Fisheries Centre Research Reports

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**By Dave Preikshot and
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UBC Fisheries Centre, Jun. 2001**

A report, prepared for the Northwest Indian Fisheries Commission, on an investigation of changes in the South Puget Sound ecosystem, from 1970 to 1999, using a dynamic mass balance model (Ecopath with Ecosim), with special reference to chinook salmon (*Oncorhynchus tshawytscha*) and coho salmon (*O. kisutch*).

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GLOSSARY

ALPI: Aleautian Low Pressure Index
B: Biomass
BA: Biomass Accumulation
DC: Diet Composition
DO: Dissolved Oxygen
DPS: Distinct Population Segment
EE: Ecotrophic Efficiency
ENSO: El Niño Southern Oscillation
ESA: Endangered Species Act
EwE: Ecopath with Ecosim
g: gram
Lc: Length at First Capture in a Fishery
m: meter
mg: milligram
NOAA: National Oceanic and Atmospheric Administration
NWIFC: North West Indian Fisheries Commission
P/B: Production Divided by Biomass
PAH: polycyclic aromatic hydrocarbon
PCB: polychlorinated biphenyl
PDO: Pacific Decadal Oscillation
PNI: Pacific Northwest Index
PSWQAT: Puget Sound Water Quality Action Team
Q/B: Consumption Divided by Biomass
SPASM: South Puget Sound Nutrient Study Model
SPS: Puget Sound south of the Tacoma Narrows
SS: Sum of Squares
SSB: Spawning Stock Biomass
UBCFC: University of British Columbia Fisheries Centre
UW: University of Washington
WCCSBRT: West Coast Chinook Salmon Biological Review Team
WDE: Washington State Department of Ecology
WDFW: Washington State Department of Fish and Wildlife
WDNR: Washington State Department of Natural Resources
Y: Fisheries Yield

AUTHOR'S NOTE

At several points in this report the reader will note references to a CD-ROM with raw data for analysis. This CD-ROM was made available for the initial distribution of the report to the funding agency, the Northwest Indian Fisheries Commission. The CD-ROM was not included for distribution with as part of this volume of the Fisheries Centre Research Report series. Instead, all of the data, incuding a downloadable PDF version, can now be found in a folder at the UBC Fisheries Centre ftp site:

www.fisheries.ubc.ca/SPuget/

If you wish to run the model itself or inspect the data please use these files. We welcome suggestions to improve the performance of the model and hope that with such help we can form a collaborative process to understand the whole of the Puget Sound / Strait of Georgia area.

DIRECTOR'S FORWARD

If you got a hammer, it's great to find a nut. Thus, it is especially pleasing when some hammer-less person comes along and asks you to help crack their nut. This is what happened when groups concerned with the future of the southern Puget Sound ecosystem asked the Fisheries Centre and its partners to help in a pilot ecosystem analysis. There were worries that the ecosystem was in a state of decline and a desire to track the many human-induced changes that had a occurred in the area, with a special focus on changes to local salmonid stocks. The Fisheries Centre team tells me it was a pleasure and privilege to be able to tap into all the knowledge and experience of the many colleagues south of the border in this project, especially Native Americans whose vibrant culture was built upon salmon and shellfish resources.

This report, the latest in a series of ecosystem modelling reports since 1996, documents the Fisheries Centre modelling team's efforts on Puget Sound and points the way for future cooperative work. The team also tell me that this work on Puget Sound stretched

the capabilities of the Fisheries Centre's Ecopath with Ecosim suite of modelling tools to the limit. Finding ways of incorporating all those migrating salmon species was a real challenge. And, at the end of the project, we are not quite sure if the nut is cracked yet or not. But we all learned a lot trying.

The Fisheries Centre Research Reports series publishes results of research work carried out, or workshops held, at the UBC Fisheries Centre. The series focusses on multidisciplinary problems in fisheries management, and aims to provide a synoptic overview of the foundations, themes and prospects of current research. Fisheries Centre Research Reports are distributed to appropriate workshop participants or project partners, and are recorded in the Aquatic Sciences and Fisheries Abstracts. A full list appears on the Fisheries Centre's Web site, www.fisheries.ubc.ca. Copies are available on request for a modest cost-recovery charge.

Tony J. Pitcher
Professor of Fisheries
Director, UBC Fisheries Centre

1. INTRODUCTION
DAVE PREIKSHOT, UNIVERSITY OF BRITISH COLUMBIA FISHERIES CENTRE, VANCOUVER, BC

The impetus for this study arose from the shocking declines in early marine survival rates of South Puget Sound (SPS) coho salmon (*Oncorhynchus kisutch*) after 1990. This phenomenon coincided with declines in other species and prompted an inter-agency working group[1] to seek ways of investigating the ecological relationships between salmon and other marine organisms in SPS. Ecosystem modelling, and the Ecopath with Ecosim (EwE) software in particular were determined as the most efficient method to summarize marine organism relationships in response to changing anthropogenic and environmental stressors. In general, it was hoped that EwE could address the following areas of concern:

- assimilate the available data on the SPS area,
- organize that data in terms of biomass,
- determine the reliability of the available data, and
- determine relative marine productivity in SPS.

