Exxon Valdez Oil Spill
Restoration Project Final Report

Trends in Adult and Juvenile Herring Distribution and Abundance in Prince William Sound

Restoration Project 070830
Final Report

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Study History: A collapse of the Prince William Sound (PWS) herring population was detected after the 1989 *Exxon Valdez* Oil Spill (EVOS). The population appeared to recover in the mid-1990s, but collapsed again after a renewed commercial fishery and has been at a low level for over a decade. Although reasons for the decline are not fully understood, it is likely that the spill was a factor. The EVOS Trustee Council has classified the Pacific herring population in PWS as a resource that has not recovered from the effects of the spill and is funding research to facilitate its restoration.

This project, "trends in adult and juvenile herring distribution and abundance in Prince William Sound", was designed to obtain information on several critical barometers of the PWS herring population, including annual estimates of the adult population size and the juvenile abundance going into and coming out of the long Alaskan winter period (October to March). Such information is needed as a basis for any effort to restore the Prince William Sound herring population, detect its natural recovery, or protect it from future damage. The project was conducted over a three-year period. The initial cruise took place in fall 2006, the last in spring 2009.

Abstract: We conducted a three-year investigation of both adult and juvenile herring abundance and habitat utilization in Prince William Sound, Alaska, beginning in fall 2006. The goals of the project were to continue a long-term database on the adult abundance and to better understand the factors that govern juvenile herring survival, particularly during their initial year. The three years of adult monitoring were the fifteenth, sixteenth and seventeenth consecutive annual surveys using hydroacoustic assessment techniques. The spring 2009 adult herring survey produced an estimate of 20,400 metric tons, with 95% confidence limits of 17,600 to 23,100 metric tons. Earlier research during the Sound Ecosystem Assessment (SEA) program had generally described juvenile herring distribution and had suggested that mortality over the first winter was critical. The relatively large size of PWS necessitated the application of hydroacoustic surveys, so our initial objective was to determine the distributional characteristics of age 0 herring that could be used to identify the presence of these fish. Our study design focused on pre- and post-winter sampling to investigate over-winter mortality and complemented other studies that looked at energetic characteristics of the young herring. We compared several areas, including four bays that were a focus of the SEA program research: Whale Bay, Eaglek Bay, Simpson Bay and Zaikof Bay. We found that age 0 herring were typically located near the heads of bays in relatively shallow water and could often be identified from their hydroacoustic characteristics. Greater abundances of age 0 herring were found in Whale Bay, Simpson Bay and Eaglek Bay. Whale Bay showed the smallest decrease in numbers over the winter, Simpson Bay the greatest. Whale Bay also had the smallest abundance of other fishes, which might be a key to the apparently higher over-winter survival of age 0 herring at this location.

Key Words: hydroacoustic surveys, Pacific herring, Prince William Sound, restoration, juveniles, marine survival, abundance, distribution, fish habitat.

Project Data: Data collected as part of this project include hydroacoustic surveys and direct capture information. The data include raw acoustic data in .dt4 format and Excel workbooks. Custodian of the data is Richard Thorne, Prince William Sound Science Center, P.O. Box 705, Cordova, AK 99574, 907 424-5800, rthorne@pwssc.org.

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Executive Summary

A collapse of the Prince William Sound (PWS) herring population was detected after the 1989 *Exxon Valdez* Oil Spill (EVOS). The population appeared to recover in the mid-1990s, but collapsed again after a renewed commercial fishery and has been at a low level for more than a decade. Although reasons for the decline are not fully understood, it is likely that the spill was a factor. The EVOS Trustee Council (EVOS TC) has classified the Pacific herring population in PWS as a resource that has not recovered from the effects of the spill and is funding research to facilitate its restoration.

This project, "trends in adult and juvenile herring distribution and abundance in Prince William Sound", was designed to obtain information on several critical barometers of the PWS herring population, including annual estimates of the adult population size and the juvenile abundance going into and coming out of the long Alaskan winter period (October to March). Such information is needed as a basis for any effort to restore the Prince William Sound herring population, detect its natural recovery, or protect it from future damage. The project was conducted over a three-year period. The primary assessment tool was hydroacoustic surveys, supplemented with direct capture. The initial cruise took place in fall 2006, the last in spring 2009.

The first hydroacoustic survey of adult herring in PWS took place in 1993 and verified a population collapse. The surveys in this project were the fifteenth, sixteenth and seventeenth consecutive annual surveys using hydroacoustic assessment techniques. Spatial coverage during the spring 2007 survey was the most extensive in many years. The largest concentration of adult herring was in Port Gravina, from Red Head into Olson Bay. The second largest abundance was in Port Fidalgo. The estimate of total abundance was 20,400 mt, with 95% confidence intervals of ±5,800 mt, or a range from 14,600 mt to 26,200 mt.

An anomalous distribution of adult herring was encountered in spring 2008. It appears that the spawning migration of herring in Prince William Sound during 2008 was delayed by one to two weeks compared to normal years. As a result the estimated adult herring biomass, 10,170 metric tons, with 95% confidence limits of 7,730 to 12,600 metric tons, is most likely an underestimate of the actual total adult herring biomass.

The timing was similarly delayed in 2009, but surveys between March 31 and April 1 appeared to incorporate most of the herring. The estimated adult herring biomass based on these surveys was 20,400 metric tons, with 95% confidence limits of 17,600 to 23,100 metric tons.

The juvenile herring surveys began in fall 2006. We concentrated on areas where juvenile herring had been noted in historical surveys. A total of 10 areas were surveyed. Seven of the areas were surveyed at least 5 times. Highest abundance of age 0 herring was found in Simpson Bay, Whale Bay and Eaglek Bay.

Analysis of the juvenile survey data was in two stages. The results of the stage 1 analysis provided a detailed look at the distribution of fish biomass in the survey areas. Stage 2 was an attempt to break down the biomass by species/size groups. The results of the stage 2 analysis were biomass estimates of age 0 herring, adult herring, other juvenile herring and other fishes by time and location.

The stage 1 analysis over the 3-year period produced forty-three workbooks of hydroacoustic observations, each containing the detailed horizontal and vertical distribution of fish along with GPS locations. The stage 2 analysis produced an additional six workbooks, one for each cruise. Each workbook contains the biomass estimates by species/age group for every sampled location.

Whale Bay showed the smallest decrease in numbers over the winter, Simpson Bay the greatest. Whale Bay also had the smallest abundance of other fishes, which might be a key to the apparently higher over-winter survival of age 0 herring at this location.

General Introduction

A collapse of the Prince William Sound (PWS) Pacific herring (*Clupea pallasii*) population was detected after the 1989 *Exxon Valdez* Oil Spill (EVOS). The population appeared to recover in the mid-1990s, but collapsed again after a renewed commercial fishery and has been at a low level for more than a decade. Although reasons for the decline are not fully understood, it is likely that the spill was a factor. The EVOS Trustee Council (EVOS TC) has classified the Pacific herring population in PWS as a resource that has not recovered from the effects of the spill and is funding research to facilitate its restoration.

This project, "trends in adult and juvenile herring distribution and abundance in Prince William Sound", was designed to obtain information on several critical barometers of the PWS herring population, including annual estimates of the adult population size and the juvenile abundance going into and coming out of the long winter period (October to March). Such information is needed as a basis for any effort to restore the herring population, detect its natural recovery, or protect it from future damage. The project was conducted over a three-year period. The initial cruise took place in fall 2006, the last in spring 2009.

For convenience, this report is divided into two sections. The first details results of research on the adult herring, the second on juvenile herring.

Section 1- Trends in Adult Herring Abundance and Distribution

Introduction

Historical information on the abundance of adult Pacific herring in PWS includes (1) aerial survey estimates of the length of spawn (milt) patches along beaches, (2) estimates from egg deposition surveys, (3) age-structured analysis (ASA) model estimates and (4) hydroacoustic surveys (Becker and Biggs 1992; Biggs et al. 1992; Quinn and Deriso 1999; Hulson et al. 2008; Thorne and Thomas 2008). The Alaska Department of Fish and Game (ADF&G) has conducted the annual aerial surveys of spawn since 1973, so it is the longest and most consistent index of herring abundance. SCUBA surveys of the number of herring eggs were conducted in 1983, 1984, 1988-1992 and 1994-1997. The total egg deposition was used to calculate the herring abundance **(**Schweigert and Stocker 1988; Becker and Biggs 1992**)**. Age data from herring in PWS have been collected by ADF&G for several decades. The ASA model has been run to forecast the PWS adult herring biomass most years since 1993, and has included several versions (Quinn et al. 2001; Hulson et al. 2008). Standard practice for all model runs is to reconstruct the population history of the herring since 1980.

During spring 1993, commercial fishers in Prince William Sound could not locate fishable concentrations of herring despite a preseason forecast of substantial herring abundance from the ASA model. Concerned over the status of the stock, the Cordova District Fisherman United organization contracted with the Prince William Sound Science Center (PWSSC) to conduct an independent herring survey in fall 1993 using hydroacoustic assessment techniques. This effort began a program that has conducted surveys of the herring population in Prince William Sound at least annually since that date. Recently the surveys have been a combined cooperative effort between PWSSC and ADF&G. The PWSSC effort has had various sponsors over the years including ADF&G and the Oil Spill Recovery Institute. The National Marine Fisheries Service (NMFS) funded surveys from 2005 to 2008 as part of a study of the role of herring as a winter food supply for Steller sea lions. As part of the project reported herein, EVOS TC funded the 2009 survey and co-sponsored the 2007 and 2008 surveys with NMFS.

Methods

Pacific herring stocks from Alaska to California have been assessed using hydroacoustic techniques since the early 1970s (Thorne, 1977a, b; Thorne et al., 1983; Trumble et al., 1983). The surveys are based on echo integration (Thorne, 1971, 1983a, b; MacLennan and Simmonds, 1992; Simmonds and MacLennan 2005). The hydroacoustic survey methodology for PWS is detailed in several papers, including Thomas and Thorne (2003) and Thorne and Thomas (2008). The survey design is multi-stage: (1) locations of herring school concentrations are detected by reconnaissance surveys, (2) intense small-scale surveys are conducted over the limited area encompassing the concentrations, and (3) net sampling is conducted on the concentrations for biological information, including species and size composition (McClatchie et al. 2000). The initial survey stage, a PWS-wide reconnaissance effort guided by historical observations, is conducted to identify the overall distribution of the adult herring schools within Prince William Sound. The effort includes aerial surveys, sonar/echosounder surveys and observations from sentinel vessels including fishing vessels. Once an area of herring abundance is located, a sonar survey delineates the boundaries of the concentration. Then a series of closely-spaced zig-zag transects are run with the hydroacoustic assessment system. Typically, the series is replicated several times to determine variance and confidence intervals around estimates (Cochran 1977; Scheafer et al. 1986). Sonar monitoring continues at this stage to ensure that the survey covers the extent of the herring concentration and to detect any school avoidance (Olsen et al. 1983; Soria et al. 1996). Lastly, net sampling using purse seines and cast nets is directed toward the surveyed concentrations to obtain biological information. Most surveys are conducted at night when herring are distributed in the pelagic zone. However, there are some occasions where the herring are also pelagic and amenable to hydroacoustic survey during day.

