EVOSTC ANNUAL PROJECT REPORT

Recipients of funds from the *Exxon Valdez* Oil Spill Trustee Council must submit an annual project report in the following format by **Sept. 1 of each fiscal year** for which project funding is received (with the exception of the final funding year in which a final report must be submitted). **Please help ensure that continued support for your project will not be delayed by submitting your report by Sept. 1. Timely receipt of your report allows more time for court notice and transfer, report review and timely release of the following year's funds.**

Satisfactory review of the annual report is necessary for continuation of multi-year projects. Failure to submit an annual report by **Sept. 1** of each year, or unsatisfactory review of an annual report, will result in withholding of additional project funds and may result in cancellation of the project or denial of funding for future projects. **PLEASE NOTE:** Significant changes in a project's objectives, methods, schedule, or budget require submittal of a new proposal that will be subject to the standard process of proposal submittal, technical review, and Trustee Council approval.

Project Number: 070810
Project Title: An Ecosystem Model of Prince William Sound Herring: A Management & Restoration Tool

PI Name: Dale A. Kiefer and Evelyn Brown

Time period covered: February 15, 2008 to August 24, 2008 ???

Date of Report: August 26, 2008

Report prepared by: Dale A. Kiefer

Project website (if applicable): http://smbay.usc.edu/pws/
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Project Objectives, Hypotheses and Summarized Accomplishments

The goal of this project is to produce a spatially-explicit, life-stage, and ecosystem-based herring model that simulates intrinsic and extrinsic effects on herring survival and mortality. The model should provide reliable guidance to both future fishery management and ecological intervention. The data and model will be fully housed in a dynamic, web-based GIS (called EASy) that we have developed specifically for marine applications. The project is a 3-year effort that will provide at the end of each year model and data analysis products that are steps towards a full 3 dimensional simulation that will be used to assess restoration proposals.

During the last 12 months, the modeling team has made significant progress and will soon have the prototype simulation model completed. We believe that intelligent assessment of restoration action requires an understanding of how the herring population reached its current state as well as the ecological characteristics of this state. We have made progress toward this goal in 4 areas, which are described under the headings below:

- We have completed the framework for modeling herring dynamics in PWS. This framework provides a database by which data from field surveys can be incorporated into a tuning model to test the validity of our simulations and increase the accuracy of predictions.
- We have complete detailed routines for growth and predation for herring and other key species of the ecosystem. We have run simulations of the population dynamics of humpback whales preying upon PWS herring, which in August is being presented at an International Symposium on Herring. We have also completed a detailed bio-energetics description of herring metabolism that will support assessment of development of a herring hatchery.

- We have begun incorporating historical data ADFG and EVOS research programs into the framework as a means to test the model and tune it to make more accurate predictions of the impacts of restoration procedures

- We have continued our efforts in planning and communicating information about the Restoration Program.

Work Performed:

Completed the PWS Herring Framework

The PWS Herring Survival Model is currently being developing to analyze the root causes of herring population decline and to examine possible restoration options. As shown in Figure 1, the program is divided into four software components: EASy, Survival Framework, Survival Tuning Model, and a database.

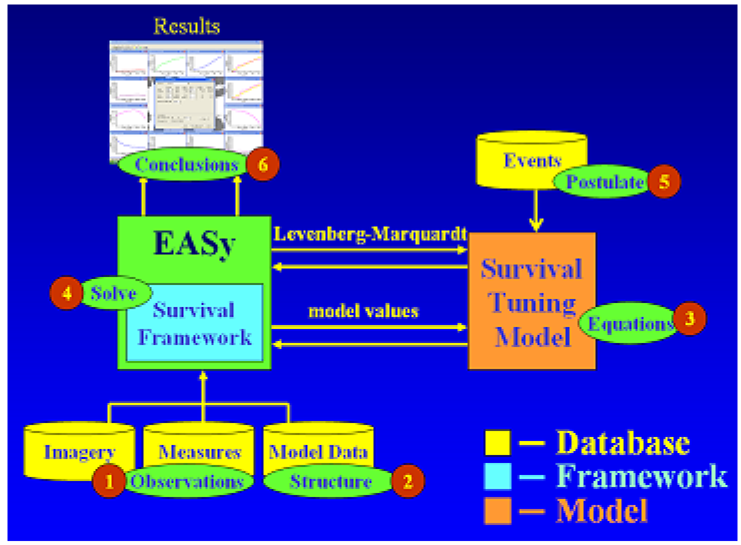

Figure 1 – The flexible herring survival model architecture tunes mathematical models using historic observation data. It then simulates the effectiveness of proposed restoration actions.