More specifically, it was hoped that the EwE approach could elucidate the factors influencing coho early marine survival rates and determine crucial trophic relationships among the organisms of SPS. The EwE modelling of SPS is envisioned as the first phase of a three-phase process to evaluate ecosystem-level processes in Puget Sound. It is hoped that additional funding might be obtained to complete phases two and three. The second phase consists of building ecosystem models for two other sub-regions of Puget Sound: Hood Canal and the 'Central Basin'. The third phase of this process involves the synthesis, evaluation, and potential application of the information derived in phases one and two for use in an ecosystem level assessment of Puget Sound.

In pursuance of the goal of constructing an EwE model of SPS, a research team was recruited from the UBC Fisheries Centre (UBCFC), led by Dave Preikshot, and includes Alasdair Beattie

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[1] Agencies represented on the working group were the Northwest Indian Fisheries Commission, the Puget Sound Water Quality Action Team, Washington State Department of Ecology, Washington State Department of Fish and Wildlife, Washington State Department of Natural Resources, Nisqually Tribe, Squaxin Island Tribe, University of Washington

(data analysis), Carl Walters (consultant), Villy Christensen (computer modeller), and Teresa Ryan (research assistant). Others involved with the project were Robert Pacht (independent consultant) and Kerim Aydin (consultant, University of Washington[UW]). Dave Preikshot and the UBCFC team were tasked with the development of a preliminary EwE SPS model for the North West Indian Fisheries Commission (NWIFC). The dynamic ecosystem model (the Ecosim component of EwE) was to represent potential changes in SPS from 1970 to 2000. Also included in the UBCFC tasking was the creation of two 'snapshot' models (the Ecopath component of EwE) representing potential states of SPS in the early 1970s and the late 1990s. Robert Pacht served as an interlocutor in the SPS area to help gather data and identify partners for the project. Kerim Aydin acted as a consultant on the bioenergetics of salmon growth and on the conflicts inherent in combining EwE with migratory species.

In order to facilitate communication between the UBCFC modelling team, local biologists and other scientists familiar with ecosystem level issues in SPS, the NWIFC hosted two workshops at their office in Olympia, WA. The data assimilation process culminated with the October 30th workshop at the Washington State Department of Ecology (WDE) office in Olympia, WA. The UBCFC team presented a preliminary SPS model at the October 30th workshop.

The following report is a detailed description of the process outlined above and the preliminary implications of the SPS EwE models. The organisation of the sections within follow a temporal sequence of the research, tempered by the logical necessities of building up the model and evaluating it. The next section is a general description of the SPS region and some of the biologically significant changes that have occurred over the last thirty years of the twentieth century. Each of the following sections describes how data were collected and applied to the SPS EwE model for different groups of species *boxes* within the model such as: birds, marine mammals, salmonids, demersal fishes, forage fishes, invertebrates, and primary producers. The last two chapters present the results of the EwE analysis by describing the Ecopath and Ecosim components and an over-all evaluation of the strengths and weaknesses of the SPS model.

In order to allow the report to have its emphasis on discussion rather than to serve as a series of

tables a CD-ROM was included with each copy of the report. On this CD-ROM you will find: spreadsheet files of original data used in the preparation of the Eopath 1990s and 1970s models, the software needed to install and run Ecopath with Ecosim (and the Ecospace software), and a user guide, in PDF format, to answer questions regarding all aspects of setting up and running EwE models. To install the EwE software run the setup.exe application. All of these tools should allow any interested parties to adapt the model to new data. Reading the user guide is highly recommended in order to get full benefit from all the options and subroutines in the package. Lastly, have fun with the models. The EwE models allow gaming out numerous scenarios, try setting up policies and see if the results 'make sense' or are surprising. Please use this opportunity to improve the model too. No model is ever finished and we welcome comments and suggestions to improve the models we have built

2. SOUTH PUGET SOUND NOW AND THEN: WHAT HAPPENED?
DAVE PREIKSHOT, UNIVERSITY OF BRITISH COLUMBIA FISHERIES CENTRE

2.1. The physical and chemical setting.

South Puget Sound (SPS) is defined in this study as the area of marine water in Puget Sound south of the Tacoma Narrows Bridge. It is the southern end of the larger Puget Sound fjord estuary complex. Many of the larger scale physical and chemical processes of Puget Sound are muted, or accentuated, in the smaller SPS sub-region. The total surface area of SPS is approximately 394 km² (W. Palsson, pers. comm.). The basin topography and hydrology present a unique set of conditions for physical and chemical interactions. Recognizing these unique physical characteristics may assist in understanding the biological changes SPS has experienced over the thirty-year period from 1970 to 2000.