The 2007 adult herring survey consisted of three cruises. Cruise 1 extended from March 8 to 14 aboard the FV *Kyle David*. Cruise 2 extended from March 18 to 26 and included both the *Kyle David* and the MV *Auklet*. Cruise 3 extended from March 29 to April 2 aboard the *Kyle David*. Both vessels deployed BioSonics Digital Scientific Echosounders. Areas covered included Sawmill Bay, Whale Bay, Port Fidalgo, Port Gravina, Zaikof Bay, Simpson Bay, Eaglet Bay, Wells Bay and Cedar Bay.

The herring survey effort during spring 2008 consisted of two cruises. The first cruise, from March 16-25, had a juvenile herring emphasis, but encountered and surveyed some concentrations of adult herring. The second cruise, from March 27-30, focused on adult herring. Areas covered included Port Fidalgo, Port Gravina and Sawmill Bay.

The herring survey effort during spring 2009 also consisted of two cruises. The first cruise, from March 17-24, had a juvenile herring emphasis, but encountered and surveyed some concentrations of adult herring. The second cruise, from March 30 to April 2, focused on adult herring in Port Fidalgo and Port Gravina (Fig. 1-2).

The hydroacoustic data are scaled by target information based on direct capture samples. These data are provided by Alaska Department of Fish and Game, Cordova. The primary sampling tool is a commercial purse seine. Additional samples are obtained with cast nets. The size composition of the herring in the net catches is used to estimate target strengths for converting backscatter to biomass (Foote 1987).

The general equation used in PWS is:

$TS_w = -5.98 \text{Log}(L) - 24.23$
Where w is weight in kg and L is length in cm.

This equation applies to the typical night-time depths of herring during the late winter/early spring period (Thomas et al. 2002). Alterations are made for different depths and seasons. All hydroacoustic systems are calibrated with standard targets using procedures detailed in Foote et al. (1987).

Results

Spring 2007: Survey coverage during spring 2007 was the most extensive in many years. The largest concentration of adult herring was in Port Gravina, from Red Head into Olson Bay (Table 1). The second largest abundance was in Port Fidalgo. Smaller abundances of probable adult herring were located in Zaikof Bay and Cedar Bay. Other locations contained primarily juveniles.

Five night series and one day series were run in Port Gravina between March 19 and April 1. There was a progressive movement of adult herring into the area. The last two series, March 31 and April 1, had the highest biomass estimates. A different pattern was seen in Port Fidalgo, where numbers decreased nearly fivefold from March 20 to March 30. It is likely that the pattern is a result of movement from Port Fidalgo into Port Gravina (Fig. 3). For purposes of total stock estimation, values for these two locations were only used for the March 29-April 1 period. Numbers in Zaikof Bay and Cedar Bay were minor and considered non-overlapping with the Port Gravina and Port Fidalgo surveys. The best estimate of total abundance was 20,400 mt, with 95% confidence intervals of ±5,800 mt, or a range from 14,600 mt to 26,200 mt (Table 1).

Survey conditions during spring 2007 were very dynamic both in terms of weather and fish distributions. Conditions during leg 1 (March 8-14) were cold and windy (Fig. 4). In contrast, conditions from March 29-April 1 were calm and clear (Fig. 5). While part of the early March effort focused on juvenile populations, it was clear that the adult schools had not entered spawning areas. The fish distribution over the time period was also clearly influenced by marine mammal predation, especially whales. Sizeable herring schools were first detected within Two Moon Bay, Port Fidalgo, on March 12. During the second visit to this area on March 20, the herring were located during the daytime offshore near the center of Port Fidalgo. They were found at depths as great as 130 m (Fig. 6), and several humpback whales were foraging in the area. The subsequent night survey could not locate these fish (weather conditions were marginal for surveys). Surveys at the end of March found only about 20% of the earlier biomass in this area. At the same time, the abundance in Port Gravina increased substantially (Fig. 3). However, these fish also showed atypical distributions: very near the bottom even during night (Fig. 7). It was only immediately adjacent to the spawning beaches that the herring came into midwater (Fig. 8). Whale predation was intense, with at least 15 humpback whales foraging on the herring concentration. There were also about 300 Steller sea lions (Thomas and Thorne 2001; Fig. 9).

While most of the fish were found in Port Fidalgo and Port Gravina, there were smaller abundances in Zaikof Bay and Cedar Bay. The fish in Cedar Bay were not sampled, but the echogram characteristics were those of adults, as were those in Zaikof Bay (Fig. 10-11). Herring in Zaikof Bay were sampled with mixed results. A cast net in close proximity of the survey caught primarily 3-year old fish. The fish in Cedar Bay were adjacent to the ice front (Fig. 12). It is possible that the herring were using the ice to avoid predation by seabirds and marine mammals.

Spring 2008: The results of the 2008 spring survey are summarized in Table 2. Some adult concentrations were encountered and surveyed during the first cruise including a sizeable concentration of fish in Simpson Bay. The ADF&G RV *Solstice* sampled these fish the next night and caught mixed juvenile herring, ages 1, 2 and 3. The estimated biomass was 1,300 metric tons. However, this survey is not included in the total estimate because of the mixed assemblage. A replicated survey was conducted in Port Gravina on March 17. Adult herring were measured within St. Mathews Bay (Fig. 13; Table 2). A replicated survey was also conducted on a herring concentration in Sawmill Bay that was most likely adult, although not sampled (Fig. 14; Table 2).

The second cruise focused on Port Gravina and Port Fidalgo, the areas where most adult herring have been observed for the past several spring periods. The herring concentration in Port Gravina was still primarily limited to St Mathews Bay. An additional replicated survey was conducted on March 27 (Table 2). Very few fish were observed in the normal spawning areas from Red Head to Olsen Bay. The herring concentration in St Mathews Bay was subject to predation by about 20 Steller sea lions and 3 whales (Fig. 15). The whales foraged all the way to the head of St Mathews Bay (Fig. 16**)**. Two major aggregations of herring were located in Port Fidalgo. One was off Irish Cove, the other outside of Two Moon Bay. Several replicated surveys were conducted on these concentations (Table 2). Both aggregations were large, 1-2 km^2 in area (Fig. 17). The aggregations were the subject of intense predation by 20-50 Steller sea lions and 5-10 whales. The total estimated adult herring biomass was 10,170 metric tons, with 95% confidence limits of 7,730 to 12,600 metric tons (Table 2).

Spring 2009: The results of the 2009 spring survey are summarized in Table 3**.** Several adult concentrations were encountered and surveyed during the first cruise. However, only a relatively small concentration of fish in Eaglek Bay was not resurveyed in greater detail during the later adult series. The fish in Eaglek Bay were not sampled, but the characteristics (massive schools) were clearly those of adult herring (Fig. 18-19). As has been the case in recent years, the adult herring in the Port Fidalgo and Port Gravina areas were dynamic, with a continuous migration out of Port Fidalgo and into Port Gravina (Thorne 2008). Consequently, we used only the March 31 and April 1 surveys for our estimate of total fish. This snapshot of the herring distribution caught the tail end of the migration, with most of the fish in Port Fidalgo located in the western portion (Fig. 20-21) and the fish in Port Gravina primarily inshore near Hells Hole. Slightly less than 1,000 mt of fish were also observed in the upper main basin of Port Gravina. The total estimated adult herring biomass was 20,400 metric tons, with 95% confidence limits of 17,600 to 23,100 metric tons.

Discussion

Spring 2007: Surveys of herring are difficult because of both weather and the dynamic nature of herring movements. Successful surveys result from a combination of luck and persistence. Persistence was the key in 2007 with multiple surveys of Port Fidalgo and Port Gravina. We have had consistent survey coverage of Port Fidalgo and Port Gravina since 2000. The abundance of herring in this region has grown from 1,800 mt in 2000 to a current value of about 20,000 mt. Similarly, the area covered by the hydroacoustic surveys in Port Fidalgo and Port Gravina has increased from less than 1 km^2 in 2000 to over 40 km^2 in 2007 (Fig. 22). While this survey coverage is larger than the actual spatial extent of herring, the sonar-guided survey procedures are such that the survey area is a reasonable indicator of the spatial extent of the herring schools. The area covered by the schools and the biomass of herring in the area were significantly correlated between 2000 and 2007 ($p \geq 0.95$). Rather than getting more crowded as the population increased, the data suggest that herring increase their spatial distribution in direct proportion to the increasing population.

The increasing population in Port Gravina and Port Fidalgo is part of a major change in adult herring distribution that we observed over an extended period. In 1997, the late winter distribution centered around Montague Island in central PWS. Over the next few years the distribution shifted to NE PWS, especially Port Gravina (Fig. 23). The locations are approximately 40 miles apart. The change may have been a response to increasing whale predation, with the herring population moving further away from the Gulf of Alaska. We observed extensive whale predation on the over-wintering herring prior to the change. In contrast, we did not observe any whale predation on the herring in Port Gravina and Port Fidalgo for the next few years after the change.

Spring 2008: Typically, we have seen an offshore distribution of herring in Port Fidalgo in mid March, rather than late March when it was observed in 2008. It appears that the spawning migration of herring in Prince William Sound during 2008 was delayed by one to two weeks compared to normal years. The winter was unusually cold. Time series of estimates typically show increasing biomass as herring move into the prespawning areas of PWS (Fig. 22). In 2008, the substantial delay in migration behavior and a fixed shiptime budget precluded later surveys when the herring would most likely be more amenable to hydroacoustic surveys. Consequently, the 2008 survey is very likely to have produced an underestimate of the actual total adult herring biomass. Survey results by ADF&G, which extended later into April, produced a substantially greater biomass estimate (about 18,000 mt; Steve Moffet, ADF&G, personal communication).

