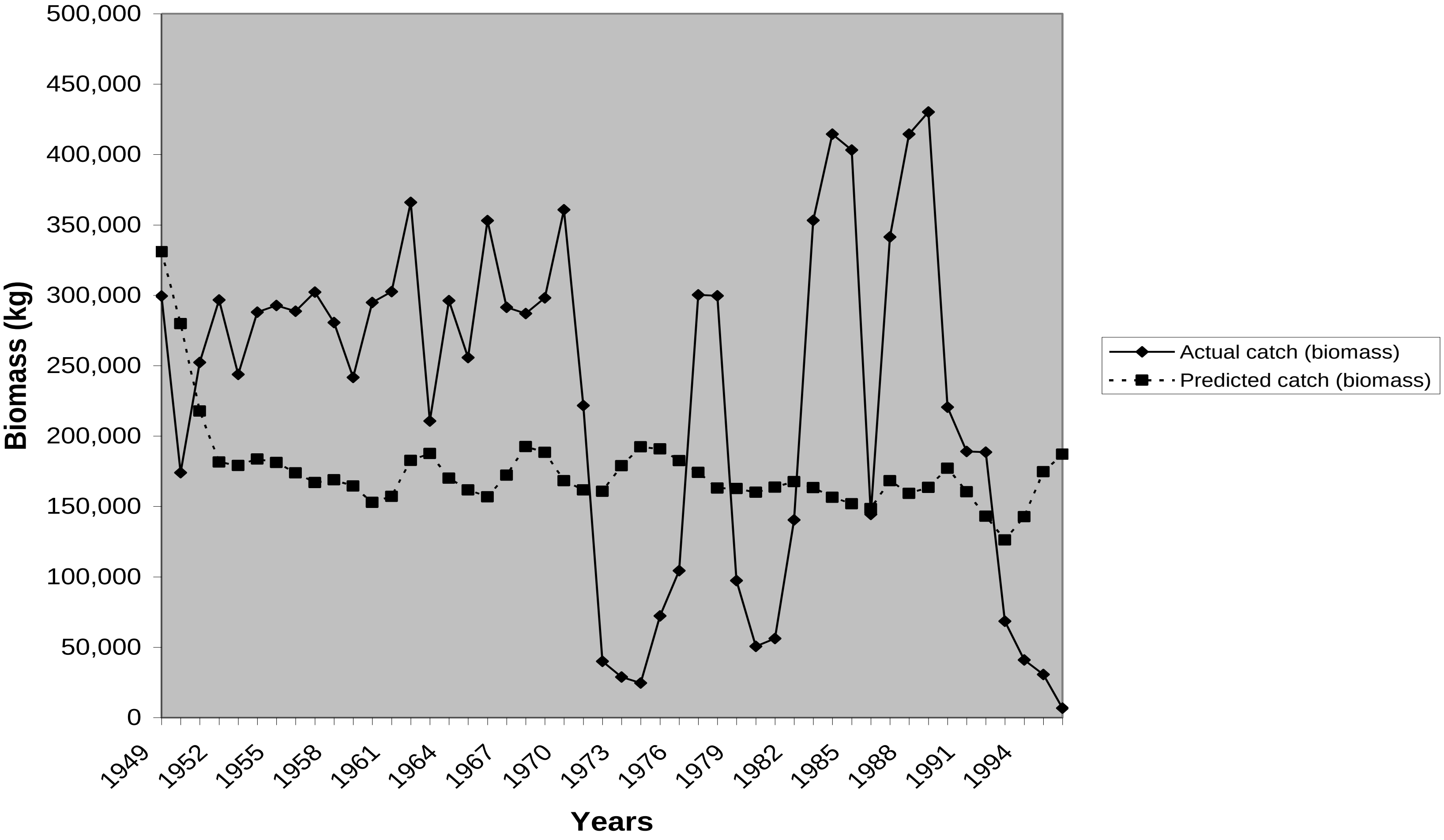

Figure 14. Predicted and actual catch per year for the years 1949-1996 using the DDM1; catch measured in kilograms of walleye.

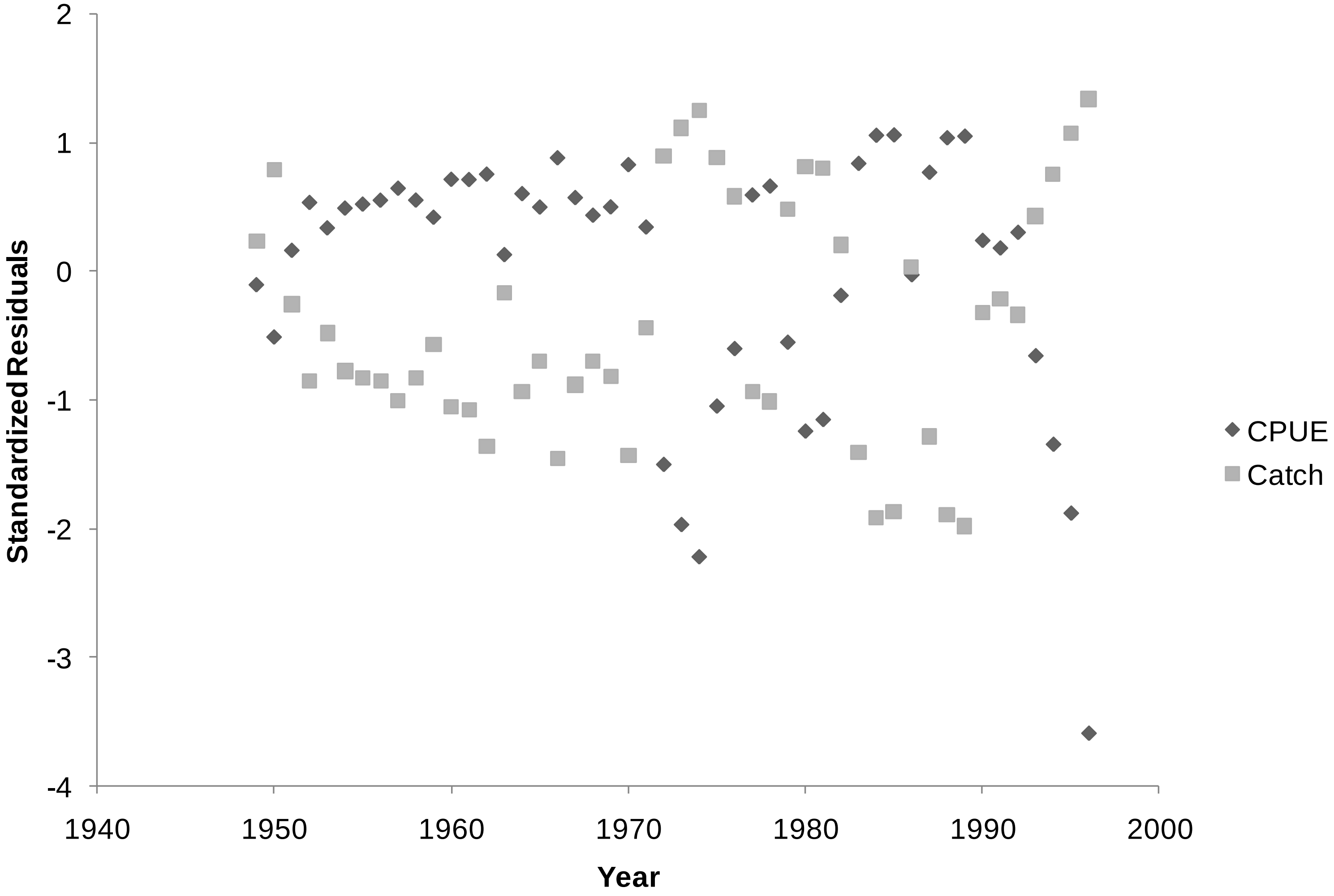

Figure 15. Standardized residuals for CPUE and catch of DDM1 for the years 1949-1996.

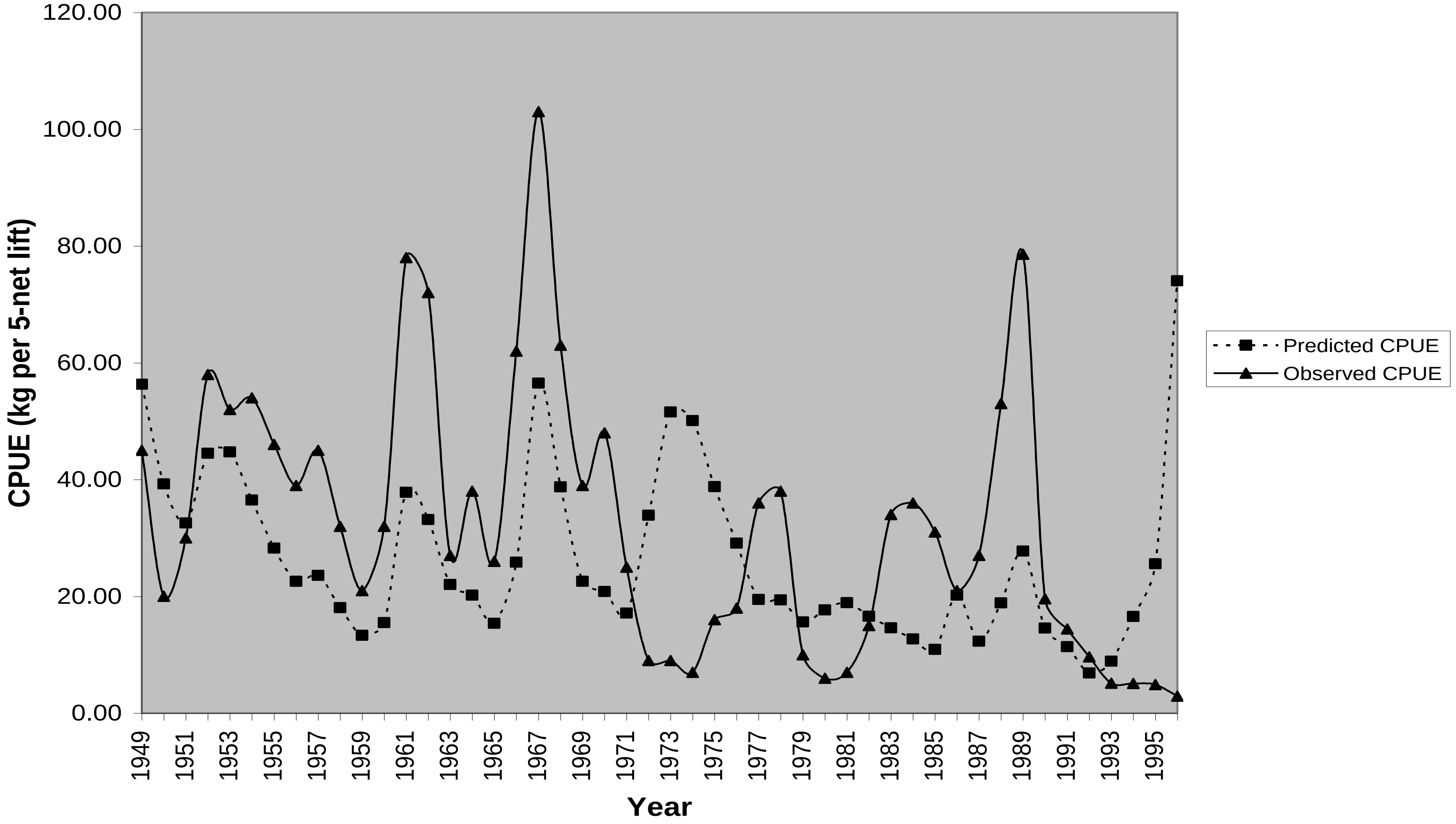

Figure 16: Predicted and observed CPUE for the years 1949-1996 using DDM2 settings. CPUE measured in kilograms of walleye per 5 net lift.

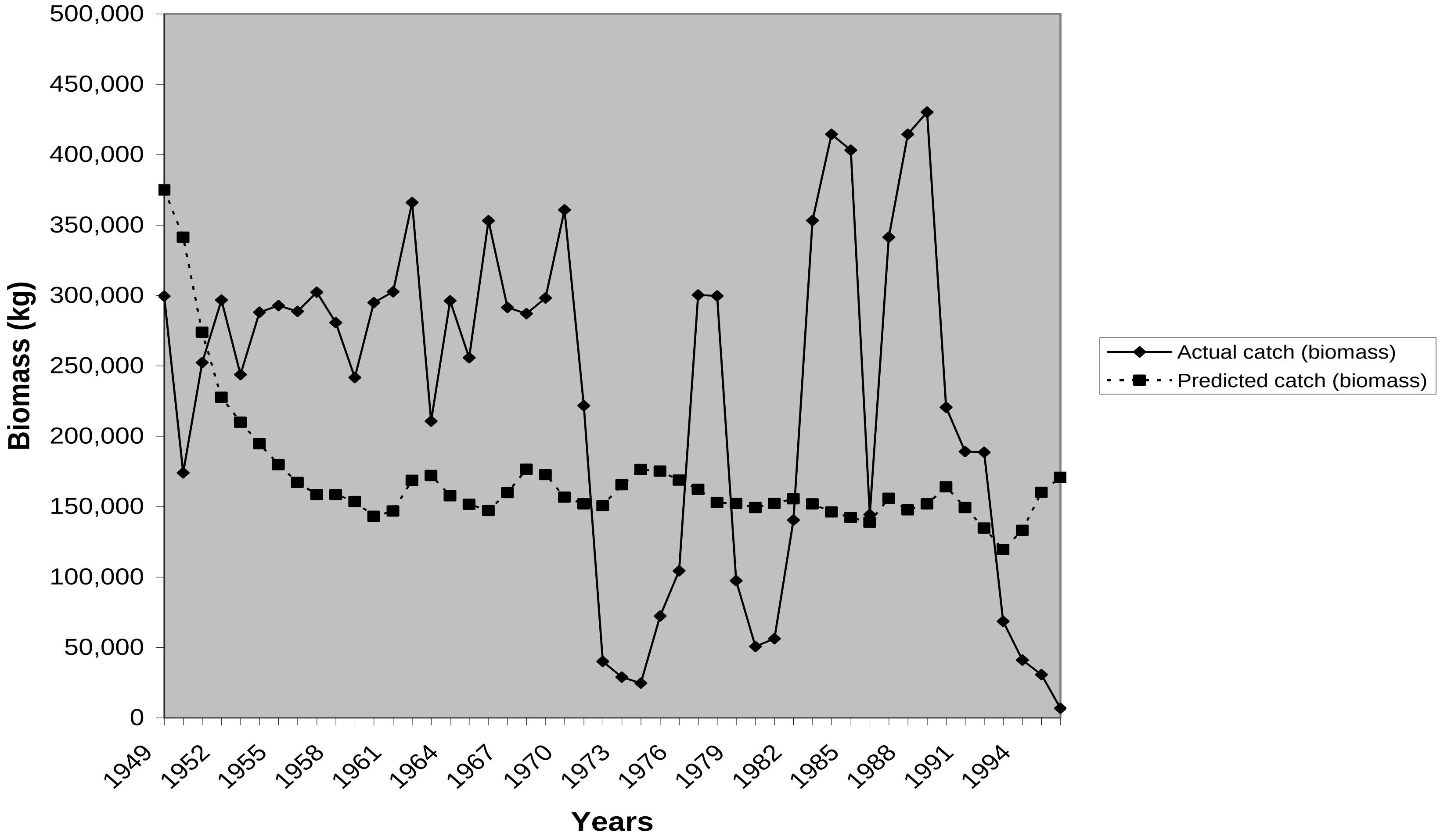

Figure 17. Predicted and actual catch per year for the years 1949-1996 using the DDM2 settings; catch measured in kilograms of walleye.

Figure 18. Standardized residuals for CPUE and catch of DDM2 for the years 1949-1996.

catch increase in the final years and CPUE residuals decrease in the final years (Figure 18).

The inclusion of the year effect coefficients in the simulations was performed for three eras. None of the simulations indicated the decline in CPUE that occurred in 1973-1975, though DDM3 remained slightly higher from 1972-1985 with a residual sum of squares of 29,707.5 (Figure 19). The addition of the walleye growth factors that were calculated and used in DDM3 reduced the variation found within the delay-difference model (Table 4, Figure 20). Again the standardized residuals for CPUE in recent years showed a decline (Figure 21). The model variant, DDM4, which includes the regressed yellow perch environmental coefficient factors split into two periods had the greatest degree of correlation, particularly prior to the fluctuations in catch that occurred in the 1970's. Correspondence was also seen in the concordance sum of squares (CSS), though that analysis indicated the best fit with the DDM3 formulation (Table 4). The correlation analysis showed no statistically significant relationships between the predicted and actual catches.

Table 4: Comparisons between the different alterations for the delay-difference model settings DDM1, DDM2, DDM3, DDM4, DDM5 (explanations in table 3).

1949-1996	DDM1	DDM2	DDM3	DDM4	DDM5
R-value	0.1645	0.1550	0.1966	-0.0273	0.2686
CSS	7.96E+11	8.08E+11	7.18E+11	9.54E+11	7.76E+11

DDM6 growth functions for 1945-1960 were fitted to two different measures, CPUE and catch. The predicted and observed CPUE values showed limited fit, with a general pattern match but generally lower values with a residual sum of squares of 460.6 (Figure 22). The fit of the predicted catch biomass to the observed catch biomass had lower correspondence (Figure 23). The standardized residuals showed an increase in

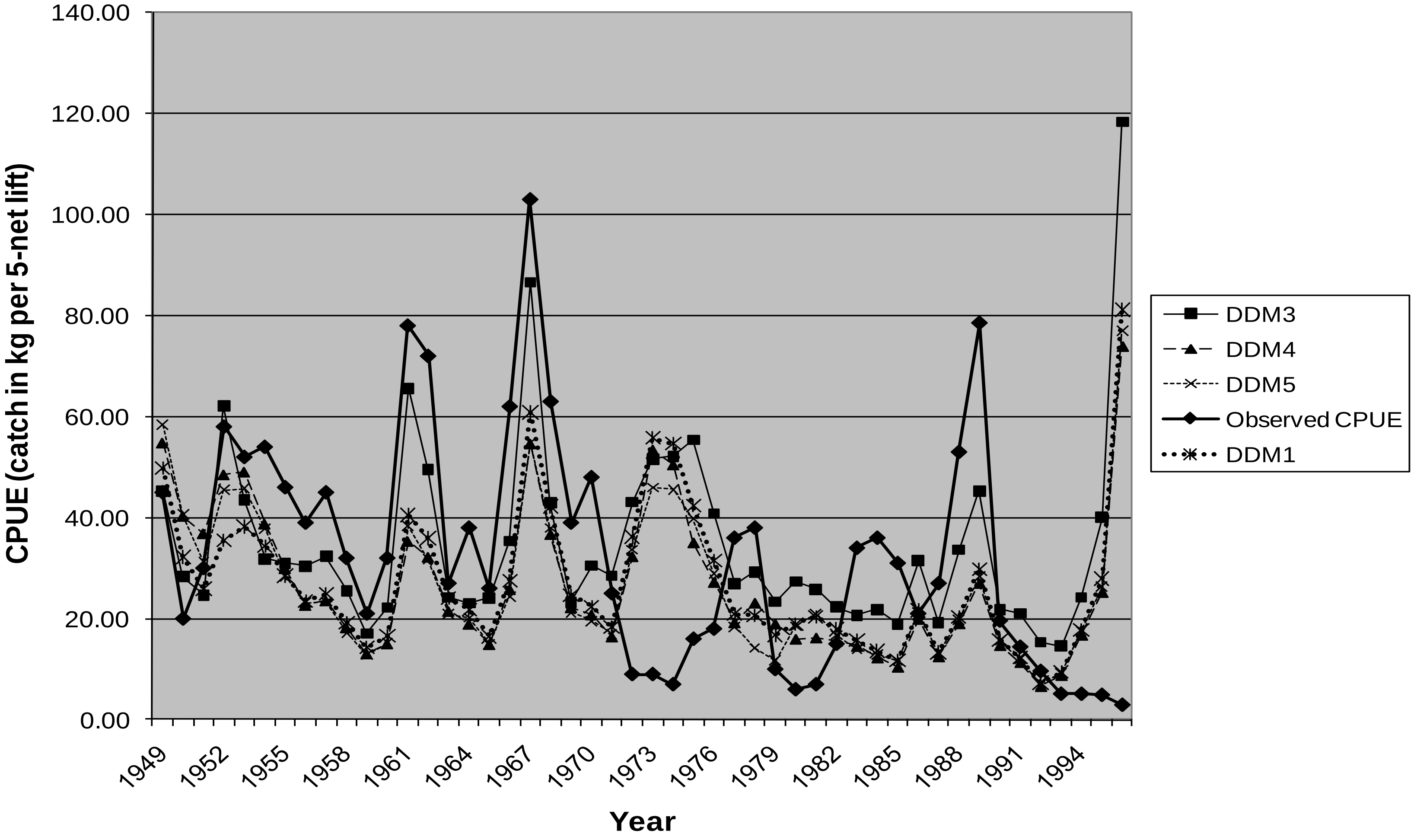

Figure 19. Catch-per-unit effort, both observed and predicted by the delay difference model for the three different environmental growth effect inclusions: DDM3, DDM4 settings, and DDM5 settings.

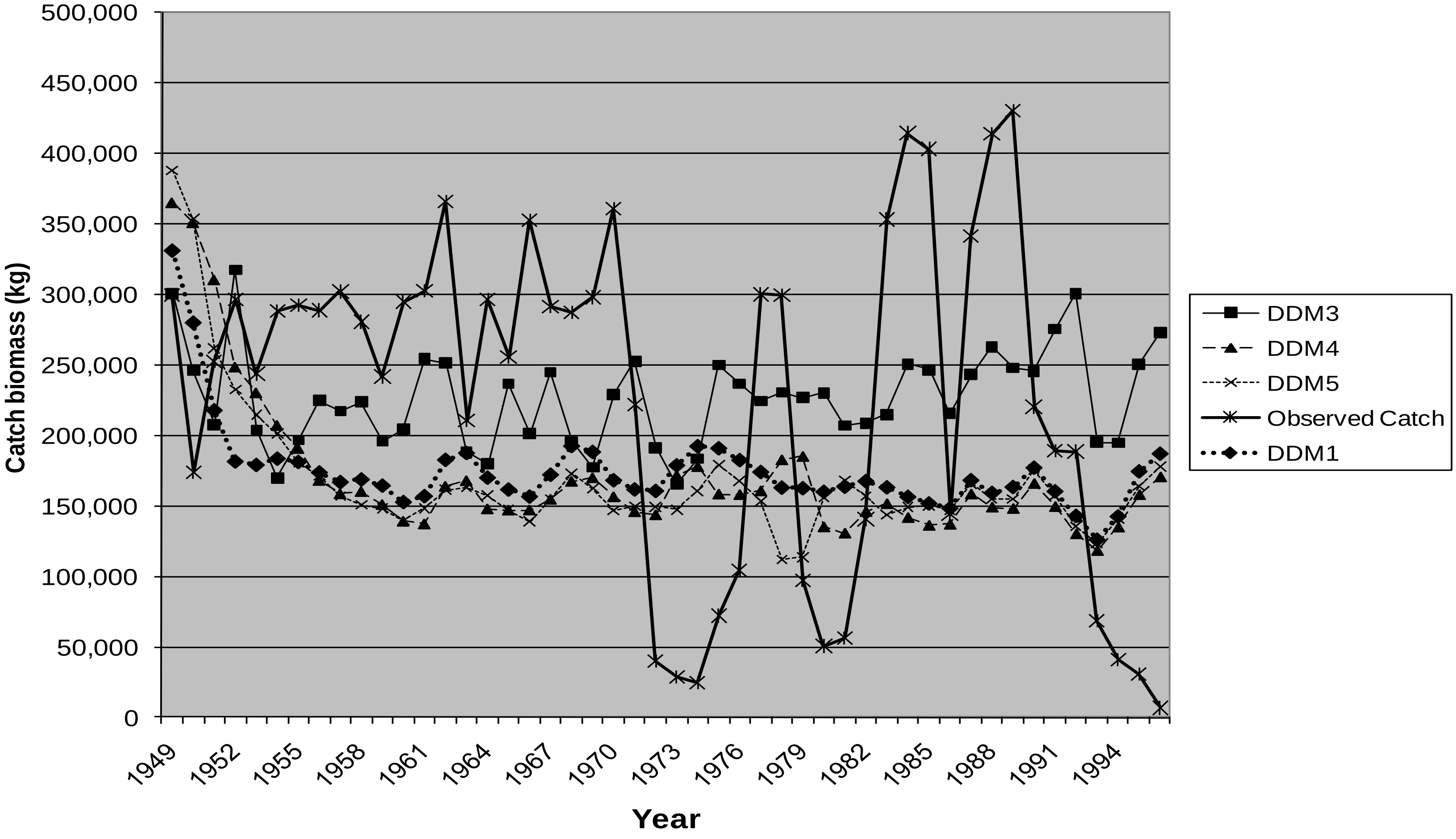

Figure 20. Catch biomass comparison in kilograms for the actual catch and three different environmental growth effect inclusions: DDM3, DDM4 settings, and DDM5 settings. Descriptions of settings are in table 3 and table A.1.2.

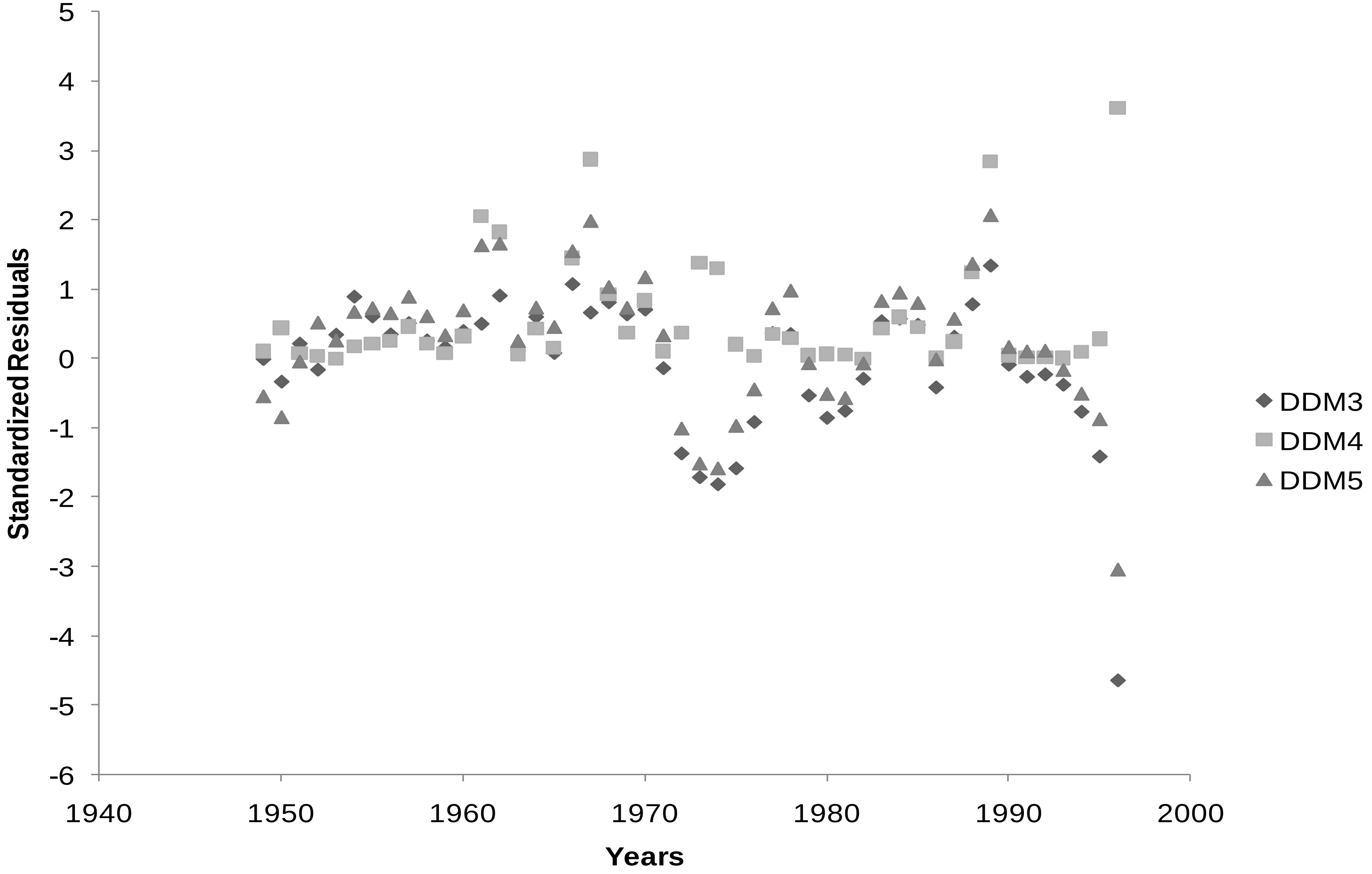

Figure 21. Standardized residuals for the CPUE of DDM3, DDM4, and DDM5 for the years 1949-1996.

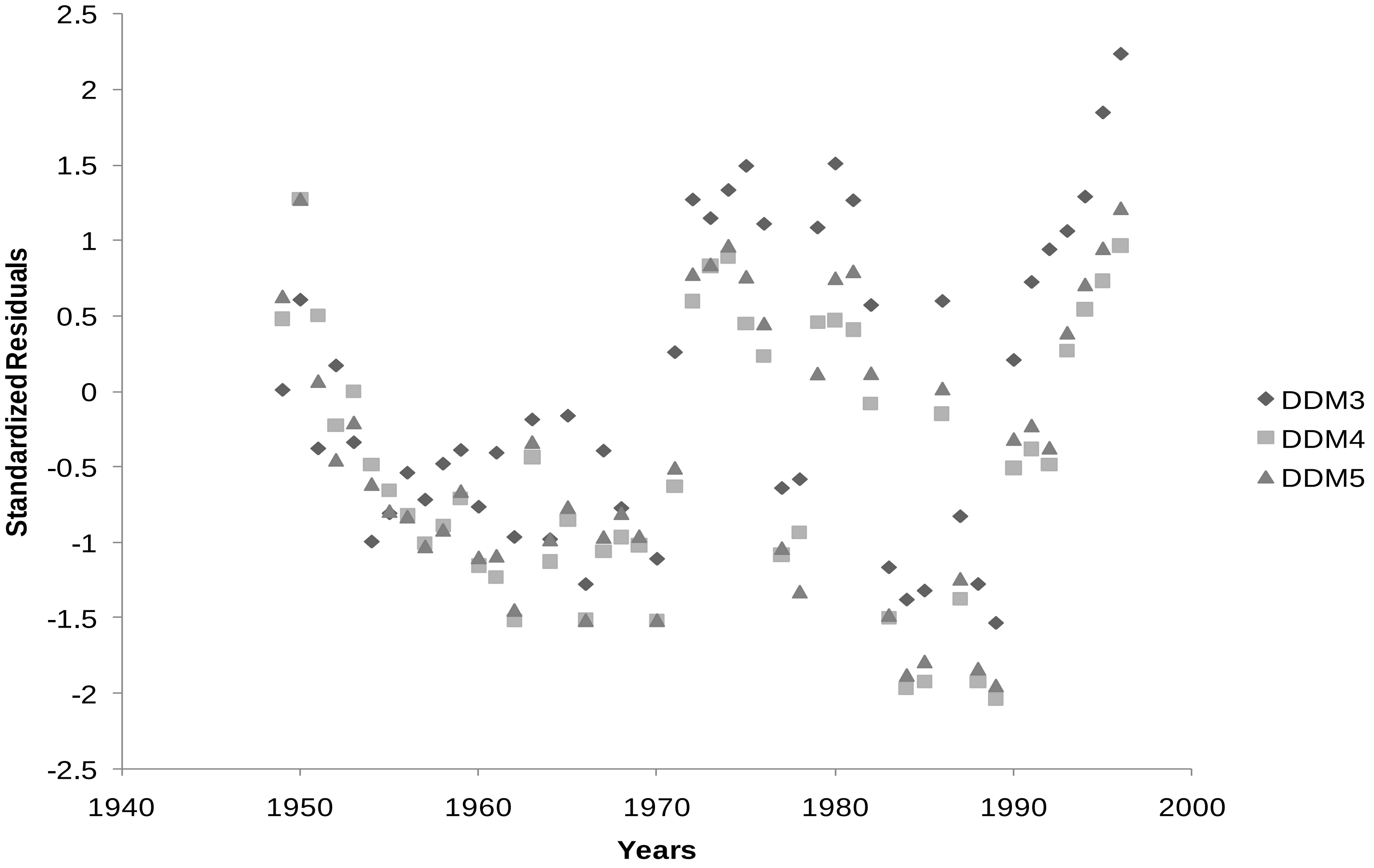

Figure 22. Standardized residuals for the catch of DDM3, DDM4, and DDM5 for the years 1949-1996.

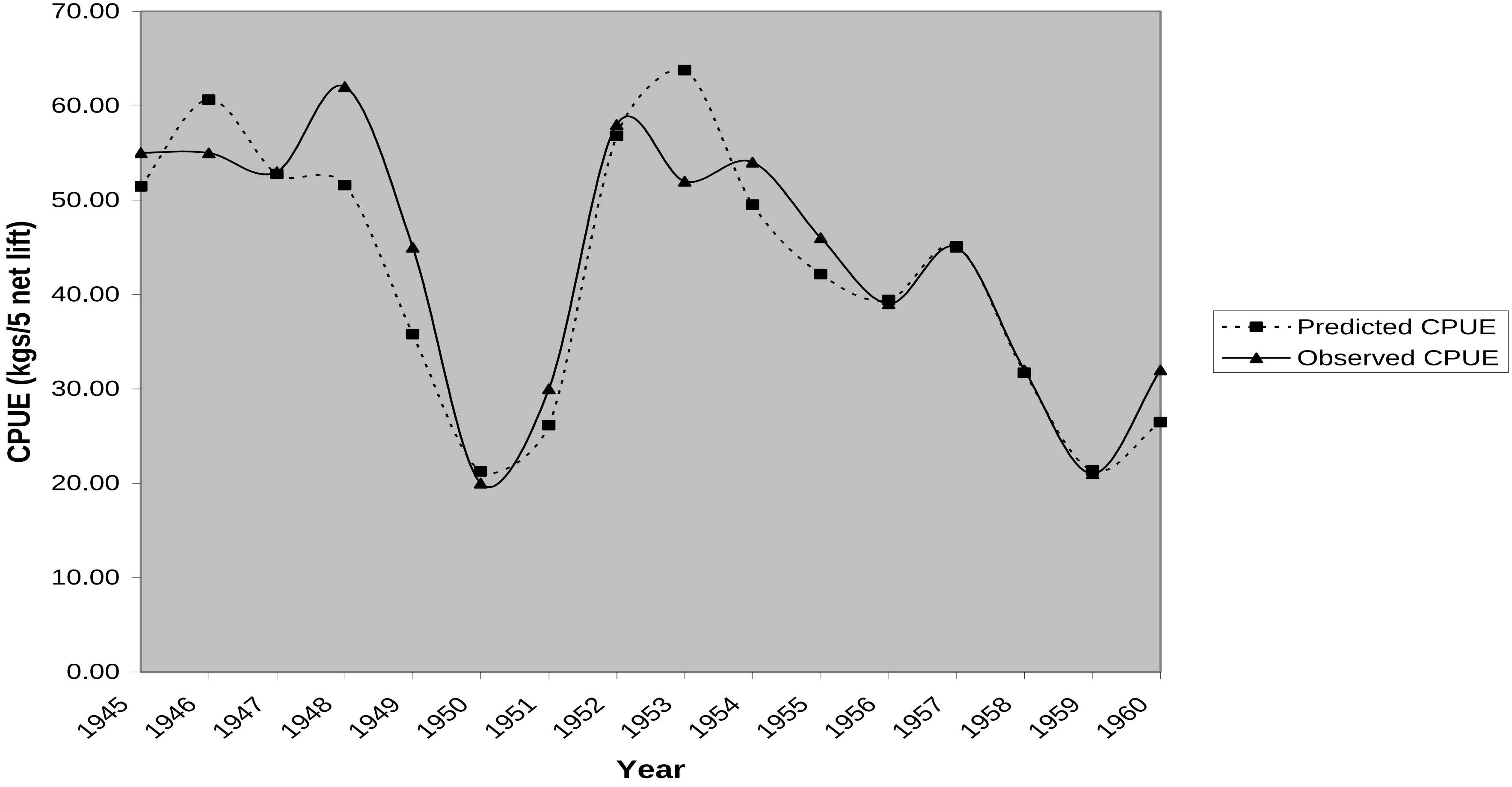

Figure 23. Catch- per unit effort, both observed and predicted by the delay difference model for the DDM6 settings for the years 1945-1960.