As seen in Table 2.1, more than 50% of SPS is less than 36.6 m deep. Indeed, only a very small percentage is more than 100 m deep. Many of the shorelines are characterized by sandy beaches, often teeming with sand dollars. The relative shallow nature of SPS contrasts sharply with the rest of Puget Sound, such as the central basin, which has depths that often exceed 200m (National Oceanic and Atmospheric Administration [NOAA], National Ocean Service, 2000). This topographic contrast influences the manner in which waters are circulated through SPS. In the central or main basin of Puget Sound

(e.g., from Tacoma Narrows north to Admiralty Inlet), classic estuarine circulation of less saline water flows 'out' on the surface, while more dense saline and nutrient rich water flows 'in' near the bottom. Under favourable wind conditions, this circulation pattern provides an upwelling of nutrient rich waters to the photic zone in the southern part of the main basin that provides a high production of phytoplankton (Strickland, 1983). This 'conveyor belt' of production does not function as profoundly in SPS where seasonal production is heavily influenced by episodic weather events on the circulation in the inlets that dominate the physical structure of SPS.

Table 2.1: Constituent areas of South Puget Sound as defined by depth (Palsson, pers. comm. Washington Department of Fish and Wildlife, 600 Capitol Way N., Olympia, WA 98501-1091). Note that this table does not account for the intertidal zone.

Depth (fathoms, *meters*)	Area (km²)	% of total SPS area
1.0-5.0, *1.83-9.15*	109.17	27.72
5.0-20, *9.15-36.6*	127.15	32.28
20-40, *36.6-73.2*	94.62	24.02
40-60, *73.2-109.8*	33.9	8.61
>60, *>109.8*	29.04	7.37
Total	393.88	100.00

Figure 2.1: Map of the major physical features of South Puget Sound, waters north of Tacoma Narrows and within Hood Canal were not part of this study. Picture generated with TOPO! © 1998, Wildflower Productions (now National Geographic, see http://maps.nationalgeographic.com/topo/).

Case Inlet and Carr Inlet are larger and deeper than any other SPS inlets. These two inlets are positioned on a north/south axis, (i.e., causing prevailing winds to attenuate tidal flushing), and combined with relatively low freshwater input at their heads, results in poor mixing. Thus, these inlets tend to have episodic plankton blooms promoted by still water conditions, which quickly exhaust nutrients (Strickland, 1983). The other inlets and bays are quite shallow and branched, resulting in poor flushing and a similar pattern of blooms as Case and Carr Inlets. These poor flushing characteristics of SPS and the concomitant long residence time of its water, have raised concerns over the potential for both the build up of anthropogenic nutrients and pollutants combined with stratification, resulting in oxygen depletion (Puget Sound Water Quality Action Team, 2000). Budd Inlet, in particular, has been under scrutiny because of persistent problems of low dissolved oxygen (DO), due to persistent stratification and the decay of phytoplankton blooms. The direct influence of terrestrial derived nutrients and anthropogenic impact on the magnitude of low DO in Budd Inlet has been harder to prove though (Eisner and Newton, 1997). The dynamics of water movement and the chemical properties in SPS appear to have only recently come under close scrutiny with the development of longer time series data (Eisner and Newton, 1997). Studies for wider ranging analyses have been recommended to help prise apart the differences between daily, seasonal, and inter-annual changes in water quality (PSWQAT, 2000).

Another concern raised by long water residency is the potential of anthropogenic pollutants building up to levels that harm the florae and faunae of SPS. Landahl *et al.* (1997) found evidence of a linkage between three types of pollutants (polycyclic aromatic hydrocarbons [PAHs], polychlorinated biphenyls [PCBs], and metals) and depressed fecundity and survival rates in English sole (*Pleuronectes vetulus*) populations in the main basin of Puget Sound. Given the previous mention of estuarine circulation differences in SPS, long water residency reduces the flushing potential of anthropogenic pollutants, although it should be noted that SPS is more distant from Puget Sound's major pollutant sources, e.g., the industrial areas of Commencement Bay (Tacoma) and Elliott Bay (Seattle).

In addition to hydrodynamic and chemical differences between SPS and the rest of Puget Sound, there are also important distinctions in the characteristic substrata of the two regions. The shallow nature of SPS provides a greater amount of sandy habitat than found in the rest of Puget Sound. Two consequences of such conditions are: 1) different florae and faunae associate with the different sediment and benthos of SPS, and 2) an increased risk of pollutant concentration from land derived sediments in the SPS catchment. Llansó (1998) investigated these types of effects and found that inlet ends of SPS had lower species diversity compared to the rest of Puget Sound, and species present appear to be associated with a combination of fine sediments and low DO. The effect of accumulated pollution in the sediments and their associated faunae, however, is unclear.