The Survival Tuning Model houses biological based mathematical equations that describe herring and predator life cycle growth and survival factors.

The program database consists of a collection if information that includes the model structure (e.g. species growth states, predator/prey, and meta-population relationships), historic observation measurements, and historic and proposed events such as fishing limitations and proposed restoration actions.

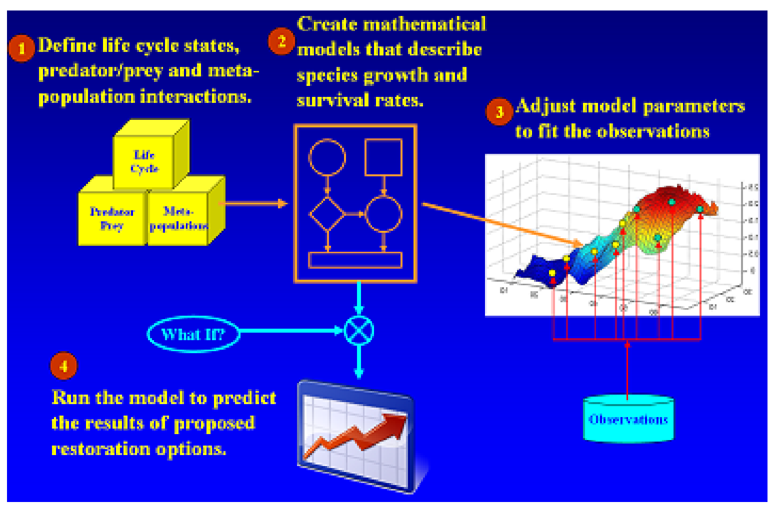

Figure 2 - The analysis process includes four steps: definition of herring and predator life cycle structure, development of mathematical models, tuning of mathematical models to historic observations, and prediction of expected benefit of proposed restoration options.

The Survival Framework integrates the model equations with the program database. It then matches the modeled equations to the historic data to "tune" free model parameters. Finally, it simulates the tuned model forward in time to project the effects of proposed restoration actions.

The entire program is built into the EASy geographical information system that integrates the other model components and provides desktop plotting and analysis capabilities. In addition, EASy provides a capability to display model results over the Internet to standard browsers in formats that include GoogleEarth, GoogleMaps, and NetViewer display servers.

As shown in Figure 2, implementation of the herring survival model consists of four steps. First, the structure of the model is defined by entries in the database. This structure includes definition of the life cycle stages of herring and predator species, the description of all predator/prey relationships, and the sub-categorization of species into meta-populations. Second, the mathematical equations that describe species growth and survival properties are implemented in Visual Basic. Third, historic observations are compared with the mathematical model results and model parameters are adjusted to most closely match the model to available measurements. Finally, the tuned model is simulated into the future to evaluate the effects of proposed restoration efforts.

The framework is designed to be accessable to all interested restoration participants so they can make entries into the database and/or so that they can evaluate their own bio-dynamic algorithms. Dr. Brown has helped guide the design of the framework and entered data into the model's database. An example of the types of information that can be extracted from the framework data base is shown in the Figure 2.

The Survival Framework also includes a phenomenological model of herring population dynamics that describes each stage in the fish life cycle, from fertilized eggs, to larvae, to juveniles, to all year classes of adults. This simplified framework model has already been used to explore the effectiveness of enhancing herring stock with hatchery. The phenomenological equations of the model are place-holders for biological based routines that are being developed with the help of Brown by Kiefer and Patrick. We are in the process of replacing the phenomenological equations with these mechanistic models.