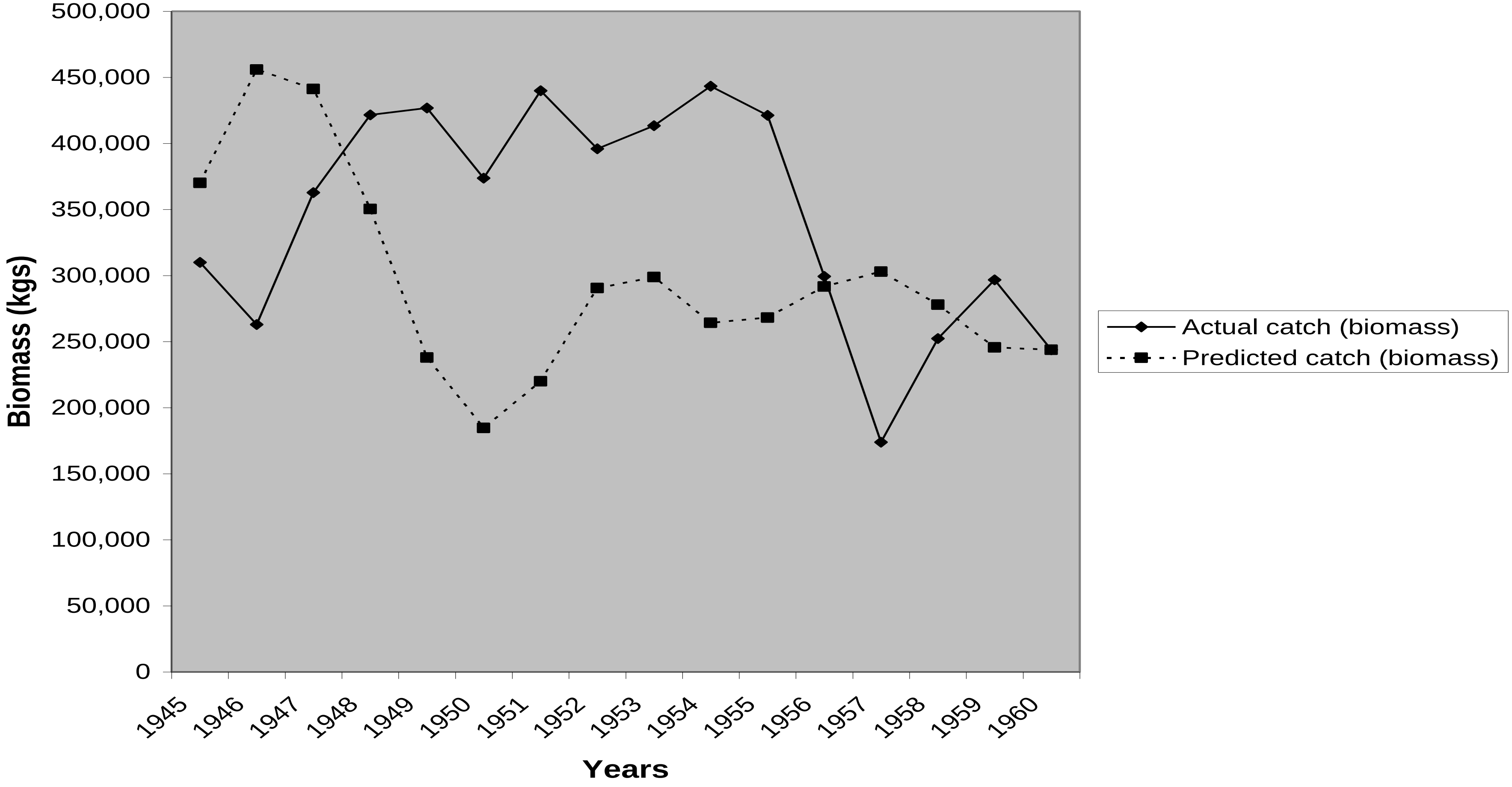

Figure 24. Catch biomass in kilograms, both observed and predicted by the delay difference model for the DDM6 settings for the years 1945-1960.

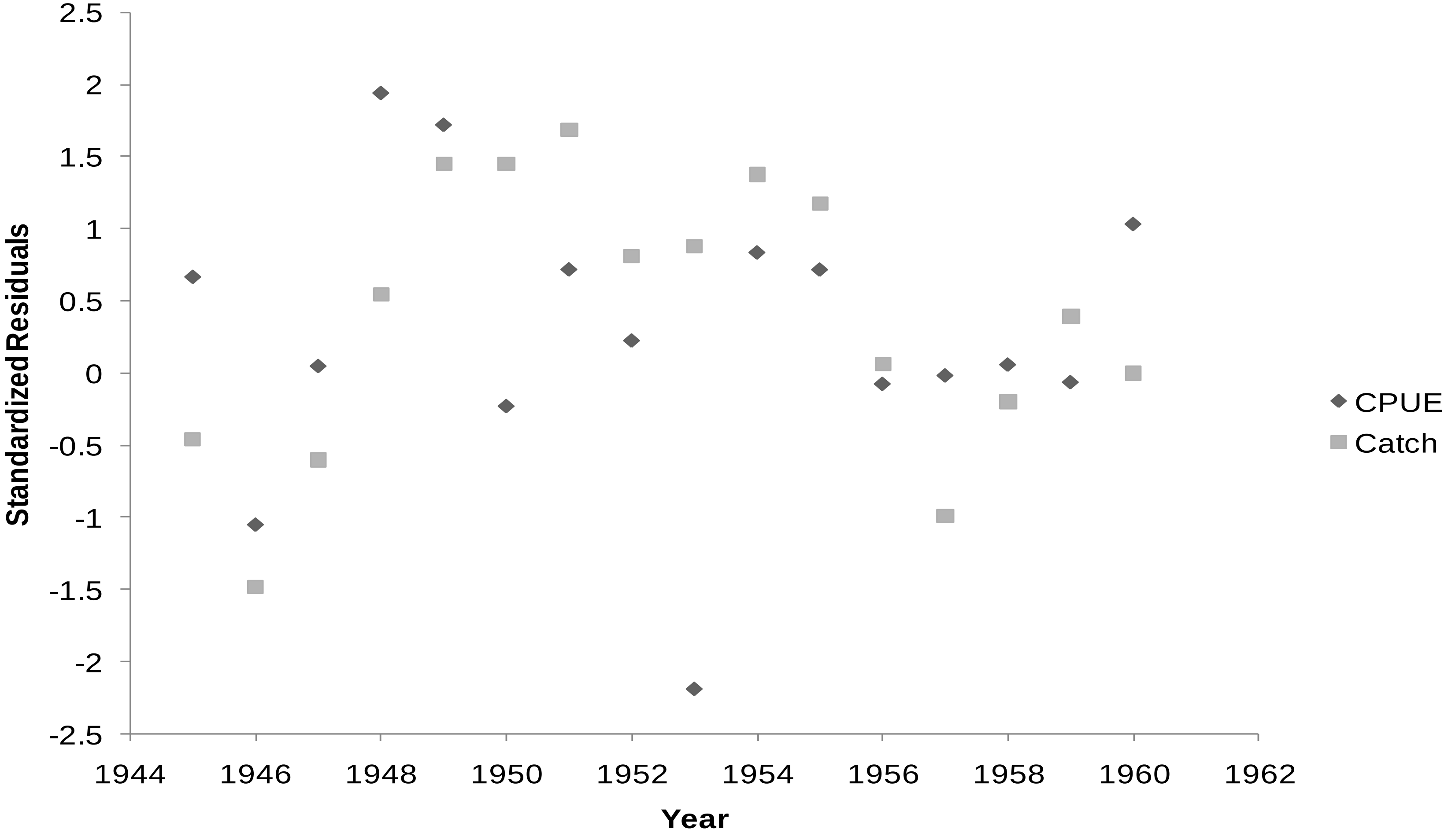

Figure 25. Standardized residuals for the CPUE and catch of DDM6 for the years 1945-1960.

catch residuals in the final years (Figure 24). The regressed yellow perch year-class strength factor appears to introduce variation for the predicted CPUE (Figure 23). However, the predicted catches do not track in unison the variation in the actual catch during the middle of the time series (Figure 24). The standardized residuals were not similar but neither show trend over time (Figure 25).

Age-Structured Models

The predicted abundances for the three catch-at-age models showed different estimates of abundance for 1949-1957 (Table 5, Figure 26). Until 1954 the abundance numbers for the ADAPT and Lowestoft VPA methods are fairly similar. However, the VPA then increased over the rest of the time series, reaching an estimate of 15,543,000 fish, more than three times the estimate calculated by ADAPT (4,878,611). The spreadsheet method estimated a higher initial population than the ADAPT method and decreased throughout the time period.

Predicted catch in kilograms per year for the four overall models examined, the three catch-at-age type models and the delay difference model (DDM1), for the time span 1949-1957, shows that the age-structured methods all have a high level of correspondence to the actual catch in both pattern and biomass numbers and a residual sum of squares of 1.63E+10 (Figure 27). The VPA and ADAPT models predict near identical catch biomasses, with residual sum of squares of 4.17E+09 for both. The analysis for the delay-difference method showed the poorest correspondence between actual and predicted catches. The weighted spreadsheet method showed the highest level of correspondence, though all three methods appeared to perform similarly. The standardized residuals mirror these results (Figure 28). Correlations and CSS values indicate that the DDM1 had the least effective fit (Table 8).

The predicted abundances for the three catch-at-age models indicate different levels of abundance for 1959-1969 (Table 6, Figure 29). All three models predict

Table 5: Abundance estimates at age in thousands of fish for the three age-structured methods for the time period 1949-1957

Year	2	3	4	5	6	7	8	9	10	Total
ADAPT										
1949	3,034	2,033	236	394	351	38	67	68	8	6,229
1950	1,118	2,478	1,633	163	163	142	23	20	24	5,763
1951	1,157	915	2,019	1,259	96	74	63	11	15	5,608
1952	896	947	746	1,575	748	48	41	33	11	5,046
1953	1,020	733	771	591	1,051	397	26	23	21	4,634
1954	1,026	836	597	615	430	630	203	16	29	4,381
1955	1,342	839	680	477	428	241	293	86	27	4,413
1956	1,527	1,097	679	540	337	236	104	103	53	4,675
1957	1,467	1,249	895	529	376	172	85	35	70	4,879
VPA										
1949	3,280	2,122	248	421	385	49	82	103	12	6,702
1950	1,243	2,680	1,706	173	184	170	32	32	38	6,258
1951	1,573	1,018	2,183	1,319	104	92	85	18	25	6,417
1952	1,185	1,288	831	1,710	797	55	56	51	9	5,982
1953	1,188	970	1,050	660	1,162	438	32	35	2	5,537
1954	2,030	973	791	844	487	720	235	21	12	6,113
1955	2,340	1,662	792	636	615	287	366	112	18	6,828
1956	8,462	1,913	1,352	632	467	389	142	162	36	13,555
1957	4,904	6,927	1,564	1,081	451	278	209	66	63	15,543
Spreadsheet										
1949	1,485	1,216	996	815	667	546	447	366	1,654	8,194
1950	1,240	1,215	987	769	574	455	371	304	1,371	7,286
1951	1,370	1,014	990	781	577	423	334	272	1,230	6,992
1952	1,150	1,120	823	762	545	389	284	224	1,007	6,303
1953	1,179	940	907	628	520	358	254	185	804	5,777
1954	1,273	964	762	696	434	346	237	168	655	5,535
1955	943	1,040	779	572	455	270	214	147	509	4,929
1956	948	771	840	583	371	280	165	131	401	4,491
1957	1,111	775	623	631	382	231	174	102	330	4,360

Table 6: Abundance estimates at age in thousands of fish for the three age-structured methods for the time period 1959-1969.

Year	2	3	4	5	6	7	8	9	10	Total
ADAPT										
1959	1,368	1,377	826	406	146	36	11	16	21	4,206
1960	1,012	1,016	974	500	267	87	17	3	25	3,900
1961	668	747	672	557	300	175	61	10	20	3,210
1962	897	538	577	369	292	134	116	41	23	2,988
1963	1,349	689	412	337	142	88	50	68	42	3,176
1964	2,388	1,070	525	260	200	48	39	18	77	4,626
1965	2,304	1,859	780	246	102	94	15	18	68	5,486
1966	1,325	1,837	1,387	444	124	37	58	3	64	5,279
1967	975	1,009	1,287	803	253	59	16	43	54	4,498
1968	1,655	770	763	903	524	105	13	1	74	4,809
1969	1,539	1,352	617	526	540	253	77	11	62	4,976
VPA										
1959	1,367	1,353	817	296	102	30	12	8	10	3,995
1960	866	1,015	954	492	177	51	12	3	12	3,582
1961	670	627	671	542	293	102	31	7	0	2,943
1962	866	540	479	368	279	129	56	17	1	2,735
1963	1,129	663	413	257	141	78	46	19	6	2,752
1964	1,771	891	504	261	135	47	30	15	14	3,668
1965	1,314	1,354	633	229	102	41	15	11	8	3,707
1966	787	1,026	974	324	110	37	14	3	4	3,279
1967	643	568	624	465	155	48	16	8	0	2,527
1968	409	499	402	360	248	26	4	1	1	1,950
1969	902	333	394	231	98	30	12	3	0	2,003
Spreadsheet										
1959	960	786	643	527	431	353	289	237	1,069	5,295
1960	1,194	758	576	446	360	294	240	197	889	4,952
1961	1,054	932	537	379	288	231	189	154	697	4,461
1962	1,302	820	653	348	241	182	146	119	538	4,349
1963	1,689	995	544	389	201	139	105	84	378	4,524
1964	2,574	1,328	722	371	261	135	93	70	309	5,863
1965	2,132	1,996	923	461	232	163	84	58	236	6,285
1966	1,462	1,676	1,445	628	309	155	108	56	196	6,034
1967	1,637	1,136	1,172	932	396	194	97	68	158	5,792
1968	1,310	1,289	827	804	630	267	131	65	152	5,475
1969	1,568	1,029	931	561	535	418	177	87	144	5,450

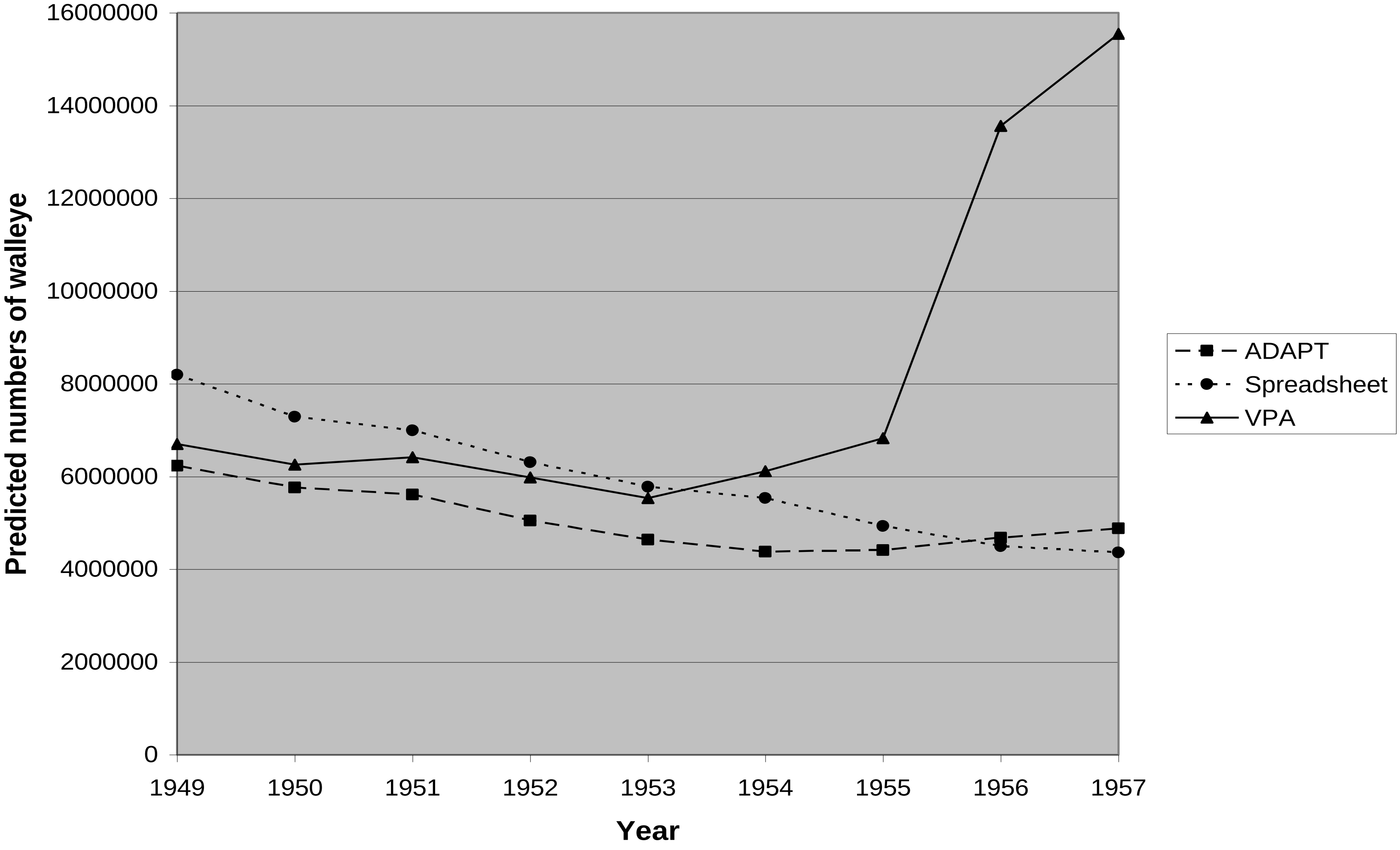

Figure 26. Predicted abundances in numbers of fish for the spreadsheet, ADAPT, and VPA models, 1949-1957.

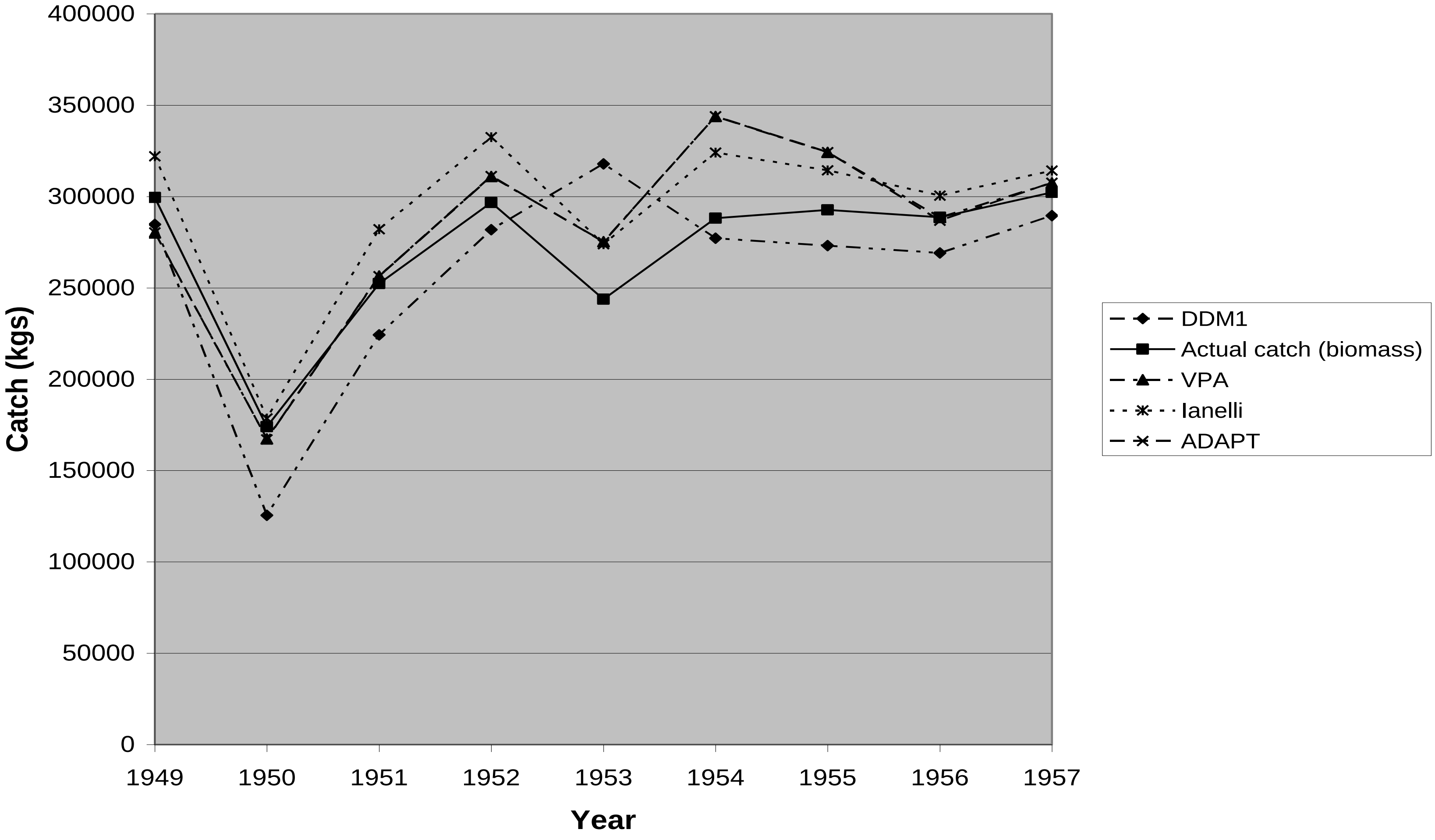

Figure 27. Observed catch in kilograms and the predicted catches in kilograms of the DDM1, ADAPT, VPA and spreadsheet models, for the years 1949-1957.

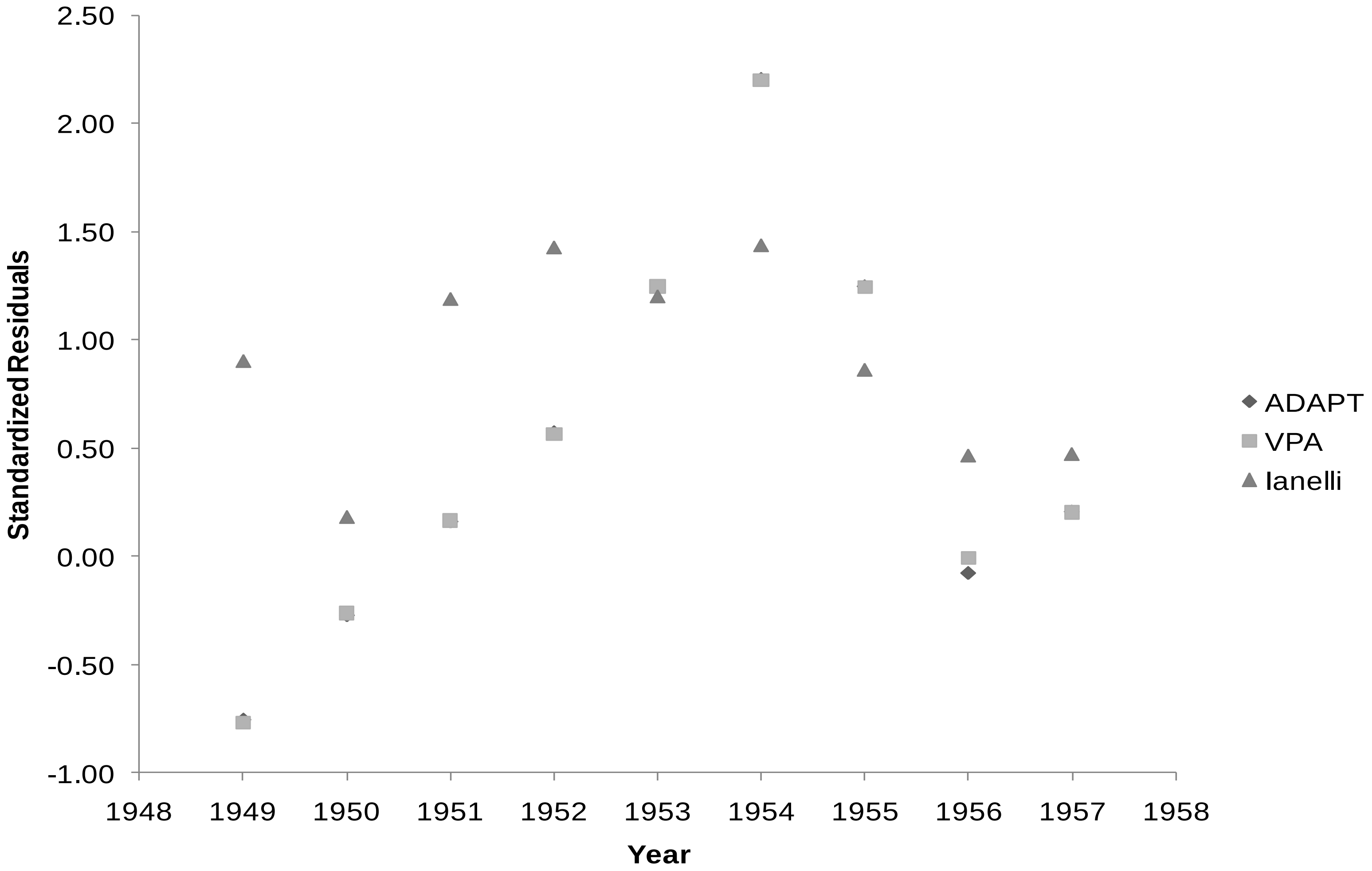

Figure 28. Standardized residuals for the ADAPT, VPA, and Ianelli spreadsheet catches for the years 1949-1957.

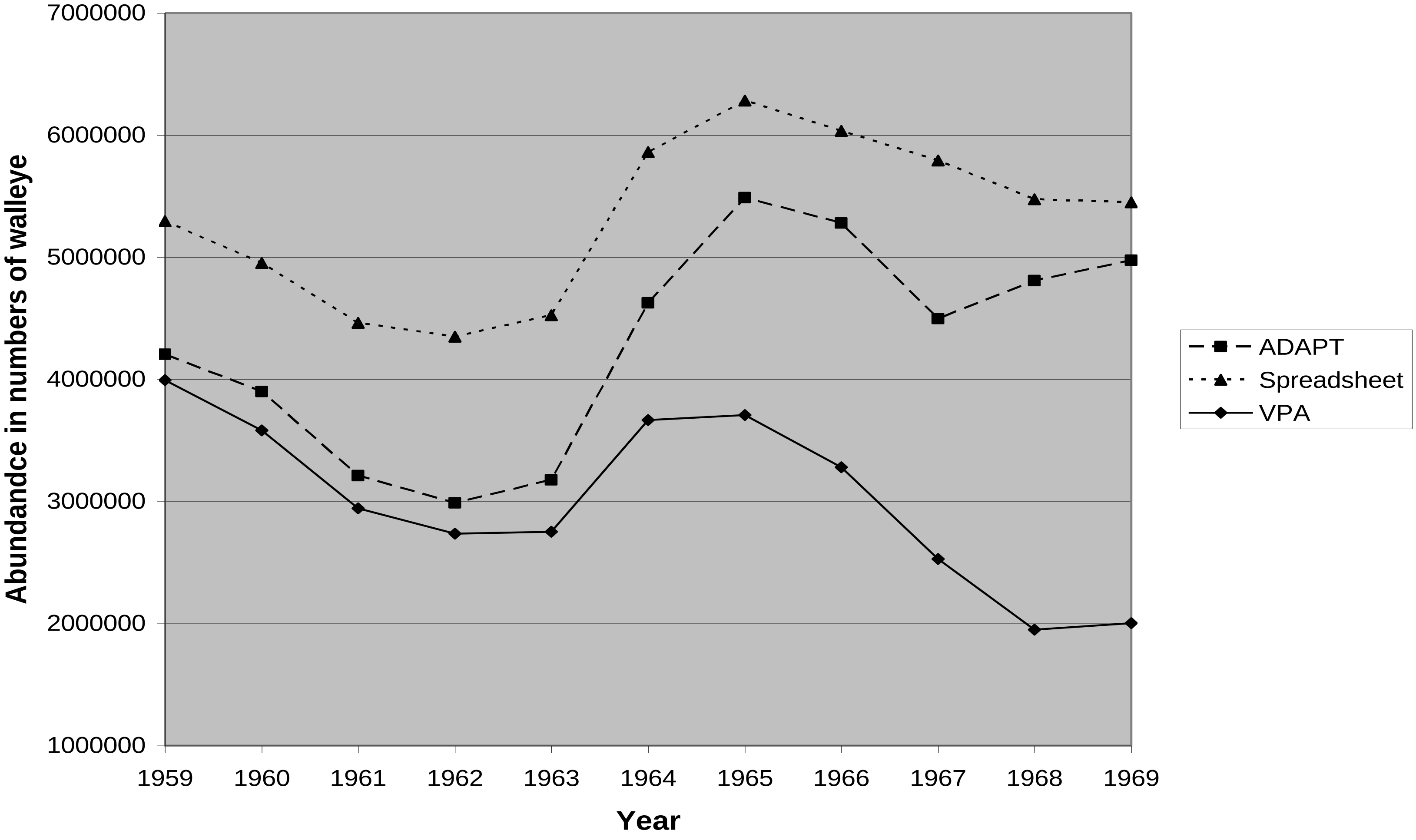

Figure 29. Predictions of total fishable abundance for the spreadsheet, ADAPT and VPA models, 1959-1969.

abundances with similar patterns of change over time. The estimates for ADAPT and VPA were also quite similar in the first half of the time series; however, about 1964, the estimates begin to have a greater variance, with the spreadsheet method predicting higher estimates and the Lowestoft VPA predicting lower abundance. Predicted catch in kilograms per year for the three catch-at-age type models and the delay difference model (DDM1), for 1959-1969 shows that the VPA has the highest level of correspondence to the actual catch in both pattern and biomass with a residual sum of squares of 1.12E+06 (Figure 30). The closest correspondence with the actual catch was the VPA simulation, which nearly matches the actual catch. The ADAPT simulation predicts higher catches starting in 1965 when compared to the VPA and the spreadsheet simulation initially predicts higher catches. The only the ADAPT showed any trend in the standardized catch residuals (Figure 31). These observations were confirmed by the results of the correlation and CSS analyses (Table 8).

The predicted abundances for the three catch-at-age models showed varying levels of abundance for 1949-1969 (Table 7, Figure 32). Initially, abundance in all the simulations declined, though the decline in the VPA was far more pronounced than the other methods. The spreadsheet model estimated uniformly higher abundances than the estimated abundances from the other models. After 1956, all the simulations were similar in predicted abundance estimates and pattern.

For 1949-1969, the age-structured methods had a high level of correspondence between actual and predicted catch in both pattern and biomass, except in 1959, over the delay difference model (DDM1) (Figure 33). The large predicted catch estimates when

Table 7: Abundance estimates at age in thousands of fish for the three age-structured methods for the time period 1949-1969 (continued on next page)

Year	2	3	4	5	6	7	8	9	10	Total
			ADAPT							
1949	3,033	2,029	235	394	351	38	67	68	8	6,223
1950	1,099	2,477	1,630	162	163	142	23	20	24	5,739
1951	1,092	899	2,018	1,256	95	74	62	11	15	5,522
1952	1,315	894	734	1,574	746	48	41	33	11	5,395
1953	644	1,076	727	580	1,051	396	26	23	21	4,543
1954	694	527	878	579	422	630	201	16	28	3,976
1955	664	568	427	707	398	234	292	85	27	3,403
1956	730	542	457	333	525	212	99	102	52	3,052
1957	1,605	597	441	348	207	326	65	31	69	3,687
1958	1,704	1,313	466	318	155	63	183	2	48	4,251
1959	1,359	1,336	797	290	98	27	9	5	33	3,954
1960	864	1,008	940	476	173	48	10	1	26	3,546
1961	665	626	666	530	280	98	29	4	20	2,917
1962	888	535	478	364	270	118	53	15	18	2,739
1963	1,284	681	409	256	138	70	37	16	17	2,909
1964	2,446	1,017	519	258	134	45	24	8	14	4,465
1965	2,048	1,906	737	240	100	40	13	6	8	5,099
1966	1,185	1,627	1,426	408	120	35	14	1	5	4,822
1967	882	894	1,115	834	224	56	15	7	4	4,031
1968	1,655	694	669	762	550	82	10	0	5	4,427
1969	1,539	1,352	554	449	425	274	57	8	4	4,664
			VPA							
1949	11,557	13,278	2,184	4,098	4,595	728	2,746	4,397	513	44,096
1950	2,157	9,457	10,840	1,758	3,194	3,615	588	2,213	2,586	36,408
1951	1,342	1,766	7,732	8,797	1,402	2,555	2,905	473	653	27,625
1952	1,394	1,099	1,443	6,253	6,919	1,117	2,072	2,360	434	23,091
1953	654	1,141	895	1,161	4,880	5,448	901	1,686	86	16,852
1954	701	535	931	717	897	3,764	4,337	733	430	13,045
1955	668	573	434	750	511	623	2,857	3,470	550	10,436
1956	735	544	461	339	561	304	416	2,200	494	6,054
1957	1,638	601	443	351	211	355	140	290	279	4,308
1958	1,727	1,340	469	319	158	67	207	62	204	4,553
1959	1,368	1,355	819	293	100	29	12	22	28	4,026
1960	866	1,016	956	494	175	50	11	3	12	3,583
1961	670	627	672	543	295	100	30	6	0	2,943
1962	866	540	479	369	280	130	54	16	1	2,735
1963	1,128	663	413	257	142	79	47	18	5	2,752
1964	1,768	889	504	261	135	48	31	16	14	3,666
1965	1,308	1,352	632	229	102	41	16	12	9	3,701
1966	760	1,021	972	323	110	37	14	3	4	3,244
1967	627	546	620	464	154	48	16	8	0	2,483
1968	448	485	384	357	247	26	4	1	1	1,953
1969	891	364	383	216	96	29	12	3	0	1,994

Table 7, continued: Abundance estimates at age in thousands of fish for the three age-structured methods for the time period 1949-1969

Year	2	3	4	5	6	7	8	9	10	Total
			Spreadsheet							
1949	1,385	1,134	929	760	623	510	417	342	1,543	7,643
1950	1,285	1,118	886	699	564	460	376	308	1,391	7,089
1951	1,201	1,043	890	690	540	434	354	290	1,308	6,749
1952	1,328	969	814	669	511	398	320	261	1,177	6,446
1953	1,369	1,067	746	598	482	366	285	229	1,030	6,172
1954	1,231	1,102	826	553	435	349	265	206	911	5,879
1955	988	985	838	593	388	303	243	185	778	5,301
1956	849	789	744	594	410	266	208	167	660	4,688
1957	1,541	678	594	525	408	280	182	142	563	4,913
1958	1,717	1,225	504	409	351	271	185	120	467	5,247
1959	1,659	1,357	894	336	263	224	172	118	373	5,396
1960	1,362	1,321	1,015	624	228	177	150	116	330	5,323
1961	1,255	1,079	972	688	408	148	115	97	289	5,051
1962	1,356	994	793	658	449	265	96	74	250	4,935
1963	1,506	1,064	709	508	403	273	160	58	196	4,877
1964	1,965	1,202	803	502	351	276	187	110	174	5,569
1965	1,727	1,553	878	536	323	224	176	119	180	5,717
1966	1,412	1,373	1,157	607	360	215	149	117	199	5,590
1967	1,470	1,111	990	756	381	223	133	92	196	5,353
1968	1,368	1,167	823	678	501	250	147	88	189	5,211
1969	1,410	1,085	863	562	448	328	164	96	181	5,138

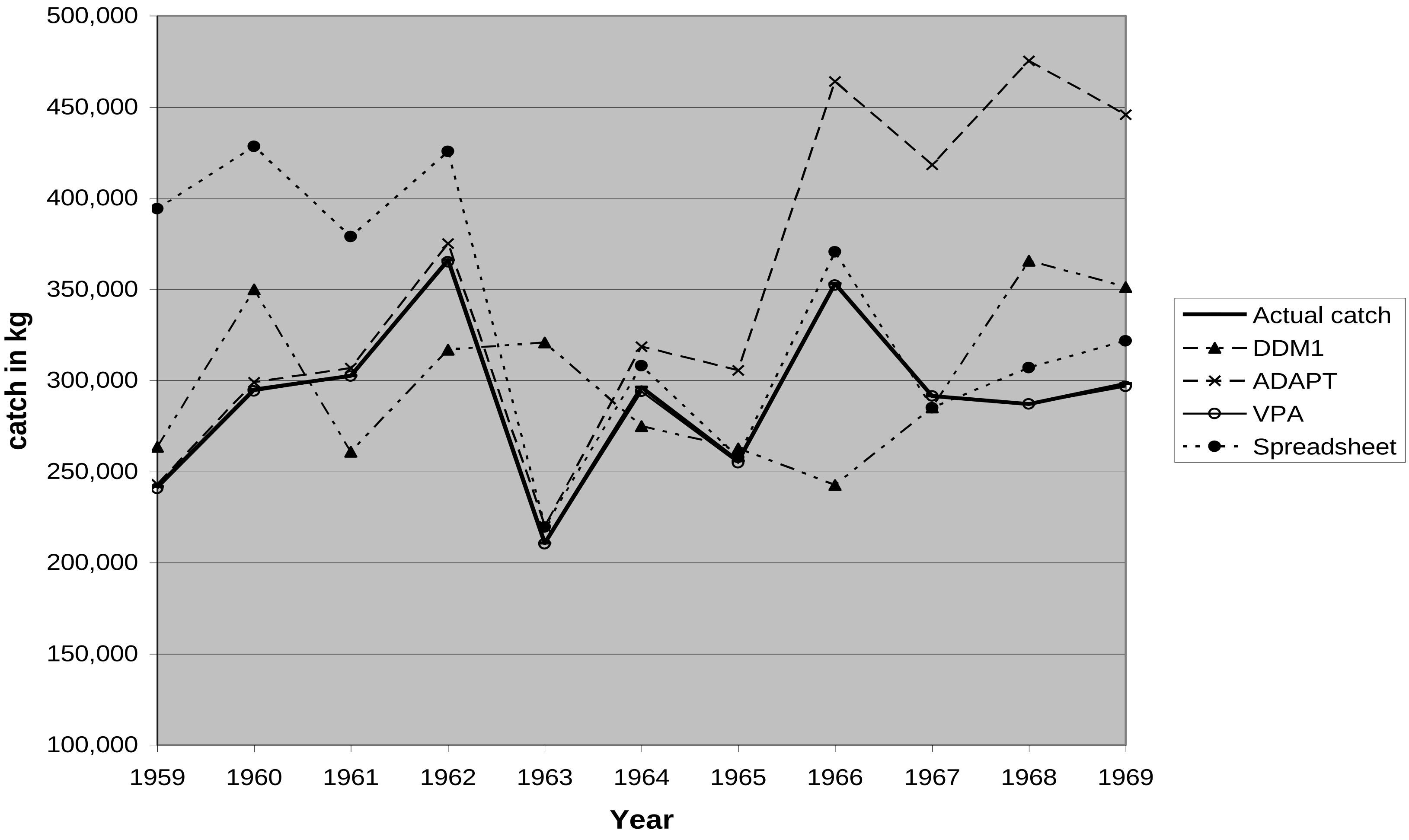

Figure 30. Comparison between observed fishery catch in kilograms and the delay-difference, VPA, ADAPT, and spreadsheet models' predicted catches for the years 1959-1969.