Spring 2009: Based on the length information from ADF&G, we used a sigma of 0.00062, corresponding to a fish length of about 21 cm, to estimate the biomass of the relatively large herring in Port Fidalgo, and a sigma of 0.00071, corresponding to about a 16 cm herring, for other locations. There were likely some adult herring in other areas, but the amounts are believed to be relatively small and within the confidence intervals of the survey. On the other hand, the attribution of the 900 metric tons in north central Port Gravina to adult herring (Table 3) is speculative. This concentration might have been younger herring. The dynamic nature of the prespawning herring movements continues to challenge the survey methodology. Precise estimates are difficult to obtain when the herring movements require a snapshot survey with limited replications. A later survey period may provide a better estimate, as was seen in the 2007 survey.

General: Thomas and Thorne (2003) showed that the cumulative mile-days of milt index from the aerial surveys by ADF&G correlated well with the hydroacoustic estimates from 1993 to 2002 and used the regression relationship to convert the mile-days index to an absolute estimate of herring abundance. They also pointed out that there was a disparity between the ASA estimates based on the original model and the abundance estimates from the mile-days of milt index between 1989 and 1993 (Fig. 24). The mile-days index showed a multiple-year decline that began immediately after the oil spill rather than a one-year collapse in 1993.

Thorne and Thomas (2008) argued that the disparity with the mile-days index from 1989 to 1993 reflected error in the ASA estimates that resulted from an underestimation of mortality, and that the 1989 *Exxon Valdez* oil spill was the source of the increased mortality. Proponents of the ASA model argued for a single-year collapse in 1993 that was caused by a disease outbreak (Hulson et al. 2008). However, the current (2005) ASA model does not show any extraordinary decline between 1992 and 1993 (Fig. 25). In fact, once the fishery is accounted for the annual decline from 1992 to 1993 was actually less than that for 1989-90 and 1990-91, the two years following the spill (Fig. 26). It is clear that the actual decline took place over a multi-year period that began immediately after the spill and was only briefly interrupted by the initial contribution of a relatively large 1988 year class in 1992. There were 65,000 metric tons of fishery harvests during this time period, with the largest harvest, 27,700 metric tons, occurring in 1992. The 1992 harvest was the largest since the early 1940's reduction fishery (Funk and Sandone 1990; Brown 2007).

There were neither hydroacoustic surveys nor disease monitoring until after spring 1993. However, both the mile-days index and the hydroacoustic estimates clearly show that the ASA model substantially overestimated the herring abundance again in 1998 and 1999. The herring population had begun to recover in 1996. By 1997 the hydroacoustics, mile-days and ASA estimates all agreed that the population had built to a level of more than 30,000 mt, and a commercial fishery was reopened. However, both the hydroacoustic and mile-days estimates declined in 1998 (Fig. 25). In the case of the hydroacoustics, the decline was substantial. By 1999, both the hydroacoustics and mile-days estimates showed a substantial decline, but the

ASA forecast remained high. Again, a hindcast using the current ASA model agreed that a decline had occurred by 1999 (Fig 25**)**. The original ASA forecasts did not detect a decline until 2000, two years after the two direct measurement techniques, and even the 2000 decline in the ASA forecast did not match the magnitude of either of the two direct measures or the hindcast of the 2005 ASA. The 9,000 tons of harvest in 1997-1999 was the last fishery to date on this stock.

The estimates from the egg deposition method are puzzling. There was a huge increase in the estimate between 1989 and 1990 (Fig. 24). No other measure of abundance suggested an increase between these two years, and in fact, the mile-days of spawn index was decreasing precipitously.

The hydroacoustic survey provides a fishery-independent, real-time estimate of fishery abundance. The mile-days index provides a post-fishery measure of population size. However, the ASA forecasts are based on the previous year's data. Actual measures of subsequent mortality and recruitment are not included. This was likely a root cause of the first herring population collapse described here, since the oil spill added an undetected mortality on the adult herring in 1989. However, the lag time for the ASA is clearly more than one year, as seen in both instances. Inherent averaging functions in the model structure may add inertia that leads to greater lag. The results provide a caution to the widespread dependence on fishery-dependent models for management (Quinn and Deriso 1999; Quinn 2003**)**, especially those without fishery-independent means to verify model estimates (Gunderson 1993; Anon. 1998).

Section 2- Trends in Juvenile Herring Distribution and Abundance

Introduction

The Sound Ecosystem Assessment (SEA) program, supported by the *Exxon Valdez* Oil Spill Trustee Council from 1994-1999, studied factors that affect juvenile herring survival including habitat characteristics (Stokesbury et al. 2000; Brown and Norcross 2001; Foy and Norcross 2001; Norcross et al. 2001). Age 0 herring were found to be distributed primarily in shallow water near the heads of bays. Temperature and length of winter were documented to be critical factors in determining juvenile herring growth and over-winter survival (Paul and Paul 1998; Paul et al. 1998; Foy and Paul 1999). In particular, over-winter survival of age 0 herring appeared to be a critical factor in determining year class strength.

The objective on this project was to further develop and quantify the distributional characteristics and abundance of juvenile herring, especially age 0. The relatively large size of PWS necessitated the application of hydroacoustic surveys, so our initial objective was to determine the distributional characteristics of age 0 herring that could be used to identify the presence of these fish. Our study design focused on pre- and post-winter sampling to investigate over-winter mortality and complemented other studies that looked at energetic characteristics of the young herring and predation by seabirds on juvenile herring.

Methods

The study began in fall 2006. We concentrated on areas where juvenile herring had been noted in historical surveys (Stokesbury et al. 2000). These included the four bays that had been a focus of research during the SEA program: Simpson, Eaglek, Whale and Zaikof. Surveys were conducted twice yearly, in fall and late winter/early spring (typically mid-March, but referred to for convenience as "spring" surveys). Table 4 summarizes the locations covered during the 3-year period. We used hydroacoustic techniques combined with direct sampling with a variety of capture gears. The hydroacoustic equipment included a 120 kHz BioSonics DT echosounder and a 70 kHz BioSonics DX system (Fig 27**).** A set of standard transects were designed for each area sampled. Criteria were time (2-3 hours to complete) and emphasis on heads of bays where age 0 herring were likely to be located. Fig 28 illustrates an example of the coverage, from Simpson Bay. Transects were run both during day and during night. Night is more amenable to the hydroacoustics because of the more pelagic distribution of herring during this time, but the day runs allow collection of information on bird and mammal distributions within the survey areas.

A variety of methods were used to obtain biological data. Initially, we developed and used a small mid-water trawl (Fig 29). However, this took considerable effort to obtain adequate sample sizes. Consequently we developed and applied a multi-mesh gill net (Fig 30). Both gears were deployed after the night transects and were directed to locations where concentrations of fish, especially age 0 herring, had been observed during the hydroacoustic survey. In addition, we periodically sampled with cast nets (Fig 31) and jigs (Fig. 32). These activities usually took place at anchor after the transect series.

Data analysis was in two stages. Both used echo integration (Thorne 1983a,b). In the first stage, a generalized target strength equivalent to a sigma of 0.0006 was used to estimate kilograms of fish biomass. This procedure was used rather than a specific length-based target strength (Thomas et al. 2002) because of the variety of sizes and species that were encountered during these juvenile-focused surveys. The direct capture effort associated with the surveys was insufficient to fully characterize the complete target assemblage. Results were partitioned by depth and time along transects (5-m intervals and one-minute durations). The results of the stage 1 analysis provided a detailed look at the distribution of fish biomass in the survey areas.

Stage 2 was an attempt to break down the biomass by species/size groups. Since we were particularly focused on age 0 herring, a key to the success was identification of the echo characteristics of age 0 herring. This effort required a substantial data base where we could compare echo traces with subsequent direct capture results. At the latter stage of the study we were confident we could identify the echo characteristics of many age 0 concentrations. These were typically located near the mouths of bays, often near shore, and always near surface (upper 20 m). The echo trace showed relatively small targets, but relatively dense concentrations and high spatial coherence (Figs. 33-35). Sections of the hydroacoustic data with these characteristics were reanalyzed using a sigma value of .00095 as appropriate for the size of age 0 herring. We were also able in most cases to identify and partition adult herring and other juvenile herring. The results of the stage 2 analysis were biomass estimates of age 0 herring, adult herring, other juvenile herring and other fishes by time and location.

Results

The stage 1 analysis over the 3-year period produced forty-three workbooks of hydroacoustic observations, each containing the detailed horizontal and vertical distribution of fish along with GPS locations. Biomass distributions tended to be dominated by adult herring when present. However, age 0 herring showed distributions near surface and near the heads of bays (Figs. 36-38). The stage 2 analysis produced an additional six workbooks, one for each cruise. Each workbook contains the biomass estimates by species/age group for every sampled location. Limited direct capture information did not allow much species/size partition during the fall 2006 and spring 2007 surveys. Age 0 herring were abundant in Simpson Bay, Zaikof Bay, Whale Bay and Eaglek Bay in fall 2007, but abundance was limited to Whale Bay in spring 2008 (Fig 39). A similar result was seen between the fall 2008 survey and spring 2009 survey, where abundance was high in Simpson Bay and Whale Bay in fall, but only in Whale Bay in spring (Fig 40). The results suggest that over-winter mortality was relatively low in Whale Bay. Whale Bay also showed the smallest abundance of both older herring and all other species (Fig. 41). The lack of competitors and predators may be a key to the apparently higher age 0 herring survival in this area.

Discussion and Conclusions

Our understanding of the factors affecting juvenile herring survival and herring year class strength would be greatly enhanced by a better understanding of the abundance and distribution of the various juvenile herring age classes. Hydroacoustics is likely the only methodology that has the sampling power to achieve accurate assessment over the large spatial scales of fish stocks. We have achieved accuracy in the assessment of the adult herring population through many years of research. However, this success has been accomplished because the adult herring congregate over relatively small spatial scales, so virtually the entire stock can be surveyed with reasonable effort. Juvenile herring are much more dispersed. The documentation that age 0 herring are primarily restricted to the heads of bays reduces the scope of the survey effort, but even this limitation results in a substantial survey task. This program, with the resources to achieve 7-10 day surveys on juvenile herring, covered 6-9 bays out of hundreds in Prince William Sound. The results indicate that the age 0 herring in Whale Bay had relatively good survival over the winters of 07-08 and 08-09, and that the better survival may be the result of less competition and predation at this site. However, the substantial decreases in age 0 abundance that we observed in most other bays might have an alternative explanation, such as emigration between fall and spring. Skokesbury et al. (2000) suggested some movement of age 0 herring into deeper water in March, and hypothesized that the movement represented a shift from a non-feeding mode to a feeding mode of activity. We did not observe such migrations. Stokesbury et al. (2000) did not document the specific dates of their observations in March. Our juvenile surveys were typically mid-month, and our adult surveys at the end of the month. Conditions changed dramatically over this time, as illustrated in Figures 4 and 5. There was little indication of feeding by age 0 herring during our surveys (Tom Kline, personal communication), so we don't believe the changes we observed between our November and March surveys could be explained by a feeding migration. However, we did on one occasion observe some change in the age 0 herring distribution in Whale Bay from the East Arm to the West Arm. It is possible that some migration of age 0 herring does occur over winter, possibly in response to predation. Consequently, we can not eliminate migration as a factor in the changes of abundance that we observed between the two seasons. Such behavior could only be documented by surveys with more extensive spatial and temporal coverage than was possible with the resources of this project.