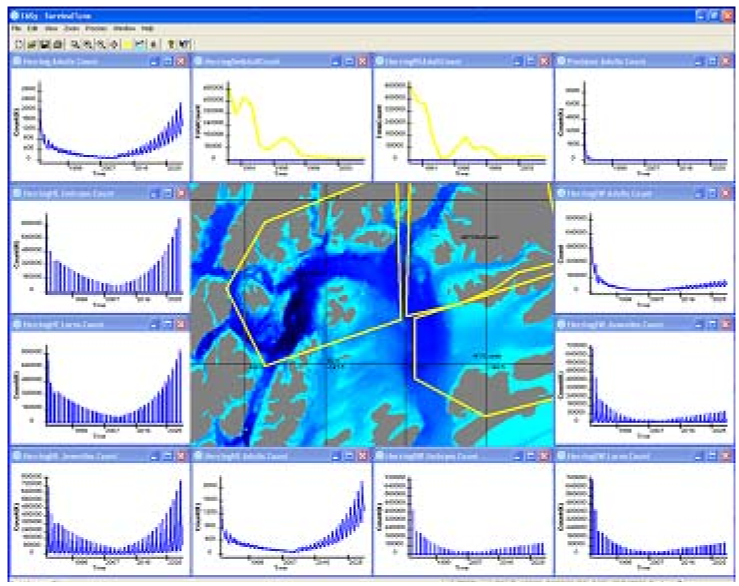

Figure 3 – Preliminary model results using a simplified life cycle model shows how herring population recovery may be achieved by predator abatement. Plots show herring recovery through 2030 to juvenile predator abatement starting in 2010.

Preliminary results from the current Survival Framework are shown in Figure 3. The particular run of the model assumed a level of juvenile predator abatement starting in 2010 and extending to 2030. The plots in this scenario show the resulting recovery of the defined North East and South West herring meta-populations. Individual plots show projected embryo, larva, juvenile, and adult population growth.

Completed Predation and Growth Routines for Herring

Dr. Kiefer with the help of Drs. Brown and Patrick has completed routines for the growth of herring growth as well as the predation by humpback whales upon herring. Both routines will soon be incorporated into the Simulation and Framework Models. Rather than describe both the routines, we will provide a brief description of the outputs of the whale predation routine. This routine describes the schooling of adult herring in PWS, the search, encounter, and ingestion of food by adolescent whales in the Sound during their winter residency, and the recruitment of juvenile herring into the adult schools during the late summer and early fall. Although not fully vetted, our simulations clearly indicate how predation can create stable prey populations at either high density or low density states. If predation bottlenecks exist at the low density state, restoration must be designed to overcome it.

Figure 4 is an example of one of our 30 year simulations in which the PWS winter whale population is kept constant at 150 and the PWS krill population is kept constant at 10^10. The concentration of herring

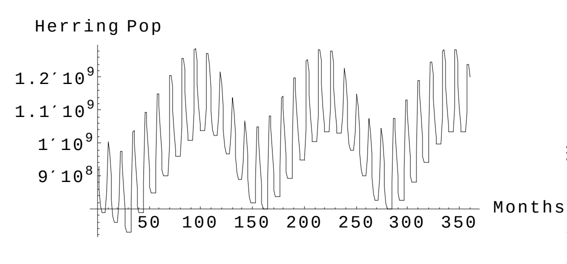

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Figure 4 - A 30 year simulation of herring polulation in PWS where the winter whale population is kept constant.

at the start of the simulation was 1*10^9, and calculations result a herring population that oscillated around a high density stable node of about 1*10^9. This value for the population of PWS herring is similar to the peak values that occurred in the 1980s. The intra-annual oscillations are caused by seasonal variations in whale predation, which occurs in the winter, and recruitment, which occurs in early spring. The ten year oscillation is an emergent property of the model, probably the result of a 2.5 year lag between spawning and recruitment.

Figure 5 shows the results of a second simulation under identical conditions with the exception the initial population of adult herring at 0.4 *10^9 rather than 1*10^9. As the simulation progress the population of herring declines until after 5 years in reaches a value of 1.2*10^8. This value is in fact close to the population found in PWS from 1993 to present. During the remaining 25 years of the simulation, the population oscillates about this value largely because of the seasonal cycles of recruitment and whale predation. These two figures provide a clear demonstration of how a natural population can be found in stable states of high and low density. We have found that if our simulation begins above a value of 0.7*10^9, the population will increase until it reaches the high density state of Figure 4, if it starts below this value, it will decrease until it reaches the low density state of Figure 5.