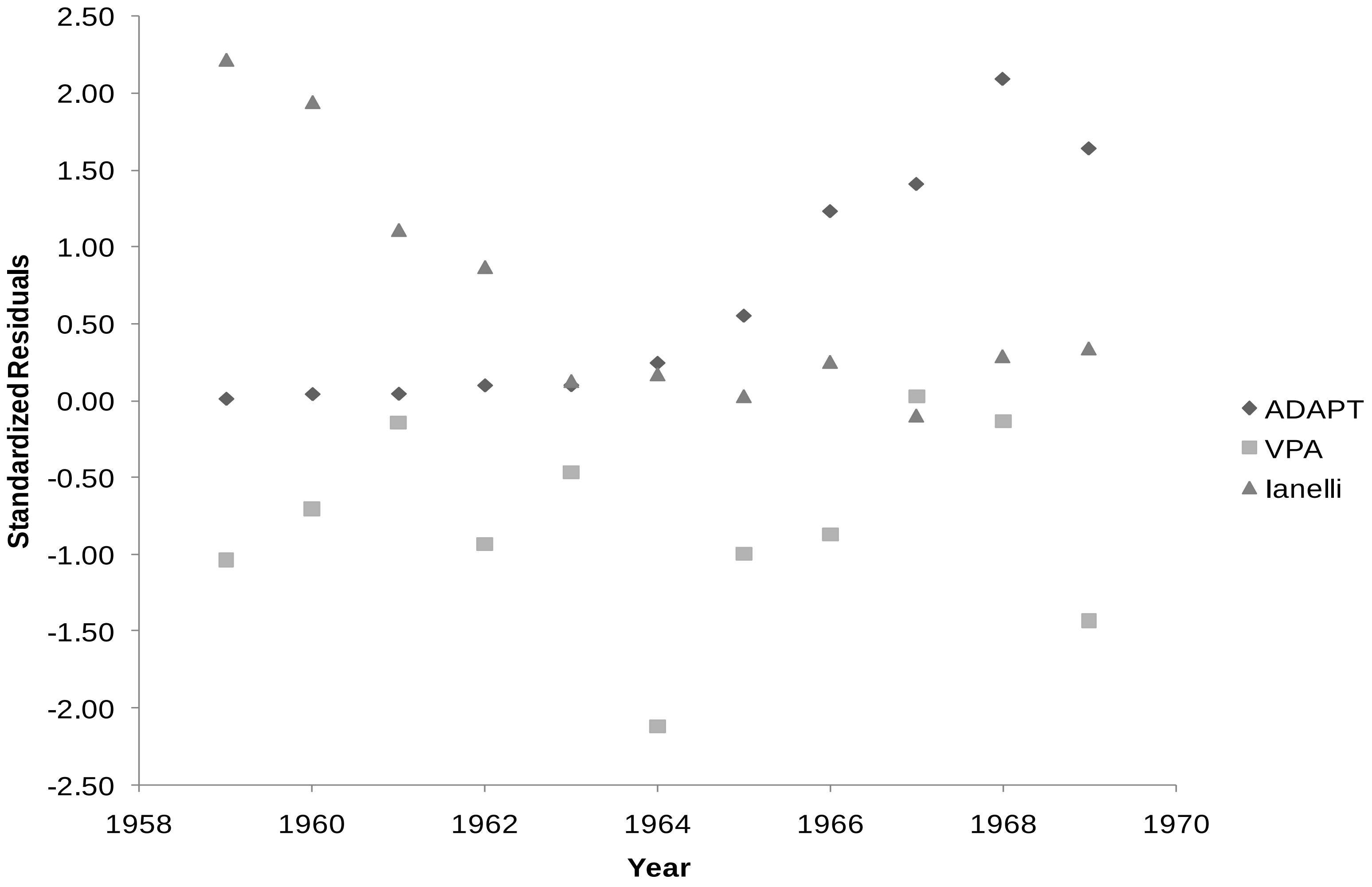

Figure 31. Standardized residuals for the ADAPT, VPA, and Ianelli catch for the years 1959-1969.

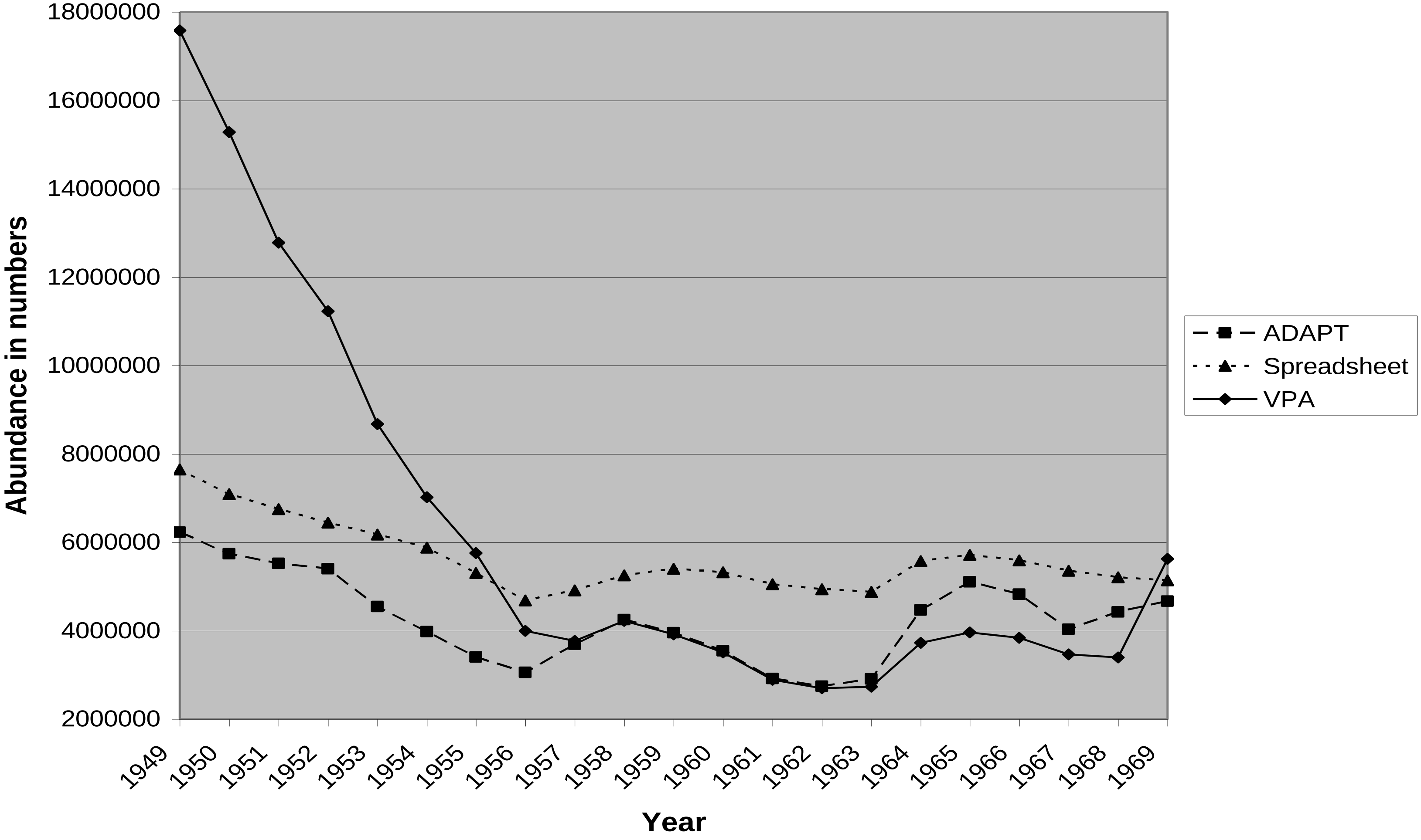

Figure 32. Estimated abundance of fishable population in numbers for the years 1949-1969; estimates generated by the ADAPT, spreadsheet, and VPA simulation methods.

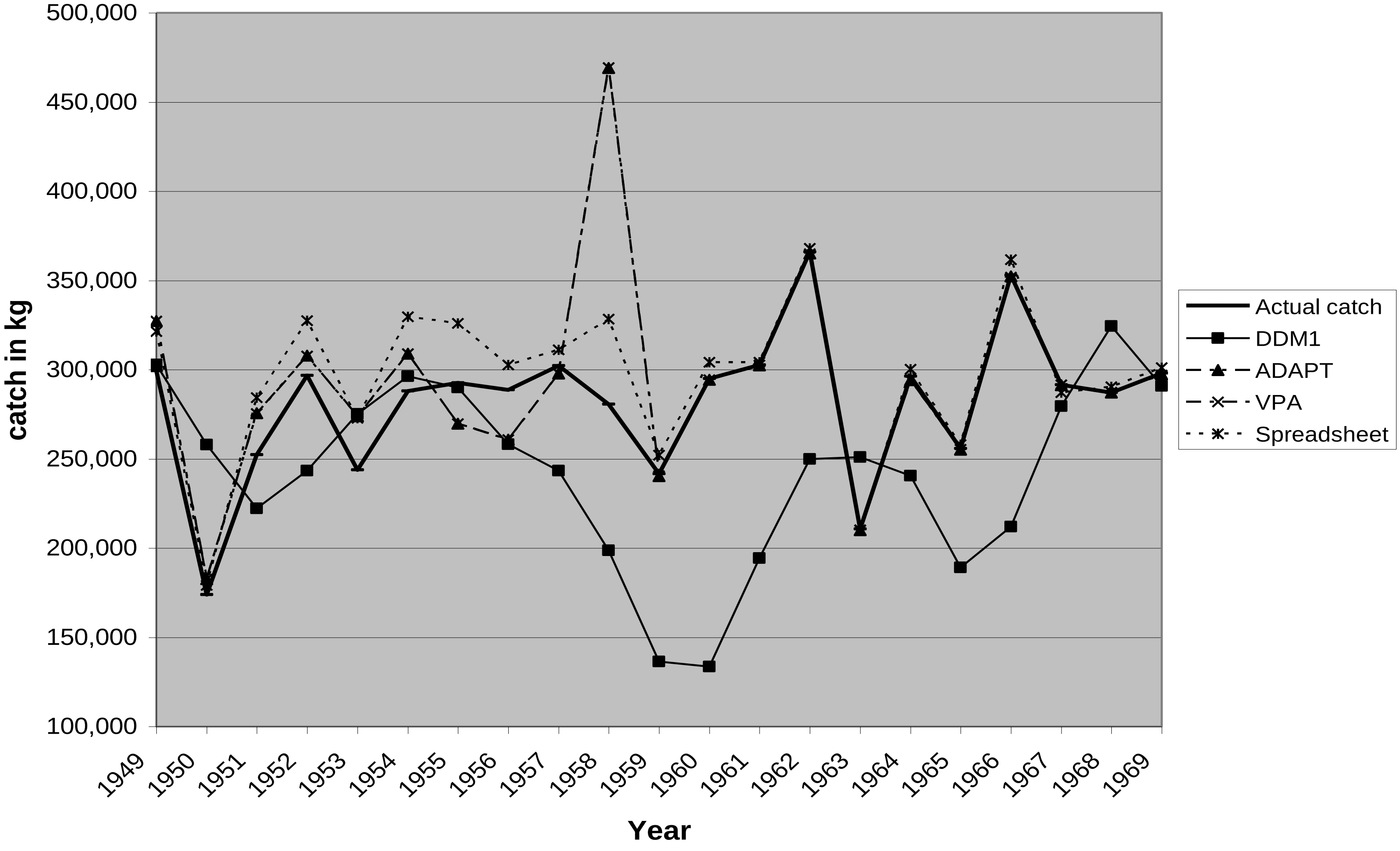

Figure 33. Predicted catches in kilograms for the delay-difference, ADAPT, VPA, and spreadsheet simulations for 1949-1969; compared to the actual catches over that time period.

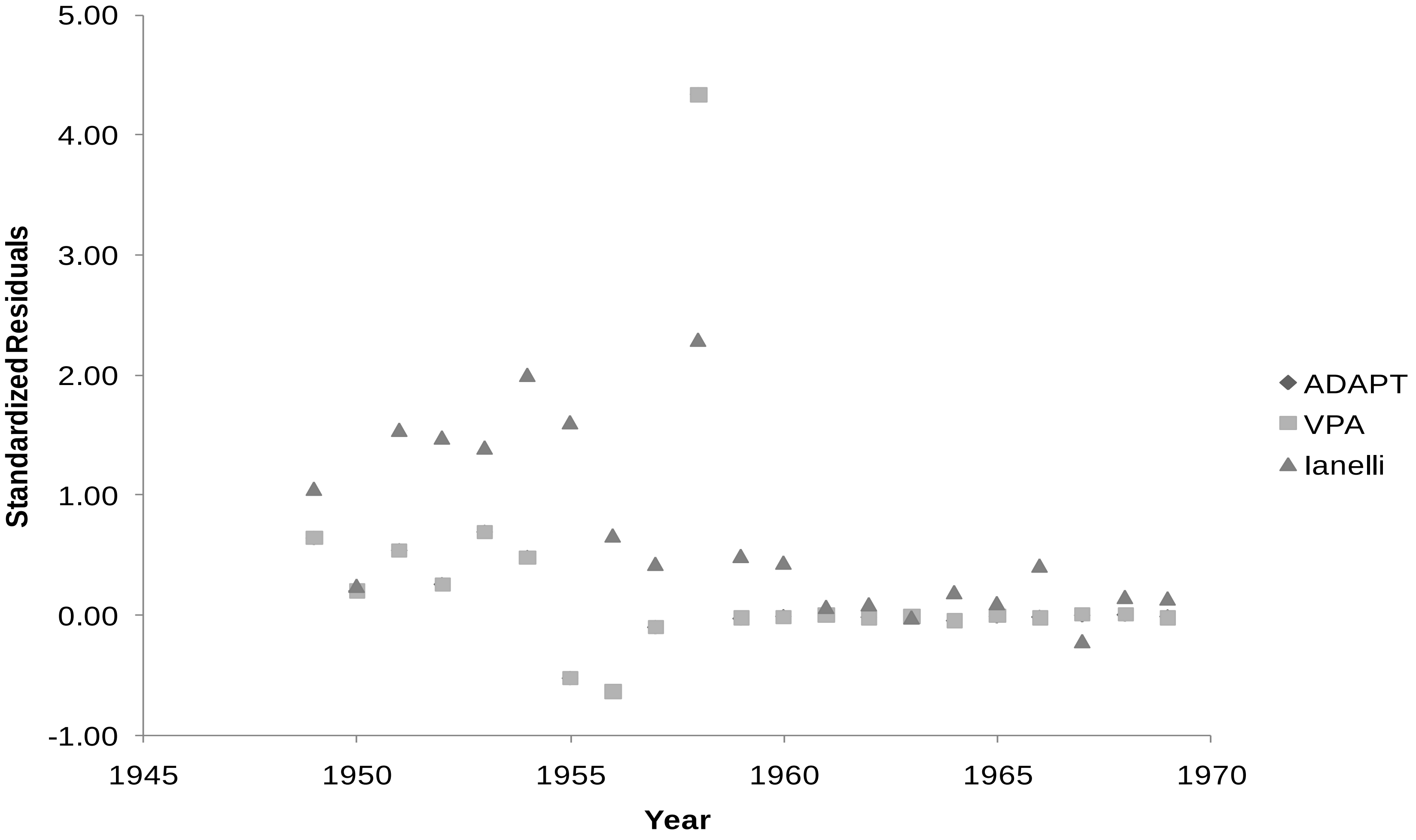

Figure 34. Standardized residuals for the ADAPT, VPA, and Ianelli catch for the years 1949-1969.

Table 8: The comparisons between the delay-difference DDM1 settings, ADAPT, spreadsheet, and VPA models for two time spans (1949-1957, 1959-1969, and 1949-1969).

1949-1957	DDM1	ADAPT	VPA	Spreadsheet
R-value	0.8012	0.8953	0.8693	0.9185
CSS	1.01E+10	3.98E+03	4.17E+09	3.81E+09
AIC	56.3495	108.3220	90.3232	80.4634

1959-1969	DDM1	ADAPT	VPA	Spreadsheet
R-value	-0.0603	0.6473	0.9999	0.6155
CSS	4.15E+10	8.88E+10	1.23E+07	5.19E+10
AIC	86.4298	108.4596	90.3861	94.4381

1949-1969	DDM1	ADAPT	VPA	Spreadsheet
R-value	0.0557	0.6742	0.6732	0.9523
CSS	1.16E+11	3.97E+10	3.98E+10	8.47E+09
AIC	146.8488	188.7726	188.7726	178.3893

compared to the actual catch resulted in greatly reduced correspondence for the VPA and ADAPT models. The standardized residuals in the second half of the time series tended to be around zero (Figure 34). Excluding 1959, the overall correspondence is very good. The delay-difference predictions decline in 1959 and then remain below the actual catch. The weighted spreadsheet simulations reflect the actual catch amounts and fluctuation most accurately for the correlation and CSS, except in the 1959-1969 period where the separable VPA reflected catch most accurately and had a residual sum of squares of 3.98E+10 (Table 8). The AIC calculations (low scores reflecting greater parsimony) indicated that the delay difference models always had the lowest values, whereas the spreadsheet model was the most parsimonious for 1949-1957 and 1949-1969 and that the VPA was most parsimonious for 1959-1969 (Table 9). Complete estimate tables can be found in appendix 5.

Estimation of Black Market Catch

Figure 23 contains the simulated catches that have been altered to include black market (BM) catch estimates of 10, 15, 20, and 100 percent of the reported catch. The total catch estimates therefore include both the reported catch and the estimated BM catch. A 10% unknown catch resulted in a fluctuating catch level similar to the actual catch until an estimated drop in catch in 1969, but then catch levels increased after three years and a residual sum of squares of 1.12E+12. That increase occurred during one of the lowest observed catches in the time series. A 15% unknown catch resulted in a fluctuating catch level and a drop in catch levels after the early 1970s, though similar levels of catch with a residual sum of squares of 1.19E+12, CPUE, and fluctuations were clearly exhibited with a black market catch of 10% (Figures 35 and 39). A 20% increase from unknown catch resulted in similar estimates of catch when compared to the 10% and 15% black market simulations, and exhibited the same pattern as those runs (Figures 37 and 41). A 100% increase in simulated catch resulted in slightly improved correspondence with catch and CPUE, but it did not match the post-1970 catch pattern. Increasing the catch and effort in two steps, the first in 1960 and the second in 1970, decreased the predicted catch and a residual sum of squares of 2.49E+12, but did not correspond to the observed catch or CPUE after 1970 (Figure 39 and 41). Increasing catch and effort at different rates also resulted in predicted values that did not correspond to catch or CPUE after 1970 (Figures 37 and 41). Of all the catch residuals, the 100% increase shoed the smallest amount of pattern over the entire time series (Figures 36 and 38). The standardized CPUE residuals all have some pattern in the final years of the analysis, regardless of estimated increase of catch (Figures 40 and 42). The 20% BM

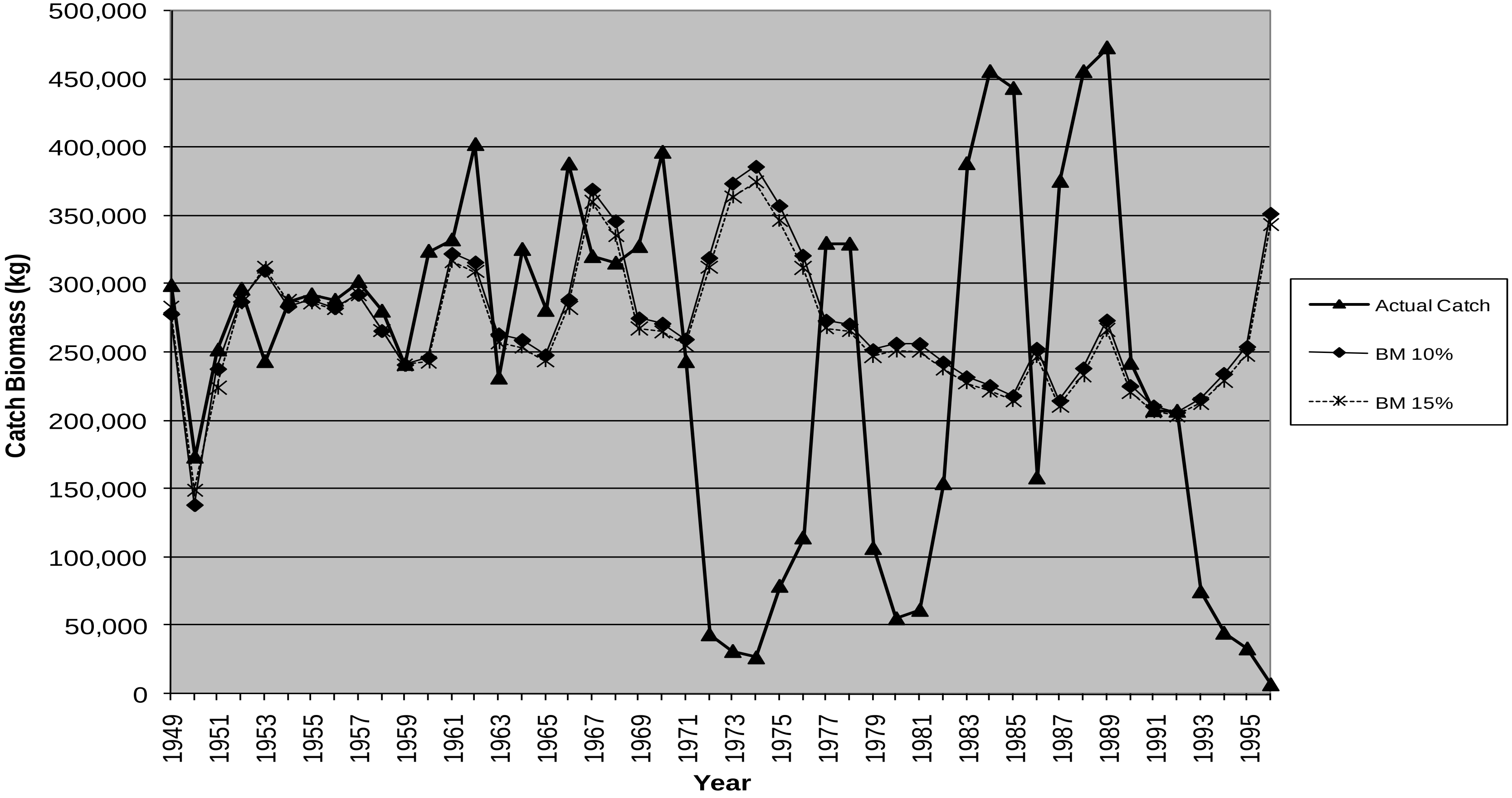

Figure 35. Fit of predicted catch biomass for DDM1 with an additional 10% and 15% catch to comprise reported commercial catch and black market catch, 1949-1996.

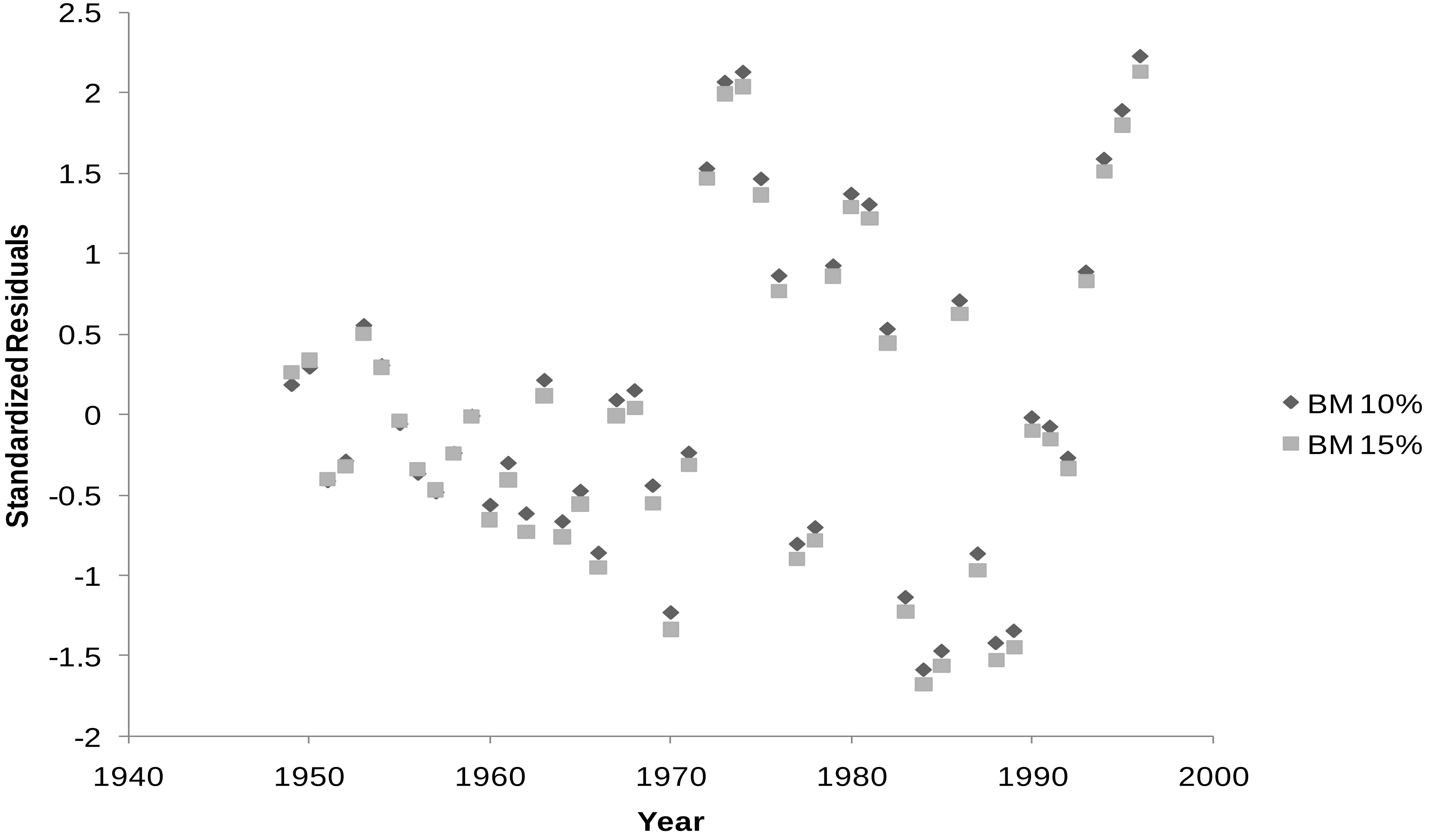

Figure 36. Standardized catch residuals for DDM1 with an additional 10% and 15% catch to comprise reported commercial catch and black market catch, 1949-1996.

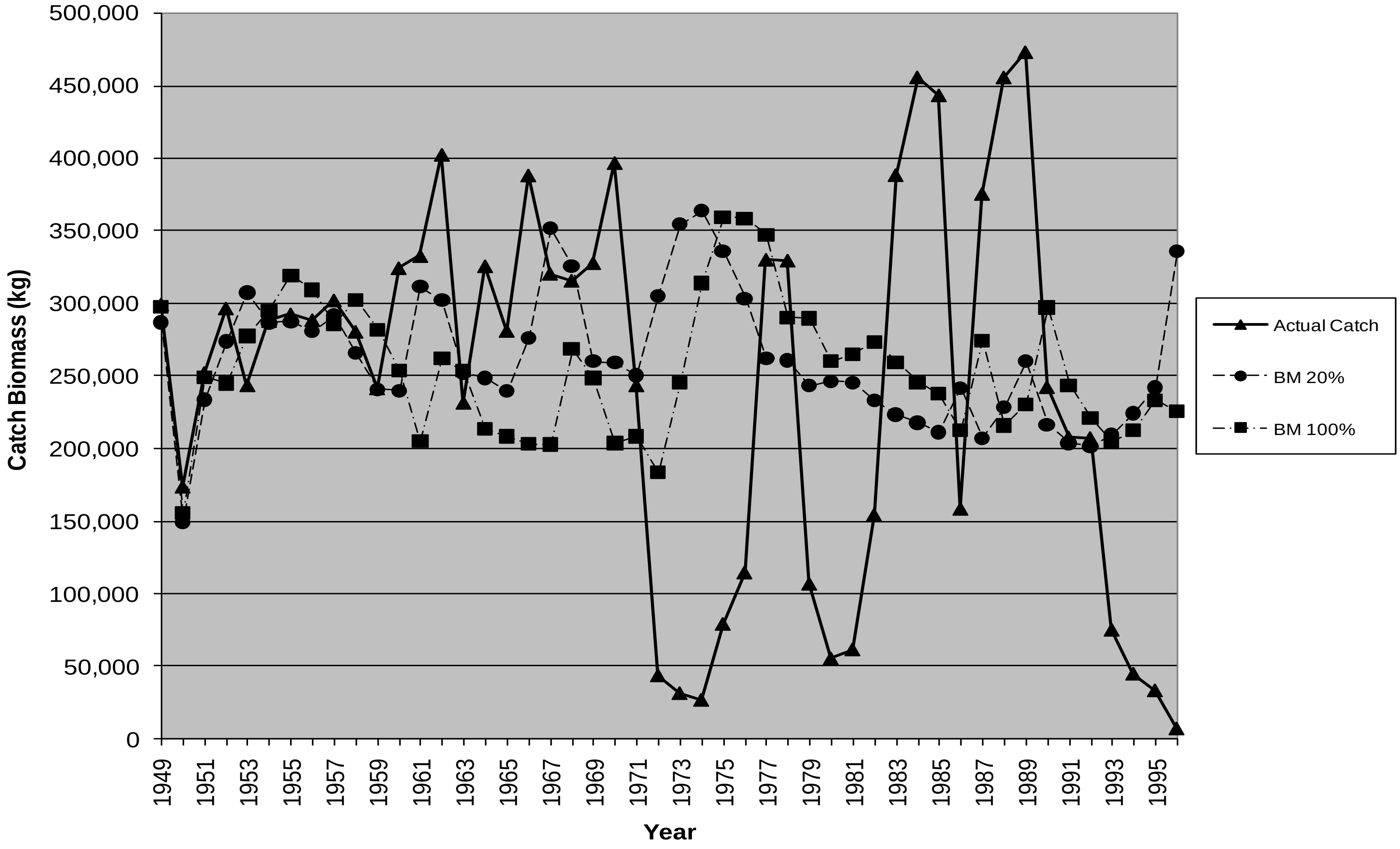

Figure 37. Fit of predicted catch biomass for DDM1 with an additional 20% and 100% catch to comprise reported commercial catch and black market catch, 1949-1996.

Figure 38. Standardized catch residuals for DDM1 with an additional 20% and 100% catch to comprise reported commercial catch and black market catch, 1949-1996.

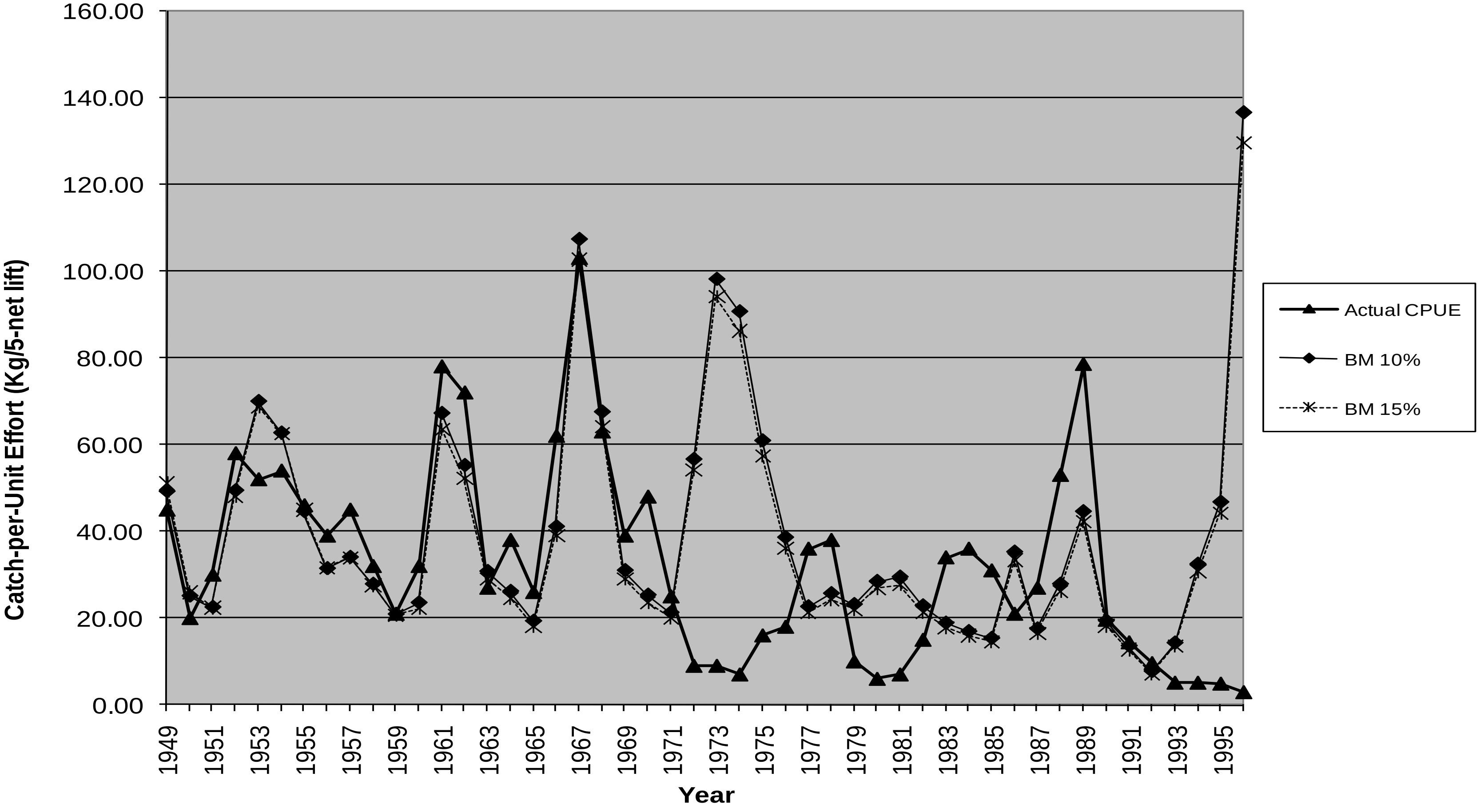

Figure 39. Fit of predicted CPUE for DDM1 with an additional 10% and 15% catch to comprise reported commercial catch and black market catch, 1949-1996.

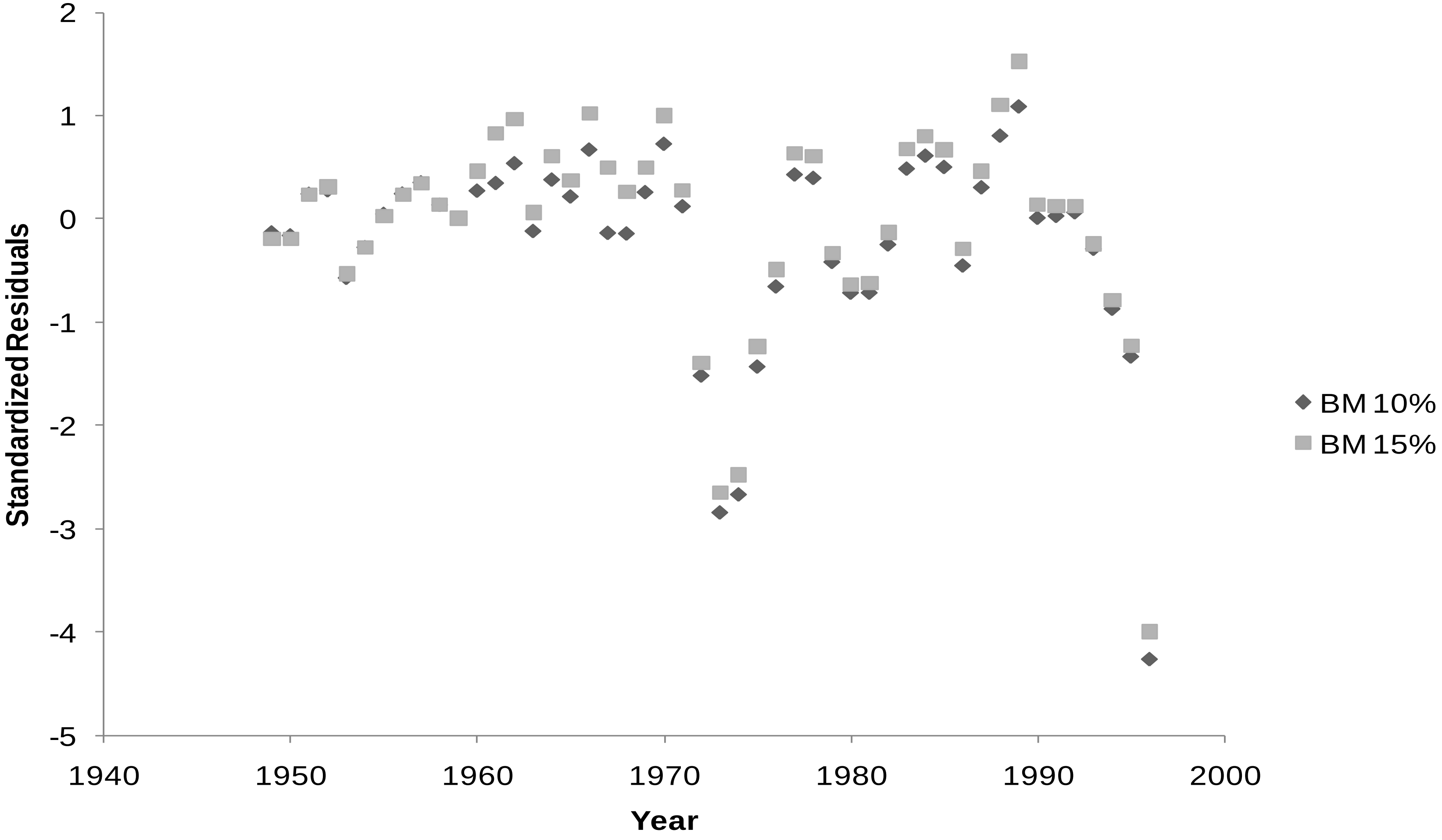

Figure 40. Standardized CPUE residuals for DDM1 with an additional 10% and 15% catch to comprise reported commercial catch and black market catch, 1949-1996.