We used established target strength relationships (Thomas et al. 2002) to estimate the absolute biomass of age 0 herring. We have a long history of hydroacoustic surveys on adult herring, and a good understanding of both the adult herring distributions and the accuracy of biomass estimates. Such a history and understanding is limited for juvenile herring. Many factors can impact the accuracy of estimates, of which the major factor is a lack of knowledge about the comprehensive distribution of juvenile herring. Our estimates of age 0 herring are probably reasonable in the limited locations and circumstances where we were able to identify and comprehensively survey age 0 distributions, but these are minor compared to the size and complexity of PWS. Age 0 herring are widely distributed. Due to their near-surface and relatively shallow water distribution, some age 0 herring may avoid the transecting vessel or be located in waters to shallow to navigate (Drastik and Kubecka 2005). Consequently, density estimates should be used cautiously and are best viewed as a relative index of the abundance of age 0 herring at selected locations and times. Further, the limited direct sampling capability was not adequate to characterize species and size distributions in all cases, so age 0 herring may contribute to biomass estimates in many cases where specific identification and categorization were not possible.

Despite these limitations, we gained considerable information on the distributional characteristics and relative abundance of juvenile herring as well as direct samples for other studies that are useful as indicators of survival capability. This study confirmed the tendency of age 0 herring to reside near the heads of protected bays during winter. We gained considerable information on the hydroacoustic characteristics of age 0 herring concentrations that will be useful in future studies. We were able to detect differences in abundance of age 0 herring in various locations and before and after the long winter period. This information will contribute to our understanding of survival factors and will be valuable in guiding future studies.

Herring begin to recruit to the adult population at age 3. The strength of the year class is the ultimate outcome of the characteristics monitored during this project. A long-term goal is to gain insight into how the abundance, distribution and environmental factors observed during this and similar research impact the overall survival and recruitment to the adult population. Further understanding of these processes will result from the eventual recruitment into the adult population of the age 0 herring monitored in this project.

Acknowledgments

Richard Crawford and James Thorne of PWSSC contributed substantially to the success of this project. We shared manpower and logistics efforts with two other PWSSC projects, headed by Mary Ann Bishop and Tom Kline and also funded by EVOS TC. We acknowledge their contributions and those of their staffs. We appreciate the services of the captains and crews of the FV *Kyle David* and the MV *Auklet*. Special thanks to Richard Brenner and Steve Moffitt of ADF&G, Corodva for data on herring length, weight and age. This project was funded by the *Exxon Valdez* Oil Spill Trustee Council. During the initial two years of this project, the research was a cooperative effort with related research funded by the National Marine Fisheries Service under grant # NA04NMF4390161.

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Table 1. Summary of spring 2007 acoustic surveys of herring

Location	Date	Run	Area sq.km	Density kg/sq.m	Biomass 1000 mt
Port Gravina	19-Mar	1-Day	19	0.002	0.04
		1-Night	19	0.140	2.65
	25-Mar	1-Night	20	0.123	2.46
	29-Mar	1-Night	19	0.740	14.06
	31-Mar	1-Night	12	1.566	18.79
	1-Apr	1-Night	12	1.719	20.63
Port Fidalgo	12-Mar	1-Night	5	1.365	6.82
	20-Mar	1-Day	25	0.329	8.23
	21-Mar	1-Night	30	0.094	2.82
	30-Mar	1-Night	13	0.123	1.60
Zaikof Bay	24-Mar	1-Night	7	0.112	0.79
Wells/Cedar Bay	23-Mar	1-Night	7	0.027	0.19
Non-overlapping total					20.4

Table 2. Summary of spring 2008 adult herring biomass estimates (1000 mt)

Location	Date	Run	Area	Density	Biomass	Average
St Mathews	17-Mar	1	7.5	0.65	4.9	
	27-Mar	1	7.5	0.23	1.7	
		2	7.5	0.45	3.4	3.3
Irish Cove	28-Mar	1	1.0	2.11	2.1	
		2	1.0	2.91	2.9	
	29-Mar	1	2.0	0.30	0.6	
		2	2.0	1.19	2.4	2.5
Two Moon	29-Mar	1	1.0	2.11	2.1	
		2	1.0	2.64	2.6	2.4
Sawmill Bay	21-Mar	1	2.0	0.66	1.8	1.8
Simpson Bay	16-Mar	1	7.0	0.19	1.3	0.3
					Total	10.2

Table 3. Summary of spring 2009 adult herring biomass estimates (1000 mt)

Location	Date	Density kg/m^2	Area km^2	Biomass 1000 mt	Comment
Port Gravina	18-Mar	0.02	12	0.3	Juvenile Series
	30-Mar	0.18	15	2.4	Traditional Area
	1-Apr	0.88	15	11.2	Traditional Area
	1-Apr	0.05	20	0.9	North/central basin
Eaglek Bay	22-Mar	0.06	7	0.4	Juvenile Series
Port Fidalgo	23-Mar	0.09	25	2.2	Juvenile Series
	31-Mar	0.41	20	7.9	Plus Goose Island Channel
Non-Overlapping Total				20.4	

Table 4. Locations and times of various juvenile surveys

Location	Fall 06	Spring 07	Fall 07	Spring 08	Fall 08	Spring 09
Simpson Bay	X	X	X	X	X	X
Port Gravina	X	X	X	X	X	X
Port Fidalgo	X	X		X	X	X
Eaglek Bay	X	X	X	X	X	X
Whale Bay		X	X	X	X	X
Zaikof Bay	X	X	X	X	X	X
Sawmill Bay	X	X	X	X	X	X
Windy Bay	X					
Galena Bay		X				
Wells Bay		X				

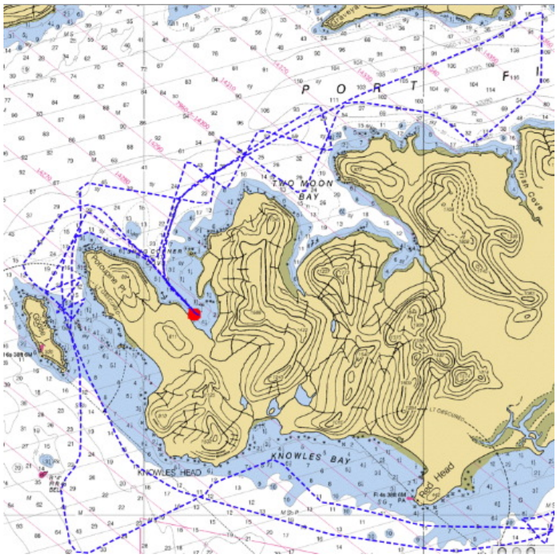

Fig. 1-Vessel track and transects in Port Fidalgo and Knowles Bay during 2009 survey

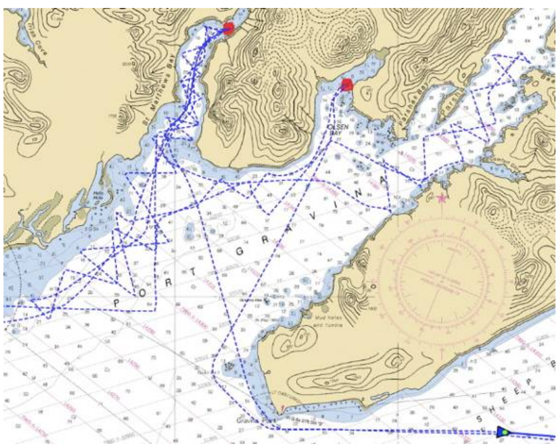

Fig. 2-Vessel track and transects in Port Gravina during 2009 survey

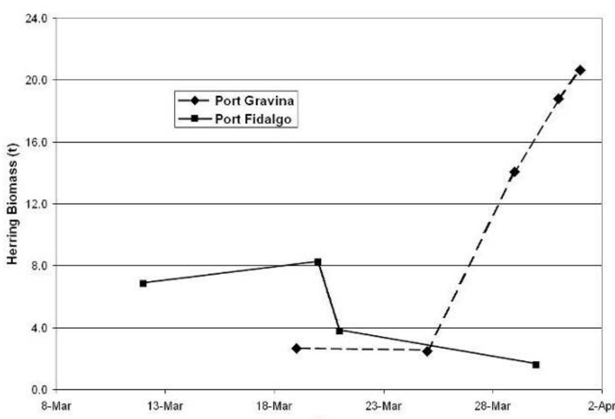

Fig. 3. Change in fish distribution between Port Fidalgo and Port Gravina from March 12 to April 1, 2007.

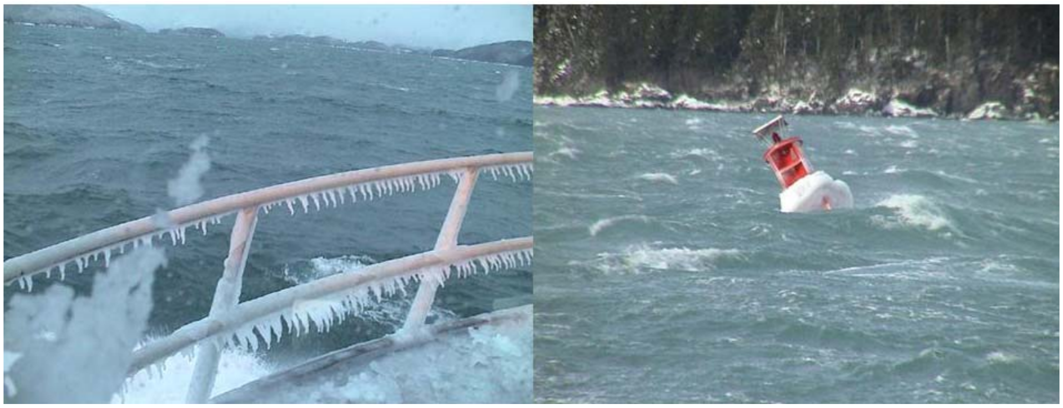

Fig. 4. Winter scenes from leg one of the spring 2007 survey.

Fig. 5. Scene in Port Gravina during leg 3 of the spring 2007 survey.