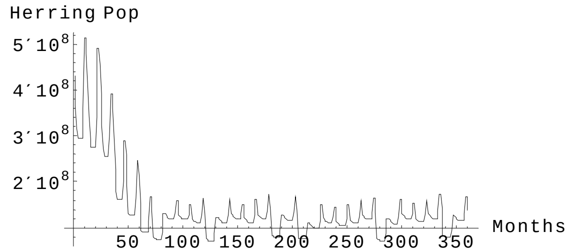

Figure 5 – A 25 year simulation of herring population demonstrates how natural populations may stabilize in high or low states.

We examine the dynamics of predation at a time step of 7 days in Figures 6 and 7. Figure 6 shows the decline in herring during the 7th year of the simulation for the low density state. This pattern is repeated throughout the simulation. After the whale enter the bay on week 363 there is a rapid decline in population as the whales target herring alone; however on week 370, the herring population has dropped to level at which the whales expand their diet to include krill; this rate of decline decreases dramatically. The whales depart on week 378. Figure 6, which shows the specific rate of predation during this period, provides a closer look at these dynamics. After the whales fully enter the bay by week 364, about 1% of the herring population is lost to the whales each day. This rate increases over the next 6 weeks it increases slightly as herring population declines and thus the rates of encounter between whales and herring declines. However, on week 370, the whales expand their diet to include krill and thereafter only 0.1% of the herring population is lost each day.

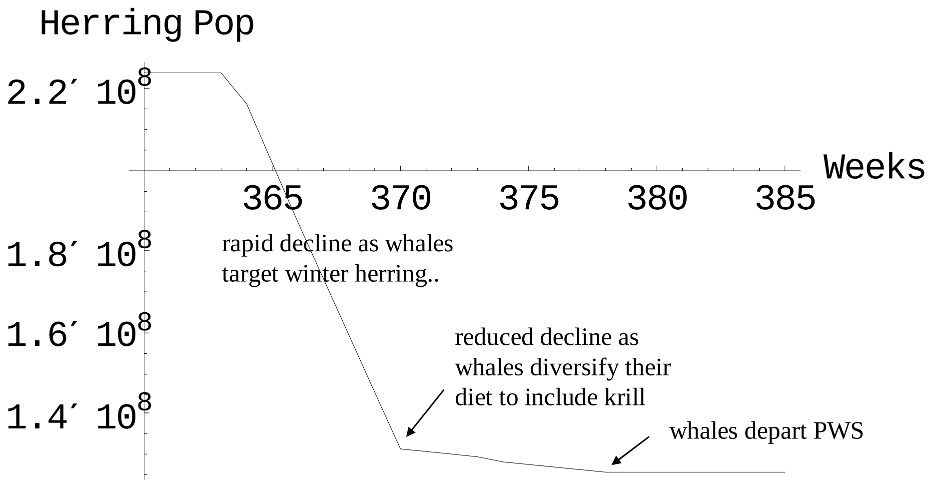

Figure 6. Herring population during the residence of whales during the 7th year of the simulation for the low density state. After the whales enter the bay on week 363 there is a rapid decline in population, but after 7 weeks of predation, week 370, the whales expand their diet to include krill and the rate of decline decreases dramatically. The whales depart on week 378.

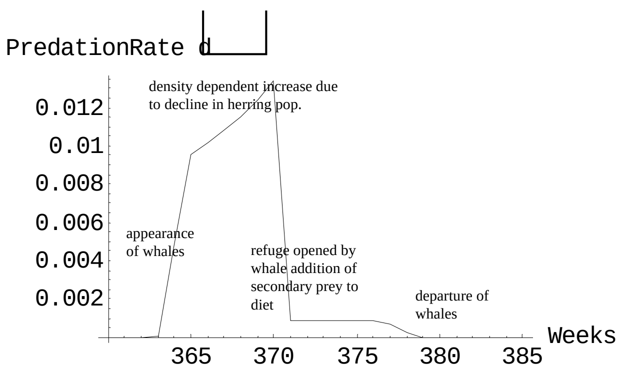

Figure 7. The daily specific rate of predation on herring by whales during their residence in year 7 of the simulation. After the whales fully enter the bay by week 364 the specific predation rate reaches a value of 0.01/day. However, as the herring population declines to 0.12*10^9 (figure 8) on week 370, the whales expand their diet to include krill and the rate of predation drops by an order of magnitude and thereby protecting the population from further rapid decline.