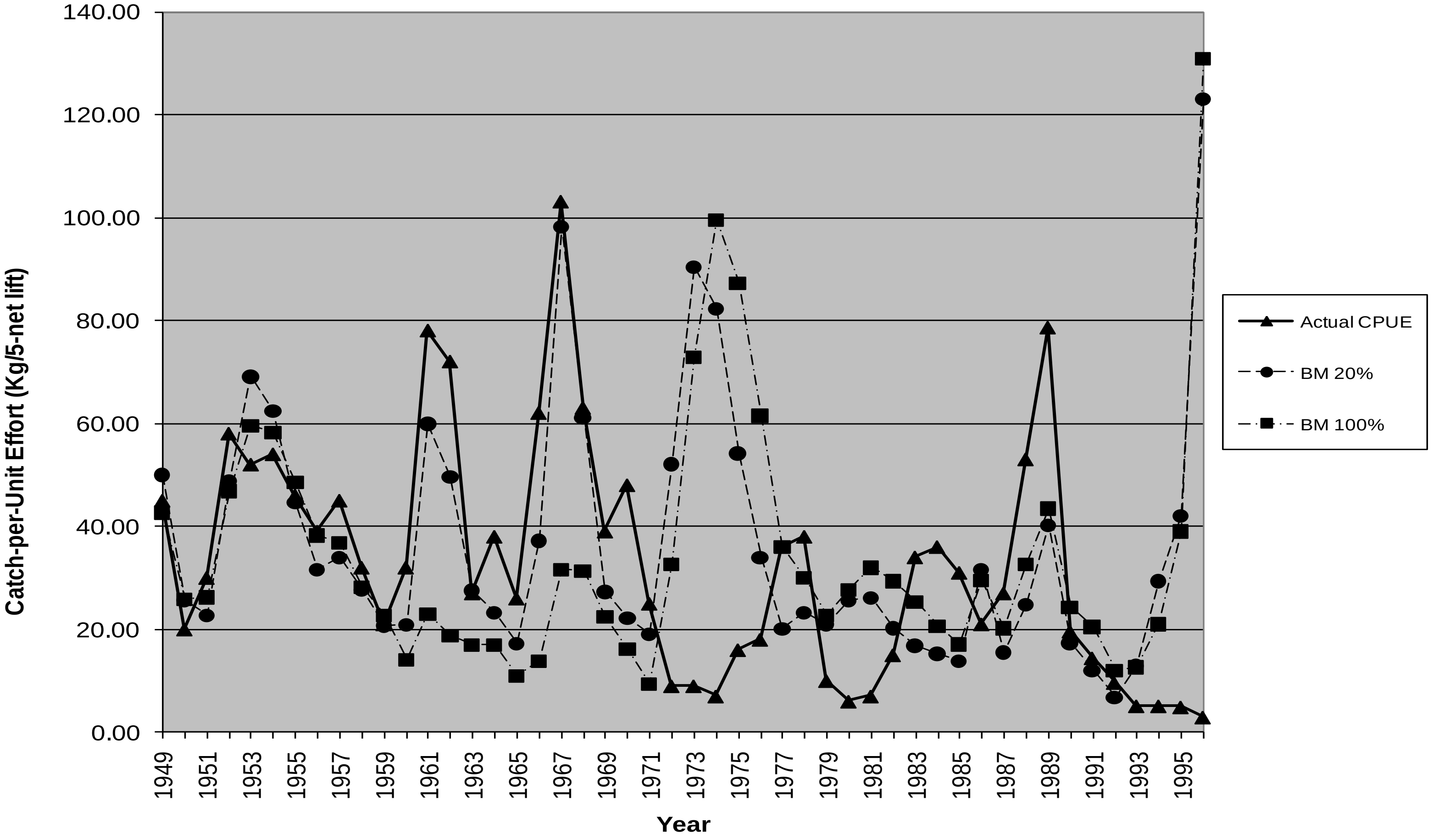

Figure 41. Fit of predicted CPUE for DDM1 with an additional 20% and 100% catch to comprise reported commercial catch and black market catch, 1949-1996.

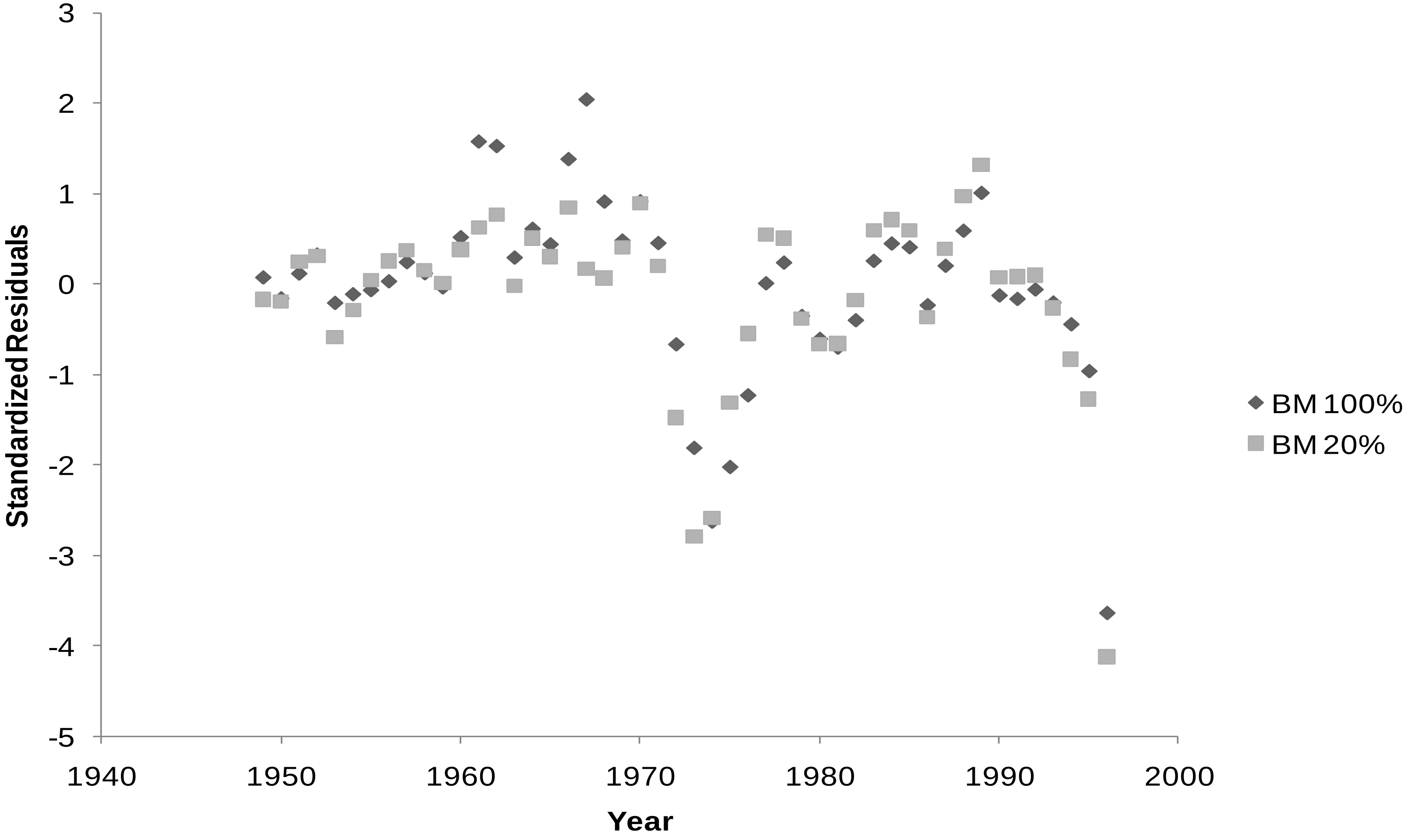

Figure 42. Standardized CPUE residuals for DDM1 with an additional 20% and 100% catch to comprise reported commercial catch and black market catch, 1949-1996.

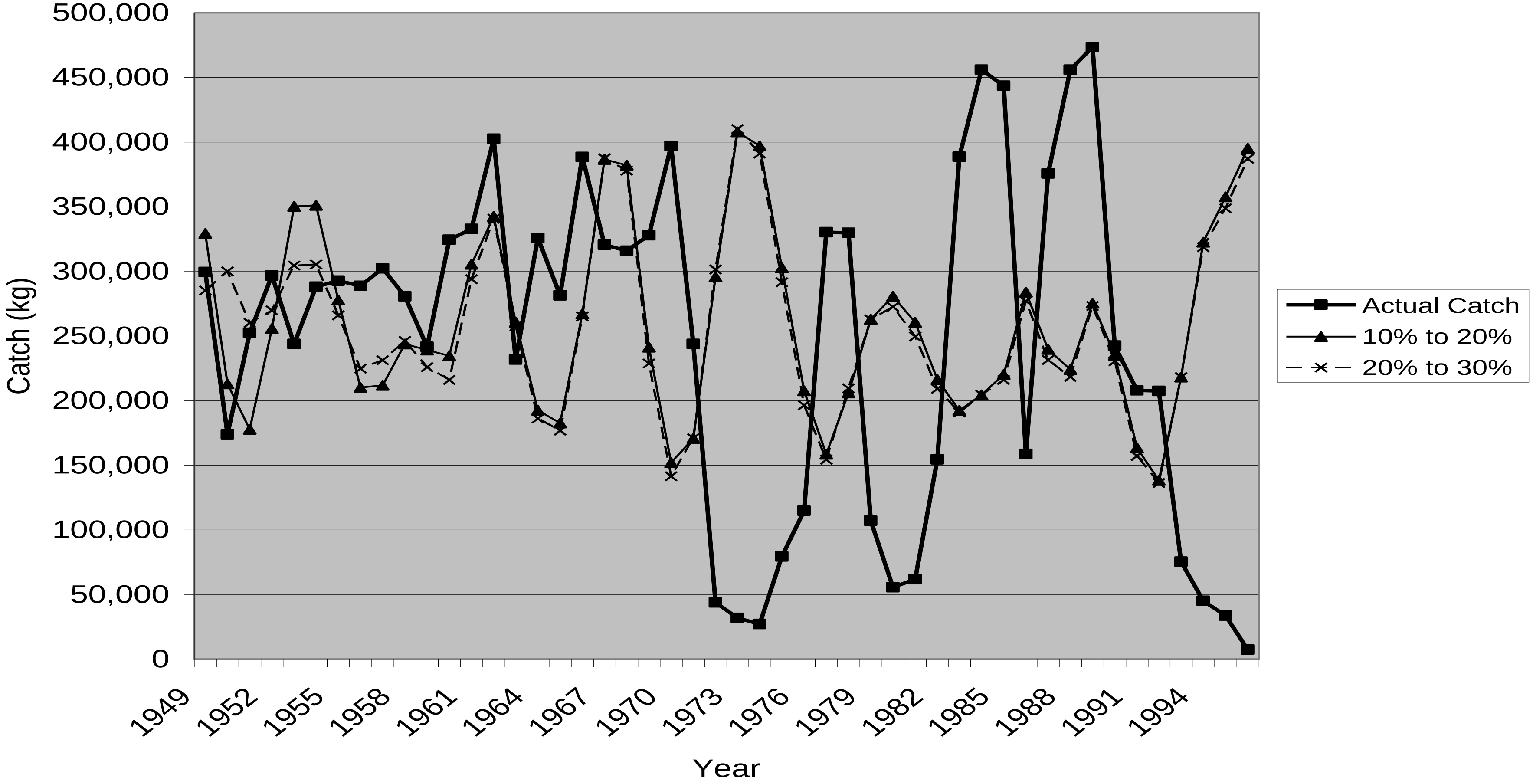

Figure 43. Fit of predicted catch biomass for DDM1 with an additional catch of 10% or 20% from 1960-1969 and increased to 20% or 30% from 1970 on to comprise reported commercial catch and black market catch, 1949-1996.

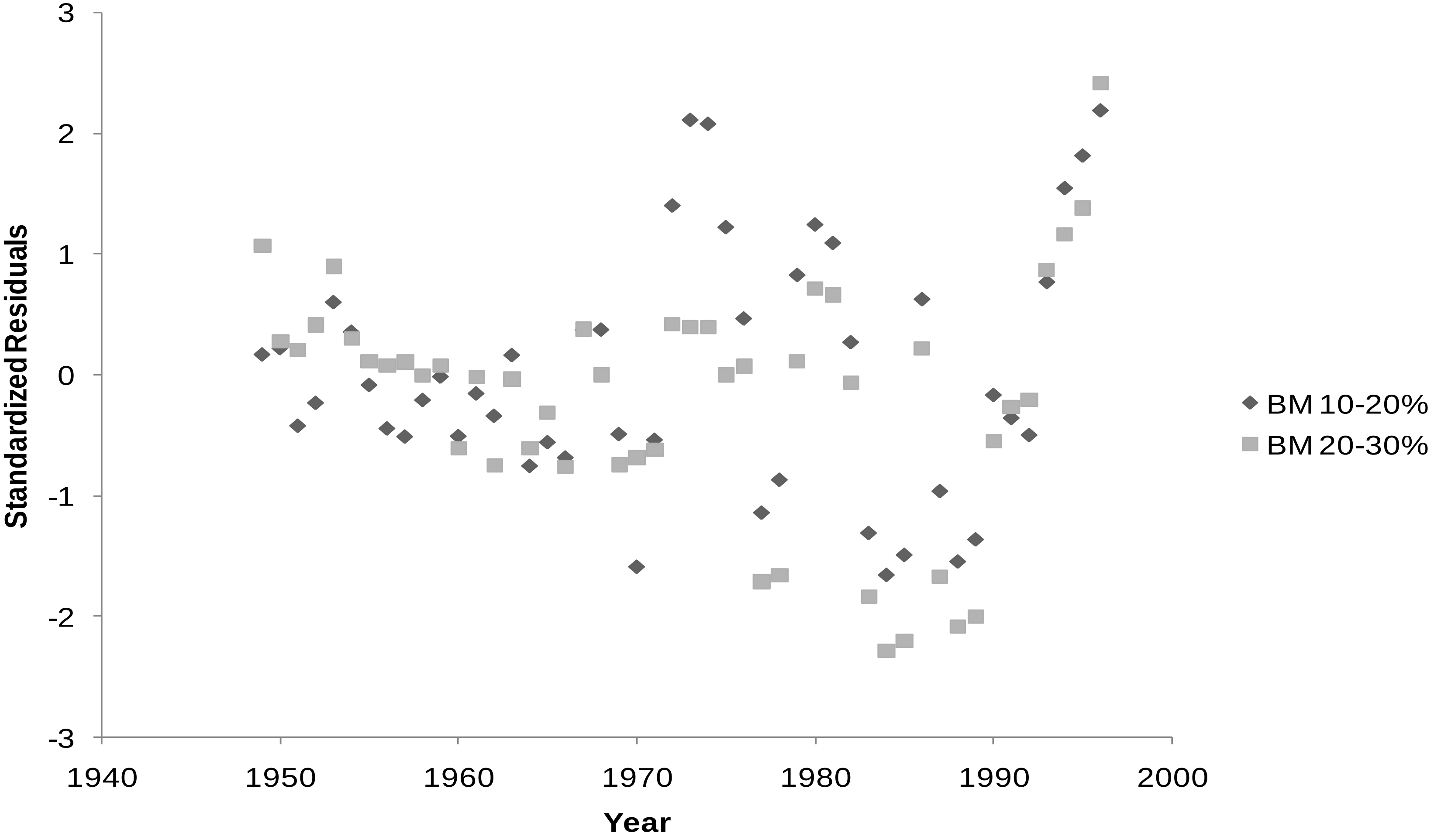

Figure 44. Standardized catch residuals for DDM1 with an additional catch of 10% or 20% from 1960-1969 and increased to 20% or 30% from 1970 on to comprise reported commercial catch and black market catch, 1949-1996.

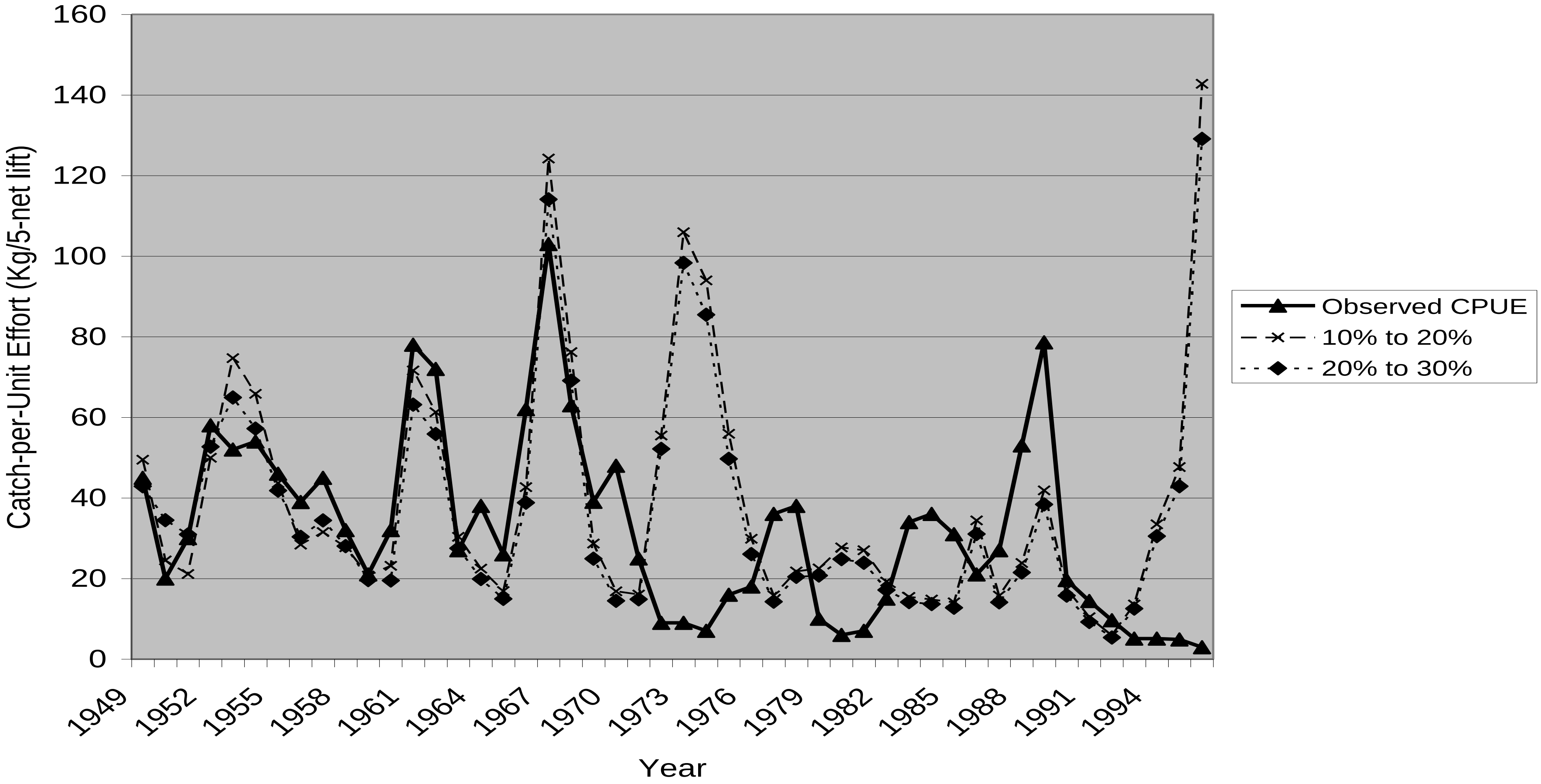

Figure 45. Fit of predicted CPUE for DDM1 with an additional catch of 10% or 20% from 1960-1969 and increased to 20% or 30% from 1970 on to comprise reported commercial catch and black market catch, 1949-1996.

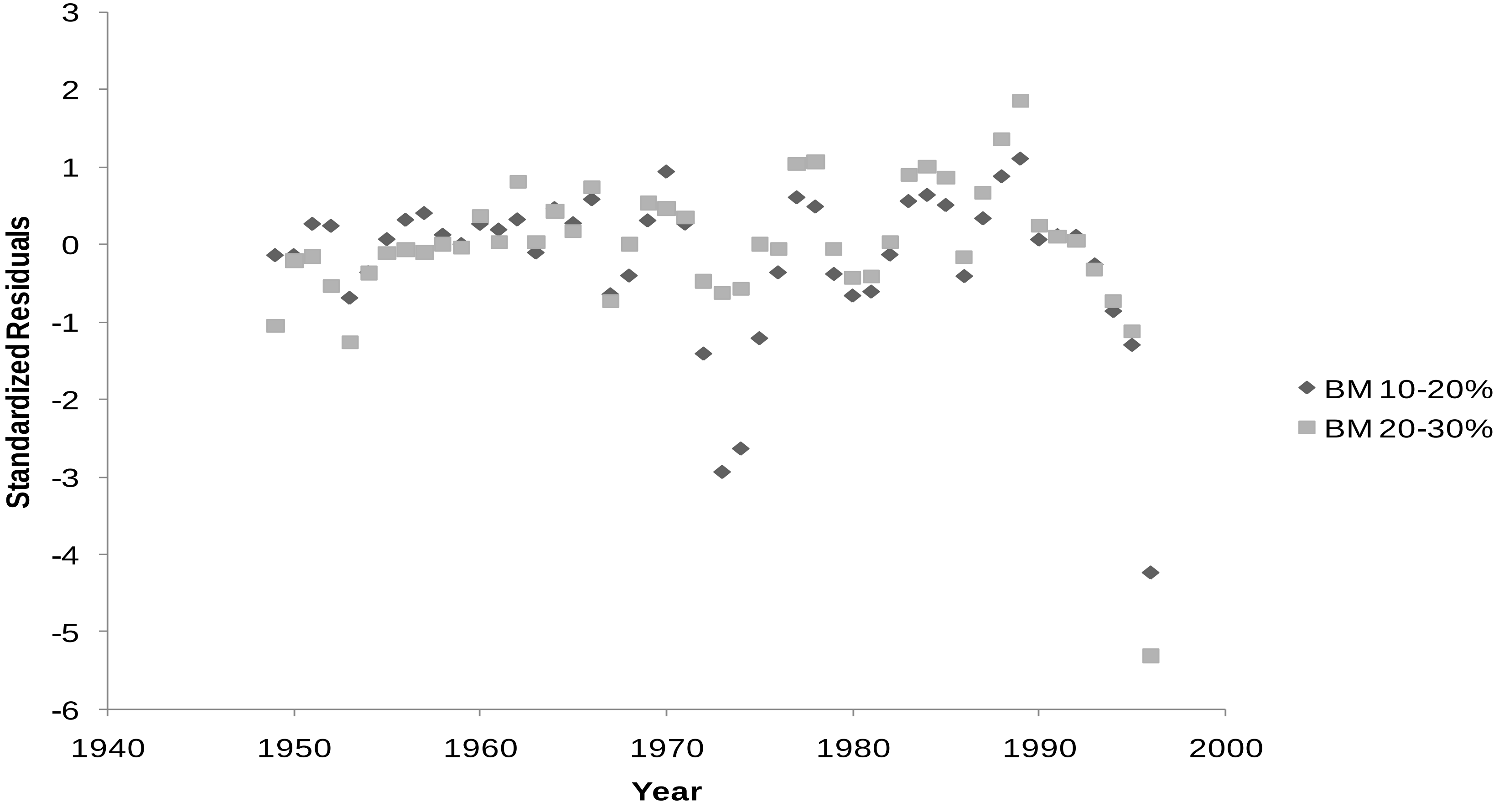

Figure 46. Standardized CPUE residuals for DDM1 with an additional catch of 10% or 20% from 1960-1969 and increased to 20% or 30% from 1970 on to comprise reported commercial catch and black market catch, 1949-1996.

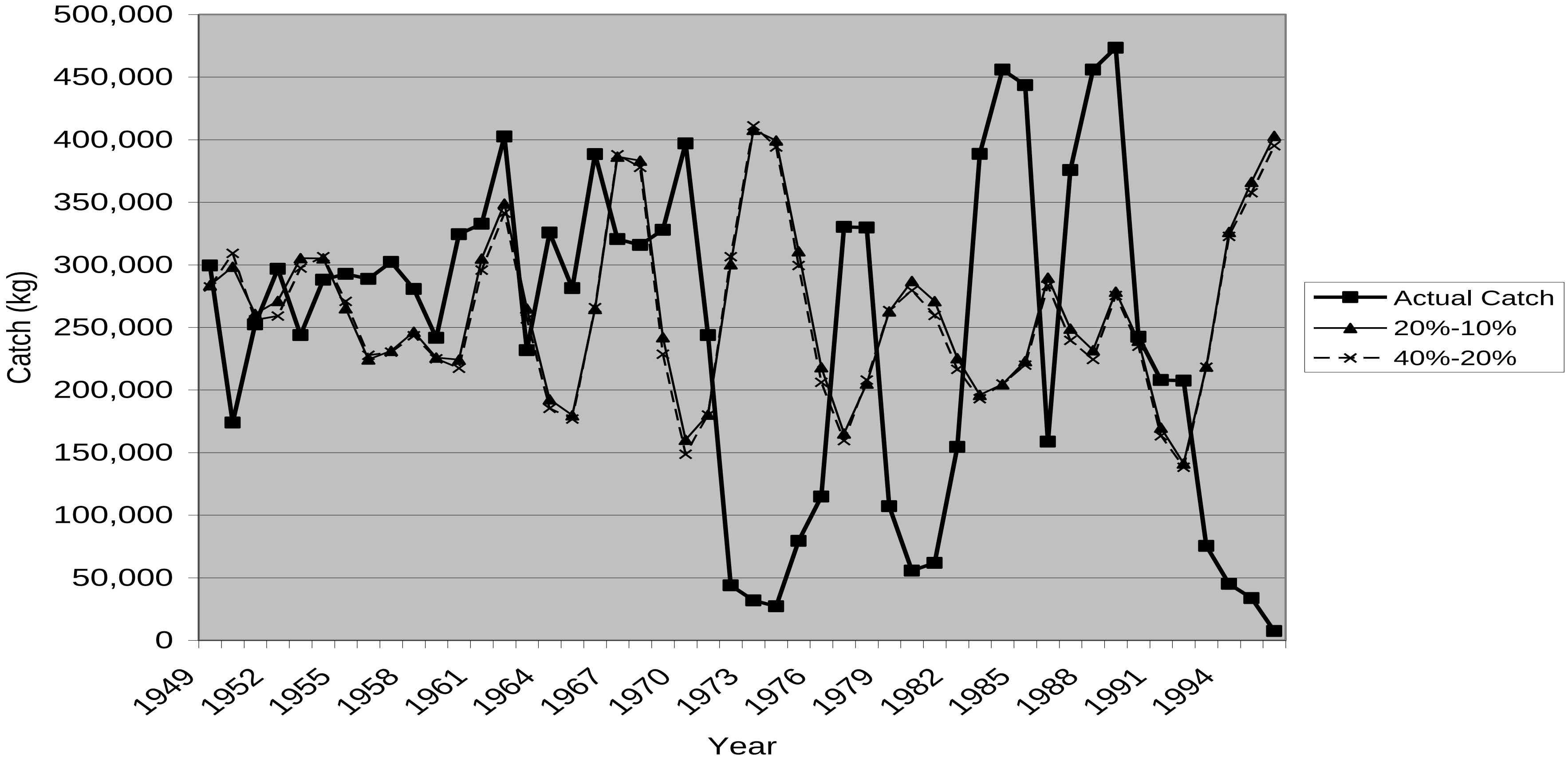

Figure 47. Fit of predicted catch biomass for DDM1 with an additional catch of 20% or 40% and increased effort of 10% or 20% to comprise reported commercial and black market catch and effort, 1949-1996.

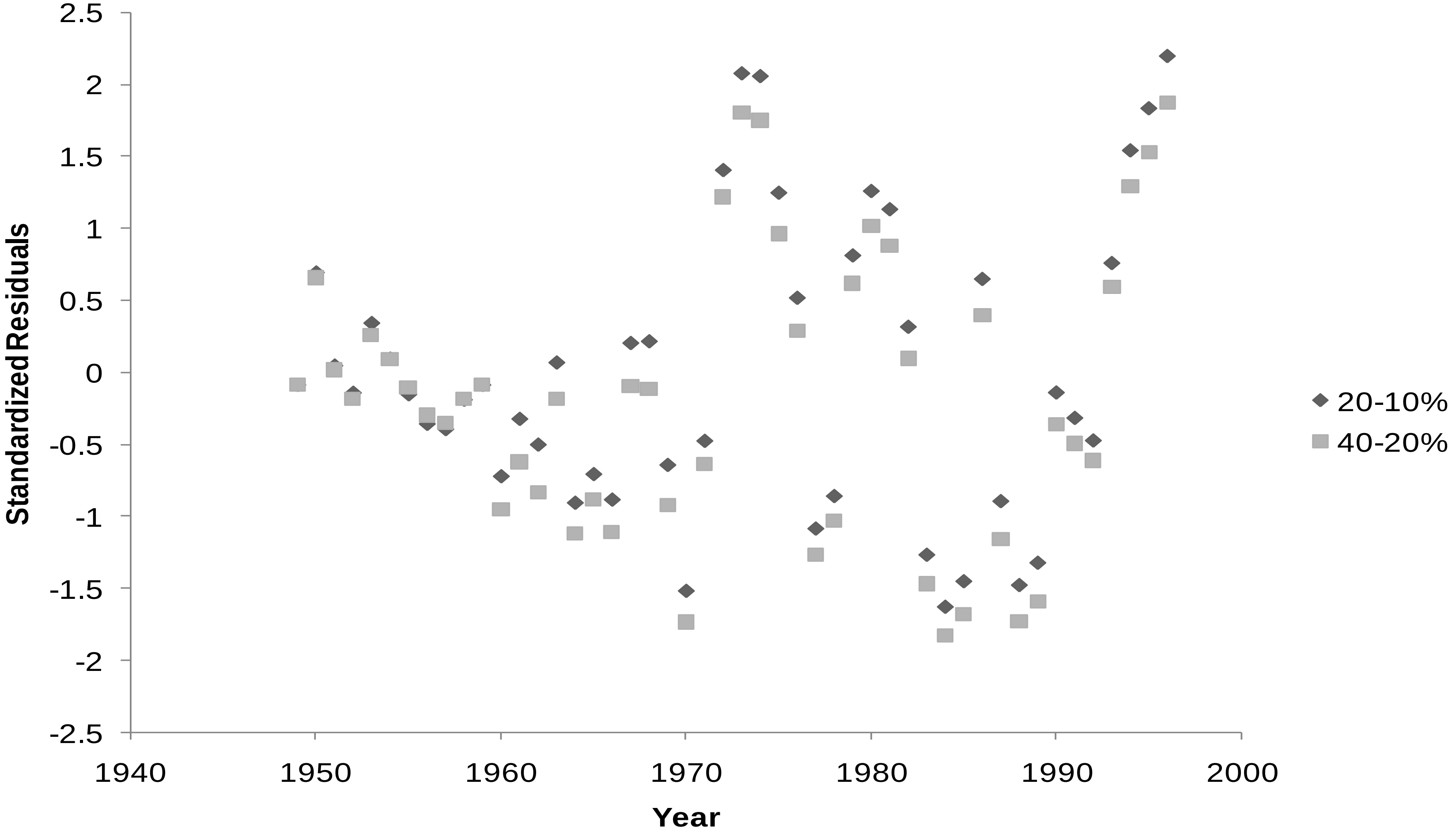

Figure 48. Standardized catch residuals for DDM1 with an additional catch of 20% or 40% and increased effort of 10% or 20% to comprise reported commercial and black market catch and effort, 1949-1996.

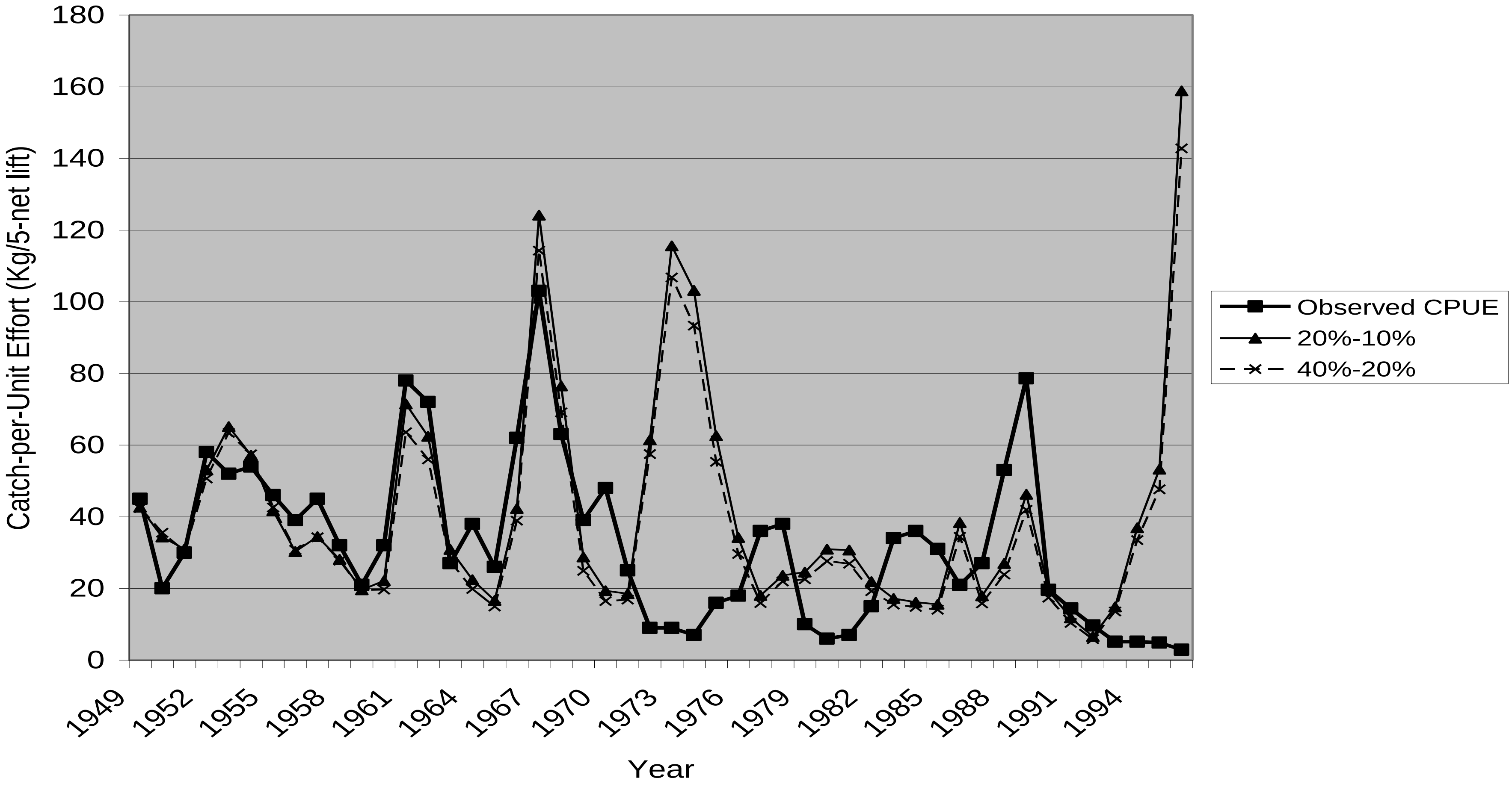

Figure 49. Fit of predicted CPUE for DDM1 with an additional catch of 20% or 40% and increased effort of 10% or 20% to comprise reported commercial and black market catch and effort, 1949-1996.

Figure 50. Standardized CPUE residuals for DDM1 with an additional catch of 20% or 40% and increased effort of 10% or 20% to comprise reported commercial and black market catch and effort, 1949-1996.

catch increase and 10% BM effort increase scenario showed similar variation to the observed catch until 1969, when predicated catches dropped with a residual sum of squares of 1.55E+12. This scenario did not simulate the drastic drop in catches that occurred starting in 1970. The 40% BM catch increase and 20% BM effort increase scenario resulted in slightly lower overall catch estimated, but the same pattern as the previous 20%-10% scenario and a residual sum of squares of 2.03E+12 (Figure 47). Both scenarios had negative correlations, -0.414 for 20%-10% and -0.410 for the 40%-20% scenarios. A Pearson correlation test resulted in values of -0.202 for the 10% BM scenario, -0.195 for the 15% BM scenario, -0.187 for the 20% BM scenario, and -0.056 for the 100% BM scenario. The highest correlation for this simulation was for the 100% BM scenario, though the results were still a negative correlation and were not significant.