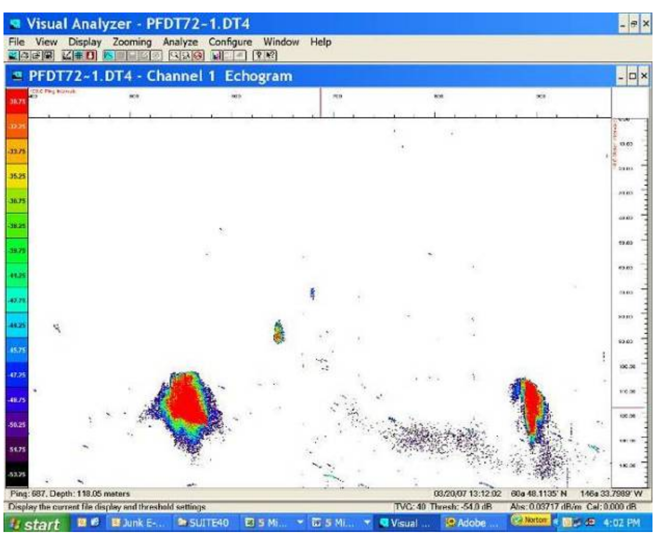

Fig. 6. Deep herring schools during daytime in Port Fidalgo, March 20, 2007. Depth scale is 150 m.

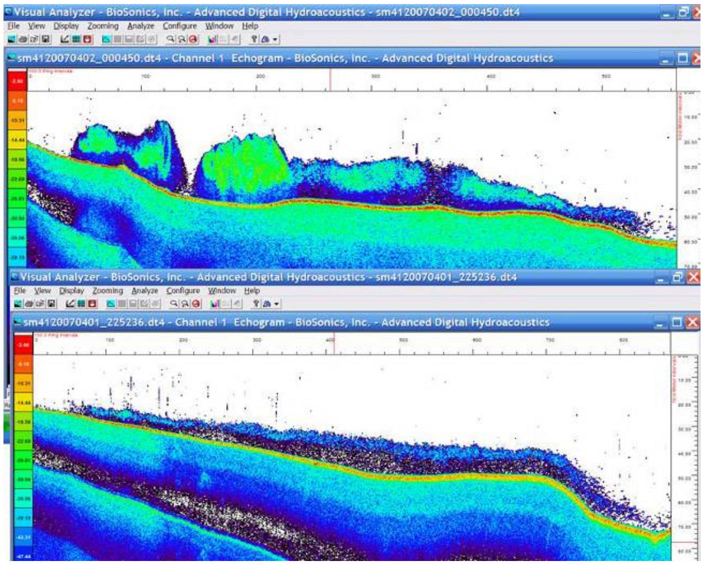

Fig. 7. Near-bottom distributions of herring at night in Port Gravina, April 1, 2007

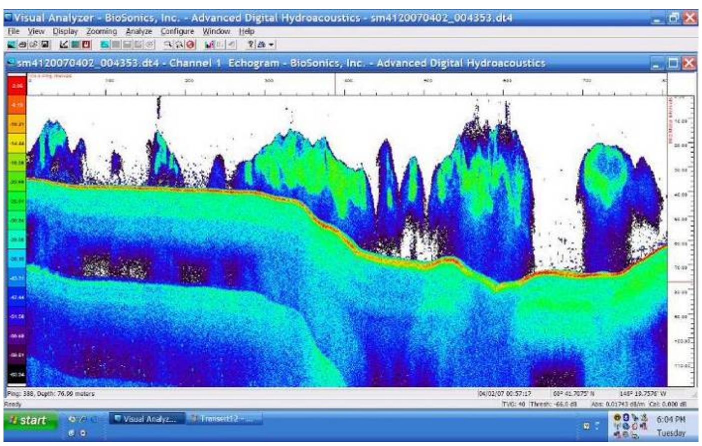

Fig. 8. Mid-water distributions of herring off Hells Hole, at night, April 1, 2007


Fig. 9. A group of Steller sea lions foraging in Port Gravina during leg 3 of the March 2007 survey

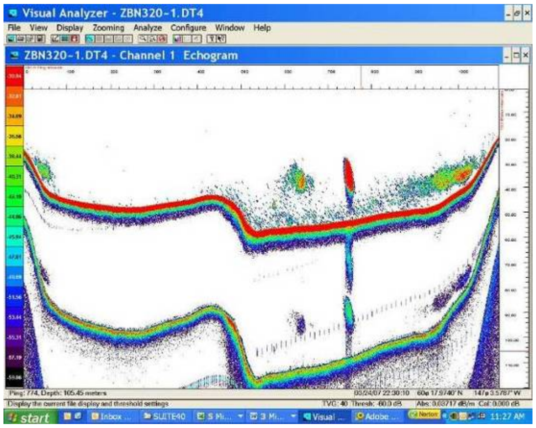

Fig. 10. Echogram of herring schools at night in Zaikof Bay, March 24, 2007

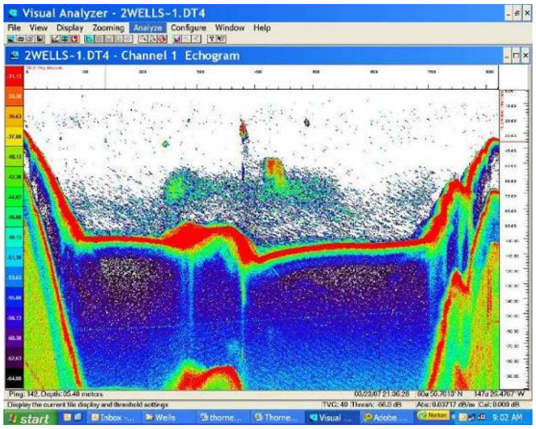

Fig. 11. Schools of herring in Cedar Bay just off the ice edge, March 23, 2007

Fig. 12. Towing the acoustic transducer along an ice edge (photo courtesy of David Janka, Auklet Charter Services)

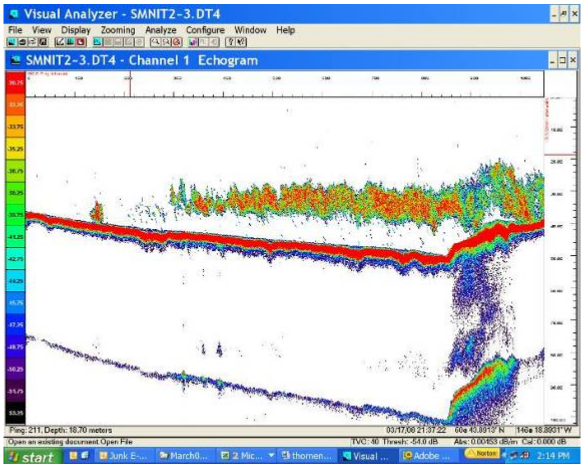

Figure 13. Echogram of herring in St Mathews Bay, March 17, 2008

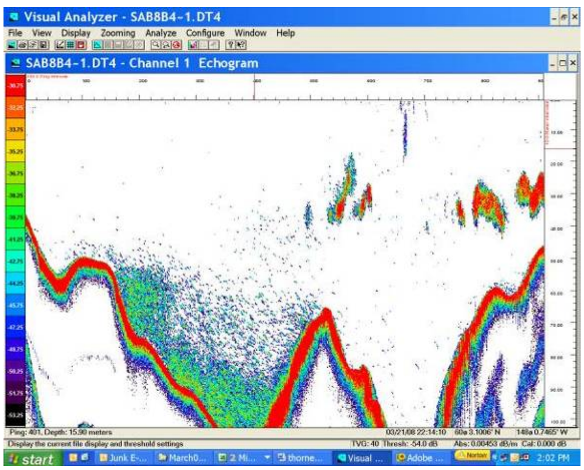

Figure 14. Echogram of herring schools from transect in Sawmill Bay, March 21, 2008


Figure 15. Steller sea lions in St Mathews Bay, March 29, 2008

Figure 16. Whale cruising the shoreline at the head of St Mathews Bay, March 29, 2008

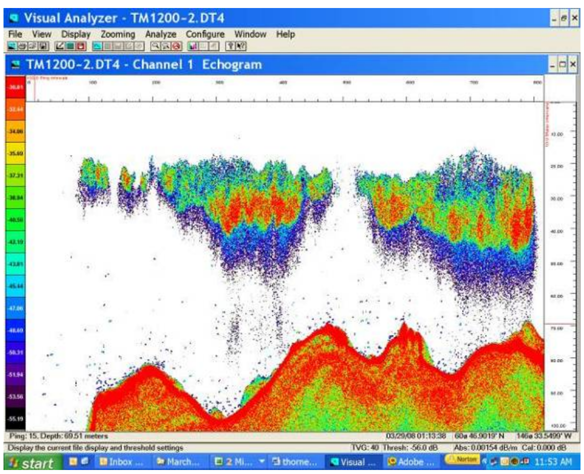

Figure 17. Large herring aggregation off Two Moon Bay, Port Fidalgo, March 28, 2008. Depth scale is 100 m.

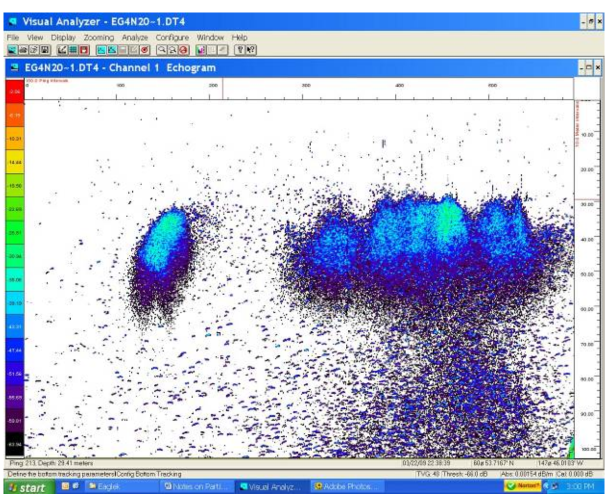

Fig. 18. Echogram from Eaglek Bay at night showing massive herring schools, 2009. Depth scale is 100 m

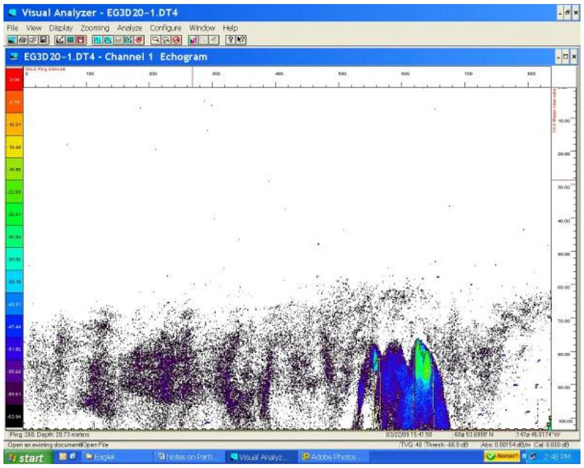

Fig. 19. Echogram from Eaglek Bay during day showing large deep herring school, 2009. Depth scale is 100 m.