Although the simulations shown are only a "first-cut", and coefficients and inputs to the simulation must be reviewed by experts, the results are a good illustration of how the bi-stable state of PWS herring may occur. The existence of the bi-stable state and its characteristics are also supported by data on recruitment and standing stock that is part of Fish and Game's annual stock assessment. Figure 8 is a graph that Dr. Patrick plotted recently. It shows as a time series of the recruitment in PWS as "recruits per spawner" as a function of the spawning biomass. The time series, begins in 1980 and ends in 2001, shows both the progression of the herring's decline and the dynamics of this process. Our interpretation of this figure is that in 1980 the population was in the stable, high density state like that which appears in our whale predation routine as shown in figure 4. Despite large annual variations in recruitment, the population remained in this state until 1989. From 1989 to 1993 there is both an absence of strong recruitment (expected in 1992) and higher rates of adult mortality as indicated by the large decreases in population. Such conditions drove the population to the low density state at which it is presently found. This state is also a feature of our whale predation routine as shown in figure 5. The figure also includes a series of red lines in the lower part of the graph that are labeled with values ranging from 0.1X to 30X. These lines are a calculation of the number of recruits (y axis) produced by the spawning biomass (x axis) is the average weight of the spawning population is 120 g. ,and the average number of recruits produced by each fish in the spawning population is equal to the value indicated by the label on each of the red lines. Thus, the red line labeled 0.5 indicates the number recruits produced by a spawning population in which each fish within the population produces 0.5 recruits. These lines are most important since they determine whether to population subject to a given mean mortality rate will increase, decrease, or sustain its current size. Fish and Game's calculation of adult mortality indicate that the mean value for recruit per spawner must be between 0.3 and 0.5 if the population is to sustain its current size.

It is also interesting to note that recruits vary by at least an order of magnitude in both the low density and high density states. Our routine provides a quantitative justification for bi-stable states (as defined by the two rectangles) separated by a region of instability. It does not however provide an explanation for the large annual variations in spawning success. These are features are determined by the dynamics of pre-adult stages consisting of eggs, larvae (metamorph in figure 8), and juveniles of ages 1, 2, 3 years. The red lines in the upper part of the graph are calculations of the number of individuals of at each of these 5 stages of the pre-adults expected for a given spawning biomass under conditions in which the spawning population remains unchanged with time. If the vertical distance between the "egg" line and the line for juveniles of age 3 decreases, recruitment will increase and the population will increase. Likewise, if the vertical distance between the "eggs" line and the line for juveniles of age 3 increases, recruitment will decrease and the population will decrease. Such changes will occur of course if there are changes in the mortality rates at any of the stages between eggs and juveniles of age 3. The model team is now focusing much of its work on these pre-adult stages, since large variations in the mortality rate can drive the adult population from one density state to the other. Unfortunately, data on the pre-adult population is limited. The Integrated Herring Restoration Program will fill this critical data gap, and the modeling team will help support this effort and transform this data into information to guide restoration.