Environmental Coefficients and Population Abundance Estimates

Coefficients of environmental effect for walleye and the estimates of population abundance were split into three groups using the 1949-1957, 1959-1969, and 1949-1969 time series to determine if there were differences between shorter and longer time series. There were no statistically significant relationships for the different methods and time scales (Table 9). A statistically significant correlation occurred with a two-year negative lag with the spreadsheet model (Table 10). Correlations between abundance and negative walleye coefficient percent changes were not statistically significant between positive percent changes and their related same-year abundances for ADAPT and VPA (Table 11).

Table 9: The correlation R values (upper row for each period) and their corresponding p-values (lower row) for each of the three catch-at-age models used in analysis and the time spans examined including the Weisberg walleye year-effect coefficients and the estimates of population abundance (in numbers of fish) for each model.

	ADAPT	Spreadsheet	VPA
1949-1969	0.17842	0.17899	0.17025
	0.4391	0.4376	0.4606
1959-1969	0.13127	0.13716	0.23395
	0.7004	0.6876	0.4887
1949-1957	0.19412	0.14489	-0.06039
	0.6167	0.7099	0.8774

Table 10: The correlation R-values and their corresponding p-values for each of the three catch-at-age models used in analysis for the two year lag. The correlations were between the Weisberg walleye year effect coefficients and the estimates of population abundance (in numbers of fish) for each model.

1949-1969	ADAPT	Spreadsheet	VPA
R-value	0.36503	0.45677	0.39171
p-value	0.1037	0.0374	0.0791

Table 11: Correlations for the walleye coefficient percent change for the three catch-at-age methods. Neg is for years that experienced a negative percent change in coefficient and Pos is for years that experienced a positive percent change in coefficient.

Neg	ADAPT	VPA	Spreadsheet
R-value	-0.35543	-0.1897	-0.1136
p-value	0.2569	0.5548	0.7252
Pos	ADAPT	VPA	Spreadsheet
R-value	0.90598	0.79966	0.64277
p-value	0.0008	0.0097	0.0619

Discussion

This research found that:

1. Generally, the age-structured models performed better than the delay-difference model. The performances of the models were examined through the greatest verisimilitude of the models (Figures 18, 20, 22).
2. The inclusion of the walleye environmental coefficients improved the fit of the delay-difference model (Figure 13).
3. The assumed black market catch resulted in only limited improved fit of the delay-difference model with general increases in fishing effort (Figures 23-28).
4. Environmental coefficients had limited explanatory power in changes in population abundance. Overall, more detailed models exhibited better fit than simpler models, including additional coefficients. For simpler models there is a need for very accurate data, and that environmental coefficients may not be a good method for tracking population abundance.

The objective of this dissertation was to use available data from the historical Red Lakes walleye fishery in model simulations to determine a potentially appropriate method for future monitoring. The two main model classes that were examined were the delay-difference model and three age-structured models. The delay-difference model had difficulties in fitting the extremely low walleye catches in the early 1970's. The delay-difference model also underwent several modifications using additional factors, like the Weisberg coefficients, to simulate changes in growth.

Delay-Difference

Generally, the delay-difference model CPUE estimates corresponded with the observed CPUE before the 1970s and show relatively good correspondence (Figures 9 and 11). The model does not predict the recruitment failure that appeared to occur in 1973, and thereafter the model does not fluctuate in the same manner as the observed catch. The predicted and observed catches and CPUE estimates appeared to be inversely proportional between 1970 and 1987, after which the predicted and observed CPUE are concordant (Figures 9 and 11). The failure in correspondence may relate to parameters being held constant over time, especially for the stock-recruitment relationship or the time of recruitment (Hilborn and Walters 1992). The stock-recruitment relationship implies that numbers of fish entering the fishery are entirely dependent on past stock sizes and some degree of stochasticity or environmental influence may be present. Previous research on the Red Lakes has indicated that year-class size is not closely related to parent stock size (Smith 1977). Future research should examine other stock-recruitment relationships, such as a stochastic relationship that is not strictly dependent on previous stock sizes.

Inclusion of Weisberg Coefficients in Delay-Difference Model

In general, the inclusion of Weisberg model coefficients improved the predictive ability of the delay-difference model to estimate catch. An issue that was particularly evident when attempting to estimate longer time series was that the catch estimates did not accurately reflect the magnitude of CPUE after 1973. These additions were not successful in improving the verisimilitude after 1973 (Figure 13). While the Weisberg age coefficients ρ values did not improve the correlation with the actual catch, it may remain of use rather than constructing Ford-Walford plots containing growth factors that may change from year to year (Table 3).

Including the environmental coefficients improved the predictive ability of the model (Figures 13 and 14). Predicted catches more closely matched reported catches when there was greater variation in observed catch estimates from year to year and those estimates are more similar to the actual catch levels. The inclusion of the environmental growth factors increased the variation and more closely matched the reported catch and CPUE of the model, but the estimates did not match up with the extent of the variation in the reported catch and did not predict the period from 1970-1987. The greatest improvement in matching the observed variation was seen with the inclusion of walleye year effect coefficient, whereas the regression relationships between walleye year coefficients and a number of yellow perch coefficients showed estimates with notably lower variation. The issue is that while there was improvement in the overall variation and specifically in the pattern, it did not closely match the reported catch. The most important aspect of the analysis was that it demonstrates that including a yearly growth factor had a positive effect on the performance and estimates of the model.

The regression between walleye year coefficients and yellow perch year coefficients (DDM5) was most effective at increasing the correlation when there were two different relationships modeled, though DDM3 had the best CSS (Table 4). Relationships have been found between walleye and yellow perch, in Red Lakes and other locations (Lake Oneida, Lake Mille Lacs, and Lake Winibegoshish) and have generally been described as predator-prey relationships (Forney 1974, Smith and Krefting

1954, Maloney and Johnson 1957). However, these relationships would comprise only a portion of the year-related growth experienced by walleye. The result of the DDM5 modifications may be further confirmation of the predator-prey relationship, because yellow perch growth increased as the walleye population collapsed through the 1980s and 1990s.

The yellow perch year-class strength analysis was an attempt to gain further insight into the predator-prey relationship between walleye and yellow perch. Walleye, in general, tend of feed largely on young-of-year (YOY) yellow perch, though in Lake Oneida they were also observed consuming yearling walleye in the months of May and June (Forney 1974). It may be that YOY walleye that have benefited from increased levels of yellow perch growth will not begin to appear in the fishery (and in the subsequent CPUE) for at least two years. Also, age-0 and age-1 walleye typically do not have the same diets as older walleye that are vulnerable to harvest (Hartman and Margraf 1992). However, previous analysis using walleye year-effect coefficients did not find a significant correlation between first year walleye growth and yellow perch year class strength (Ostazeski 1998). Yellow perch year-class strength, showing good concordance with the predicted and actual walleye CPUE, indicates that yellow perch are an important food source to the fishable population, but provides no further insight into potential predator-prey relationships that may exist for walleye under age 2+ (Figure 15).

Age-Structured Models

Age-structured models were evaluated to determine how these models functioned in relation to each other. The natural assumption would be to expect similar abundance levels and patterns given that the models are based on the same theory and similar equations. In general, the VPA showed the greatest deviation from the other models in terms of both pattern and abundance levels (Figures 17, 19, 21). However, the VPA did match the actual catch well, to the same degree as the ADAPT model. The extreme departure seen in the 1949-1957 series when there is a large increase in abundance after 1954 is an excellent example (Figure 17). It is possible that the predictions used for Figure 21 were influenced by the unusual catch-at-age numbers estimated for 1949. The unusual catch-at-age numbers included a catch of age-two fish that was nearly 7,000 fish, noticeably higher than seen for any other age-two fish for that time series. The ADAPT method performed best when comparing predicted and actual catch numbers.

Several important issues related to both data and calculation methods were uncovered using the catch-at-age models with the historical data. Backward-calculating models generally have the assumption that catch-at-age is estimated without error, particularly true of the ADAPT method (Gavaris 1988). A catch-at-age matrix includes aged fish with recorded lengths, length frequency, length-weight, and the total catch of the fishery. At each step the potential for error, even rounding error, is increased. There is also the issue of how to handle situations where the length frequency data fall outside the range of values from the length-at-age collection. The two most obvious ways of dealing with out of range lengths would be to either exclude all fish outside the length-at-age series (as was done in this analysis) or include them as part of the nearest age-class to that length. Although neither situation is entirely satisfactory when compared to a length-at-age data set with all possible ages and lengths.

Another consideration occurred when the two data sets were joined through the estimation procedure described in Appendix 4. The estimated year of 1958 diverged from the actual catch for that year in all of the catch-at-age simulations. Also, results from the VPA and the spreadsheet showed differences between the two data sets. The combined data set diverged in the early years when estimating abundance. It is possible that the sample of fish that were aged was skewed and did not properly reflect actual age distributions.

Residuals and retrospective analyses are typically used as diagnostics for model behavior. The standardized residuals were able to be calculated for all the model types. There were technical issues with calculating the retrospective analyses for the age-structured models. The retrospective analyses are, however, and extremely important diagnostic as they can indicate systematic data issues through the amount of pattern. A limited retrospective analysis was conducted on the spreadsheet model for the 1949-1969 time series (Appendix 6). Future stock assessments that conduct retrospective analyses as a standard diagnostic.

Model Comparison

The comparison between predicted catches with the observed catch allowed for comparison between the delay-difference model and the age-structured models. The comparison would demonstrate if a model was consistently less accurate or if two different methods could be used in conjunction. The most precise method should be the one employed for long-term monitoring and estimation. The measures of precision in this study were the ability of the models to predict the observed catch and fishery CPUE.

Fishery CPUE would preferred measure of precision as a CPUE should be a better reflection of stock abundance than overall catch, as it standardizes for fishery effort.

Clearly, the data required for the catch-at-age models is greater than is required for the delay-difference model. However, the age-structured models can be quite useful in conjunction with the delay-difference models as I describe below. One use is that they allow the user to do without the stock-recruitment relationship that was used throughout much of the analysis, instead, relying on the age-structured estimates at age for the numbers of recruits in a year. Catch-at-age analysis allows for refinement of delay-difference parameters, such as those gained from the Ford-Walford plot. Therefore, a functional catch-at-age type model in use would allow parameters to be adjusted rather than assuming that they remain constant for all time periods.

The delay-difference model showed good agreement when there were data that were an accurate reflection of the fishery. The data were assumed to be accurate reflections of the fishery prior to the beginning of the black market fishery, as the majority to all of the catch would have been recorded. Good agreement is also to be expected from the delay-difference model, to the point that it can be of concern as the delay-difference model may agree with unrealistic parameter estimates (Hilborn and Walters 1992). The Red Lakes fishery is relatively simple, consisting of a commercial catch and a survey index, although, as shown here, an unreported or, "black market" catch may add complexity. When the delay-difference model was compared to the more complex age-structured models, the spreadsheet model was found to be the most parsimonious. Thus, when properly weighted, a spreadsheet model is as informative as a more complicated model. Future assessments may only need a modified spreadsheet method to accomplish precise results given the parsimony of the spreadsheet model. There did not appear to be a great difference between the forward and backward calculating models.

Black Market Catch

The inclusion of black market catch improved the predicted catches of the delay-difference model. The improvement of estimates may shed further light on the difficulties that occurred with the predicted catch estimates in the delay-difference model. It appears that the commercial fishery data must be very accurate catch data or the model will fail to predict catch accurately. The delay-difference model's poor ability to predict catch began around the time that the black market selling of walleye began or increased. Improved quantification of the unknown sources of catch and effort (black market, recreational, subsistence) will shed light on the influence of the black market on the trajectory of the fishery, including, perhaps, the eventual collapse of the fishery in the early 1990s.

While the inclusion of the black market catch did improve the predicted catch estimates, the period between approximately 1973 and 1987 varies in a nearly inverse manner. The hope was that introducing the black market catch would aid in explaining the differences between the predicted and reported catches, which did not occur. It is not clear what further influences may have caused the great variation in the observed catches. The population was observed to be at low levels in the 1970's and many fishermen were known to have stopped fishing and were engaged in higher paying jobs (Smith 1977). The delay-difference model did not estimate low population levels for any of the simulations (Figures 23-25). This may indicate a couple of things: that there are processes occurring within the population that the model cannot simulate with these data, or that the assumptions of black market catch are not correct. Processes in the population could be recruitment related, as recruitment has been previously noted as being highly variable and was speculated to be related to the environmental conditions (Smith 1977). If recruitment is highly variable, for reasons like variable reproductive success and growth variation, then a clean stock-recruitment relationship would not entirely explain recruitment relationships. Another possible reason could be that the black market catch magnitude and effort varied greatly from year to year, which was not reflected in the calculation method used. A possible way to evaluate which reason may have occurred would be model the population for a period of time where all or the vast majority of the catch removals are accounted for. This would give insight into the effect of the variable recruitment on model. Another possible evaluation method would be an improved stock-recruitment model that could predict the highly variable stock recruitment.

Environmental Coefficients and Population Abundance Estimates

Previously a positive correlation was found between walleye CPUE and walleye year effect coefficients with a positive one year lag (Cyterski 1995). The interest in the abundance estimates in relation to the Weisberg coefficients is that CPUE has been used as a proxy for abundance, which was the case in the previous analysis (Cyterski 1995, Ostazeski 1998). The relationship that showed a significant correlation was not at a positive one year lag, but at a positive two year lag (where the estimated abundance correlated with the coefficient two years previous, see Table 11). The lags may be a representation of a phenomenon that has been observed on Red Lakes, where non-constant recruitment had occurred to the fishery (Smith and Pycha 1961). Fishery recruitment could be confounded by variable reproductive success and variation in growth of different year classes. Non-constant recruitment in a fishery has also been noted on other lakes that experience heavy exploitation (Chevalier 1977, Regier et al. 1969). As a result, the changes in growth may be related to the size of the population in the first year of life. A large population may be depressing the growth of that year, as was detected in perch on Lake Windermere (Craig and Kipling 1983), and, possibly, delaying the age at recruitment to one year later. Another possibility is that increased growth will tend to result from a larger potential spawning base, though earlier work on Red Lakes found no relationship between brood stock and large year classes (Smith and Krefting 1953, Smith 1977). The recent rebuilding of the Red Lakes walleye may give more insight into the relationship between brood stock size and year class strength. While there were negative correlations found between percent change and fishable abundance, there was not a statistically significant relationship found. There were some statistically significant positive relationships found between positive percentage changes and the population abundances. There was, however, no clear evidence from these analyses that population size has a depressive effect on growth from year to year or that a smaller population size has the opposite negative effect by promoting greater growth than the previous year through a lack of competition or cannibalism. Previous Red Lakes research has found relationships with YOY yellow perch abundance, temperature, and environmental growth of YOY walleye (Cyterski 1995, Ostazeski 1998, Smith 1977). Previous positive correlations for year class strength in other walleye populations have been found with brood stock abundance as well as some climate related factors (Busch et al. 1975, Chevalier 1977).

Overall Conclusions and Recommendations

This research found that: 1. Generally, the age-structured models performed better than the delay-difference model. The model performance was evaluated through a criterion of greatest verisimilitude of the models examined (Figures 18, 20, 22). 2. The inclusion of the walleye environmental coefficients improved the fit of the delay-difference model (Figure 13). The inclusion of annually variable growth coefficients allowed the model to predict based on a more realistic and variable growth pattern. 3. The assumed black market catch resulted in only limited improved fit of the delay-difference model with general increases in fishing effort (Figures 23-28). 4. However, the anomalous 1973-87 era in the time period covered by this research (Figure 25) could not be explained by the delay-difference model. This time period was only covered in the delay-difference model, therefore it is not possible to evaluate the delay-difference model's performance against any other modeling technique. The anomaly was so strong that the extreme action of simulating a 100% BM catch was unable to reshape the inverse relationship between predicted catch and observed catch during this era. Unknown catch can be a significant contribution to many fisheries assessments regardless of the reason for the missing data, whether it is catch sold on the black market or significant discarding of dead fish that goes unrecorded.

The Red Lakes walleye population has recently been declared recovered and the fishery was re-opened in the summer of 2006. The analyses that were conducted in this dissertation gave further guidance to the status of the population. The models require continuing data collection and monitoring, particularly since recreational catch and effort can be difficult to regularly collect. Continued monitoring, data collection, and the use of one of the more informative models by management agencies could aid in ensuring that the recovery is sustained over the long-term.

One outcome of this research would be a recommendation on the method for future modeling. The results indicate that the forward projecting spreadsheet model was the most parsimonious, even with the high number of parameters. The delay-difference model with Weisberg coefficients included was the best performing delay-difference model. If management were interested in using the delay-difference model with Weisberg coefficients, further refinement of the model may be needed and it should be run in conjunction with another model for a period of time. The research does not indicate a reason to adopt a VPA or ADAPT model for this stock.

For any model used to manage the system, considerable care should be taken in the data collection. The attempt to correct the delay-difference model with a black market correction illustrates the need for the removal data to closely reflect the fish actually removed from the system. In a system with both recreational and commercial fisheries, both fisheries need to have their removals precisely captured through their data collection processes on an annual basis. If age-structures are to be used in a modeling technique, sufficient age-structures must also be collected on an annual basis.

Further research should continue in two areas, refinement of the use of the Weisberg coefficients in fishery modeling and continued research into the historical long-term modeling of the Red Lakes fishery. As growth has historically not been able to include environmental growth variation, determining possible other ways to incorporate this information into modeling would be beneficial in the general process of including environmental information in stock assessments. The Red Lakes walleye stock also has a long time series of data that will eventually cover the process of the fishery's collapse and recovery. Many fishery data sets are referred to as "one-way trips" and cover only the decline or recovery of a stock. Both sides of the "trip" may give better insight into the overall population parameters than would be possible in a one-way trip.

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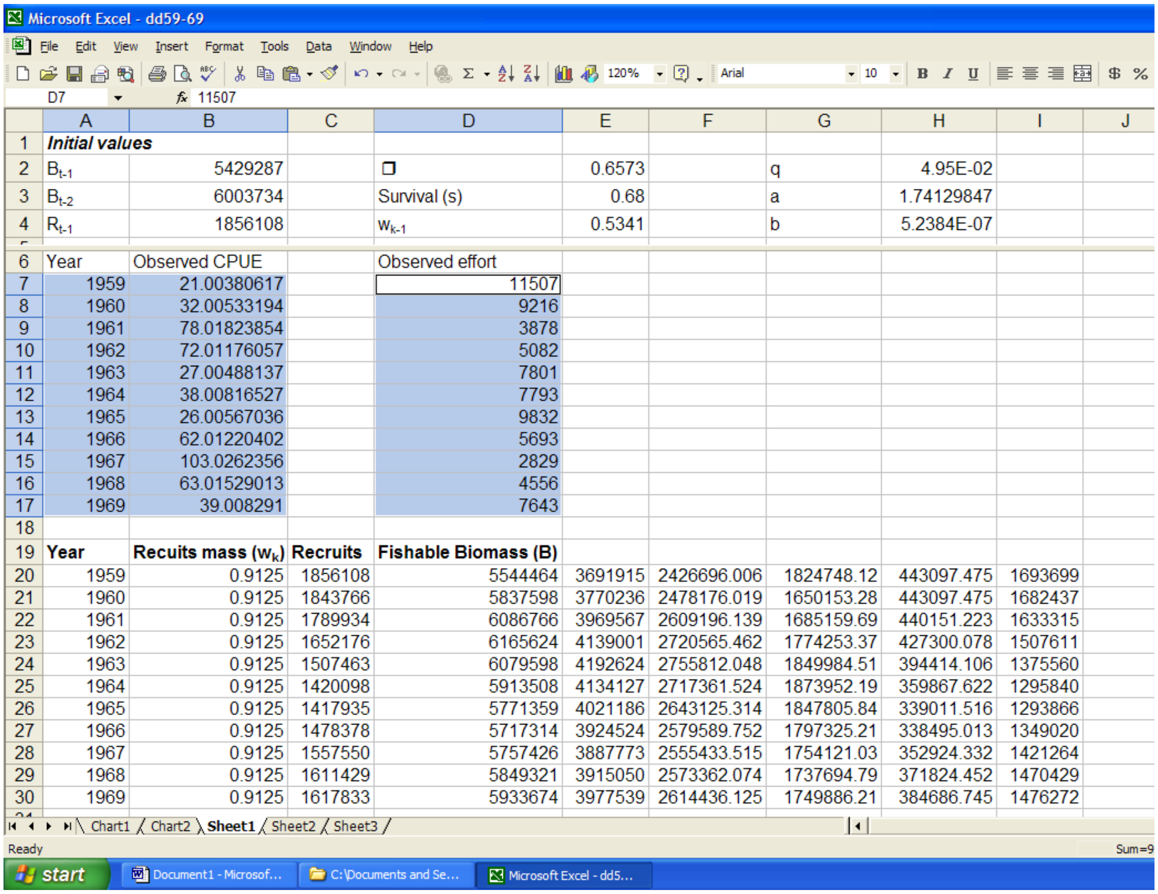
Appendix 1: Delay-difference Excel© calculation method

The Deriso-Schnute delay-difference model computations were performed using the functions found in Microsoft Excel$^{©}$. What follows is a set of instructions for setting up and calculating estimates using this model and program.

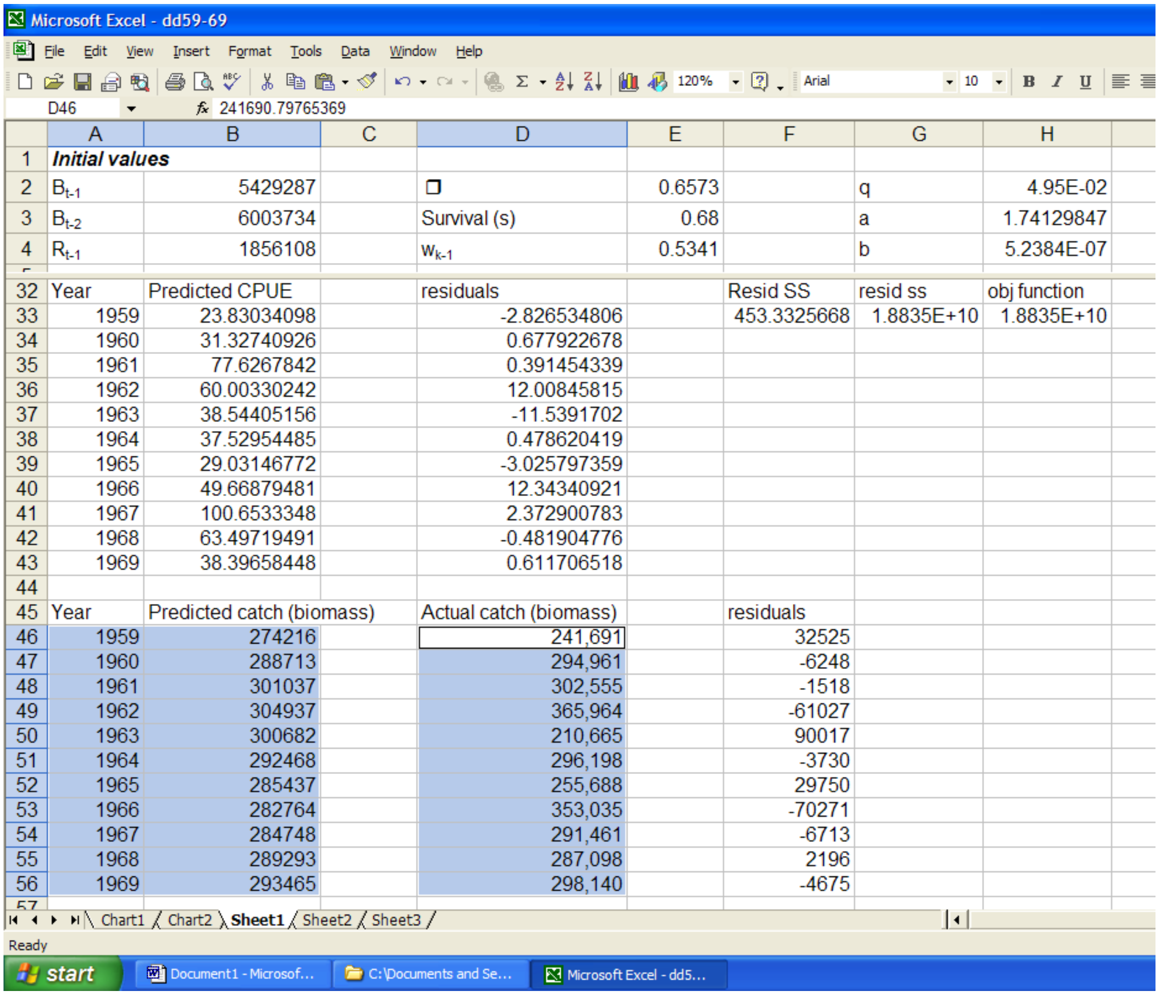
1. Enter the time period being analyzed actual CPUE, and actual fishing efforts into columns A, B, and D, respectively; beginning at row 7 (Figure A.1.1).



	A	B	C	D	E	F	G	H	I	J
1	***Initial values***									
2	B_{t-1}	5429287		❐	0.6573		q	4.95E-02		
3	B_{t-2}	6003734		Survival (s)	0.68		a	1.74129847		
4	R_{t-1}	1856108		w_{k-1}	0.5341		b	5.2384E-07		
6	Year	Observed CPUE		Observed effort						
7	1959	21.00380617		11507						
8	1960	32.00533194		9216						
9	1961	78.01823854		3878						
10	1962	72.01176057		5082						
11	1963	27.00488137		7801						
12	1964	38.00816527		7793						
13	1965	26.00567036		9832						
14	1966	62.01220402		5693						
15	1967	103.0262356		2829						
16	1968	63.01529013		4556						
17	1969	39.008291		7643						
18										
19	**Year**	**Recuits mass (w_k)**	**Recruits**	**Fishable Biomass (B)**						
20	1959	0.9125	1856108	5544464	3691915	2426696.006	1824748.12	443097.475	1693699	
21	1960	0.9125	1843766	5837598	3770236	2478176.019	1650153.28	443097.475	1682437	
22	1961	0.9125	1789934	6086766	3969567	2609196.139	1685159.69	440151.223	1633315	
23	1962	0.9125	1652176	6165624	4139001	2720565.462	1774253.37	427300.078	1507611	
24	1963	0.9125	1507463	6079598	4192624	2755812.048	1849984.51	394414.106	1375560	
25	1964	0.9125	1420098	5913508	4134127	2717361.524	1873952.19	359867.622	1295840	
26	1965	0.9125	1417935	5771359	4021186	2643125.314	1847805.84	339011.516	1293866	
27	1966	0.9125	1478378	5717314	3924524	2579589.752	1797325.21	338495.013	1349020	
28	1967	0.9125	1557550	5757426	3887773	2555433.515	1754121.03	352924.332	1421264	
29	1968	0.9125	1611429	5849321	3915050	2573362.074	1737694.79	371824.452	1470429	
30	1969	0.9125	1617833	5933674	3977539	2614436.125	1749886.21	384686.745	1476272	

Figure A.1.1. Initial data inputs of years (highlighted portion of column A), observed CPUE (highlighted portion of column B), and observed effort (highlighted portion of column D), using the 1959-1969 time period as an example.

2. Insert the actual catch amount (in column D under "Actual catch (biomass)" heading) and ensure that under all headings "Year" the correct time range is entered and all equations have been copied down to match (Figure A.1.2). Ensuring that all the years and equations will fit, it may be necessary to insert rows to have enough space. There should be four distinct regions with years; the observed CPUE, the recruits and fishable biomass, the predicted CPUE, and the predicted catch.

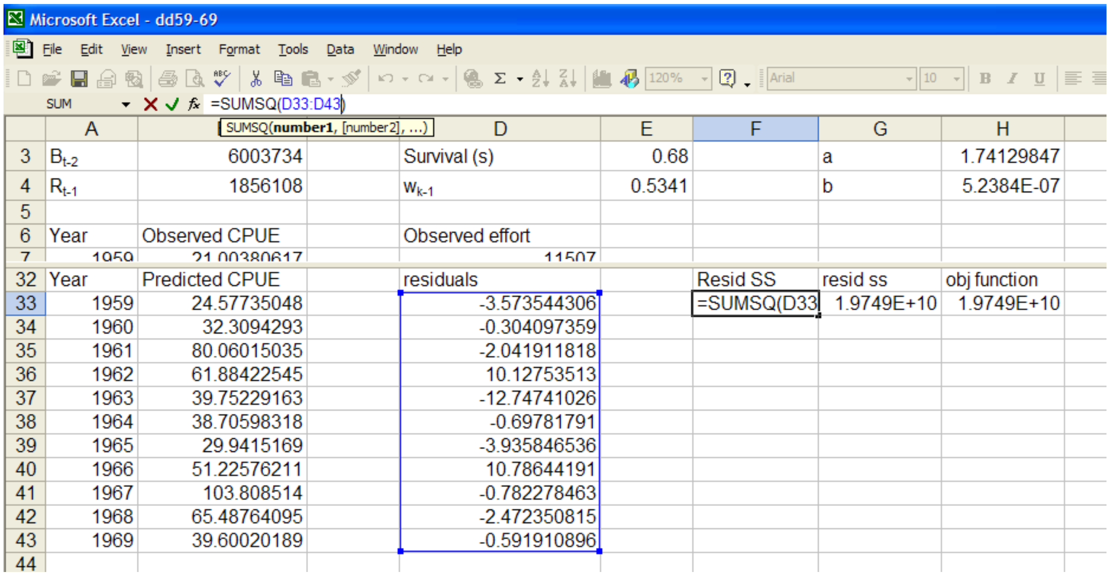


D46 241690.79765369

	A	B	C	D	E	F	G	H
1	***Initial values***							
2	B_{t-1}	5429287		❒	0.6573		q	4.95E-02
3	B_{t-2}	6003734		Survival (s)	0.68		a	1.74129847
4	R_{t-1}	1856108		w_{k-1}	0.5341		b	5.2384E-07
32	Year	Predicted CPUE		residuals		Resid SS	resid ss	obj function
33	1959	23.83034098		-2.826534806		453.3325668	1.8835E+10	1.8835E+10
34	1960	31.32740926		0.677922678				
35	1961	77.6267842		0.391454339				
36	1962	60.00330242		12.00845815				
37	1963	38.54405156		-11.5391702				
38	1964	37.52954485		0.478620419				
39	1965	29.03146772		-3.025797359				
40	1966	49.66879481		12.34340921				
41	1967	100.6533348		2.372900783				
42	1968	63.49719491		-0.481904776				
43	1969	38.39658448		0.611706518				
44								
45	Year	Predicted catch (biomass)		Actual catch (biomass)		residuals		
46	1959	274216		241,691		32525		
47	1960	288713		294,961		-6248		
48	1961	301037		302,555		-1518		
49	1962	304937		365,964		-61027		
50	1963	300682		210,665		90017		
51	1964	292468		296,198		-3730		
52	1965	285437		255,688		29750		
53	1966	282764		353,035		-70271		
54	1967	284748		291,461		-6713		
55	1968	289293		287,098		2196		
56	1969	293465		298,140		-4675		

Figure A.1.2. Actual catch amounts (column D starting at row 46 in example) and ensure that under all headings "Year" have correct time range is entered and all equations have been copied down to match.

3. Ensure that the residual sum of squares for the CPUE includes the correct residuals range (Figure A.1.3).

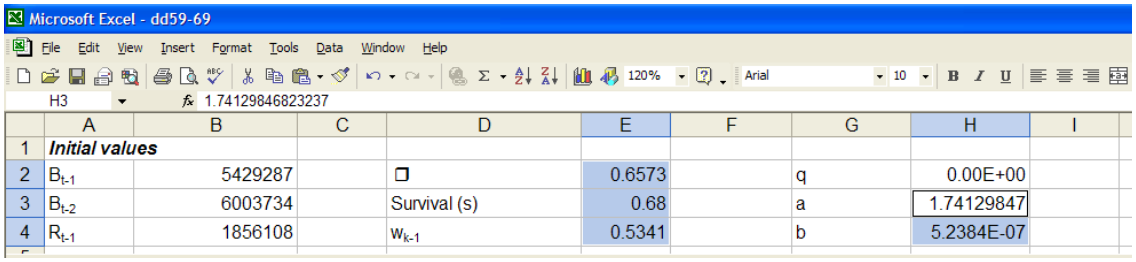


=SUMSQ(D33:D43)

	A	B	C	D	E	F	G	H
3	B_{t-2}	6003734		Survival (s)	0.68		a	1.74129847
4	R_{t-1}	1856108		w_{k-1}	0.5341		b	5.2384E-07
5								
6	Year	Observed CPUE		Observed effort				
7	1959	21.00380617		11507				
32	Year	Predicted CPUE		residuals		Resid SS	resid ss	obj function
33	1959	24.57735048		-3.573544306		=SUMSQ(D33	1.9749E+10	1.9749E+10
34	1960	32.3094293		-0.304097359				
35	1961	80.06015035		-2.041911818				
36	1962	61.88422545		10.12753513				
37	1963	39.75229163		-12.74741026				
38	1964	38.70598318		-0.69781791				
39	1965	29.9415169		-3.935846536				
40	1966	51.22576211		10.78644191				
41	1967	103.808514		-0.782278463				
42	1968	65.48764095		-2.472350815				
43	1969	39.60020189		-0.591910896				
44								

Figure A.1.3. Residuals for the CPUE (with the form “observed CPUE – predicted CPUE”) and the residual sum of squares (Excel formula “=SUMSQ(D33:D43)” in example.

4. Enter estimates for the initial values ρ, survival (s), w_{k-1}, *a* and *b* (Figure A.1.4). These are located in column E, rows 2 through 4 and column G, rows 3 and 4 respectively.

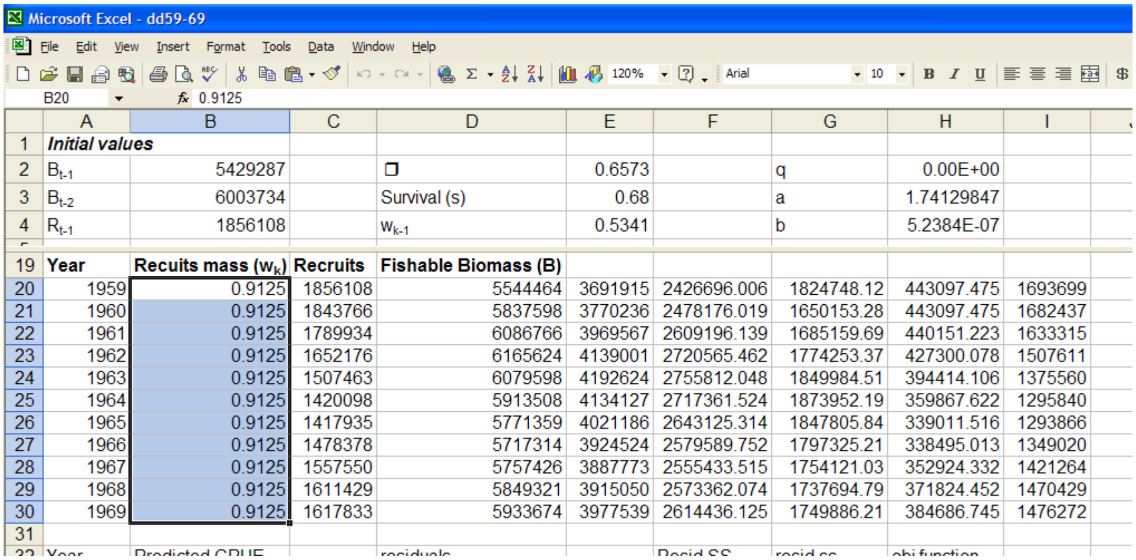


1.74129846823237

	A	B	C	D	E	F	G	H	I
1	***Initial values***								
2	B_{t-1}	5429287		☐	0.6573		q	0.00E+00	
3	B_{t-2}	6003734		Survival (s)	0.68		a	1.74129847	
4	R_{t-1}	1856108		w_{k-1}	0.5341		b	5.2384E-07	

Figure A.1.4. Estimated parameters for ρ, survival (s), and w_{k-1} (column E, rows 2 through 4) and stock-recruitment parameters *a* and *b* (column G, rows 3 and 4).

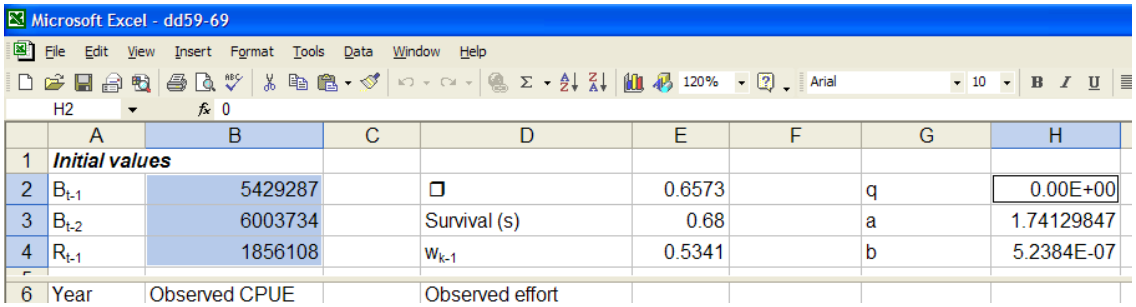
5. Enter the weight at recruitment, w_k in column B under the heading “Recruits mass (w_k)” (Figure A.1.5).