Thus, fundamental aspects of the physical and chemical quality of SPS and Puget Sound, in general, have been poorly characterised. Statements presented here about the nature of these characteristics in SPS are qualitative for the best data available at this time. Nevertheless, one physical process that has been under close scrutiny of late is the effect of changing weather patterns on physical and chemical processes in SPS. Indeed, this has been a growing area of research for the past twenty years in the Northeast Pacific. Beamish (1995) found significant correlations between climate changes and fish populations for many fish species, including salmonids (genus *Oncorhynchus*), Pacific herring (*Clupea pallasii*), Pacific cod (*Gadus macrocephalus*), walleye pollock (*Theragra chalcogramma*), and species of zooplankton upon which many fish depend for food. Indices such as the El-Niño Southern Oscillation (ENSO), the Aleutian Low Pressure Index (ALPI), and interdecadal temperature regime shifts have been tied to the production of several major stocks of fish in the northeast Pacific (Ware, 1995; Beamish and Bouillon, 1995). Similarly, the Pacific Northwest Index (PNI) measures spring flow into Puget Sound and sea surface temperature for an index of climate change and suggests that higher marine survival of coho salmon is associated with cool wet years (Pinnix, 1998). Changes in primary production and physical oceanographic conditions in SPS caused by global warming, due to the accumulation of greenhouse gases, and inter-decadal climate patterns imply profound disturbances to SPS salmonid stocks.

This quick overview shows that several potential candidates exist in the realm of physical and chemical dynamics to help explain some of the biological characteristics of SPS. There seems to be a good mechanistic connection between SPS

in a physical sense and its creatures in a general sense. Unfortunately, assessments of long-term qualitative changes to Puget Sound, and SPS in particular, have failed to produce reliable time series data that allow more specific comparisons of how various species and physical parameters have co-varied.

2.2. Changes in the biological community of South Puget Sound: Into the Abyss

If inter-annual and decadal shifts in physical and chemical qualities of SPS have been hard to identify, it seems that there is more certainty in identifying declines in several of the animal and plant species found there. Still, although the direction of these shifts is often known, the exact magnitude has often been difficult to gauge. Another biological shift that has been obvious is the introduction of exotic species to Puget Sound. At least 52 non-indigenous species are identified in Puget Sound (PSWQAT 2000). Although the number that have penetrated to SPS itself is likely smaller, the effect might be even more profound due to the aforementioned species sparseness that is characteristic of many SPS habitats. Introduced species not only create new predation and competition for local species, they also confound baseline indicators for assessing populations, by shifting trophic linkages. The unpredictability of these shifts is often difficult to predict in both direction and magnitude. If a goal of modelling the SPS ecosystem is to observe how biomasses and trophic linkages between species of interest have shifted over the period from 1970 to 2000, then introduced species can only obscure many crucial changes. Examples of such effects can be seen in many of the commercially introduced bivalves in SPS, e.g., Manila clam, *Tapes philippinarium*, and Pacific oyster, *Crassostrea gigas* (Cheney and Mumford 1986 and Washington Sea Grant Program 1998). It would be difficult to conclude whether the decline of the local Olympia oyster, *Ostrea lurida*, has been due to fishing, competition from the introduced Pacific oyster, habitat changes, or some combination thereof.

One of the most critical declines is the marine survival rate of Puget Sound coho salmon, and in particular, the nose-diving marine survival rates of SPS coho. The Puget Sound coho marine survival pattern of the last 25 years is well represented with tagged of wild coho stocks from the Big Beef (Hood Canal), Deschutes (deep SPS), SF Skykomish (Central Puget Sound), and Baker (North Puget Sound) systems, has declined from a range of 16 to 23% in the mid

1970s to 2 to 20% by the mid 1990s, see Figure 1.2. From the mid 1970's to the mid 1980's overall Puget Sound marine survival hovered around 20%, with SPS exhibiting the highest rates while SF Skykomish, to the north, showed the lowest rates, see figure 1.2. During the late 1980's there was a generalized stepped decrease to roughly a 15% marine survival level, but now SPS began to show the lowest rates. Another step decline occurred in the early 1990's, and varied around the 10% level through the decade for three of the stocks. However, SPS coho continued their own downward trajectory, dropping further below the pack, and nose-diving from approximately 5% for the 1994-96 smolts to the 0.5%-2% level for the 1997-98 smolt years. Hatchery stocks have mirrored these overall patterns, but at even lower survival levels (A. Rankis pers. comm., Northwest Indian Fisheries Commission 6730 Martin Way E. Olympia, WA 98516-5540).