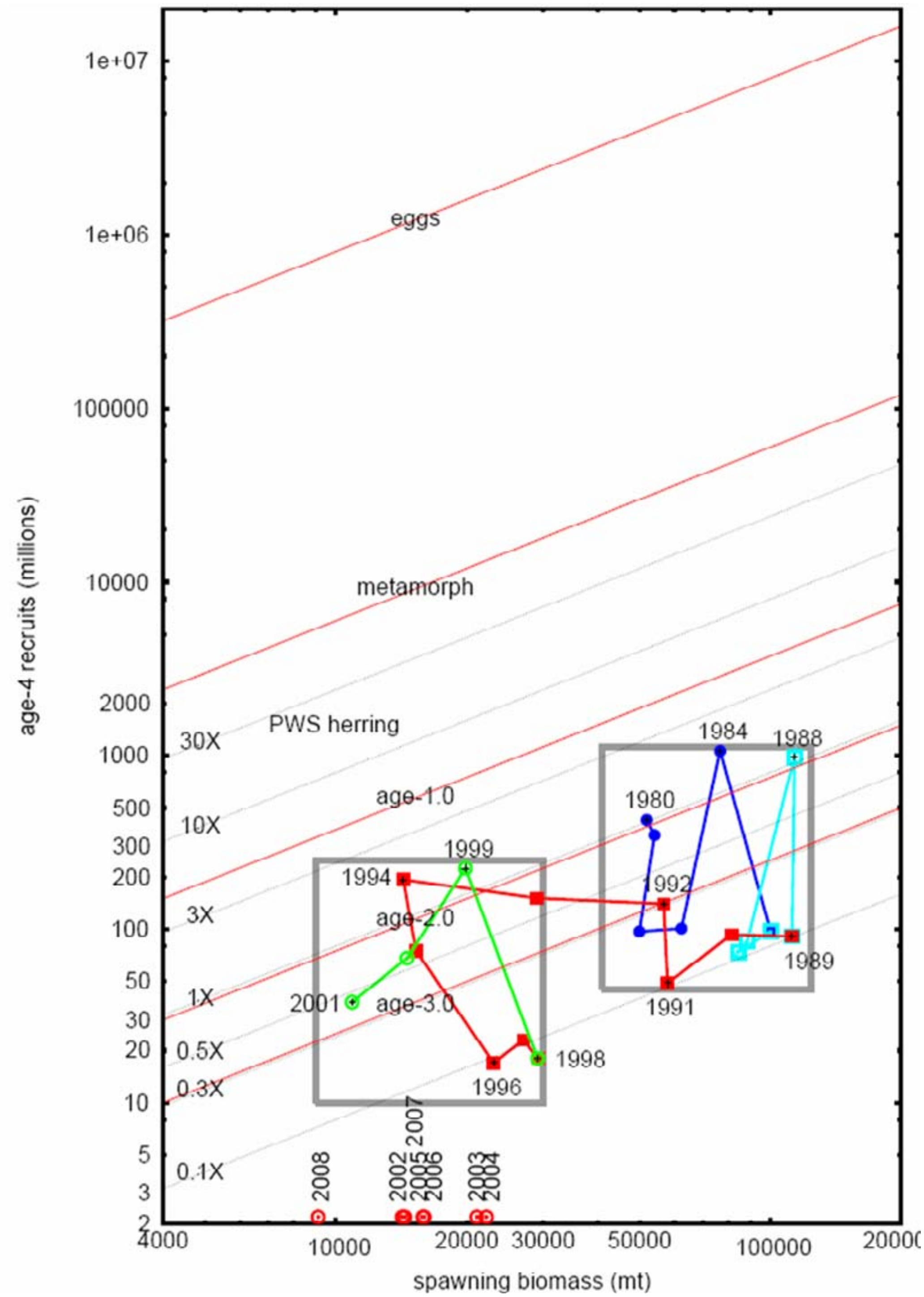

Figure 8 - Graph shows a time series of recruits as a function of total spawning population.

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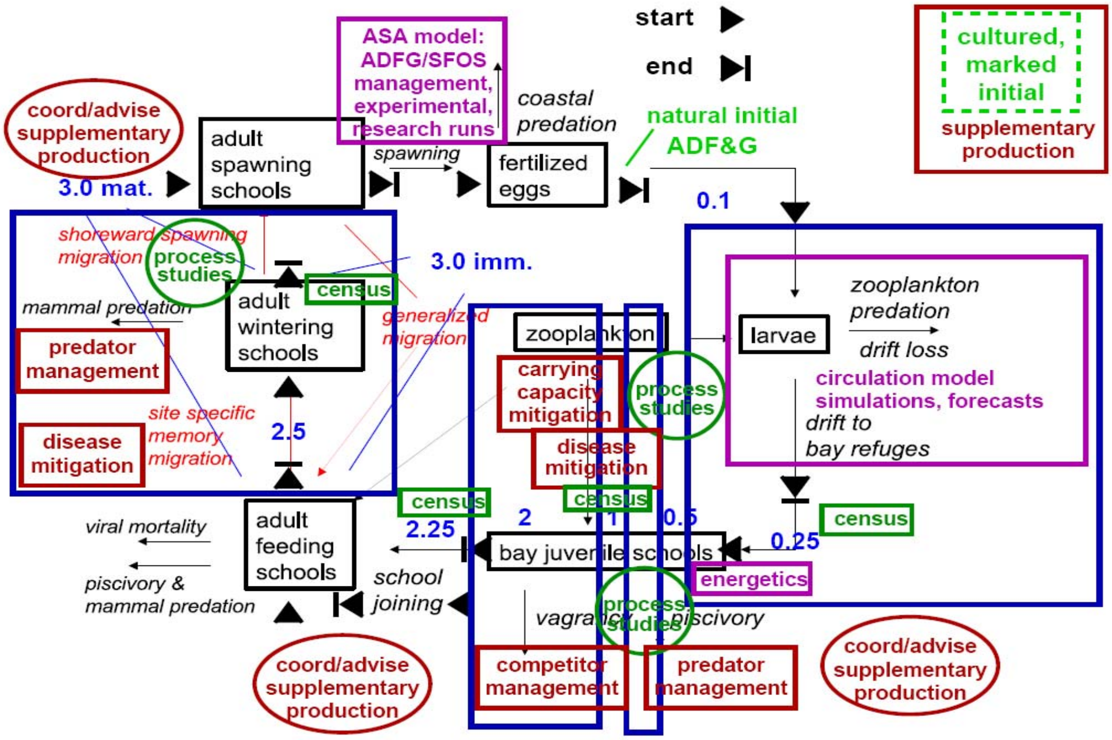