	A	B	C	D	E	F	G	H	I
1	***Initial values***								
2	B_{t-1}	5429287		❐	0.6573		q	0.00E+00	
3	B_{t-2}	6003734		Survival (s)	0.68		a	1.74129847	
4	R_{t-1}	1856108		w_{k-1}	0.5341		b	5.2384E-07	
19	**Year**	**Recuits mass (w_k)**	**Recruits**	**Fishable Biomass (B)**					
20	1959	0.9125	1856108	5544464	3691915	2426696.006	1824748.12	443097.475	1693699
21	1960	0.9125	1843766	5837598	3770236	2478176.019	1650153.28	443097.475	1682437
22	1961	0.9125	1789934	6086766	3969567	2609196.139	1685159.69	440151.223	1633315
23	1962	0.9125	1652176	6165624	4139001	2720565.462	1774253.37	427300.078	1507611
24	1963	0.9125	1507463	6079598	4192624	2755812.048	1849984.51	394414.106	1375560
25	1964	0.9125	1420098	5913508	4134127	2717361.524	1873952.19	359867.622	1295840
26	1965	0.9125	1417935	5771359	4021186	2643125.314	1847805.84	339011.516	1293866
27	1966	0.9125	1478378	5717314	3924524	2579589.752	1797325.21	338495.013	1349020
28	1967	0.9125	1557550	5757426	3887773	2555433.515	1754121.03	352924.332	1421264
29	1968	0.9125	1611429	5849321	3915050	2573362.074	1737694.79	371824.452	1470429
30	1969	0.9125	1617833	5933674	3977539	2614436.125	1749886.21	384686.745	1476272
31									
32	Year	Predicted CPUE		residuals		Resid SS	resid ss	obj function	

Figure A.1.5. Enter the estimates weight at recruitment under the "Recruits mass" heading (column B, starting at row 20 in example).

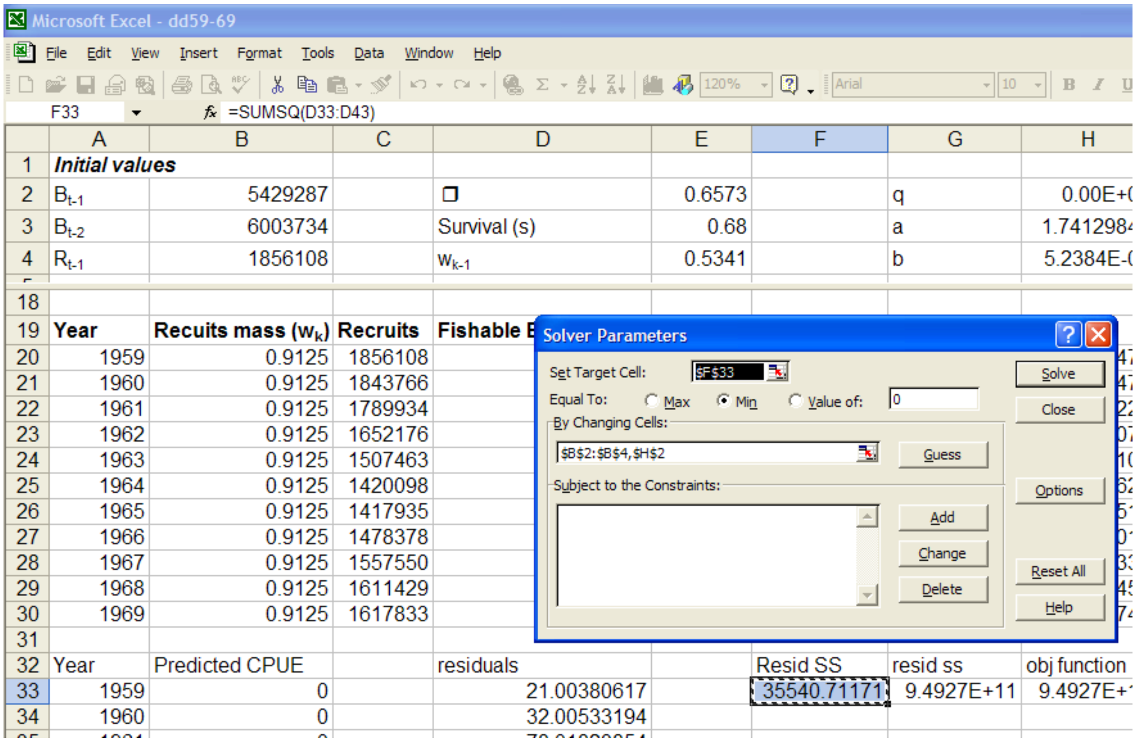
6. Enter estimates for B_{t-1}, B_{t-2}, and R_{t-1}; which are the estimates of fishable biomass at time t-1 and t-2 and number of recruits at time t-1. These estimates go in column B, rows 2-4 respectively (Figure A.1.6). Also, set *q* (in cell H2) to 0.



	A	B	C	D	E	F	G	H
1	***Initial values***							
2	B_{t-1}	5429287		❐	0.6573		q	0.00E+00
3	B_{t-2}	6003734		Survival (s)	0.68		a	1.74129847
4	R_{t-1}	1856108		w_{k-1}	0.5341		b	5.2384E-07
6	Year	Observed CPUE		Observed effort				

Figure A.1.6. Enter estimates for B_{t-1} (fishable biomass), B_{t-2} (fishable biomass), R_{t-1} (recruitment), and R_{t-2} (recruitment) in column B and rows 2-5.

7. Under the 'Tools' menu, click on "solver". It should bring up a dialog box with the settings to minimize the reduced sum of squares CPUE cell by changing cells B2-B5 and H2 (A.1.7). If correct, press "OK" then keep results.



F33 =SUMSQ(D33:D43)

	A	B	C	D	E	F	G	H
1	***Initial values***							
2	B_{t-1}	5429287		☐	0.6573		q	0.00E+
3	B_{t-2}	6003734		Survival (s)	0.68		a	1.741298
4	R_{t-1}	1856108		w_{k-1}	0.5341		b	5.2384E-
18								
19	**Year**	**Recuits mass (w_k)**	**Recruits**	**Fishable**				
20	1959	0.9125	1856108					
21	1960	0.9125	1843766					
22	1961	0.9125	1789934					
23	1962	0.9125	1652176					
24	1963	0.9125	1507463					
25	1964	0.9125	1420098					
26	1965	0.9125	1417935					
27	1966	0.9125	1478378					
28	1967	0.9125	1557550					
29	1968	0.9125	1611429					
30	1969	0.9125	1617833					
31								
32	Year	Predicted CPUE		residuals		Resid SS	resid ss	obj function
33	1959	0		21.00380617		35540.71171	9.4927E+11	9.4927E+
34	1960	0		32.00533194				

Solver Parameters

Set Target Cell: $F$33

Equal To: ○ Max ● Min ○ Value of: 0

By Changing Cells: $B$2:$B$4,$H$2

Subject to the Constraints:

Figure A.1.7. The “solver” dialog box under the Tools menu, settings should minimize the reduced sum of squares CPUE cell by changing cells B2-B5 and H2.

8. Graphs for predicted vs. actual CPUE and predicted vs. actual catches can be found on included charts 1 and 2 (not pictured). Axes and data sets may have to be re-established to include all results.

Appendix 2: Actual and estimated data inputs for the delay-difference model.

Table A.2.1: Data set used for calculation of the delay-difference model. It includes the years 1938-1996 for catch-per-unit effort (kilograms per 5-net lifts), fishing effort in number of commercial catch lifts, and catch biomass in kilograms. CPUE was calculated from the observed catch and effort data. From the Red Lakes Fishery Assessment Unit.

Year	Observed CPUE	Observed effort	Actual catch (biomass in kg)
1938	102.6178	3020	309,906
1939	68.5279	3836	262,873
1940	80.7753	4491	362,762
1941	76.7851	5491	421,627
1942	48.5860	8784	426,779
1943	37.1268	10065	373,682
1944	76.6197	5740	439,797
1945	55.0170	7195	395,847
1946	55.0071	7516	413,433
1947	53.0074	8364	443,354
1948	62.0091	6792	421,166
1949	45.0063	6653	299,427
1950	20.0033	8695	173,929
1951	30.0073	8408	252,301
1952	58.0146	5115	296,745
1953	52.0064	4688	243,806
1954	54.0091	5334	288,085
1955	46.0114	6361	292,679
1956	39.0066	7401	288,688
1957	45.0074	6716	302,270
1958	32.0043	8770	280,678
1959	21.0038	11507	241,691
1960	32.0053	9216	294,961
1961	78.0182	3878	302,555
1962	72.0118	5082	365,964
1963	27.0049	7801	210,665
1964	38.0082	7793	296,198
1965	26.0057	9832	255,688
1966	62.0122	5693	353,035
1967	103.0262	2829	291,461
1968	63.0153	4556	287,098
1969	39.0083	7643	298,140
1970	48.0063	7516	360,815
1971	25.0038	8863	221,608
1972	9.0012	4442	39,983
1973	9.0019	3208	28,878
1974	7.0004	3520	24,641

Table A.2.1 continued.

Year	Observed CPUE	Observed effort	Actual catch (biomass in kg)
1975	16.0039	4513	72,226
1976	18.0037	5797	104,368
1977	36.0065	8339	300,258
1978	38.0063	7886	299,718
1979	10.0012	9734	97,351
1980	6.0007	8434	50,610
1981	7.0012	8031	56,226
1982	15.0029	9363	140,472
1983	34.0053	10388	353,247
1984	36.0064	11511	414,470
1985	31.0049	13005	403,219
1986	21.0037	6869	144,274
1987	27.004	12646	341,492
1988	53.0092	7818	414,426
1989	78.5851	5475	430,254
1990	19.608	11243	220,452
1991	14.4198	13108	189,015
1992	9.6268	19595	188,637
1993	5.1149	13400	68,540
1994	5.1055	8035	41,022
1995	4.8935	6253	30,599
1996	2.9249	2306	6,745

Appendix 3: Catch-at-age estimates for 1949-1969, age-length keys, and the instructions for calculating the estimates in Excel©.

Table A.3.1. Commercial walleye catch in numbers at age for the Red Lakes commercial gillnet fishery 1949-1969.

Year	2	3	4	5	6	7	8	9	10
1949	6,221	34,497	33,856	179,081	162,654	9,239	39,212	38,873	4,540
1950	103	11,697	86,885	41,578	66,180	60,269	8,904	10,684	12,486
1951	14	3,010	85,915	313,812	33,525	21,582	20,739	4,802	6,633
1952	392	5,513	22,727	264,847	240,032	15,028	11,803	13,454	2,472
1953	0	3,364	17,241	59,237	256,481	137,136	5,712	8,397	429
1954	376	4,597	13,435	84,554	123,457	249,572	89,529	6,861	4,030
1955	2,606	9,275	18,302	58,867	127,383	104,287	153,820	37,810	5,988
1956	936	2,906	29,162	73,969	116,279	121,712	56,237	52,286	11,750
1957	1,374	25,005	48,108	145,083	119,010	92,883	59,045	19,386	18,645
1958	65,554	308,755	101,214	181,856	113,747	48,794	169,049	2,027	6,701
1959	115,501	170,252	196,652	72,628	35,870	13,597	6,895	2,492	3,250
1960	90,519	177,907	267,062	121,838	48,245	11,920	4,104	500	1,766
1961	9,996	38,166	201,457	183,319	124,435	30,562	9,229	2,306	91
1962	50,790	32,010	150,835	179,366	169,796	67,283	30,097	11,490	539
1963	37,694	43,146	85,394	83,986	77,074	37,660	25,280	10,985	3,369
1964	106,585	106,379	205,861	124,949	78,375	26,508	15,039	5,851	5,368
1965	55,181	149,298	217,166	85,869	52,120	21,564	10,768	4,088	3,077
1966	83,995	240,634	370,860	123,542	47,660	15,836	4,714	640	887
1967	31,013	69,886	167,732	148,121	113,668	39,922	13,737	4,924	40
1968	2,327	15,780	109,886	221,194	196,893	10,591	71	142	71
1969	66,591	119,017	246,285	139,583	75,460	22,948	8,767	2,519	230

Table A.3.2. Age-length key for the regular walleye catch from 1959-1969.

Lgth intervals	**III**	**IV**	**V**	**VI**	**VII**	**VIII**	**IX**	**X**
10.5-10.8	1							
10.9-11.2	1							
11.3-11.6	1							
11.7-12.0	1							
12.1-12.4	1							
12.5-12.8	1							
12.9-13.2		1						
13.3-13.6	1							
13.7-14.0	0.35	0.65						
14.1-14.4	0.0526	0.6316	0.1579	0.1053	0.0526			
14.5-14.8	0.0714	0.5714	0.2857	0.0238	0.0238	0.0238		
14.9-15.2	0.0227	0.5	0.3636	0.0909				
15.3-15.6		0.1957	0.5652	0.2174	0.0217			
15.7-16.0		0.0556	0.4167	0.4722	0.0556			
16.1-16.4			0.1111	0.7778	0.0741	0.037		
16.5-16.8			0.0667	0.4	0.4667	0.0667		
16.9-17.2					0.5714	0.2143	0.2143	
17.3-17.6					0.3333	0.5	0.1667	
17.7-18.0					0.3333	0.5	0.1667	
18.1-18.4						1		
18.5-18.8						0.5	0.5	
18.9-19.2							0.6667	0.3333
19.3-19.6								1
19.7-20.0								1
20.1-20.4								1
20.5-20.8								1
20.9-21.2								1
21.3-21.6								1
21.7-22.0								1
22.1-22.4								1
22.5-22.8								1
22.9-23.2								1
23.3-23.6								1
23.7-24.0								1
24.1-24.4								1
24.5-24.8								1

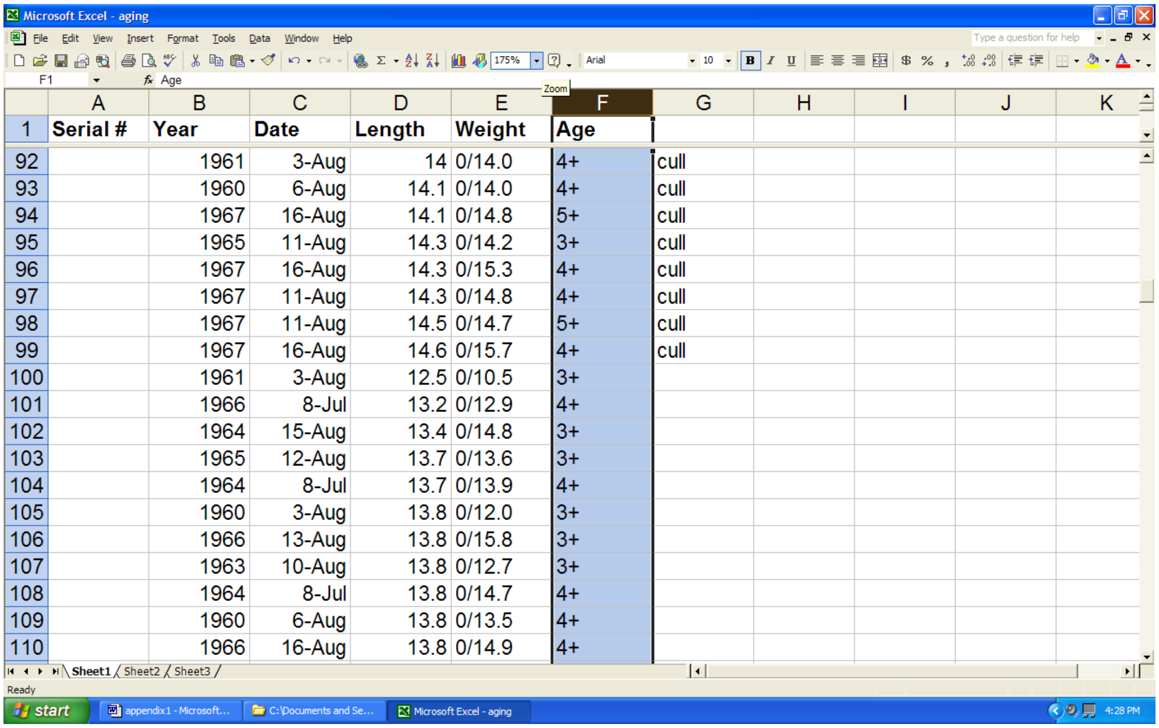
Table A.3.3. Age-length key for the cull walleye catch from 1959-1969.

Lgth intervals	I	II	III	IV	V
7.3-7.6	1				
7.7-8.0	1				
8.1-8.4	1				
8.5-8.8	1				
8.9-9.2	1				
9.3-9.6	1				
9.7-10.0	1				
10.1-10.4		1			
10.5-10.8		1			
10.9-11.2		1			
11.3-11.6	0.2	0.7	0.1		
11.7-12.0		0.75	0.125	0.125	
12.1-12.4		0.6	0.4		
12.5-12.8		0.2267	0.7333		
12.9-13.2		0.1875	0.6875	0.125	
13.3-13.6		0.2727	0.4545	0.2727	
13.7-14.0		0.1429	0.2857	0.5714	
14.1-14.4			0.2	0.6	0.2
14.5-14.8				0.5	0.5
14.9-15.2					3
15.3-15.6					1
15.7-16.0					1
16.1-16.4					1

Procedure for calculating age frequency distribution for the commercial catch from an aged sub-sample.

In the procedures described below, all calculations were based upon the original (English) units of measurement. Where necessary for reporting purposes (main text) English units have been converted to metric units.

1. A portion of the catch was aged for the given year. Fish ages were recorded with their corresponding lengths and the fish's commercial grade (regular or cull), (Fig. A.3.1). The commercial cull grade was transformed by the same process as the marketable catch but utilized different weights at age and age fractions than occurred in the regular commercial catch. Cull fish were treated separately from the regular catch as it was assumed that the cull fish have different length and age characteristics than the regular catch because the cull fish were considered unmarketable otherwise.

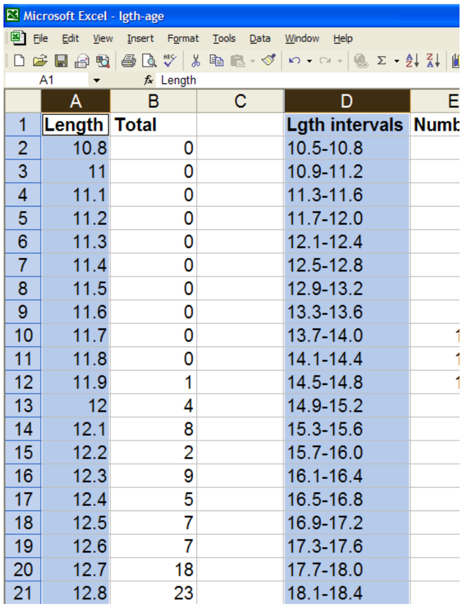


1	Serial #	Year	Date	Length	Weight	Age	
92		1961	3-Aug	14	0/14.0	4+	cull
93		1960	6-Aug	14.1	0/14.0	4+	cull
94		1967	16-Aug	14.1	0/14.8	5+	cull
95		1965	11-Aug	14.3	0/14.2	3+	cull
96		1967	16-Aug	14.3	0/15.3	4+	cull
97		1967	11-Aug	14.3	0/14.8	4+	cull
98		1967	11-Aug	14.5	0/14.7	5+	cull
99		1967	16-Aug	14.6	0/15.7	4+	cull
100		1961	3-Aug	12.5	0/10.5	3+	
101		1966	8-Jul	13.2	0/12.9	4+	
102		1964	15-Aug	13.4	0/14.8	3+	
103		1965	12-Aug	13.7	0/13.6	3+	
104		1964	8-Jul	13.7	0/13.9	4+	
105		1960	3-Aug	13.8	0/12.0	3+	
106		1966	13-Aug	13.8	0/15.8	3+	
107		1963	10-Aug	13.8	0/12.7	3+	
108		1964	8-Jul	13.8	0/14.7	4+	
109		1960	6-Aug	13.8	0/13.5	4+	
110		1966	16-Aug	13.8	0/14.9	4+	

Figure A.3.1. Example of age and market classification assignments to length intervals in sub-samples of catches from the 1960s.

2. Lengths were separated into intervals of 0.4 inch.

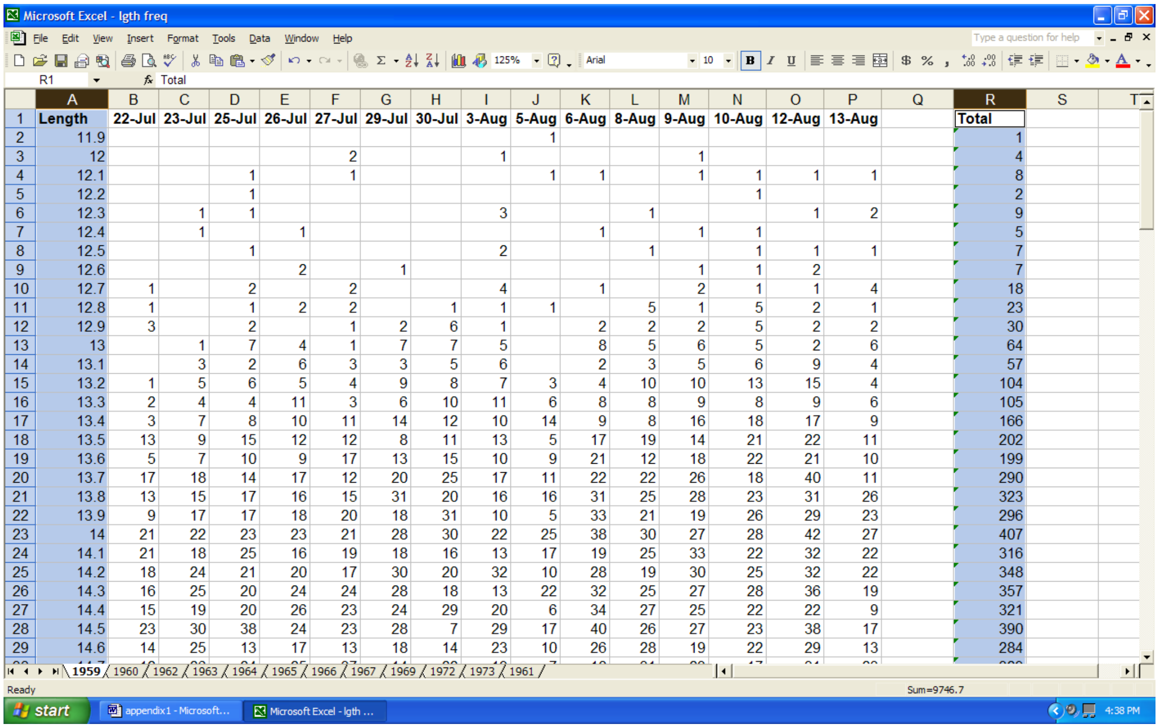
3. For the aged sub-sample, the number of fish at age in each length-interval was counted, figure A.3.2.



1	Length	Total		Lgth intervals	Numb
2	10.8	0		10.5-10.8	
3	11	0		10.9-11.2	
4	11.1	0		11.3-11.6	
5	11.2	0		11.7-12.0	
6	11.3	0		12.1-12.4	
7	11.4	0		12.5-12.8	
8	11.5	0		12.9-13.2	
9	11.6	0		13.3-13.6	
10	11.7	0		13.7-14.0	1
11	11.8	0		14.1-14.4	1
12	11.9	1		14.5-14.8	1
13	12	4		14.9-15.2	
14	12.1	8		15.3-15.6	
15	12.2	2		15.7-16.0	
16	12.3	9		16.1-16.4	
17	12.4	5		16.5-16.8	
18	12.5	7		16.9-17.2	
19	12.6	7		17.3-17.6	
20	12.7	18		17.7-18.0	
21	12.8	23		18.1-18.4	

Figure A.3.2. The 0.4 inch length intervals and the summation of the total numbers of sampled fish per length within the length interval.

4. Yearly length-frequency data were used, separating lengths into the length intervals as were created in step 2. This created a total number of fish sampled that fell within each length interval (Figure A.3.3).

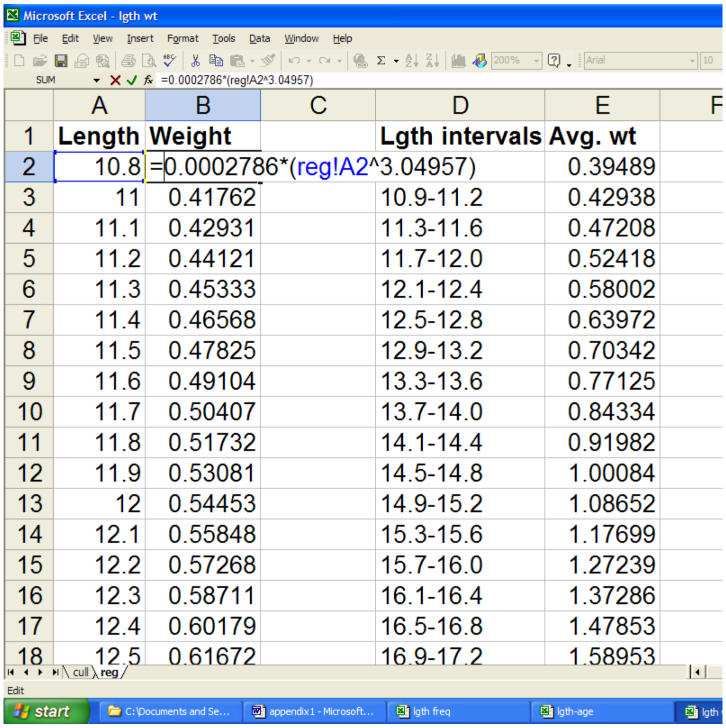


Length	22-Jul	23-Jul	25-Jul	26-Jul	27-Jul	29-Jul	30-Jul	3-Aug	5-Aug	6-Aug	8-Aug	9-Aug	10-Aug	12-Aug	13-Aug	Total
11.9									1							1
12					2			1				1				4
12.1			1		1				1	1		1	1	1	1	8
12.2			1										1			2
12.3		1	1					3			1			1	2	9
12.4		1		1						1		1	1			5
12.5			1					2			1		1	1	1	7
12.6				2		1						1	1	2		7
12.7	1		2		2			4		1		2	1	1	4	18
12.8	1		1	2	2		1	1	1		5	1	5	2	1	23
12.9	3		2		1	2	6	1		2	2	2	5	2	2	30
13		1	7	4	1	7	7	5		8	5	6	5	2	6	64
13.1		3	2	6	3	3	5	6		2	3	5	6	9	4	57
13.2	1	5	6	5	4	9	8	7	3	4	10	10	13	15	4	104
13.3	2	4	4	11	3	6	10	11	6	8	8	9	8	9	6	105
13.4	3	7	8	10	11	14	12	10	14	9	8	16	18	17	9	166
13.5	13	9	15	12	12	8	11	13	5	17	19	14	21	22	11	202
13.6	5	7	10	9	17	13	15	10	9	21	12	18	22	21	10	199
13.7	17	18	14	17	12	20	25	17	11	22	22	26	18	40	11	290
13.8	13	15	17	16	15	31	20	16	16	31	25	28	23	31	26	323
13.9	9	17	17	18	20	18	31	10	5	33	21	19	26	29	23	296
14	21	22	23	23	21	28	30	22	25	38	30	27	28	42	27	407
14.1	21	18	25	16	19	18	16	13	17	19	25	33	22	32	22	316
14.2	18	24	21	20	17	30	20	32	10	28	19	30	25	32	22	348
14.3	16	25	20	24	24	28	18	13	22	32	25	27	28	36	19	357
14.4	15	19	20	26	23	24	29	20	6	34	27	25	22	22	9	321
14.5	23	30	38	24	23	28	7	29	17	40	26	27	23	38	17	390
14.6	14	25	13	17	13	18	14	23	10	26	28	19	22	29	13	284

Figure A.3.3. Tabulation of length frequency totals by length in fish sampled from the 1959 commercial catch.

5. The aged data set was used to determine the percentage of each age-class that occurred for each length interval.

6. Smith and Pycha's (1960) equation was used to determine weights at length ($W=0.0002786 * L^{3.04957}$) for each length class (Fig. A.3.4). This determined the average weight for fish in each length interval.

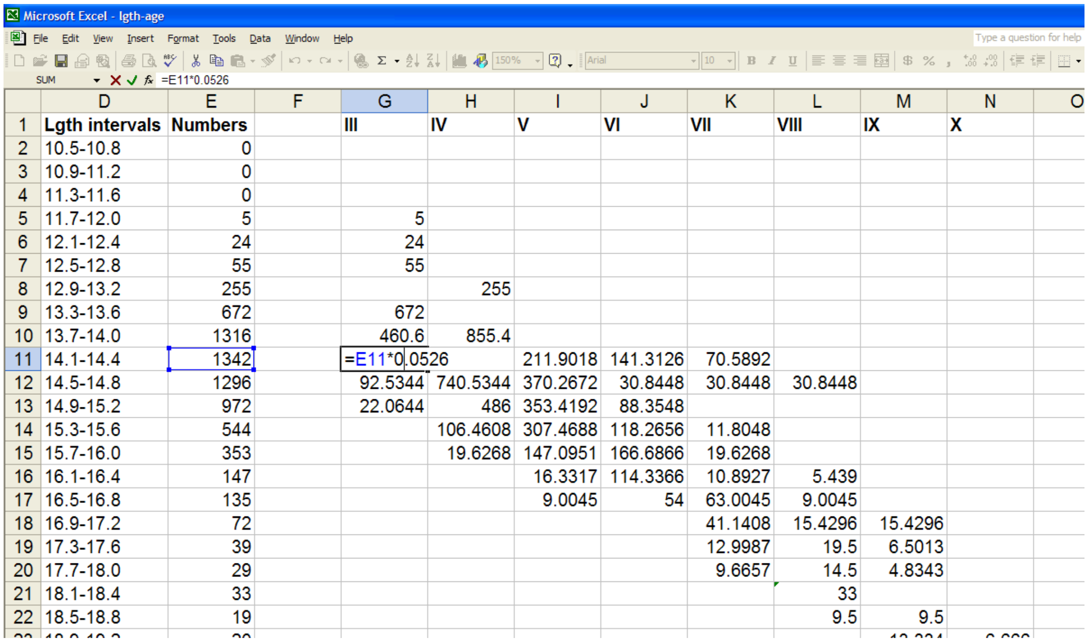


SUM =0.0002786*(reg!A2^3.04957)

	A	B	C	D	E
1	Length	Weight		Lgth intervals	Avg. wt
2	10.8	=0.0002786*(reg!A2^3.04957)			0.39489
3	11	0.41762		10.9-11.2	0.42938
4	11.1	0.42931		11.3-11.6	0.47208
5	11.2	0.44121		11.7-12.0	0.52418
6	11.3	0.45333		12.1-12.4	0.58002
7	11.4	0.46568		12.5-12.8	0.63972
8	11.5	0.47825		12.9-13.2	0.70342
9	11.6	0.49104		13.3-13.6	0.77125
10	11.7	0.50407		13.7-14.0	0.84334
11	11.8	0.51732		14.1-14.4	0.91982
12	11.9	0.53081		14.5-14.8	1.00084
13	12	0.54453		14.9-15.2	1.08652
14	12.1	0.55848		15.3-15.6	1.17699
15	12.2	0.57268		15.7-16.0	1.27239
16	12.3	0.58711		16.1-16.4	1.37286
17	12.4	0.60179		16.5-16.8	1.47853
18	12.5	0.61672		16.9-17.2	1.58953

Figure A.3.4. Illustration of the computation of average weight for each length based on Smith and Pycha's formula (see formula in cell B2--W=0.0002786 * L $^{3.04957}$).

7. The two length-interval data sets (regular and cull) were multiplied by the numbers of fish lengths per length-class, then by the percent of ages per length-class (Figure A.3.5).

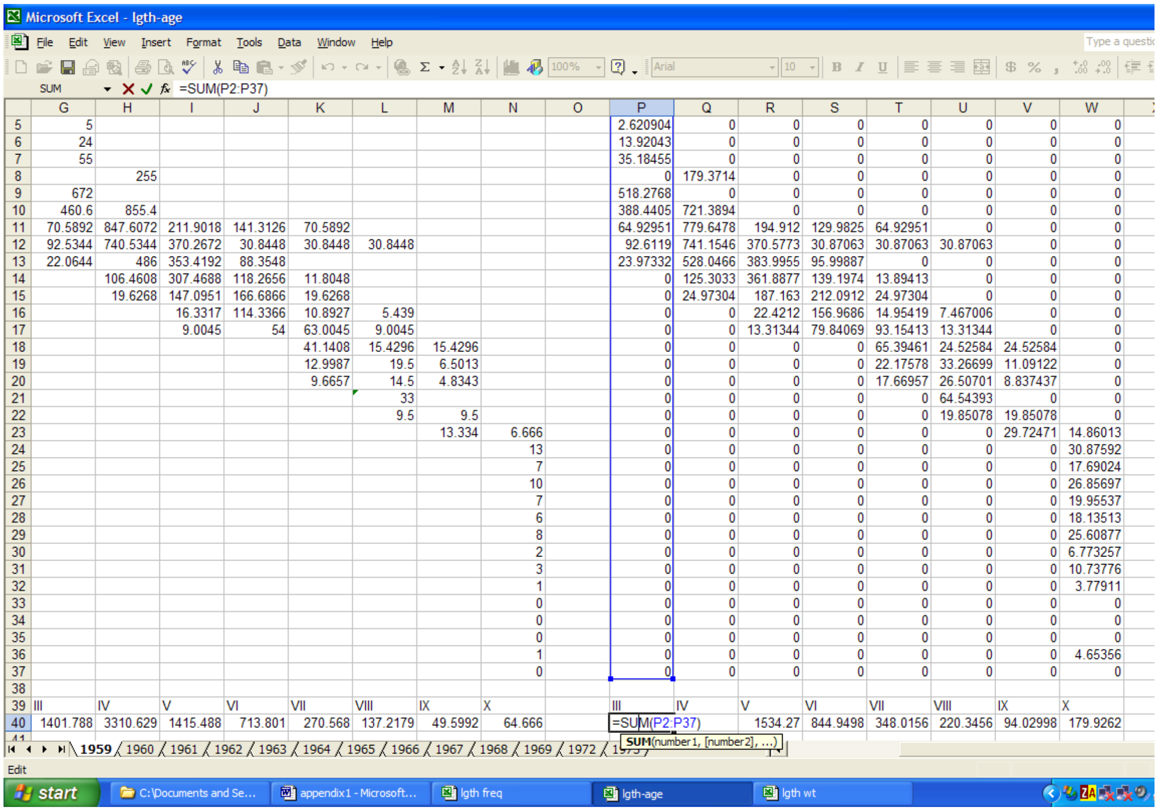


SUM =E11*0.0526

	D	E	F	G	H	I	J	K	L	M	N
1	Lgth intervals	Numbers		III	IV	V	VI	VII	VIII	IX	X
2	10.5-10.8	0									
3	10.9-11.2	0									
4	11.3-11.6	0									
5	11.7-12.0	5		5							
6	12.1-12.4	24		24							
7	12.5-12.8	55		55							
8	12.9-13.2	255			255						
9	13.3-13.6	672		672							
10	13.7-14.0	1316		460.6	855.4						
11	14.1-14.4	1342		=E11*0.0526		211.9018	141.3126	70.5892			
12	14.5-14.8	1296		92.5344	740.5344	370.2672	30.8448	30.8448	30.8448		
13	14.9-15.2	972		22.0644	486	353.4192	88.3548				
14	15.3-15.6	544			106.4608	307.4688	118.2656	11.8048			
15	15.7-16.0	353			19.6268	147.0951	166.6866	19.6268			
16	16.1-16.4	147				16.3317	114.3366	10.8927	5.439		
17	16.5-16.8	135				9.0045	54	63.0045	9.0045		
18	16.9-17.2	72						41.1408	15.4296	15.4296	
19	17.3-17.6	39						12.9987	19.5	6.5013	
20	17.7-18.0	29						9.6657	14.5	4.8343	
21	18.1-18.4	33							33		
22	18.5-18.8	19							9.5	9.5	

Figure A.3.5. Illustration of the computation of the number of fish per length interval per age, shown as the numbers of age 3 fish in the 14.1-14.4 inch length interval.