Figure 2.2. Marine survival rates for coho salmon since 1976, figure provided by D. Seiler (WDFW, 600 Capitol Way North, Olympia, WA 98501-1091). Note that preliminary data for the 1999 smolts shows increased survivasl rates (A. Rankis pers. comm. Northwest Indian Fisheries Commission, 6730 Martin Way E. Olympia, WA 98516-5540.
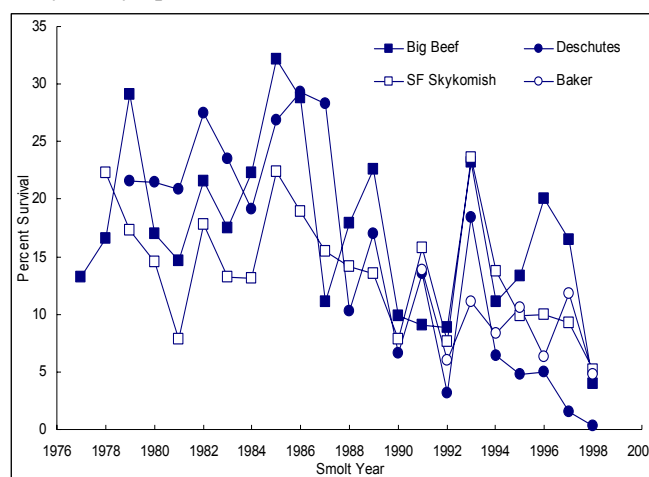
One potential explanation for this may be density dependent decreases in size, growth, and marine survival as observed in coho and sockeye (*Oncorhynchus nerka*) in the Northeast Pacific during periods of changing environmental conditions (Peterman 1984, 1991). The mechanisms through which density dependence operates are: 1) intra-specific competition affected by time and size of juveniles entering the marine environment; 2) inter-specific competition with other stocks when entering the oceanic environment; and 3) inter-species processes such as predation by marine birds that is often easy to underestimate (Peterman, 1991).

Density dependent decreases in survival rates should be of particular concern for hatchery programs. Wild fish unavoidable vary their overall abundance in response to existing environmental conditions, but hatchery production levels follow set programs that do not considered the marine conditions receiving their smolts.

Over the period from the late 1970s until the present, South Puget Sound has been subject to a dramatic change in salmon production strategies. This is particularly exemplified by coho salmon production. In the wake of the Boldt decision in U.S. v Washington, salmon management changed from wild stock management to hatchery management with concomitant increases in hatchery production. While several Tribes initially resisted the State of Washington efforts in this regard, the last agreement came in 1982, when, as a settlement of a Fishery Advisory Board dispute, the Squaxin Island Tribe agreed to hatchery management in South Puget Sound conditioned on a netpen enhancement program to boost production. Their concern was that fishing at a higher hatchery management rate in the intense Area 10 commercial net fishery would batter SPS wild coho stocks without a substantial presence of hatchery origin fish to buffer the impact. As a result of the agreement, hatchery origin production of coho smolts in deep SPS increased by over 2 million fish. While this production level initially saw very high survival rates, by the late 1990s survival had fallen to just a few percent.

Dr. Ray Hilborn (1992) provides some bleak graphs and poignant historical cases from British Columbia and Oregon to show that coho and chinook hatcheries tend to show initially high ocean survival rates that drop off as time passes. In "Salmon Without Rivers," Lichatowich (1999) provides a well-documented long-term history of the biological and political function that hatcheries have played in the Pacific Northwest. In his historical account, he notes:

> *Consistent with its history since 1872, hatchery enhancement in the 1970s was a house of cards – a house built on the shaky foundation of blind optimism, ideology, and shifting weather patterns. When the collapse came, it was impossible to sort through the cards to determine which one had caused the collapse. A task force of scientists assigned to evaluate the limited information available concluded that there were several possible explanations for the downturn in coho production, but the information was not adequate to determine which was the actual cause (Lichatowich, 1999).*

The case of SPS coho may be a similar "house of cards", thus we are seeking a tool to evaluate hatchery production in response to changing marine conditions, and potentially adjust hatchery production levels to respond to changing marine conditions.

The declines in coho stocks have been mirrored, even exceeded, by marine survival rate declines in SPS hatchery yearling chinook salmon, as seen in reduced catches of resident fish (the local blackmouth sport fishery) since the early 1980's, with a virtual collapse of the fishery throughout the 1990's (Doty, 1994). Interestingly, survival rates of hatchery sub-yearling fall chinook <u>have not</u> shown a similar dramatic downward trend; while the predominantly wild chum populations (also sub-yearling migrants) have actually seen steadily increasing abundance levels. Our challenge is to reflect these trends in the EwE modeling.