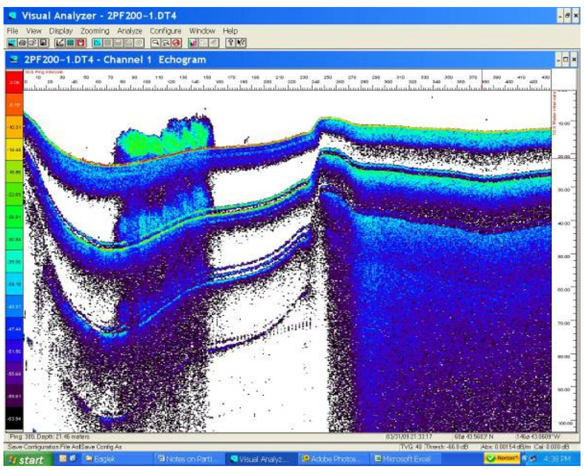

Fig. 20. Echogram from trench inside Goose Island showing dense herring school moving out of Port Fidalgo toward Port Gravina at night, 2009 survey.

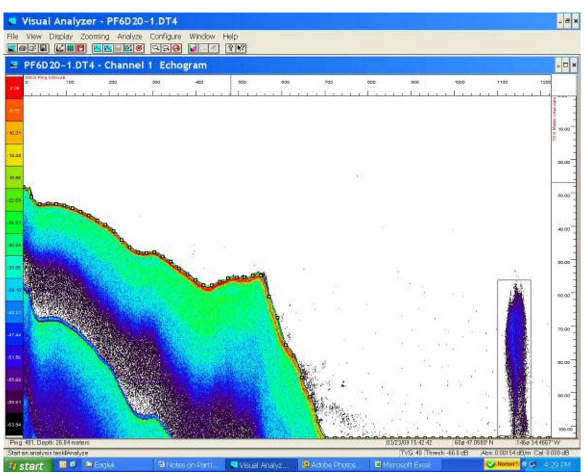

Fig. 21. Echogram from deep offshore herring school during day in Port Fidalgo, 2009. Depth scale is 100 m.

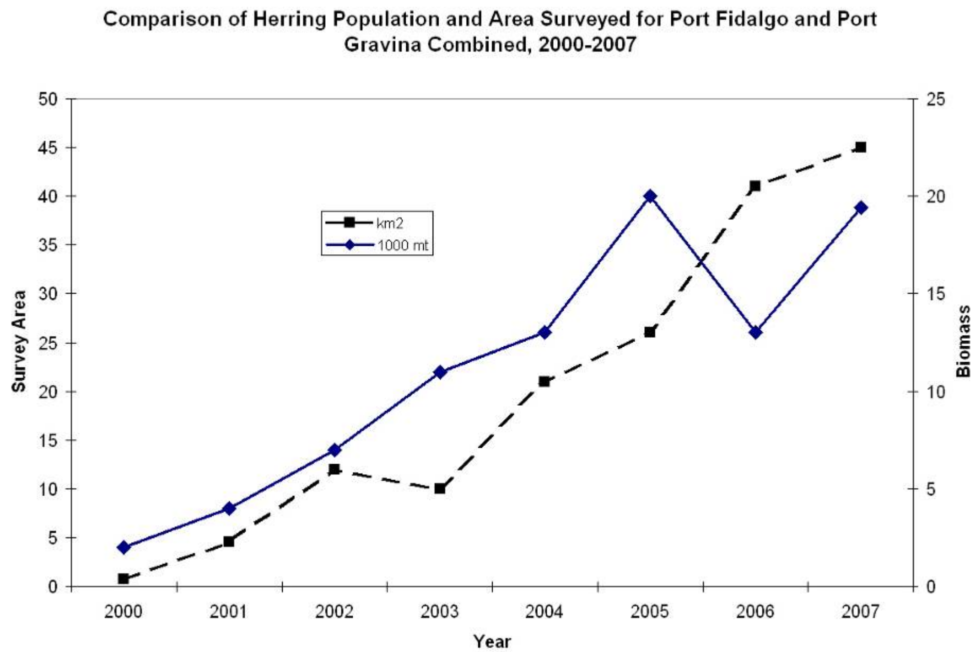

Figure 22. Comparison of herring biomass and extent of surveyed area in Port Fidalgo and Port Gravina combined, 2000-2007.

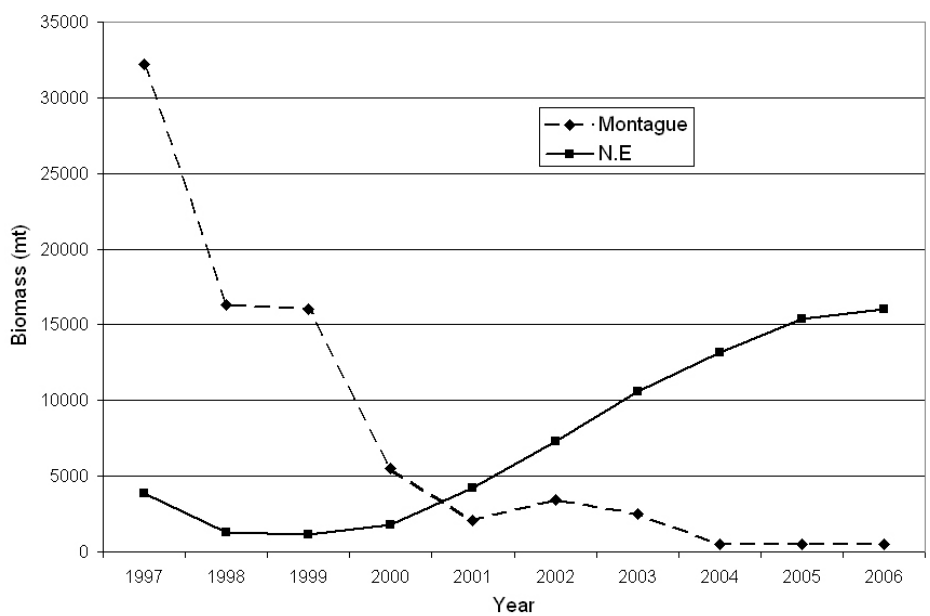

Fig. 23. Regional change in herring pre-spawning distribution from 1997 to 2006.

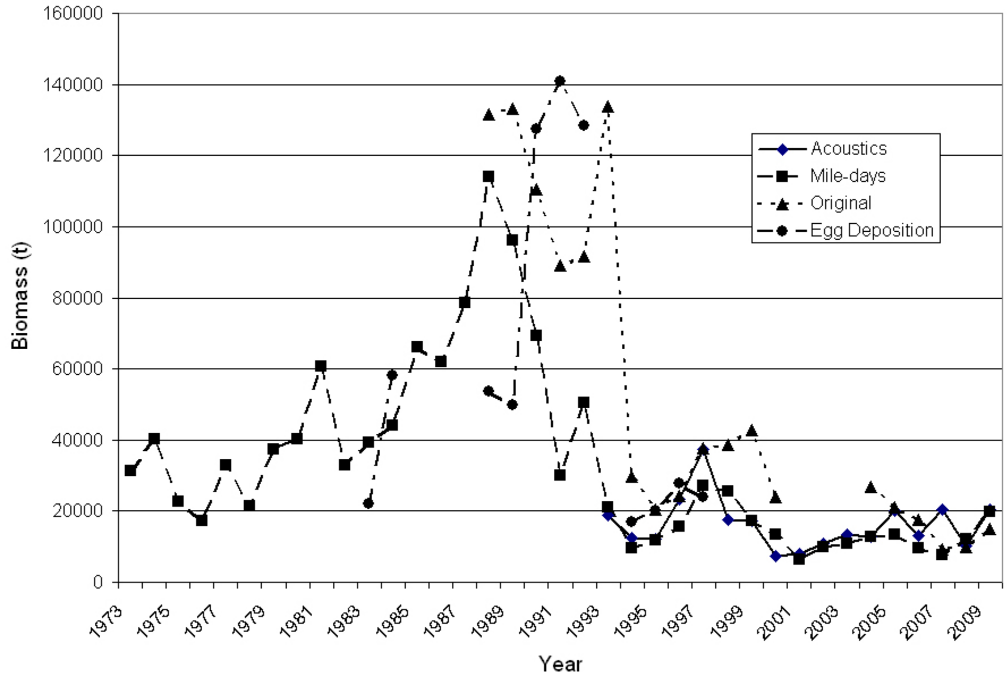

Fig. 24. Comparison of various estimators of herring abundance, 1973 to 2009. Mile-days is the mile-days index expressed in absolute units through its regression with the hydroacoustic estimates. Original is the ASA preseason forecasts except for 1988-1992, which are hindcasts from the 1993 model.

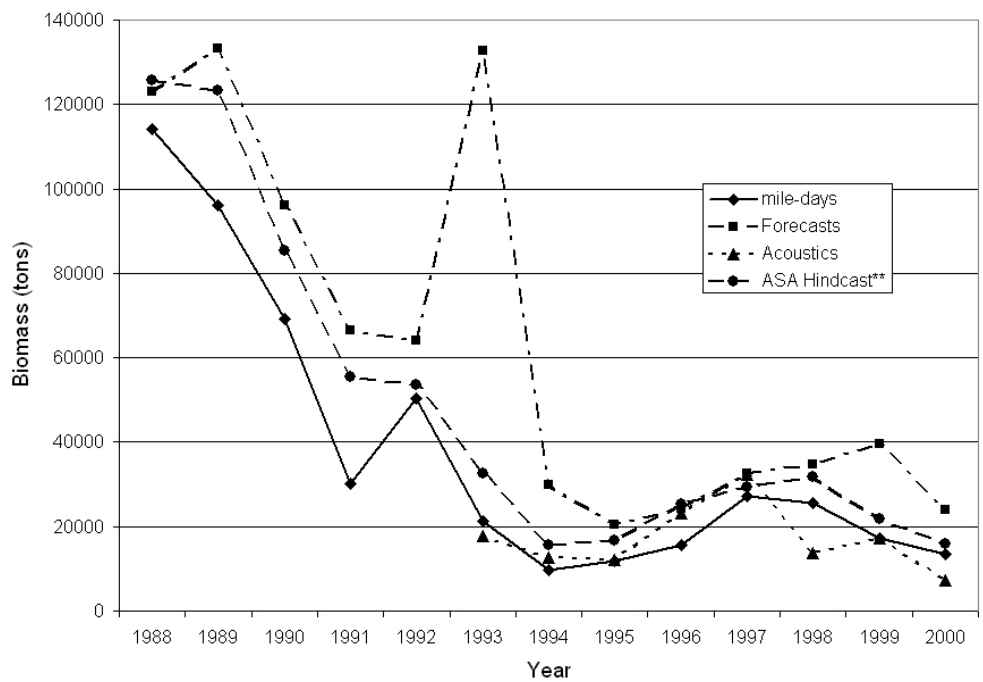

Fig 25. Estimates of herring biomass from the mile-days, hindcasts from the 2005 model, forecasts as defined in fig. 24, and hydroacoustics, all standardized as post fishery.