8. Weights and lengths were added together for each age class (Figure A.3.6).

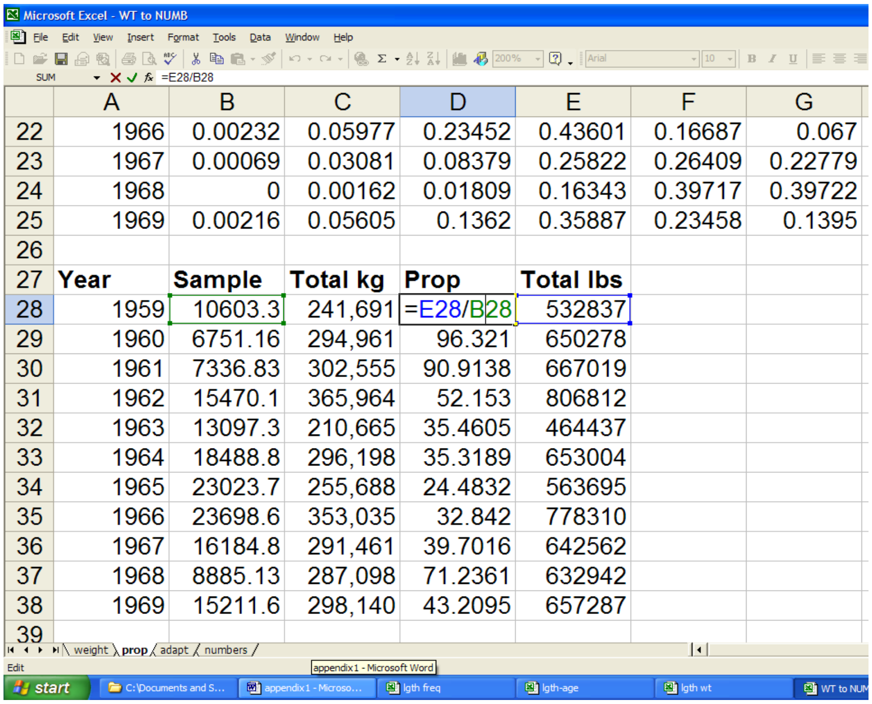


	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W
5	5									2.620904	0	0	0	0	0	0	0
6	24									13.92043	0	0	0	0	0	0	0
7	55									35.18455	0	0	0	0	0	0	0
8		255								0	179.3714	0	0	0	0	0	0
9	672									518.2768	0	0	0	0	0	0	0
10	460.6	855.4								388.4405	721.3894	0	0	0	0	0	0
11	70.5892	847.6072	211.9018	141.3126	70.5892					64.92951	779.6478	194.912	129.9825	64.92951	0	0	0
12	92.5344	740.5344	370.2672	30.8448	30.8448	30.8448				92.6119	741.1546	370.5773	30.87063	30.87063	30.87063	0	0
13	22.0644	486	353.4192	88.3548						23.97332	528.0466	383.9955	95.99887	0	0	0	0
14		106.4608	307.4688	118.2656	11.8048					0	125.3033	361.8877	139.1974	13.89413	0	0	0
15		19.6268	147.0951	166.6866	19.6268					0	24.97304	187.163	212.0912	24.97304	0	0	0
16			16.3317	114.3366	10.8927	5.439				0	0	22.4212	156.9686	14.95419	7.467006	0	0
17			9.0045	54	63.0045	9.0045				0	0	13.31344	79.84069	93.15413	13.31344	0	0
18					41.1408	15.4296	15.4296			0	0	0	0	65.39461	24.52584	24.52584	0
19					12.9987	19.5	6.5013			0	0	0	0	22.17578	33.26699	11.09122	0
20					9.6657	14.5	4.8343			0	0	0	0	17.66957	26.50701	8.837437	0
21						33				0	0	0	0	0	64.54393	0	0
22						9.5	9.5			0	0	0	0	0	19.85078	19.85078	0
23							13.334	6.666		0	0	0	0	0	0	29.72471	14.86013
24								13		0	0	0	0	0	0	0	30.87592
25								7		0	0	0	0	0	0	0	17.69024
26								10		0	0	0	0	0	0	0	26.85697
27								7		0	0	0	0	0	0	0	19.95537
28								6		0	0	0	0	0	0	0	18.13513
29								8		0	0	0	0	0	0	0	25.60877
30								2		0	0	0	0	0	0	0	6.773257
31								3		0	0	0	0	0	0	0	10.73776
32								1		0	0	0	0	0	0	0	3.77911
33								0		0	0	0	0	0	0	0	0
34								0		0	0	0	0	0	0	0	0
35								0		0	0	0	0	0	0	0	0
36								1		0	0	0	0	0	0	0	4.65356
37								0		0	0	0	0	0	0	0	0
38																	
39	III	IV	V	VI	VII	VIII	IX	X		III	IV	V	VI	VII	VIII	IX	X
40	1401.788	3310.629	1415.488	713.801	270.568	137.2179	49.5992	64.666		=SUM(P2:P37)		1534.27	844.9498	348.0156	220.3456	94.02998	179.9262

Figure A.3.6. Summation of the number of fish per age class, shown as the numbers of age 3 in column P.

9. The total weight of the sample was divided by the weight of each class.

10. The total weight of the fish caught was divided by the sample weight for a given year (Figure A.3.7). This was the proportion needed to determine the numbers of fish caught.

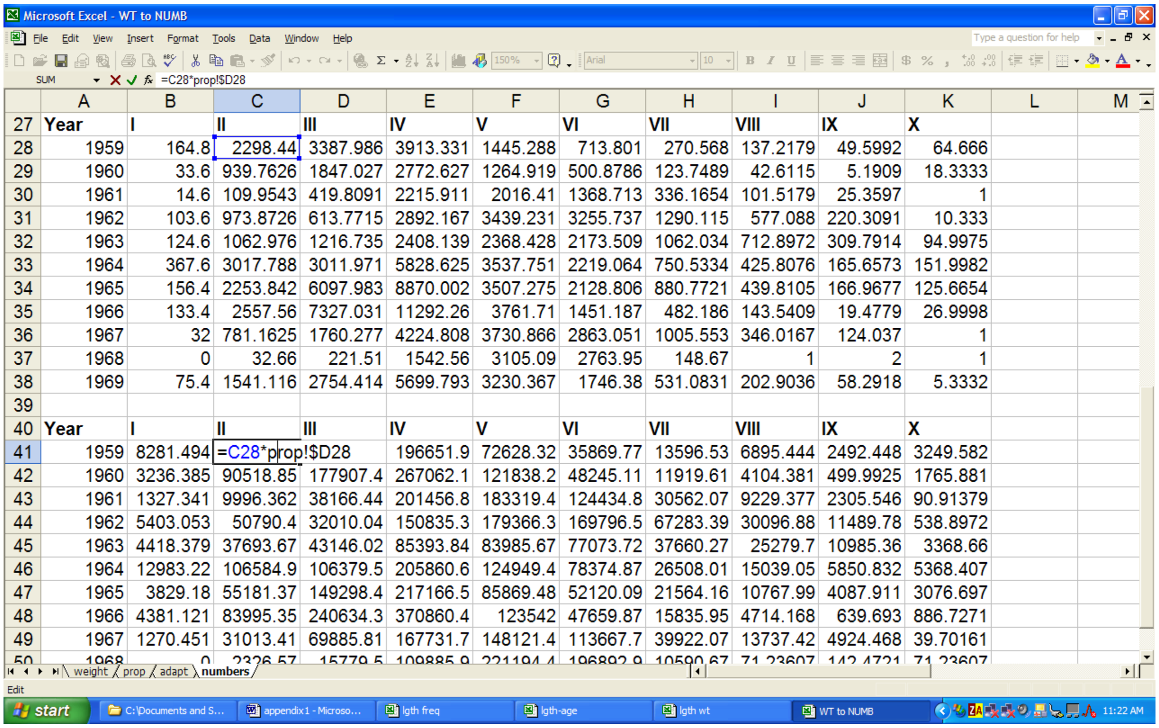


=E28/B28

	A	B	C	D	E	F	G
22	1966	0.00232	0.05977	0.23452	0.43601	0.16687	0.067
23	1967	0.00069	0.03081	0.08379	0.25822	0.26409	0.22779
24	1968	0	0.00162	0.01809	0.16343	0.39717	0.39722
25	1969	0.00216	0.05605	0.1362	0.35887	0.23458	0.1395
26							
27	Year	Sample	Total kg	Prop	Total lbs		
28	1959	10603.3	241,691	=E28/B28	532837		
29	1960	6751.16	294,961	96.321	650278		
30	1961	7336.83	302,555	90.9138	667019		
31	1962	15470.1	365,964	52.153	806812		
32	1963	13097.3	210,665	35.4605	464437		
33	1964	18488.8	296,198	35.3189	653004		
34	1965	23023.7	255,688	24.4832	563695		
35	1966	23698.6	353,035	32.842	778310		
36	1967	16184.8	291,461	39.7016	642562		
37	1968	8885.13	287,098	71.2361	632942		
38	1969	15211.6	298,140	43.2095	657287		
39							

Figure A.3.7. The sample weight (column B) for a given year was divided by the total catch weight (column E) for the proportion of the total catch sampled.

11. The proportion for catch per year found in step 11 was multiplied by the sample numbers-at-age (Figure A.3.8). This was the estimated catch at age.



=C28*prop!$D28

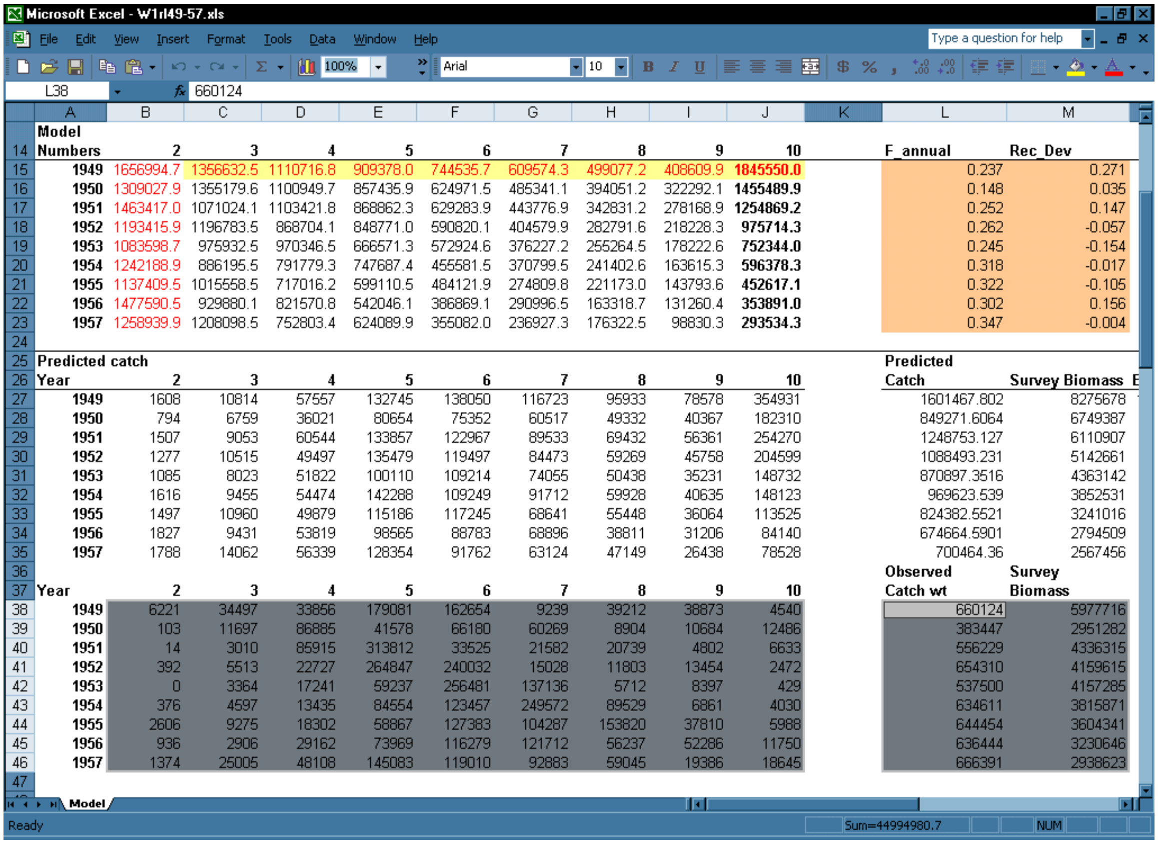
	A	B	C	D	E	F	G	H	I	J	K	L	M
27	Year	I	II	III	IV	V	VI	VII	VIII	IX	X		
28	1959	164.8	2298.44	3387.986	3913.331	1445.288	713.801	270.568	137.2179	49.5992	64.666		
29	1960	33.6	939.7626	1847.027	2772.627	1264.919	500.8786	123.7489	42.6115	5.1909	18.3333		
30	1961	14.6	109.9543	419.8091	2215.911	2016.41	1368.713	336.1654	101.5179	25.3597	1		
31	1962	103.6	973.8726	613.7715	2892.167	3439.231	3255.737	1290.115	577.088	220.3091	10.333		
32	1963	124.6	1062.976	1216.735	2408.139	2368.428	2173.509	1062.034	712.8972	309.7914	94.9975		
33	1964	367.6	3017.788	3011.971	5828.625	3537.751	2219.064	750.5334	425.8076	165.6573	151.9982		
34	1965	156.4	2253.842	6097.983	8870.002	3507.275	2128.806	880.7721	439.8105	166.9677	125.6654		
35	1966	133.4	2557.56	7327.031	11292.26	3761.71	1451.187	482.186	143.5409	19.4779	26.9998		
36	1967	32	781.1625	1760.277	4224.808	3730.866	2863.051	1005.553	346.0167	124.037	1		
37	1968	0	32.66	221.51	1542.56	3105.09	2763.95	148.67	1	2	1		
38	1969	75.4	1541.116	2754.414	5699.793	3230.367	1746.38	531.0831	202.9036	58.2918	5.3332		
39													
40	Year	I	II	III	IV	V	VI	VII	VIII	IX	X		
41	1959	8281.494	=C28*prop!$D28		196651.9	72628.32	35869.77	13596.53	6895.444	2492.448	3249.582		
42	1960	3236.385	90518.85	177907.4	267062.1	121838.2	48245.11	11919.61	4104.381	499.9925	1765.881		
43	1961	1327.341	9996.362	38166.44	201456.8	183319.4	124434.8	30562.07	9229.377	2305.546	90.91379		
44	1962	5403.053	50790.4	32010.04	150835.3	179366.3	169796.5	67283.39	30096.88	11489.78	538.8972		
45	1963	4418.379	37693.67	43146.02	85393.84	83985.67	77073.72	37660.27	25279.7	10985.36	3368.66		
46	1964	12983.22	106584.9	106379.5	205860.6	124949.4	78374.87	26508.01	15039.05	5850.832	5368.407		
47	1965	3829.18	55181.37	149298.4	217166.5	85869.48	52120.09	21564.16	10767.99	4087.911	3076.697		
48	1966	4381.121	83995.35	240634.3	370860.4	123542	47659.87	15835.95	4714.168	639.693	886.7271		
49	1967	1270.451	31013.41	69885.81	167731.7	148121.4	113667.7	39922.07	13737.42	4924.468	39.70161		
50	1968	0	2326.57	15779.5	109885.9	221194.4	196892.9	10590.67	71.23607	142.4721	71.23607		

Figure A.3.8. The catch-per-year proportion was multiplied by the sample numbers-at-age, here are two for year 1959.

Appendix 4: Ianelli Excel© spreadsheet calculation method

One of the three methods for calculating catch-at-age used the functions in Microsoft Excel©. The following contains the instructions for computing the catch-at-age estimates, including the cell equations used.

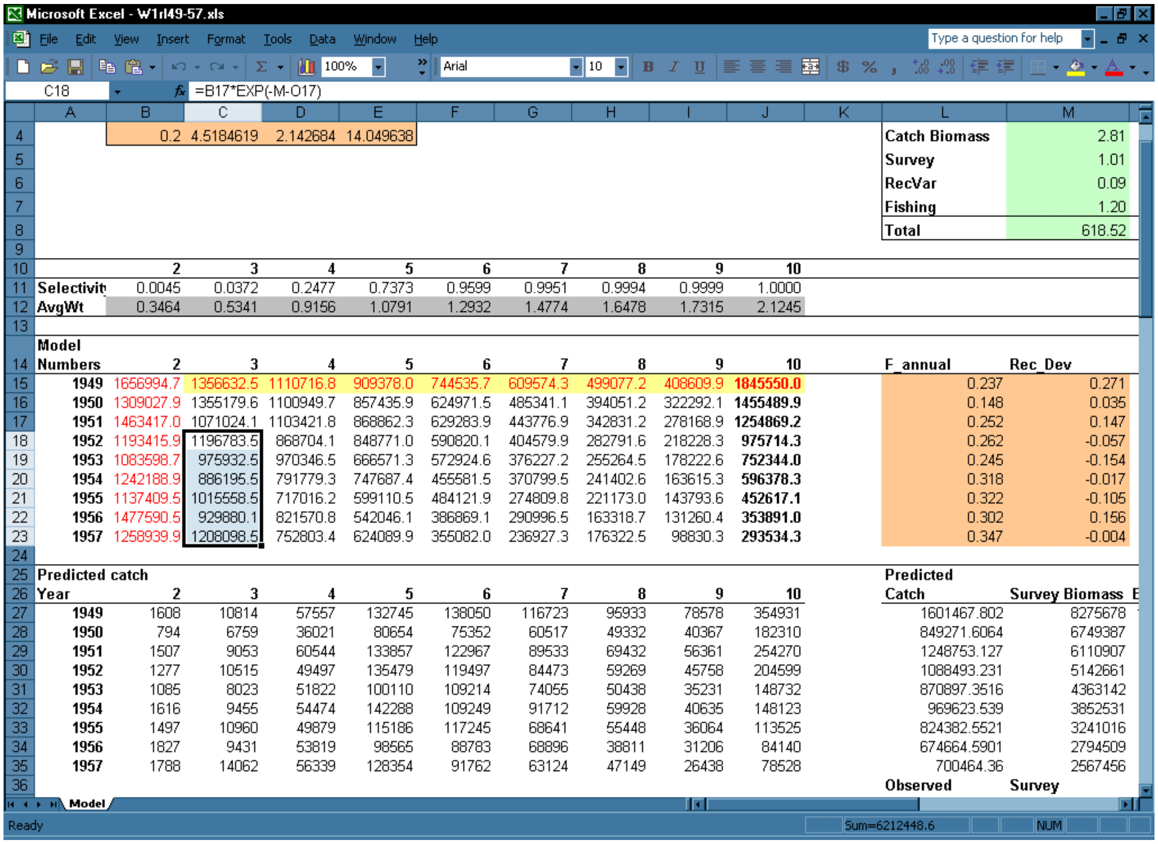
1. Insert catch-at-age, observed catch weight, and survey biomass, which in the example below begins at row 38 (Figure A.4.1). Also insert assumed natural mortality and the calculated average weight at age.



	A	B	C	D	E	F	G	H	I	J	K	L	M
14	**Model Numbers**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**		**F_annual**	**Rec_Dev**
15	**1949**	1656994.7	1356632.5	1110716.8	909378.0	744535.7	609574.3	499077.2	408609.9	**1845550.0**		0.237	0.271
16	**1950**	1309027.9	1355179.6	1100949.7	857435.9	624971.5	485341.1	394051.2	322292.1	**1455489.9**		0.148	0.035
17	**1951**	1463417.0	1071024.1	1103421.8	868862.3	629283.9	443776.9	342831.2	278168.9	**1254869.2**		0.252	0.147
18	**1952**	1193415.9	1196783.5	868704.1	848771.0	590820.1	404579.9	282791.6	218228.3	**975714.3**		0.262	-0.057
19	**1953**	1083598.7	975932.5	970346.5	666571.3	572924.6	376227.2	255264.5	178222.6	**752344.0**		0.245	-0.154
20	**1954**	1242188.9	886195.5	791779.3	747687.4	455581.5	370799.5	241402.6	163615.3	**596378.3**		0.318	-0.017
21	**1955**	1137409.5	1015558.5	717016.2	599110.5	484121.9	274809.8	221173.0	143793.6	**452617.1**		0.322	-0.105
22	**1956**	1477590.5	929880.1	821570.8	542046.1	386869.1	290996.5	163318.7	131260.4	**353891.0**		0.302	0.156
23	**1957**	1258939.9	1208098.5	752803.4	624089.9	355082.0	236927.3	176322.5	98830.3	**293534.3**		0.347	-0.004
24													
25	**Predicted catch**											**Predicted**	
26	**Year**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**		**Catch**	**Survey Biomass**
27	**1949**	1608	10814	57557	132745	138050	116723	95933	78578	354931		1601467.802	8275678
28	**1950**	794	6759	36021	80654	75352	60517	49332	40367	182310		849271.6064	6749387
29	**1951**	1507	9053	60544	133857	122967	89533	69432	56361	254270		1248753.127	6110907
30	**1952**	1277	10515	49497	135479	119497	84473	59269	45758	204599		1088493.231	5142661
31	**1953**	1085	8023	51822	100110	109214	74055	50438	35231	148732		870897.3516	4363142
32	**1954**	1616	9455	54474	142288	109249	91712	59928	40635	148123		969623.539	3852531
33	**1955**	1497	10960	49879	115186	117245	68641	55448	36064	113525		824382.5521	3241016
34	**1956**	1827	9431	53819	98565	88783	68896	38811	31206	84140		674664.5901	2794509
35	**1957**	1788	14062	56339	128354	91762	63124	47149	26438	78528		700464.36	2567456
36												**Observed**	**Survey**
37	**Year**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**		**Catch wt**	**Biomass**
38	**1949**	6221	34497	33856	179081	162654	9239	39212	38873	4540		660124	5977716
39	**1950**	103	11697	86885	41578	66180	60269	8904	10684	12486		383447	2951282
40	**1951**	14	3010	85915	313812	33525	21582	20739	4802	6633		556229	4336315
41	**1952**	392	5513	22727	264847	240032	15028	11803	13454	2472		654310	4159615
42	**1953**	0	3364	17241	59237	256481	137136	5712	8397	429		537500	4157285
43	**1954**	376	4597	13435	84554	123457	249572	89529	6861	4030		634611	3815871
44	**1955**	2606	9275	18302	58867	127383	104287	153820	37810	5988		644454	3604341
45	**1956**	936	2906	29162	73969	116279	121712	56237	52286	11750		636444	3230646
46	**1957**	1374	25005	48108	145083	119010	92883	59045	19386	18645		666391	2938623
47													

Figure A.4.1. Enter catch-at-age (columns B-J, rows 38-46 in example), observed catch weight (column L, rows 38-46), and survey biomass if available (column M, rows 38-46).

2. Extend the matrices not in dark gray to fit the time and age spans that you are analyzing under the headings of model numbers, F annual, and Rec Dev (Figure A.4.2). In the example these matrices begin at row 15 and extend to row 23. Do not forget to check the F values, which are to the right of the Rec Dev column.



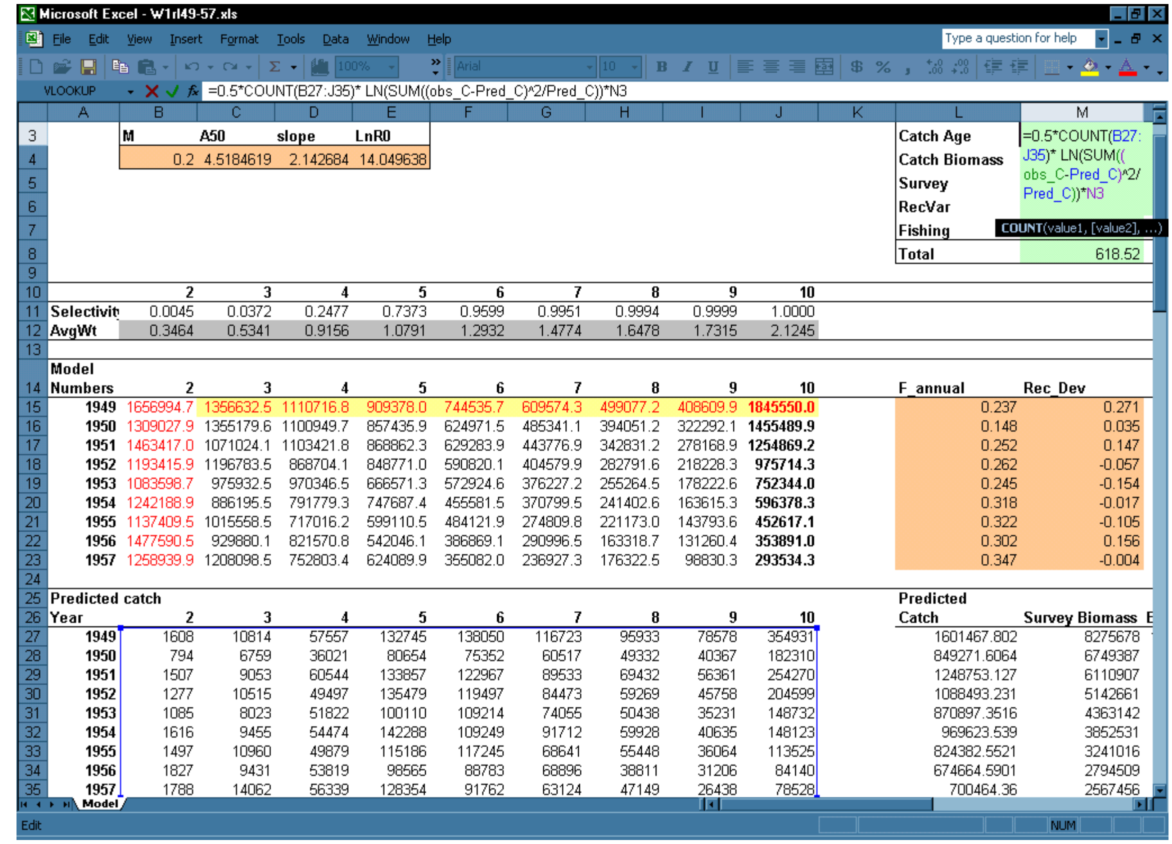
C18 =B17*EXP(-M-O17)

	A	B	C	D	E	F	G	H	I	J	K	L	M
4		0.2	4.5184619	2.142684	14.049638							**Catch Biomass**	2.81
5												**Survey**	1.01
6												**RecVar**	0.09
7												**Fishing**	1.20
8												**Total**	618.52
9													
10		**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**			
11	**Selectivit**	0.0045	0.0372	0.2477	0.7373	0.9599	0.9951	0.9994	0.9999	1.0000			
12	**AvgWt**	0.3464	0.5341	0.9156	1.0791	1.2932	1.4774	1.6478	1.7315	2.1245			
13													
14	**Model Numbers**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**		**F_annual**	**Rec_Dev**
15	**1949**	1656994.7	1356632.5	1110716.8	909378.0	744535.7	609574.3	499077.2	408609.9	**1845550.0**		0.237	0.271
16	**1950**	1309027.9	1355179.6	1100949.7	857435.9	624971.5	485341.1	394051.2	322292.1	**1455489.9**		0.148	0.035
17	**1951**	1463417.0	1071024.1	1103421.8	868862.3	629283.9	443776.9	342831.2	278168.9	**1254869.2**		0.252	0.147
18	**1952**	1193415.9	1196783.5	868704.1	848771.0	590820.1	404579.9	282791.6	218228.3	**975714.3**		0.262	-0.057
19	**1953**	1083598.7	975932.5	970346.5	666571.3	572924.6	376227.2	255264.5	178222.6	**752344.0**		0.245	-0.154
20	**1954**	1242188.9	886195.5	791779.3	747687.4	455581.5	370799.5	241402.6	163615.3	**596378.3**		0.318	-0.017
21	**1955**	1137409.5	1015558.5	717016.2	599110.5	484121.9	274809.8	221173.0	143793.6	**452617.1**		0.322	-0.105
22	**1956**	1477590.5	929880.1	821570.8	542046.1	386869.1	290996.5	163318.7	131260.4	**353891.0**		0.302	0.156
23	**1957**	1258939.9	1208098.5	752803.4	624089.9	355082.0	236927.3	176322.5	98830.3	**293534.3**		0.347	-0.004
24													
25	**Predicted catch**											**Predicted**	
26	**Year**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**		**Catch**	**Survey Biomass**
27	**1949**	1608	10814	57557	132745	138050	116723	95933	78578	354931		1601467.802	8275678
28	**1950**	794	6759	36021	80654	75352	60517	49332	40367	182310		849271.6064	6749387
29	**1951**	1507	9053	60544	133857	122967	89533	69432	56361	254270		1248753.127	6110907
30	**1952**	1277	10515	49497	135479	119497	84473	59269	45758	204599		1088493.231	5142661
31	**1953**	1085	8023	51822	100110	109214	74055	50438	35231	148732		870897.3516	4363142
32	**1954**	1616	9455	54474	142288	109249	91712	59928	40635	148123		969623.539	3852531
33	**1955**	1497	10960	49879	115186	117245	68641	55448	36064	113525		824382.5521	3241016
34	**1956**	1827	9431	53819	98565	88783	68896	38811	31206	84140		674664.5901	2794509
35	**1957**	1788	14062	56339	128354	91762	63124	47149	26438	78528		700464.36	2567456
36												**Observed**	**Survey**

Sum=6212448.6

Figure A.4.2. Extend the matrices to fit the time and age spans t under the headings of model numbers (columns B-J, rows 15-23), F annual (column L, rows 15-23), and Rec Dev (column M, rows 15-23).

3. Ensure that the equations in cells M3-M9 enclose the proper matrices and values (Figure A.4.3). NOTE: All of these equations except for “Total” are arrays, which must close by holding down control, shift, and enter.

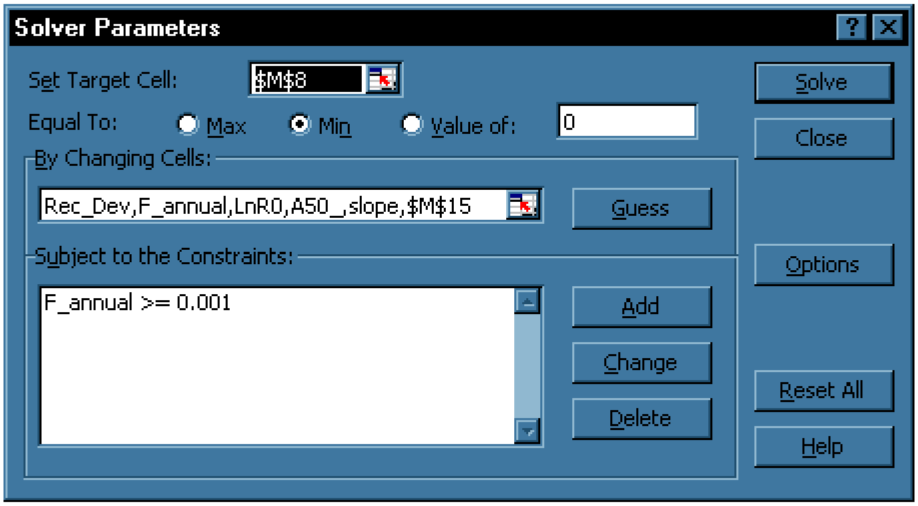


VLOOKUP =0.5*COUNT(B27:J35)* LN(SUM((obs_C-Pred_C)^2/Pred_C))*N3

	A	B	C	D	E	F	G	H	I	J	K	L	M
3		M	A50	slope	LnR0							Catch Age	=0.5*COUNT(B27:J35)* LN(SUM((obs_C-Pred_C)^2/Pred_C))*N3
4		0.2	4.5184619	2.142684	14.049638							Catch Biomass	
5												Survey	
6												RecVar	
7												Fishing	
8												Total	618.52
9													
10		2	3	4	5	6	7	8	9	10			
11	Selectivit	0.0045	0.0372	0.2477	0.7373	0.9599	0.9951	0.9994	0.9999	1.0000			
12	AvgWt	0.3464	0.5341	0.9156	1.0791	1.2932	1.4774	1.6478	1.7315	2.1245			
13													
14	Model Numbers	2	3	4	5	6	7	8	9	10		F_annual	Rec_Dev
15	1949	1656994.7	1356632.5	1110716.8	909378.0	744535.7	609574.3	499077.2	408609.9	**1845550.0**		0.237	0.271
16	1950	1309027.9	1355179.6	1100949.7	857435.9	624971.5	485341.1	394051.2	322292.1	**1455489.9**		0.148	0.035
17	1951	1463417.0	1071024.1	1103421.8	868862.3	629283.9	443776.9	342831.2	278168.9	**1254869.2**		0.252	0.147
18	1952	1193415.9	1196783.5	868704.1	848771.0	590820.1	404579.9	282791.6	218228.3	**975714.3**		0.262	-0.057
19	1953	1083598.7	975932.5	970346.5	666571.3	572924.6	376227.2	255264.5	178222.6	**752344.0**		0.245	-0.154
20	1954	1242188.9	886195.5	791779.3	747687.4	455581.5	370799.5	241402.6	163615.3	**596378.3**		0.318	-0.017
21	1955	1137409.5	1015558.5	717016.2	599110.5	484121.9	274809.8	221173.0	143793.6	**452617.1**		0.322	-0.105
22	1956	1477590.5	929880.1	821570.8	542046.1	386869.1	290996.5	163318.7	131260.4	**353891.0**		0.302	0.156
23	1957	1258939.9	1208098.5	752803.4	624089.9	355082.0	236927.3	176322.5	98830.3	**293534.3**		0.347	-0.004
24													
25	Predicted catch											Predicted	
26	Year	2	3	4	5	6	7	8	9	10		Catch	Survey Biomass
27	1949	1608	10814	57557	132745	138050	116723	95933	78578	354931		1601467.802	8275678
28	1950	794	6759	36021	80654	75352	60517	49332	40367	182310		849271.6064	6749387
29	1951	1507	9053	60544	133857	122967	89533	69432	56361	254270		1248753.127	6110907
30	1952	1277	10515	49497	135479	119497	84473	59269	45758	204599		1088493.231	5142661
31	1953	1085	8023	51822	100110	109214	74055	50438	35231	148732		870897.3516	4363142
32	1954	1616	9455	54474	142288	109249	91712	59928	40635	148123		969623.539	3852531
33	1955	1497	10960	49879	115186	117245	68641	55448	36064	113525		824382.5521	3241016
34	1956	1827	9431	53819	98565	88783	68896	38811	31206	84140		674664.5901	2794509
35	1957	1788	14062	56339	128354	91762	63124	47149	26438	78528		700464.36	2567456

Figure A.4.3. Ensure that the equations in cells M3-M9 enclose the proper matrices and values.

4. Go to Solver. The cell to be minimized is M8. The cells being changed are the Rec Dev and F annual columns, LnR0, A50, and slope (Figure A.4.4). The constraint is that F annual >=0.001. When checked, hit solve then keep results.



Set Target Cell: $M$8

Equal To: ○ Max ● Min ○ Value of: 0

By Changing Cells:

Rec_Dev,F_annual,LnR0,A50_,slope,$M$15

Subject to the Constraints:

F_annual >= 0.001

Figure A.4.4. The "solver" dialog box under the Tools menu, settings should minimize the total cell (M8) by changing cells Rec Dev, F annual, LnR0, A50_, slope, and M15.

Appendix 5: Results tables associated with the results figures

Table A.5.1: The DDM1 estimates for fishable biomass, predicted CPUE, and predicted catch biomass for the years 1949-1957 (Figures 2 and 3 with fishable biomass not shown).

Year	Fishable Biomass (B)	Predicted CPUE	Predicted catch (biomass)
1949	1,451,221	42.80	284,722
1950	639,357	14.43	125,439
1951	1,143,085	26.67	224,268
1952	1,436,502	55.10	281,834
1953	1,620,435	67.82	317,921
1954	1,413,007	51.97	277,225
1955	1,391,966	42.93	273,097
1956	1,371,407	36.35	269,063
1957	1,475,733	43.11	289,531

Table A.5.2: The DDM1 estimates for fishable biomass, predicted CPUE, and predicted catch biomass for the years 1959-1969 (Figures 4 and 5 with fishable biomass not shown).

Year	Fishable Biomass (B)	Predicted CPUE	Predicted catch (biomass)
1959	1,501,157	22.91	263,606
1960	1,992,605	37.97	349,905
1961	1,485,133	67.25	260,792
1962	1,803,776	62.33	316,746
1963	1,826,968	41.13	320,819
1964	1,565,116	35.27	274,837
1965	1,495,858	26.72	262,675
1966	1,380,897	42.59	242,488
1967	1,623,490	100.77	285,088
1968	2,081,589	80.23	365,530
1969	2,000,235	45.96	351,245

Table A.5.3: The DDM1 estimates for fishable biomass, predicted CPUE, and predicted catch biomass for the years 1949-1969 (Figures 6 and 7 with fishable biomass not shown).

Year	Fishable Biomass (B)	Predicted CPUE	Predicted catch (biomass)
1949	1,505,779	45.04	299,678
1950	976,327	22.35	194,307
1951	990,302	23.44	197,088
1952	1,213,966	47.23	241,602
1953	1,390,187	59.02	276,673
1954	1,524,378	56.88	303,379
1955	1,567,564	49.04	311,974
1956	1,518,101	40.82	302,130
1957	1,441,443	42.71	286,874
1958	1,475,041	33.47	293,560
1959	1,344,799	23.26	267,640
1960	1,214,843	26.23	241,776
1961	1,268,022	65.07	252,360
1962	1,644,126	64.39	327,211
1963	1,632,272	41.64	324,852
1964	1,407,819	35.95	280,182
1965	1,402,057	28.38	279,035
1966	1,290,918	45.13	256,917
1967	1,492,411	104.99	297,017
1968	1,920,236	83.88	382,162
1969	1,828,779	47.62	363,961

Table A.5.4: DDM1 estimates for fishable biomass, predicted CPUE, and predicted catch, 1949-1996 (Figures 8 and 9 with fishable biomass not shown).