Other valuable fish stocks in SPS have experienced dramatic declines in the recent past. For example, Palsson *et al.* (1996) found eight of eleven stocks of demersal fish were at "below average or critical conditions" for the main basin of Puget Sound and SPS. Walters (1995) describes five ecological signals of non-sustainability seen in Pacific Coast fisheries towards the end of the century: 1) decreasing biodiversity, 2) habitat loss, 3) exceeding of carrying capacity, 4) suspicious declines (i.e., species other than that targeted, but associated with it in the ecosystem through predation or competition), and 5) impacts of climate change. Over the period from 1970 to 2000 SPS has experienced all of these. In fact, it seems that as the end of the century approached these symptoms accumulated rapidly in SPS.

Other organisms have experienced dramatic population changes from 1970 to 2000, although not all are in decline like the fish stocks discussed above. For instance, Nyeswander and Evenson (1998) showed that scoters (*Melanitta spp.*) and scaups (*Aythya spp.*) in northern Puget Sound have declined approximately 66% and 70%, respectively, in the 18 years leading up to 1997. Bufflehead and goldeneye (*Bucephala spp.*) populations, however, had remained stable, or may have increased somewhat over the same period. The population of harbour seals (*Phoca vitulina*) in SPS has apparently been increasing over the recent past (S. Jeffries, pers. comm.). More problematic, in terms of defining population trends over time, are organisms on the lower levels of the trophic pyramid in SPS. For example, distribution changes of kelp and

seagrass since 1970 are known in a very rough sense, but not in detailed analysis of aerial extent or production contribution (T. Mumford, pers. comm. Washington Department of Natural Resources, Department of Natural Resources Aquatic Resources Division PO Box 47027 Olympia WA 98504-7027).

One large unknown in SPS, and indeed many ecosystems, is the role of organisms such as jellyfish (jellies). To date, there is a paucity of scientific study for these organisms in the Pacific Northwest. Previous marine ecosystem modellers have had difficulty in measuring their trophic effects on other organisms because estimates of jellyfish biomasses may be wrong by an order of magnitude (Beattie, 1999; Dalsgaard *et al.* 1998; Arai, 1996). Knowing when jellies are abundant or not may be crucial to understanding fish production. There is growing evidence (Baird and Ulanowicz, 1989; Strickland, 1983) that jellies may represent a 'trophic shunt' diverting energy flow away from fish production. Further, estimating the contribution of jellies to the diets of organisms is problematic because they are very difficult to observe in stomach content samples.

Clearly, the modelling work done for this project represents a first step in trying to understand the information at hand, its quality, and what investigations will be necessary in the future to address potential gaps present in the model. The chapters hence represent the contributions of many people and there is ample data to construct a model of SPS that is informative. Hopefully the synthesis of information will prove the value of pooling information that is a consequence of ecosystem modelling. By combining the efforts of dedicated researchers and scientists trying to understand components of SPS, we may find the sum of knowledge is greater than the total of its parts. Additionally, we may identify those data gaps most hindering responsible and informed use of the Puget Sound ecosystem.

All species groups of the ecosystem model are represented by individual species biological information. The following sections include some discussion of data input for species biomass (B), production to biomass ratio (P/B), consumption to biomass ratio (Q/B), and ecotrophic efficiency (EE) with the assumption of reader familiarity with Ecopath (consult www.ecopath.org).

3. PHYTOPLANKTON
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An estimate of the annual average wet weight of phytoplankton per square kilometre of south Puget Sound was developed from chlorophyll concentrations in samples collected for the South Puget Sound Nutrient Study Model (SPASM). Five seasonal cruises, from December 1998 through July 2000, each collected depth-profile water samples at a set of 80 sampling stations located throughout south Puget Sound (figure to be provided showing the locations of the stations). Individual chlorophyll concentration data points from each cruise; December 1998, April 1999, September 1999, December 1999 and July 2000 were manipulated by three steps to calculate the required annual average:

1) a depth integrated estimate of chlorophyll density (mg/m^2) was calculated for each station from the sample data;
2) the south Sound chlorophyll density mg/m^2 for each cruise was estimated as the unweighted mean of the depth integrated values for all the stations sampled during the cruise; and
3) estimates of chlorophyll density for each cruise were combined to generate an annual average value.

The cruise averages were applied to various portions of the year to generate an estimate of conditions across the entire year. December data represent November, December, January, and February; April data represent March, April and May; July data represent June, July and August; and September data represent September and October. Therefore the annual average chlorophyll density for south Puget Sound was calculated as 4/12 of the average for the two December cruises plus 3/12 of estimate for the April cruise plus 3/12 of the estimate for the July cruise plus 2/12 of the estimate for the September cruise.

The SPS annual average chlorophyll density was converted to a wet weight of phytoplankton biomass by application of two conversion factors used previously in regional Ecopath models (Pauly and Christensen 1996): 60:1 carbon to chlorophyll; and 10:1 carbon to wet weight.