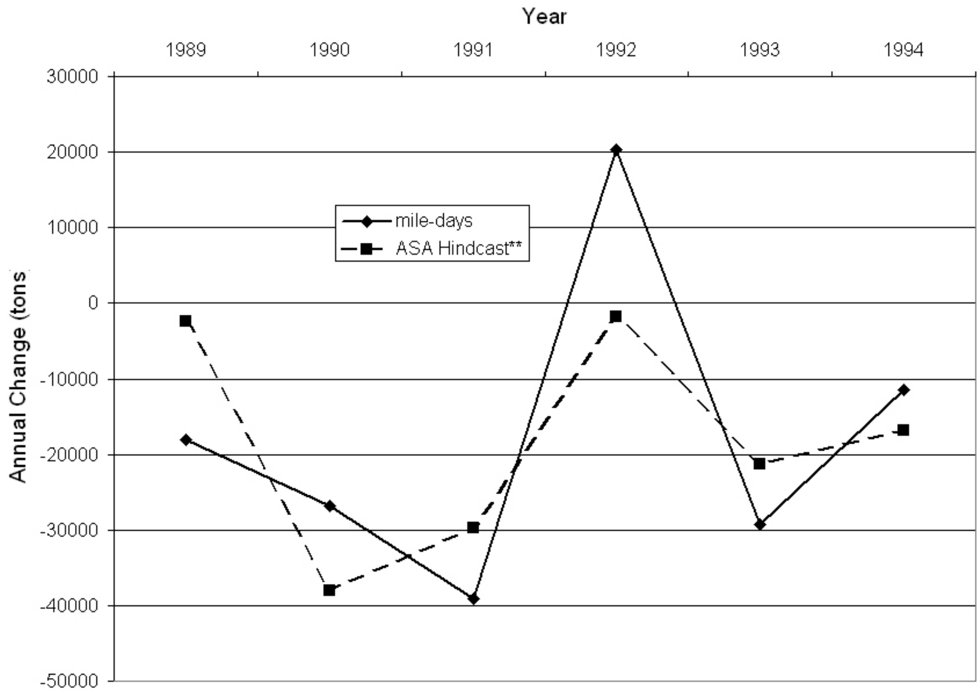

Fig. 26. Annual change in the herring population from 1988 to 1994 as estimated from the mile-days index and the 2005 ASA hindcast, after accounting for fishery removals.

Fig. 27. Deploying the acoustic towed vehicle from the MV *Auklet*

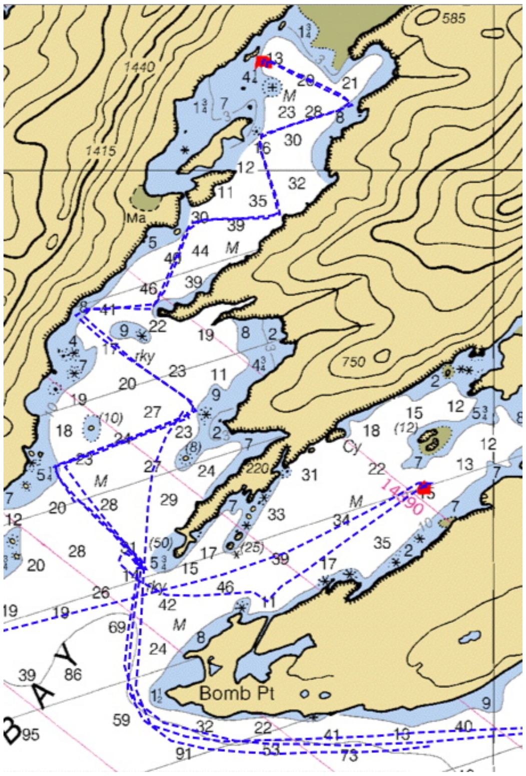

Fig. 28. Cruise track with transect locations for Simpson Bay

Fig. 29. Deploying a small mid-water trawl for age 0 herring

Fig. 30. Retrieving the multi-mesh gill net, photo courtesy of Tom Kline


Fig. 31. Deploying a cast net at night, photo courtesy of David Janka, Auklet Charter Services


Fig. 32. Age 0 herring caught on jigs.

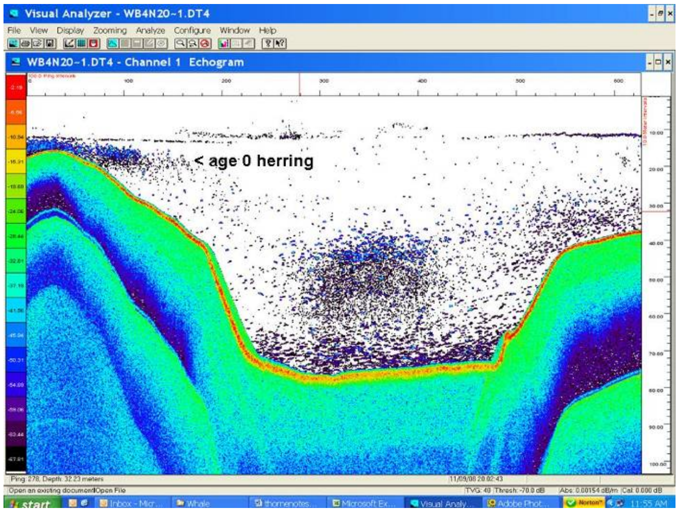

Fig. 33. Example echogram showing an age 0 distribution, from the head of Whale Bay at night during November

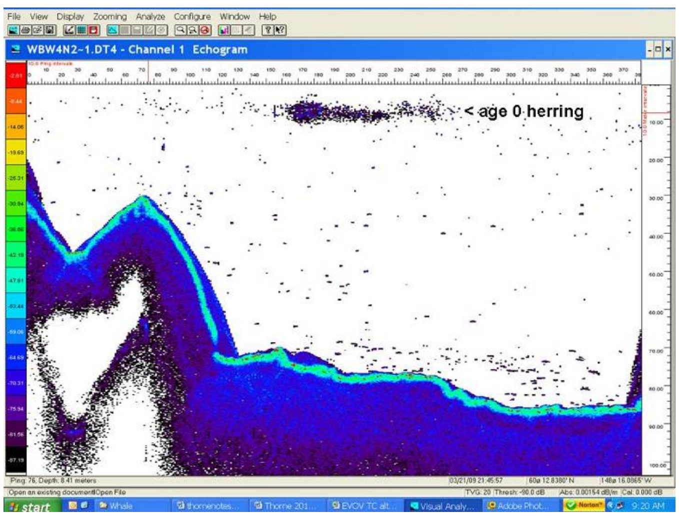

Fig. 34. Example echogram showing age 0 distribution, at night from the head of Whale Bay during March

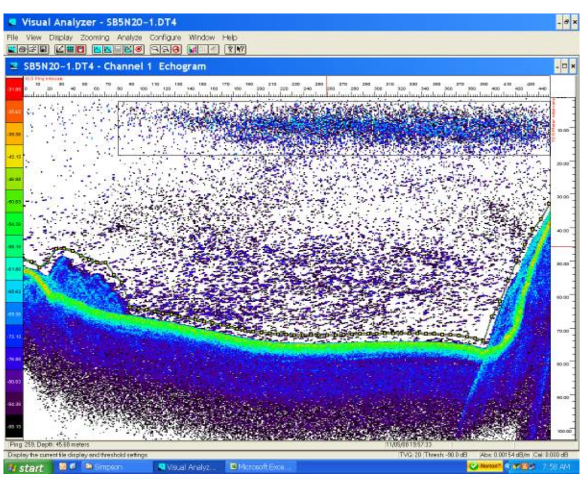

Fig. 35. Echogram showing an age 0 distribution in Simpson Bay bounded for analysis

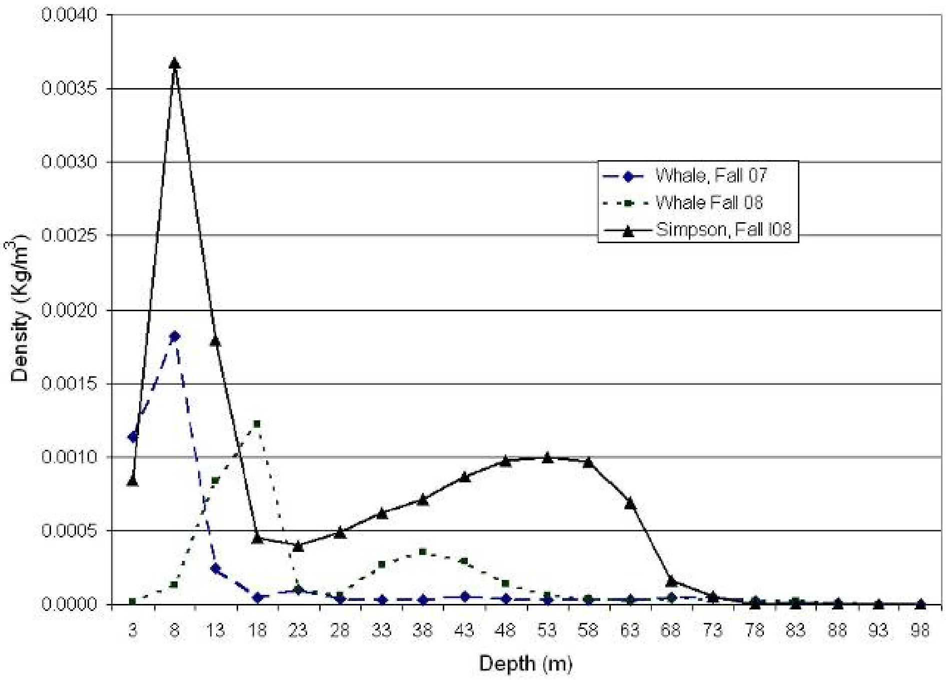

Fig. 36. Example from stage 1 analysis showing near-surface distribution of age 0 herring and deeper distributions of other fishes.