Figure 9. The 4 major components (blue rectangles) of the PWS herring model are shown in the context of both the herring life cycle and the pending activities of the Integrated Herring Restoration Program. The figure illustrates the extent of the necessary interaction between modeling and other components of the Program.

Future Work:
We have made good progress in formulating the growth of juveniles and adults and predation upon adults. The dynamics that creates a bi-stable state for the adult population is now described mathematically. Our next challenge is to understand and formulate the dynamics that underlies the large annual variations in recruitment at the low and high density states as shown in Figure 5. These dynamics occur in the pre-adult stages, embryos, larvae, and juveniles. Although the variation in recruits per spawner found in figure 5 appear random, they are not. In the 80s high rates of recruitment occurred every 4 years…a remarkable and dramatic feature of the population. Throughout the period of the low density state which began in the early 90s, the 4-cycle either collapsed or was greatly reduced; none-the-less, in the low density state annual variations do not appear random but follow a cycle in which the periodicity is not as regular as that found in the 80s. We believe that the most reasonable explanation for such variation is found in the dynamics of the juvenile populations residing in bays. The cycles may be caused by predator-prey interactions such as the predation of pollock on herring, variations in infection and immunization of juvenile populations carrying VHS, variations in food availability as determined by competition or supply, and possibly interactions between year 1 and year 2 herring juveniles.

More generally, our work will also include entering the mechanistic routines into the tuning model. This will include the routines developed by Kiefer as well as modifications of the routines that Dr. Patrick has developed for PWS pink salmon. We will then run the framework search routine comparing model predictions with data found in the framework database thereby both testing the accuracy of model and obtain optimum values for system coefficients. This process requires that we complete loading the field database into the framework. In fact obtaining such data from the last 30 years, reformatting it, and subjecting it to quality control has been a difficult and time consuming job. If funds are available, additional support for this work would be most helpful. Finally, we will begin running the tuned model to test restoration proposals.

Coordination/Collaboration:
During the last week of May, 2007 we held a workshop the University of Southern California with our consultant, Evelyn Brown, and Herring Restoration participants Michael Schlei and Rob Bochenek. This workshop focused on co-coordinating our efforts in EVOS PWS herring database, and identifying how this database can support development of the herring model. In addition we have:

1. Established a FTP-site at USC for the posting of datasets by collaborators (ftp://128.125.173.225). In parallel, Web access to SEA project data archives recently transferred to EVOS was set up by Michael Schlei (http://www.evostc.state.ak.us/herringdata).
2. Contacted several holders of relevant herring and oceanographic survey data including:
    - Evelyn Brown, for a definition of portions of the SEA dataset and pointers to other survey databases of importance.
    - Shelton Gay, for additional SEA broadscale and nearshore survey datasets.
    - Steve Moffit & Rob Bochenek for the ADFG herring survey data.
    - Richard Thorne (PWSSC), for the herring adult and juvenile acoustic survey data.

All datasets (i.e. mainly SEA data but also summaries of acoustic survey data from Thorne) have been downloaded, and carefully inspected. These data invariably take the form of diversely structured flat files, generally lacking metadata to assist with interpretation of data fields. Where necessary, data providers have been approached for further clarifications. On the recommendation of Brown, oceanographic data from the IMS/UAF online archive (http://www.ims.uaf.edu/ims-research/dataarchives.html) have also been acquired.