P/B was calculated from experimental data collected from the SPASM cruises. Five productivity measurements were collected on

each cruise as described in the Newton and Reynolds chapter of the SPASM Phase 1 report, (Washington Department of Ecology 2000). Using these experimental data to estimate productivity and the biomass estimates for each cruise, a P/B estimate was developed for each cruise. These estimates were combined in the same manner as the biomass data (Step 3) to generate annual average values of P/B.

4. ALGAE / KELPS / SEAGRASSES:
TOM MUMFORD, WASHINGTON DEPARTMENT OF NATURAL RESOURCES, OLYMPIA, WA &
DAVE PREIKSHOT, UNIVERSITY OF BRITISH COLUMBIA FISHERIES CENTRE

The waters of Washington are particularly well endowed with a diversity of more than 500 species of seaweed (Cheney and Mumford 1986) and SPS is no exception. Because tha focus of this modeling exercise was changes to vertebrates, especially fish and salmon, five groups of algae, kelps, and sea grasses were modeled for SPS: macroalgae (ulvoids), laminaria, floating kelp (*Nereocystis leutkeana*), eelgrasses (*Zostera marina* and *Zostera japonica*), and benthic diatoms. The area covered by these can vary greatly with season and substrate and it is therefore useful to keep in mind that parameters represent annual estimates and are not intended to capture the particular makeup of specific areas within SPS. Parameters for macroalgae and benthic diatoms were derived from Thom and Albright (1990) and estimated by T. Mumford. Floating kelp and laminaria parameters were also derived by T. Mumford. Parameters for eelgrasses were found in Thom (1990), Thom and Albright (1990), and estimated by T. Mumford. For the purpose of estimating biomass, these primary producers were assigned portions of an assumed habitat down to the 9m isobath, approximately 30% of SPS (see Table 2.1). Biomass for each group was then calculated as a function of production and total area occupied (see Excel® file on the attached CD-ROM).

5. ZOOPLANKTON / BENTHIC INVERTEBRATES:
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5.1. Zooplankton

Zooplankton biomass estimates come from Giles and Cordell (1998) study of zooplankton in Budd Inlet. After comparing results from 2 shallow and 2 deep water stations, measured annual average biomasses were almost the same (0.093 and 0.094 g dry weight per m3). As the average depth of Budd Inlet is 8.2 m (Eisner and Newton, 1997) and the dry to wet weight conversion is 1:9.17 (Sambilay, 1993; Purcell, 1996) for copepods, the dominant zooplankter (Giles and Cordell, 1998; Strickland, 1983: Simenstad, 1983), then the average zooplankton biomass is calculated from:

$$8.2 \text{ m depth} * 9.17 * 0.094 \text{ g/m}^3 = 7.07 \text{ g/m}^2$$

Because Venier (1996) found that half of the Strait of Georgia zooplankton biomass was herbivorous and half carnivorous, the same proportion was used here so the average biomass of each is $7.07/2 = 3.54$ g/m². Plankton P/B and Q/B estimates were taken from Dalsgaard *et al.* (1998).

Values for epibenthic zooplankton are based on Simenstad (1983) calculated standing crop of epibenthic organisms at 1.1 g/m³ within 10 cm of the bottom off Point Defiance, WA. So we can estimate the SPS epibenthic zooplankton biomass as 11 g/m² which is 0.11 tons/km². Epibenthic zooplankton P/B was set as the same value as used for herbivorous zooplankton mentioned above.

5.2. Benthic Invertebrates

Biomasses for wild shellfish, carnivorous invertebrates, and herbivorous invertebrates were based on Guenette (1996) (Appendix 1, Table L), and converted to depth strata provided by W. Palsson (pers. comm.) with SPS divided into two main areas, 0-35m, and deeper than 35m. These two depth-zones complement the benthic invertebrate habitats and were modified to agree with values in Dalsgaard *et al.* (1998). Parameterization for the farmed-bivalve groups was based on values for bivalves in Dalsgaard *et al.* (1998).

Harvests for predatory invertebrates and wild shellfish (i.e., bivalves) are based on Cheney and Mumford (1986), that shows about 2, 200,000 lbs. (i.e., 1000 tons, i.e., 2.538 ton/km²) of shellfish were harvested annually in SPS from 1978 to 1982. These catch estimates are used for predatory invertebrates and shellfish in the model, and given these groups' respective biomasses, the catch was divide up as follows: 3/7 parts (1.088 ton/km²) shellfish, and 4/7 (1.450 ton/km²) parts predatory invertebrates.

6. Herring, Forage Fishes & Demersal Fishes
Dave Preikshot, University of British Columbia Fisheries Centre,
Greg Bargmann & Wayne Palsson,
Washington Department of Fish and Wildlife, Olympia, WA.