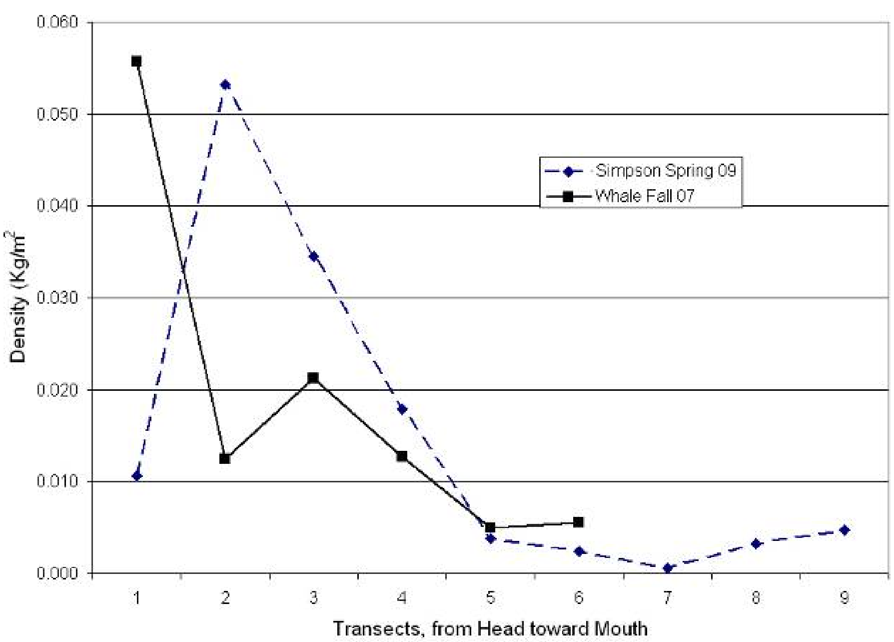

Fig. 37. Example from stage 1 analysis showing distribution of age 0 herring near the mouths of Simpson and Whale Bay.

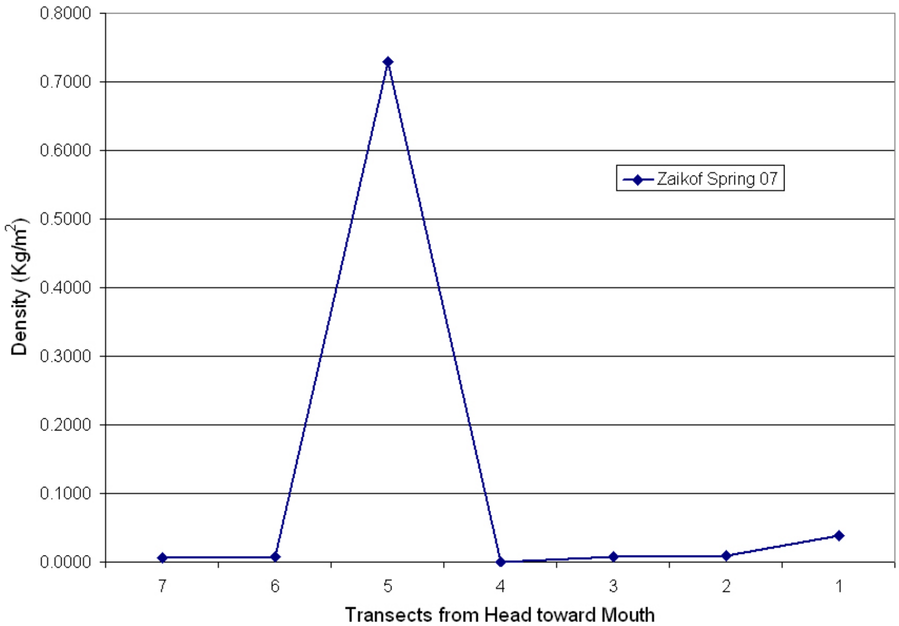

Fig. 38. Example from stage 1 analysis showing an adult herring distribution near the middle of Zaikof Bay. Note the much higher density associated with adult herring compared to the age 0 densities in Fig 37.

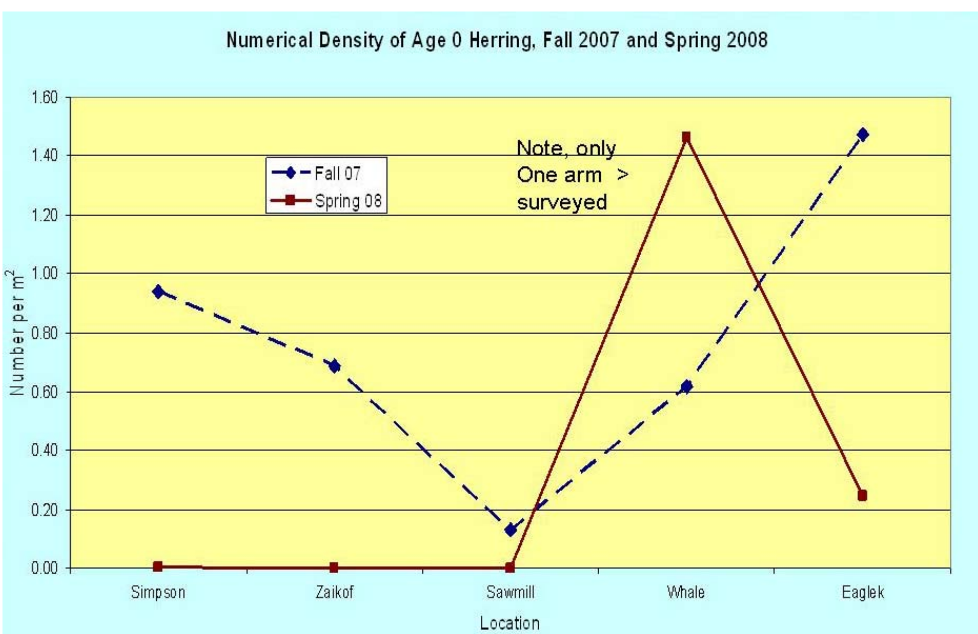

Fig. 39. Year 2 comparison of fall and spring densities of age 0 herring in five surveyed locations.

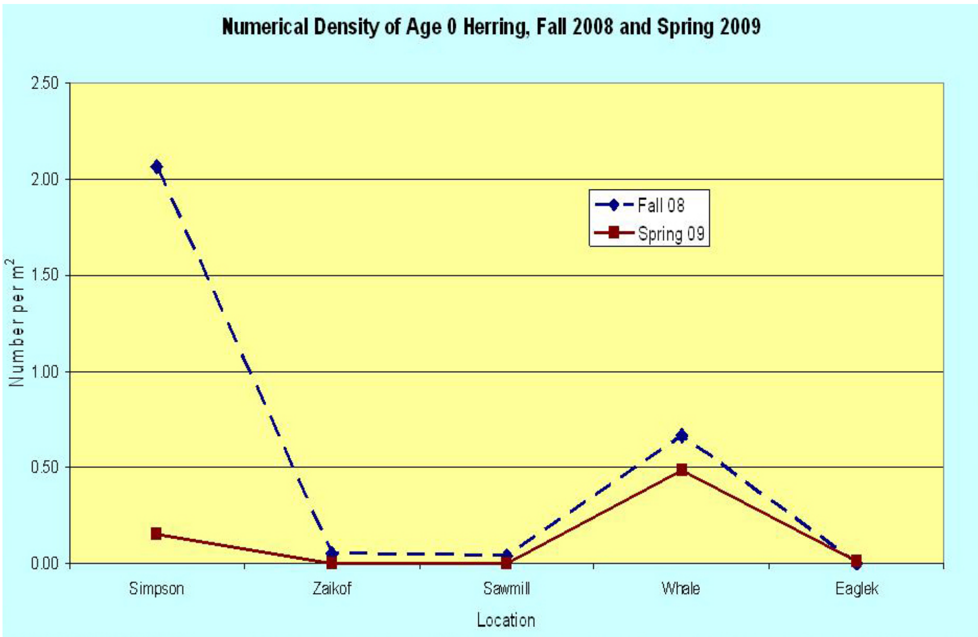

Fig. 40. Year 3 comparison of fall and spring age 0 herring densities in five surveyed areas

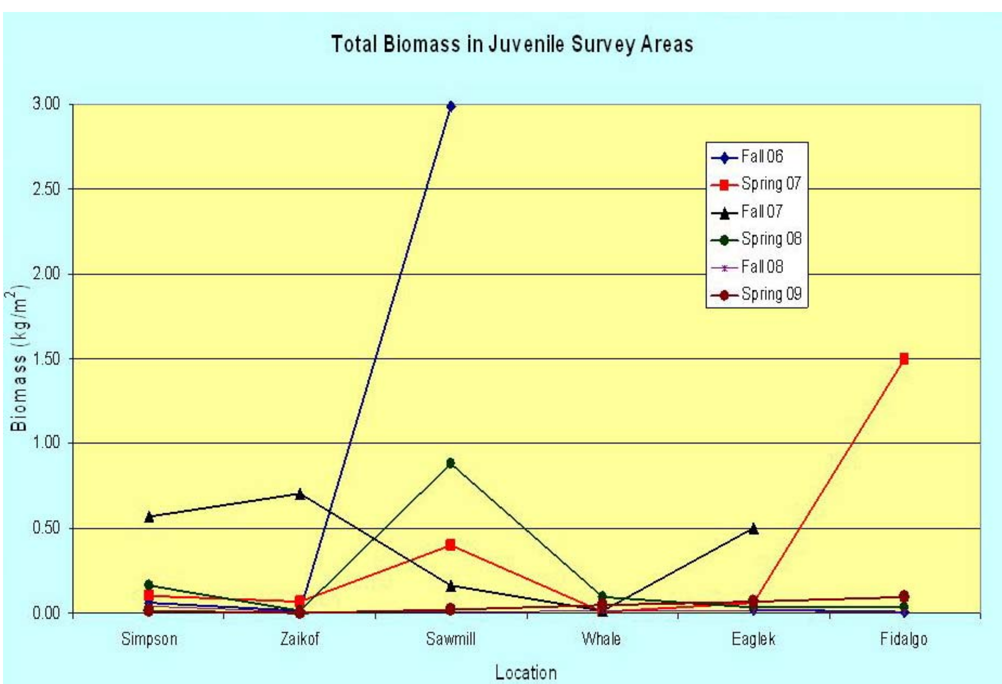

Fig. 41. Comparison of total fish biomass in six locations for all six surveys. Note the consistently low biomass in Whale Bay, where age 0 herring were most abundant.