3. Compilation of ancillary data layers for Prince William Sound and adjoining region:
    - Acquisition and processing of bathymetric soundings data for PWS from NOAA-NOS (http://oceanservice.noaa.gov/dataexplorer/welcome.html) into a synoptic bathymetric vector file for use with GIS.
    - Acquisition of a series of SST satellite imagery data from NASA PoDAAC (http://poet.jpl.nasa.gov).
    - Acquisition of NOAA nautical charts for the region in both raster (BSB) and vector (ENC) formats.
    - Sequence of shapefiles provided by Brown showing the location and extent of herring spawn.

This year we have met twice with Dr. Brown for a week each to review the model and discuss data sources to test and tune the model, and we will be meeting with Dr. Patrick during the first week of September to review the model and continue its development.

Community Involvement/TEK & Resource Management Applications:
Our modeling team has been active in planning the restoration program. Drs. Brown, Kiefer, and Patrick participated in the June Cordova meeting, and Patrick and Brown will participate the 3 follow-up meetings this year. They are also writing major sections of the restoration plan. During the June restoration planning meeting in Cordova Drs. Kiefer and Patrick met with Cordova fisherman, Ross Mullins and Ken Adams, to present both the herring model and the virtual fish farm software, called AquaModel, that Kiefer and O'Brien have created.

Information Transfer:
Our herring modeling project Website was completed during the first year of our project. It is available at http://smbay.usc.edu/pws/. Also from the start of our project we have produced quarterly electronic newsletters that will be circulated to groups and individuals interested in the PWS restoration work. Our distribution list is limited to Herring Project participants, but we will gladly expand it if the EVOS Trustee Council wishes. The basic design of the newsletter is depicted below: In addition Dr. Kiefer that a graduate course on the modeling of herring dynamics within the Department

of Biological Sciences at USC. During the first year of our project, students learned modeling techniques using the PWS Herring as a case study. Six research papers and associated models have been submitted by the students. Drs. Kiefer and Patrick will gladly teach a similar course to PWS stakeholders in Alaska and Washington states. We have missed the last issue, but will distribute an up-date covering the spring and summer for the fall quarter.

During January, Brown, Kiefer, O'Brien, and Patrick co-authored a presentation by Brown at the Alaska Marine Symposium. On August 29th, they also co-authored a presentation entitled, "The Ecosystem Model of Prince William Sound herring: A Management and Restoration Tool" at the ICES Symposium in Galway, Ireland, "Herring: Linking biology, ecology, and population status in the context of changing environments". Finally, a first draft of a research paper on our model of whale predation is nearly completed and will be submitted next week for publication.

Budget:
As discussed in "Future Work", the modeling team has a well defined set of tasks for the coming year, and a lot of work ahead of it. These tasks include:

- Importing into the framework database 30 years of dispersed and disorganized data that is relevant to the population dynamics and restoration design
- Complete derivation of mechanistic equations describing the growth and population dynamics of PWS herring
- Tune and test the framework's tuning model and thereby complete the simulation model. This will require considerable interaction with other participants in the restoration program.
- Incorporate new information into the framework database.

As indicated in figure 9 if the Integrated Herring Restoration Program is implemented, the tasks of the modeling team will significantly increase. We have examined the effort required to complete these tasks for the coming year and produced a preliminary budget of supplemental costs, which is shown below.

Task	**Personnel**	**Rate**	**Effort**	**Cost**
Refine tuning routine to accommodate data from new by-stage studies	O'Brien	800	20	16000
Llink to the realtime data of the new Integrated Restoration Projects	O'Brien	800	30	24000
Integrate and co-ordinate as part of IHRP (includes 24 days for workshops)	Patrick	800	46	36800
Advise and support start-up of herring supplement project including support tagging workshop and design	Patrick & Kiefer	800	22	17600
Total Salary				94400
Attend IHRP Meetings 2009				
ticket:2 meetingsX 3 participants (Brown,Kiefer, Patrick)		800	6	4800
Per Diem 2 meetingsX 3 participantsX4 days		150	24	3600
Total Travel				8400
Direct Costs (total travel + total salary)				102800
G&A (0.2* DC)		0.2		20560
Total Costs				123360

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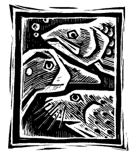

We appreciate your prompt submission of your annual report and thank you for your participation.

Submit this report via e-mail to mandy.migura@alaska.gov . Thank you!