Year	Fishable Biomass (B)	Predicted CPUE	Predicted catch (biomass)
1949	3,486,874	39.00	259,489
1950	3,105,123	26.58	231,080
1951	2,575,470	22.80	191,664
1952	2,202,816	32.05	163,931
1953	2,198,069	34.89	163,578
1954	2,457,210	34.28	182,863
1955	2,716,495	31.78	202,159
1956	2,812,725	28.28	209,320
1957	2,661,104	29.49	198,037
1958	2,681,440	22.75	199,550
1959	2,529,372	16.36	188,233
1960	2,074,238	16.75	154,363
1961	1,802,928	34.60	134,172
1962	2,196,504	32.16	163,461
1963	2,636,569	25.15	196,211
1964	2,619,005	25.01	194,904
1965	2,613,434	19.78	194,489
1966	2,198,741	28.74	163,628
1967	2,119,638	55.76	157,741
1968	2,594,943	42.39	193,113
1969	3,018,620	29.39	224,643
1970	2,856,713	28.29	212,594
1971	2,725,239	22.88	202,809
1972	2,232,531	37.40	166,143
1973	2,241,578	52.00	166,816
1974	2,588,424	54.72	192,628
1975	2,991,113	49.32	222,595
1976	3,250,767	41.73	241,919
1977	3,296,864	29.42	245,349
1978	2,815,728	26.57	209,543
1979	2,546,739	19.47	189,526
1980	2,136,825	18.85	159,020
1981	2,026,876	18.78	150,838
1982	2,147,020	17.06	159,779
1983	2,177,528	15.60	162,049
1984	2,143,600	13.86	159,524
1985	2,058,601	11.78	153,199
1986	1,743,322	18.89	129,736
1987	2,177,587	12.81	162,054
1988	1,900,293	18.09	141,418
1989	1,963,286	26.69	146,106
1990	2,489,678	16.48	185,279
1991	2,299,921	13.06	171,158
1992	2,110,503	8.02	157,061
1993	1,550,977	8.61	115,422
1994	1,480,808	13.72	110,200
1995	1,754,273	20.88	130,551
1996	1,960,278	63.26	145,882

Table A.5.5: DDM2 estimates for fishable biomass, predicted CPUE, and predicted catch, 1949-1996 (Figures 8 and 9 with fishable biomass not shown).

Year	Fishable Biomass (B)	Predicted CPUE	Predicted catch (biomass)
1949	3,042,117	33.46	222,622
1950	3,232,387	27.20	236,546
1951	2,863,193	24.92	209,529
1952	2,401,544	34.36	175,745
1953	2,367,865	36.96	173,280
1954	2,567,151	35.22	187,864
1955	2,800,858	32.22	204,967
1956	2,907,602	28.75	212,778
1957	2,754,515	30.01	201,575
1958	2,781,311	23.21	203,536
1959	2,636,469	16.77	192,937
1960	2,147,992	17.06	157,190
1961	1,820,244	34.35	133,205
1962	2,190,662	31.55	160,313
1963	2,665,518	25.00	195,063
1964	2,691,870	25.28	196,991
1965	2,716,910	20.22	198,823
1966	2,279,478	29.30	166,812
1967	2,153,048	55.69	157,560
1968	2,617,237	42.04	191,529
1969	3,084,823	29.54	225,747
1970	2,961,747	28.84	216,741
1971	2,847,543	23.51	208,383
1972	2,314,682	38.13	169,388
1973	2,273,375	51.86	166,366
1974	2,602,198	54.10	190,429
1975	3,028,835	49.11	221,650
1976	3,341,758	42.19	244,550
1977	3,444,273	30.23	252,052
1978	2,967,535	27.54	217,164
1979	2,682,509	20.17	196,306
1980	2,224,603	19.30	162,796
1981	2,072,607	18.89	151,673
1982	2,184,115	17.07	159,834
1983	2,225,339	15.68	162,850
1984	2,205,908	14.02	161,428
1985	2,127,191	11.97	155,668
1986	1,780,729	18.97	130,314
1987	2,229,287	12.90	163,139
1988	1,946,491	18.22	142,444
1989	1,993,665	26.65	145,896
1990	2,555,173	16.63	186,988
1991	2,388,228	13.33	174,771
1992	2,204,109	8.23	161,297
1993	1,591,646	8.69	116,477
1994	1,481,782	13.50	108,437
1995	1,746,431	20.44	127,804
1996	1,954,478	62.02	143,029

Table A.5.6: Estimates for predicted CPUE for DDM3, DDM4, and DDM5 simulations, 1949-1996 (Figure 12).

Year	DDM3	DDM4	DDM5
1949	46.78	32.10	33.48
1950	27.61	32.23	34.97
1951	25.31	32.52	24.91
1952	50.75	45.92	32.12
1953	37.06	46.73	31.61
1954	34.52	36.72	28.14
1955	32.37	27.96	26.41
1956	28.90	20.89	26.08
1957	30.68	21.15	29.30
1958	25.36	16.44	23.15
1959	16.95	12.00	17.51
1960	18.16	13.92	18.20
1961	44.15	33.05	36.53
1962	39.13	31.80	27.94
1963	25.38	23.29	21.27
1964	24.56	22.35	23.64
1965	22.38	17.76	19.63
1966	28.23	27.92	30.04
1967	71.39	57.31	57.75
1968	42.24	40.30	40.51
1969	27.25	25.96	27.31
1970	30.84	25.13	27.74
1971	26.89	19.50	24.00
1972	38.34	34.38	40.66
1973	51.85	55.44	46.16
1974	52.92	57.45	44.22
1975	55.54	45.22	42.31
1976	44.29	36.43	37.57
1977	32.31	24.66	28.39
1978	31.08	28.32	22.03
1979	23.16	24.36	15.30
1980	23.16	20.78	18.06
1981	21.15	18.54	18.48
1982	18.56	14.07	17.07
1983	16.41	11.41	15.89
1984	15.82	9.82	15.06
1985	13.54	8.79	13.24
1986	20.87	17.00	21.62
1987	14.93	11.57	13.97
1988	21.40	18.30	20.89
1989	31.18	28.82	28.43
1990	19.54	16.88	17.91
1991	16.89	12.97	15.64
1992	11.34	7.22	9.92
1993	9.89	7.75	10.45
1994	15.36	12.52	13.49
1995	23.93	18.97	16.73
1996	69.51	65.29	50.75

Table A.5.7: Estimates for predicted catch biomass for DDM3, DDM4, and DDM5 simulations, 1949-1996 (Figure 13).

Year	DDM3	DDM4	DDM5
1949	311,222	213,534	222,763
1950	240,068	280,238	304,049
1951	212,770	273,402	209,465
1952	259,611	234,890	164,302
1953	173,719	219,085	148,192
1954	184,143	195,861	150,086
1955	205,919	177,878	167,999
1956	213,924	154,584	193,022
1957	206,014	142,067	196,783
1958	222,386	144,194	203,041
1959	195,084	138,129	201,438
1960	167,341	128,326	167,755
1961	171,212	128,174	141,679
1962	198,884	161,592	141,967
1963	197,980	181,723	165,889
1964	191,426	174,149	184,197
1965	220,087	174,638	192,982
1966	160,734	158,953	171,027
1967	201,953	162,117	163,386
1968	192,428	183,593	184,581
1969	208,251	198,383	208,718
1970	231,816	188,914	208,465
1971	238,340	172,797	212,727
1972	170,298	152,724	180,630
1973	166,320	177,852	148,068
1974	186,289	202,231	155,666
1975	250,650	204,055	190,950
1976	256,776	211,206	217,776
1977	269,415	205,637	236,746
1978	245,071	223,357	173,751
1979	225,428	237,159	148,918
1980	195,292	175,275	152,336
1981	169,867	148,881	148,421
1982	173,765	131,696	159,785
1983	170,440	118,526	165,062
1984	182,099	113,034	173,352
1985	176,050	114,289	172,189
1986	143,373	116,764	148,508
1987	188,771	146,332	176,725
1988	167,292	143,080	163,348
1989	170,722	157,773	155,656
1990	219,650	189,771	201,418
1991	221,454	170,031	205,027
1992	222,110	141,400	194,306
1993	132,483	103,815	140,050
1994	123,380	100,580	108,390
1995	149,608	118,638	104,631
1996	160,280	150,560	117,040

Table A.5.8: DDM6 estimates for fishable biomass, predicted CPUE, and predicted catch biomass, 1945-1960 (Figure 14 and 15 with fishable biomass not shown).

Year	Fishable Biomass (B)	Predicted CPUE	Predicted catch (biomass)
1945	2,369,405	54.64	393,145
1946	2,785,204	61.49	462,136
1947	2,342,249	46.47	388,639
1948	1,890,655	46.19	313,708
1949	1,626,425	40.56	269,865
1950	1,482,346	28.29	245,959
1951	1,605,140	31.68	266,334
1952	1,670,188	54.18	277,127
1953	1,509,955	53.44	250,540
1954	1,487,070	46.26	246,743
1955	1,787,862	46.64	296,652
1956	1,974,777	44.27	327,666
1957	1,957,036	48.35	324,722
1958	1,793,065	33.92	297,515
1959	1,657,527	23.90	275,026
1960	1,686,753	30.37	279,875

Table A.5.9: Estimates for predicted black market catch biomass (10-100), incremental increases (10-20 and 20-30) and different catch and effort increases, 1949-1996 (Figures 23, 24, and 26).

Year	10%	15%	20%	100%	10%-20%	20%-30%	20%-10%	40%-20%
1949	306,751	295,681	300,545	222,622	250,979	285,452	258,574	279,801
1950	218,954	244,055	249,185	236,546	248,810	224,416	233,739	235,538
1951	221,639	231,517	237,424	209,529	202,211	186,502	189,868	196,009
1952	239,037	232,881	240,310	175,745	214,272	214,362	198,252	223,847
1953	273,982	265,903	271,802	173,280	221,234	236,018	202,472	243,925
1954	301,100	290,136	293,676	187,864	209,300	236,966	193,793	240,909
1955	291,951	282,891	283,828	204,967	187,497	217,116	176,387	218,236
1956	249,758	245,622	244,555	212,778	162,180	189,762	154,925	189,222
1957	236,459	235,851	233,842	201,575	158,478	187,388	151,879	186,585
1958	174,187	176,252	174,672	203,536	145,216	167,654	139,592	167,397
1959	98,562	100,489	100,148	192,937	123,747	139,530	118,849	140,000
1960	107,073	118,792	98,049	174,657	130,585	141,942	124,118	142,864
1961	186,783	203,270	174,289	111,232	183,792	204,246	172,520	205,805
1962	241,527	266,103	221,764	129,985	209,490	226,181	197,781	227,525
1963	204,843	239,611	176,199	149,021	176,948	178,681	170,470	179,233
1964	186,246	222,915	156,913	132,085	157,892	160,955	152,701	161,510
1965	129,203	158,528	106,957	128,227	133,422	140,200	128,807	140,818
1966	177,074	201,808	158,082	105,646	156,936	174,878	148,849	175,912
1967	279,491	303,698	258,795	109,548	214,335	246,327	200,556	247,941
1968	332,663	361,401	304,749	151,730	229,011	253,411	215,536	254,688
1969	255,389	295,739	216,510	172,801	178,614	180,435	172,069	180,837
1970	211,633	250,686	177,272	141,985	145,670	148,933	147,591	156,809
1971	142,066	173,292	117,966	131,887	122,544	130,906	127,060	140,139
1972	190,152	216,519	171,130	97,848	154,259	175,591	154,497	185,586
1973	273,204	296,023	256,544	121,140	203,013	233,798	198,993	245,723
1974	354,447	377,890	334,333	165,900	230,230	258,273	225,227	271,919
1975	393,024	424,410	362,316	208,721	222,695	238,261	220,958	252,461
1976	357,714	398,359	318,154	234,970	190,036	196,083	191,537	207,859
1977	212,016	257,016	172,334	247,093	137,396	140,331	140,511	147,437
1978	148,997	184,705	121,599	217,183	121,650	133,186	121,022	137,220
1979	87,410	108,495	74,134	198,647	112,650	127,456	109,765	130,962
1980	98,538	108,620	92,976	165,511	125,515	142,470	120,756	147,138
1981	128,739	136,311	120,815	153,703	141,715	154,661	138,156	161,563
1982	125,314	141,485	107,784	160,820	138,708	145,457	138,754	153,170
1983	104,821	128,413	84,665	163,040	129,627	134,786	131,584	141,949
1984	88,881	108,904	74,581	161,325	121,319	127,897	123,122	134,198
1985	72,844	87,970	60,986	155,529	112,489	120,622	113,295	126,123
1986	132,499	150,885	116,169	130,220	147,749	160,487	145,931	167,771
1987	69,433	94,010	47,746	163,075	124,092	126,753	126,623	134,310
1988	114,725	140,680	93,377	142,427	142,710	149,592	143,626	157,549
1989	170,683	204,282	142,168	145,897	178,113	187,397	178,008	197,419

Table A.5.9. Continued.

Year	10%	15%	20%	100%	10%-20%	20%-30%	20%-10%	40%-20%
1990	97,542	129,464	71,174	186,989	135,560	135,647	140,084	144,338
1991	61,519	83,052	43,972	174,775	106,633	112,309	108,782	117,808
1992	20,024	20,336	22,529	161,299	84,139	97,316	81,806	99,945
1993	74,863	78,768	67,040	116,477	101,744	116,984	97,237	120,758
1994	109,294	124,930	89,625	108,437	137,199	150,335	133,099	157,210
1995	134,949	161,654	107,297	127,803	167,417	176,610	165,666	186,283
1996	207,751	243,997	172,730	143,028	230,709	249,912	225,635	261,848

Table A.5.10: Estimates for predicted black market catch CPUE for incremental increases (10-20 and 20-30) and different catch and effort increases, 1949-1996 (Figures 25 and 27).

Year	10%-20%	20%-30%	20%-10%	40%-20%
1949	41.6982	41.0959	41.0554	41.5265
1950	14.7385	15.6341	14.8741	13.8207
1951	24.3050	25.2486	25.5539	28.0112
1952	58.7851	56.4542	57.8456	61.3072
1953	69.2618	68.5166	68.9034	70.4525
1954	52.2347	52.8080	52.4592	52.5906
1955	42.3976	42.7617	42.8200	43.6175
1956	36.5200	36.4309	36.5415	36.9110
1957	43.2309	43.2005	43.2372	43.4240
1958	29.0720	29.1230	29.1080	29.1801
1959	19.7088	19.7342	19.7419	19.8155
1960	24.0246	21.3572	24.0333	21.4161
1961	81.3643	71.7401	81.3858	71.8609
1962	58.6957	50.9593	58.7180	51.0230
1963	27.7824	24.4156	27.7943	24.4465
1964	28.9614	25.6551	28.9655	25.6744
1965	22.2556	19.8367	22.2567	19.8419
1966	47.7637	41.9117	47.7670	41.9236
1967	130.6601	113.5963	130.6716	113.6345
1968	71.4319	61.1056	71.4359	61.1209
1969	28.1522	24.5938	28.1526	24.5959
1970	27.3024	24.5993	30.8882	27.4822
1971	22.8629	20.6558	25.7110	22.9318
1972	60.2262	53.4812	68.2602	59.9687
1973	99.7876	87.3379	114.4132	99.0740
1974	90.6570	78.8531	105.2398	90.4356
1975	60.1592	52.4108	70.0118	60.1333
1976	40.5151	35.8589	46.3829	40.5063
1977	24.0927	21.7543	26.9490	24.0950
1978	26.9710	24.2586	30.2227	26.9718
1979	20.1746	18.0965	22.7161	20.1738
1980	24.1002	21.5014	27.3212	24.0996
1981	25.2112	22.4385	28.6854	25.2115

Table A.5.10: Continued.

Year	10%-20%	20%-30%	20%-10%	40%-20%
1982	20.2945	18.1525	22.9739	20.2946
1983	17.5479	15.7409	19.7980	17.5478
1984	15.5632	13.9909	17.5154	15.5631
1985	13.3629	12.0483	14.9924	13.3629
1986	30.4417	26.9667	34.7839	30.4417
1987	12.9479	11.6705	14.5647	12.9479
1988	24.7797	22.0685	28.1681	24.7796
1989	41.5808	36.6232	47.8160	41.5808
1990	14.9230	13.3863	16.8750	14.9230
1991	12.5144	11.3307	13.9782	12.5144
1992	8.5049	7.7404	9.4251	8.5049
1993	13.1551	11.8397	14.7792	13.1551
1994	23.7075	21.0243	27.0992	23.7075
1995	33.3162	29.3966	38.2961	33.3162
1996	136.0973	120.0813	156.1234	136.0973

Table A.5.11: Catch estimates at age in kilograms of fish for the three age-structured methods for the time period 1949-1957 (total in figure 17).

Year	2	3	4	5	6	7	8	9	10	Total
				ADAPT						
1949	1,526	11,818	14,767	90,649	90,652	5,528	28,361	31,132	5,844	280,278
1950	25	4,007	37,898	21,046	36,884	36,063	6,440	8,556	16,073	166,993
1951	3	1,031	37,475	158,849	18,684	12,914	15,000	3,846	8,539	256,342
1952	96	1,889	9,913	134,063	133,778	8,992	8,537	10,775	3,183	311,225
1953	0	1,152	7,520	29,985	142,945	82,057	4,131	6,725	552	275,068
1954	92	1,575	5,860	42,801	68,806	149,335	64,755	5,494	5,187	343,906
1955	639	3,177	7,983	29,798	70,994	62,402	111,255	30,280	7,709	324,238
1956	230	996	12,720	37,443	64,806	72,828	40,675	41,874	15,126	286,696
1957	337	8,566	20,984	73,440	66,328	55,578	42,706	15,525	24,001	307,466
				VPA						
1949	1,530	11,822	14,745	90,705	90,536	5,549	28,364	30,992	5,804	280,047
1950	28	3,985	37,914	21,059	36,812	36,028	6,510	8,521	16,449	167,305
1951	0	1,041	37,507	158,891	18,651	12,963	14,946	3,862	8,622	256,484
1952	105	1,875	9,906	134,091	133,692	8,953	8,592	10,730	3,044	310,989
1953	0	1,142	7,530	30,015	142,983	82,144	4,166	6,737	619	275,337
1954	90	1,567	5,857	42,803	68,861	149,254	64,699	5,537	5,086	343,755
1955	624	3,190	7,978	29,820	71,045	62,298	111,218	30,173	7,794	324,141
1956	188	1,009	14,729	37,436	64,772	72,913	40,692	41,824	14,939	288,501
1957	327	8,587	20,980	73,482	66,346	55,559	42,710	15,552	23,861	307,403
				Spreadsheet						
1949	618	4,381	23,045	46,935	45,958	38,458	31,564	25,849	116,756	322,051
1950	300	2,544	13,411	26,485	23,788	19,291	15,765	12,904	58,282	178,570
1951	607	3,890	24,346	47,685	42,091	31,509	24,975	20,357	91,896	282,081
1952	576	4,854	22,791	52,041	44,397	32,378	23,662	18,705	84,045	332,468
1953	557	3,841	23,747	40,659	40,200	28,270	20,120	14,664	63,656	273,885
1954	793	5,192	26,048	57,915	42,859	34,948	23,987	17,026	66,253	324,059
1955	609	5,801	27,555	49,150	46,352	28,104	22,347	15,295	53,083	314,289
1956	586	4,119	28,522	48,233	36,426	28,121	16,625	13,182	40,320	300,410
1957	791	4,760	24,173	59,130	42,341	26,196	19,721	11,626	37,401	314,168

Table A.5.12: Catch estimates at age in kilograms of fish for the three age-structured methods for the time period 1959-1969 (total in figure 19).

Year	2	3	4	5	6	7	8	9	10	Total
				ADAPT						
1959	28,932	56,876	81,576	36,628	19,606	7,997	5,047	2,175	4,162	242,999
1960	25,909	60,155	115,404	59,884	25,875	6,077	2,350	413	2,937	299,004
1961	2,607	15,677	93,819	95,848	71,413	19,480	6,104	1,726	113	306,787
1962	10,659	11,460	76,522	96,196	101,822	45,316	23,472	9,059	598	375,104
1963	11,328	14,071	38,844	49,314	46,182	26,636	20,004	9,729	3,827	219,934
1964	30,469	42,979	89,256	63,735	51,143	17,105	12,028	5,026	6,750	318,492
1965	18,956	68,642	113,116	42,351	29,060	17,294	8,600	3,762	3,772	305,554
1966	20,064	111,771	212,488	82,695	23,483	7,746	3,784	751	1,191	463,973
1967	8,168	23,126	107,821	125,575	112,558	25,587	9,816	5,584	50	418,286
1968	674	4,708	44,217	175,805	220,664	28,848	73	154	180	475,323
1969	22,461	58,776	96,720	65,144	79,653	70,525	50,300	1,835	336	445,749
				VPA						
1959	28,713	56,323	81,155	35,616	19,314	7,916	5,236	2,231	4,093	240,595
1960	24,251	59,690	114,212	59,558	25,000	5,924	2,237	372	2,972	294,216
1961	2,590	14,561	93,080	94,749	70,926	18,754	5,918	1,827	0	302,405
1962	10,644	11,387	70,796	95,150	100,149	45,051	22,398	8,676	728	364,978
1963	9,342	14,055	38,579	44,264	45,259	25,734	19,992	9,118	3,830	210,174
1964	23,154	35,247	89,182	63,191	44,014	16,441	11,223	4,998	6,505	293,954
1965	14,166	51,343	90,253	42,523	28,629	13,196	7,880	3,286	3,357	254,632
1966	21,117	82,787	153,968	58,942	23,577	7,520	2,530	559	1,116	352,116
1967	8,976	24,403	75,305	76,930	66,595	26,135	9,255	3,891	0	291,490
1968	466	5,195	46,874	114,023	114,023	6,037	74	74	188	286,954
1969	16,702	40,636	106,958	70,013	41,391	13,411	5,790	1,726	0	296,627
				Spreadsheet						
1959	10,088	31,471	57,748	69,351	65,808	59,381	60,904	58,917	390,631	804,299
1960	13,137	34,782	58,400	58,306	49,336	38,292	35,499	41,999	378,644	708,395
1961	9,765	39,487	56,409	48,795	36,929	29,358	24,510	22,826	169,550	437,630
1962	14,174	40,842	80,517	62,370	41,904	30,250	24,416	19,858	126,398	440,731
1963	13,250	28,308	36,799	36,620	21,574	13,939	10,006	7,643	43,808	211,948
1964	25,226	54,782	65,131	42,373	31,711	17,281	11,397	8,007	42,866	298,774
1965	17,672	64,096	61,773	38,937	18,854	13,068	7,587	4,628	19,510	246,125
1966	14,673	68,936	125,965	68,504	29,850	11,690	8,214	5,960	19,476	353,267
1967	13,243	31,442	78,056	80,417	33,450	14,504	6,138	4,008	9,460	270,718
1968	8,569	39,558	57,559	80,899	64,283	22,174	16,044	4,515	17,724	311,325
1969	15,583	36,687	73,501	56,276	56,781	40,199	25,240	6,823	10,073	321,163

Table A.5.13: Catch estimates at age in kilograms of fish for the three age-structured methods for the time period 1949-1969 (continued on next page, total in figure 21).

Year	2	3	4	5	6	7	8	9	10	Total
					ADAPT					
1949	1,163	9,138	16,720	102,504	113,671	7,623	34,852	36,305	5,202	327,178
1950	16	2,449	34,583	20,942	44,545	54,016	6,379	8,043	11,533	182,504
1951	2	620	37,380	166,370	23,415	17,315	19,151	4,687	6,664	275,606
1952	54	1,188	9,172	132,770	134,964	8,716	9,384	8,918	2,589	307,755
1953	0	1,105	7,483	29,046	139,093	83,042	5,966	7,626	432	273,794
1954	56	1,064	5,332	41,348	62,450	137,101	51,659	5,193	4,707	308,912
1955	442	2,183	7,252	25,529	62,194	55,885	87,772	23,846	4,580	269,683
1956	151	692	10,386	30,733	62,142	71,527	36,077	39,379	9,608	260,695
1957	272	6,009	20,390	68,086	68,546	60,315	40,141	15,704	18,269	297,732
1958	13,559	91,676	43,197	90,688	64,891	30,773	125,041	1,621	7,712	469,158
1959	28,710	56,351	81,163	35,632	19,259	7,932	5,022	2,143	4,101	240,314
1960	24,245	59,684	114,269	59,570	25,030	5,940	2,325	410	2,888	294,360
1961	2,589	14,568	93,024	94,694	71,039	18,709	5,947	1,704	111	302,384
1962	10,648	11,380	70,826	95,223	100,209	45,049	22,351	8,789	588	365,063
1963	9,344	14,058	38,575	44,267	45,413	25,682	19,844	9,097	3,711	209,990
1964	23,163	35,225	89,240	63,279	44,050	16,521	11,271	4,961	6,347	294,056
1965	14,167	51,353	90,290	42,471	28,762	13,182	7,925	3,362	3,555	255,066
1966	21,103	82,790	153,921	58,912	23,655	7,608	2,589	531	1,102	352,211
1967	8,981	24,421	75,260	76,969	66,392	26,004	9,536	3,648	46	291,257
1968	466	5,194	46,918	114,027	114,039	6,121	78	111	141	287,095
1969	16,709	40,608	106,988	69,936	41,591	13,593	5,842	1,961	264	297,491
					VPA					
1949	1,174	9,232	16,676	102,555	113,637	7,624	34,904	36,303	5,197	327,302
1950	29	2,510	34,654	20,919	44,511	54,131	6,400	7,982	11,444	182,582
1951	0	626	37,281	166,261	23,393	17,385	19,134	4,703	6,682	275,467
1952	53	1,199	9,159	132,716	134,955	8,686	9,378	8,905	2,587	307,638
1953	0	1,119	7,492	29,054	139,147	83,181	5,951	7,612	431	273,986
1954	57	1,062	5,317	41,363	62,445	137,152	51,592	5,204	4,710	308,902
1955	441	2,181	7,251	25,519	62,239	55,854	87,806	23,860	4,586	269,736
1956	150	691	10,392	30,745	62,143	71,613	36,045	39,437	9,614	260,831
1957	264	6,015	20,384	68,072	68,570	60,366	40,231	15,681	18,248	297,831
1958	13,574	91,708	43,162	90,593	65,034	30,847	125,041	1,633	7,735	469,326
1959	28,705	56,374	81,150	35,591	19,313	8,000	5,145	2,187	4,085	240,549
1960	24,251	59,676	114,296	59,575	25,045	5,998	2,242	355	2,833	294,271
1961	2,590	14,560	93,068	94,745	71,060	18,733	5,981	1,806	0	302,543
1962	10,645	11,387	70,795	95,189	100,206	44,982	22,208	8,712	776	364,899
1963	9,358	14,055	38,578	44,263	45,351	25,839	19,999	9,243	3,415	210,102
1964	23,147	35,216	89,229	63,203	44,011	16,588	11,389	5,063	6,177	294,023
1965	14,159	51,380	90,262	42,554	28,641	13,193	8,153	3,448	3,633	255,424
1966	21,112	82,786	153,930	58,929	23,609	7,527	2,529	495	988	351,905
1967	8,986	24,402	75,288	77,007	66,489	26,202	9,270	3,889	0	291,533
1968	470	5,189	46,883	114,111	114,114	6,174	75	75	191	287,283
1969	16,722	40,567	106,965	69,944	41,660	13,369	6,028	1,764	0	297,021

Table A.5.13: Catch estimates at age in kilograms of fish for the three age-structured methods for the time period 1949-1969 (continued)

Year	2	3	4	5	6	7	8	9	10	Total
					Spreadsheet					
1949	2,842	11,457	28,136	31,809	32,293	30,412	27,808	23,930	132,619	321,306
1950	1,587	6,836	16,363	17,883	17,896	16,795	15,346	13,204	73,173	179,081
1951	2,513	10,746	27,480	29,413	28,524	26,402	24,044	20,674	114,552	284,347
1952	3,523	12,598	31,598	35,769	33,842	30,329	27,237	23,340	129,222	327,458
1953	3,334	12,750	26,665	29,468	29,427	25,717	22,358	18,894	104,180	272,794
1954	3,946	17,236	38,368	35,337	34,458	31,786	26,949	22,046	119,479	329,606
1955	3,459	16,793	42,325	41,142	33,323	29,993	26,836	21,409	110,746	326,026
1956	3,076	13,905	38,808	42,570	36,344	27,163	23,712	19,964	96,969	302,511
1957	6,475	13,786	35,611	43,121	41,505	32,690	23,696	19,464	94,854	311,202
1958	8,499	29,197	35,130	39,049	41,366	36,707	28,036	19,121	91,152	328,257
1959	6,466	25,667	49,950	25,762	24,995	24,397	20,991	15,085	58,669	251,982
1960	6,265	29,352	66,213	55,680	25,162	22,515	21,312	17,254	60,351	304,104
1961	5,816	24,133	63,843	61,793	45,396	18,906	16,404	14,610	53,166	304,068
1962	8,042	28,175	65,278	73,750	62,288	42,162	17,026	13,899	57,306	367,924
1963	5,326	18,317	36,157	35,600	34,972	27,189	17,841	6,778	28,165	210,346
1964	9,709	28,602	55,909	47,802	41,287	37,417	28,213	17,420	33,887	300,246
1965	7,068	30,812	51,343	42,995	32,084	25,532	22,435	15,917	29,659	257,845
1966	7,724	36,046	88,491	63,407	46,453	31,959	24,663	20,391	42,532	361,665
1967	6,393	23,374	61,281	64,050	39,957	26,956	17,979	13,054	34,016	287,062
1968	6,031	24,876	51,569	58,199	53,207	30,599	20,018	12,562	33,259	290,320
1969	6,540	24,298	56,688	50,518	49,848	42,007	23,426	14,419	33,356	301,100

Appendix 6: Retrospective Analysis for the Spreadsheet Model, 1949-1969

Introduction and Methods

The retrospective analyses are an extremely important diagnostic as they can indicate systematic data issues through the amount of pattern. Ideally, these analyses would have been conducted for all the catch-at-age models. However, the models for both the ADAPT and separable VPA had been updated to the point that it was not possible to conduct a retrospective analysis for those models.

Given the importance of a retrospective analysis for evaluating model error, an analysis was conducted on the spreadsheet model. The analysis includes the years 1949-1969, to determine how the longest available time series functions in the analysis. The retrospective period covered the terminal years 1965-1969. All other methods are the same as those previously outlined for the spreadsheet model.

Results and Discussion

The retrospective analysis for the predicted catch had little difference between the terminal year estimates (Figure A.6.1). The estimates were all close in successive terminal years with no pattern observed over time. The retrospective analysis for the estimated total abundance was quite different than the analysis for the predicted catch. The time series did not converge for any of the terminal years examined (Figure A.6.2). There was also no pattern that could be determined for a consistent retrospective bias. The last five years of the 1969 series was higher than the 1966 series, but was lower than the 1968 series.

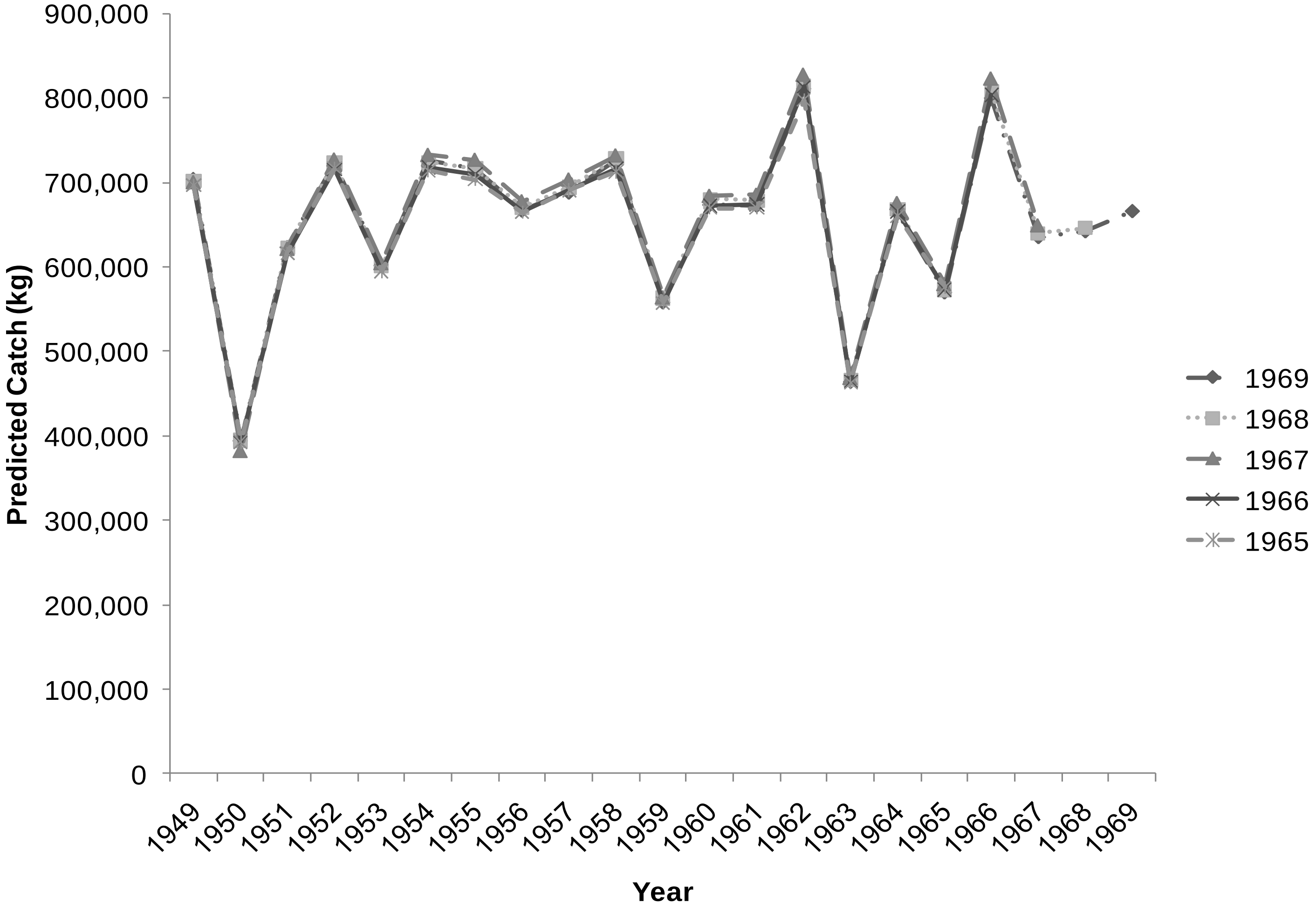


Figure A.6.1. Retrospective analysis for the spreadsheet model predicted catch for the time series 1949-1969. Catch is measured in kg.

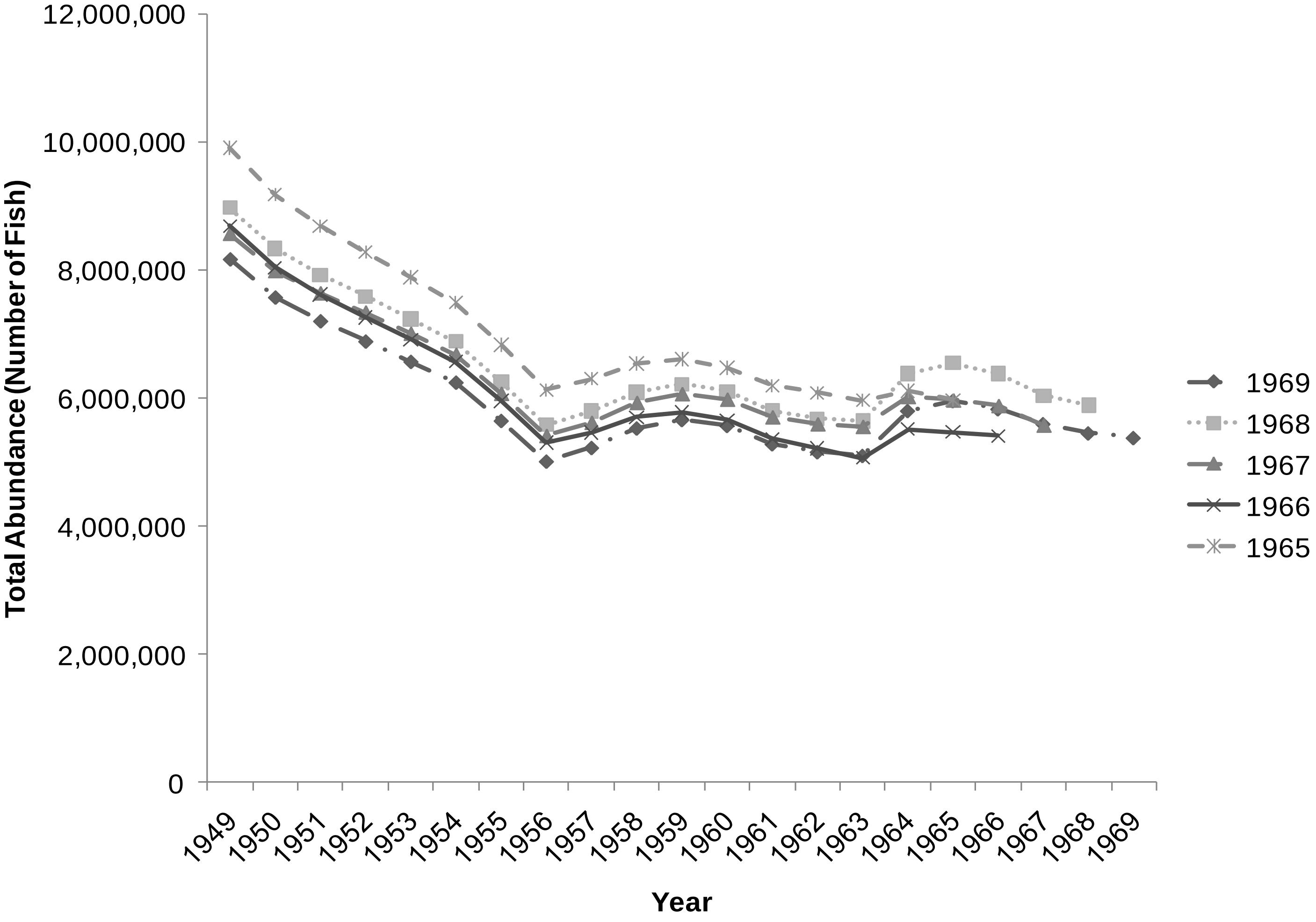


Figure A.6.2. Retrospective analysis for the spreadsheet model estimated total abundance for the time series 1949-1969. Abundance is measured in numbers of fish.

The lack of convergence of the total abundance in the retrospective analysis should be investigated further. Future stock assessments may be able to find a data configuration that does converge in a retrospective analysis with minimal bias or pattern.