6.1. Herring and Forage Fishes

Biomass for herring was based on a 10 yr mean estimate of spawning stock biomass (SSB) of Squaxin Passage and Quartermaster Harbour herring from WDFW data and Lemberg *et al.* (1997), divided by the area of SPS (394 km², see Table 2.1). The herring biomasses used were for SSB (i.e., 2 yr olds and above) and may thus underestimate true biomass in SPS. The whole Squaxin Passage SSB, and 10% of the Quartermaster Harbour SSB were used because Quartermaster Harbour is north of the SPS study area. Lemberg *et al.* (1997) state that slow growing stocks (e.g., Squaxin Passage and Quartermaster Harbour) probably spend their whole life in Puget Sound. Herring P/B was taken from Buckworth (1996a) and Q/B from Dalsgaard *et al.* (1998). Catches were derived from WDFW data (G. Bargmann, pers. comm. Washington Department of Fish and Wildlife, 600 Capitol Way N., Olympia, WA 98501-1091). Since biomass estimates for other forage fishes are simply not reliable, Q/B, P/B, and EE are based on Dalsgaard *et al.* (1998) because these are fairly conservative values (Christensen *et al.* 2000). Thus, the EwE balancing subroutine was used to set the biomass for other forage fish.

6.2. Demersal Fishes

Biomass estimates for demersal fish groups were taken from WDFW trawl surveys conducted in SPS during 1987, 1989, 1991, and 1996. A chartered fishing vessel towed a bottom trawl in a stratified systematic survey using the area-swept technique to estimate fish densities. The strata were based upon four depth categories: 5-20fathoms (fms), 21-40fms, 41-60fms, and >60fms. Determining the arithmetic mean of the densities and multiplying the averages by the area of each depth stratum estimated abundance and biomass. To approximate the 0-5fms stratum for the EwE model, the near-shore area was included in the 5-20fms stratum densities. The surveys were conducted in a larger SPS area, including areas adjacent and north of Tacoma Narrows. The 1996 survey was the only one to produce sufficient replicates within the SPS area to compute stratum means and areas. For trend analysis in the study area, the biomass estimates for the larger Puget Sound area were reduced by

the proportion of each stratum area south of the Tacoma Narrows to the original survey area.

Other trend data included catch rate indices developed from the recreational fishery for bottomfish in SPS. Annual averages for fishing success in terms of fish caught per targeted trip for bottomfish were compiled from 1977 to 1999 (see Palsson *et al.* 1997 for years and methods prior to 1995). Harvest data for fish and naturally produced shellfish were summarized from WDFW fish ticket data required of all fishers who sell commercially caught fish and shellfish. Demersal fish diets were based on three main sources: FishBase2000 (Froese and Pauly, 2001), similar groups from previous Northeast Pacific EwE models (Dalsgaard *et al.*, 1998; Beattie and Haggan, 1999; Okey and Pauly, 1999), and Casillas *et al.* (1998).

7. Salmonids
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Andy Rankis, Northwest Indian Fisheries Commission, Olympia WA, &
Kerim Aydin University of Washington School of Fisheries

7.1. General Issues

The salmon data set proved to be challenging for the parameterization of the SPS EwE models. On the one hand, there was a relative wealth of information on the numbers of salmon, due to: the commercial (fish ticket receipts) and sport catch (salmon "punch cards") accounting systems, hatchery release records, counts of adults returning to hatchery facilities, estimates of adults returning to freshwater areas, and marine distribution and survival rate information from coded wire tagging (CWT) programs. This information is generally of better accuracy and precision than for many of the other organism groups in the model. On the other hand, the focus on managing the SPS region for hatchery production has resulted in minimal assessment of natural salmonid production; the exception being the wild coho smolt (and adult) trapping and tagging program in the Deschutes River. Estimates of adult returns to freshwater streams are combinations of hatchery strays (often in systems which are, at most, only marginally suitable for limited natural juvenile production) and a few spawner indexes (often with large expansion factors). Further, no assessment exists on either juvenile salmonid usage of SPS marine waters, or the portion of yearly adult production resulting from residency

in SPS - even though historically feeding coho and chinook have always been found year-round in SPS. Over the past quarter century, large scale hatchery manipulations of release timing have been implemented to disrupt natural migration behavior of coho and chinook and encourage greater residency to support the local marine sport fishery. However, these actions were done without goals or measurements of the attainment of such goals to verify the success of such programs. In addition to the uncertainty regarding the level of production that actually does occur within the marine waters of SPS, the majority of SPS salmon move to the continental shelf, or even the open ocean of the Northeast Pacific, passing much of their lives outside of this model's area.

Figure 7.1a and 7.1b: Changes in coho juvenile and adult biomasses over time in SPS
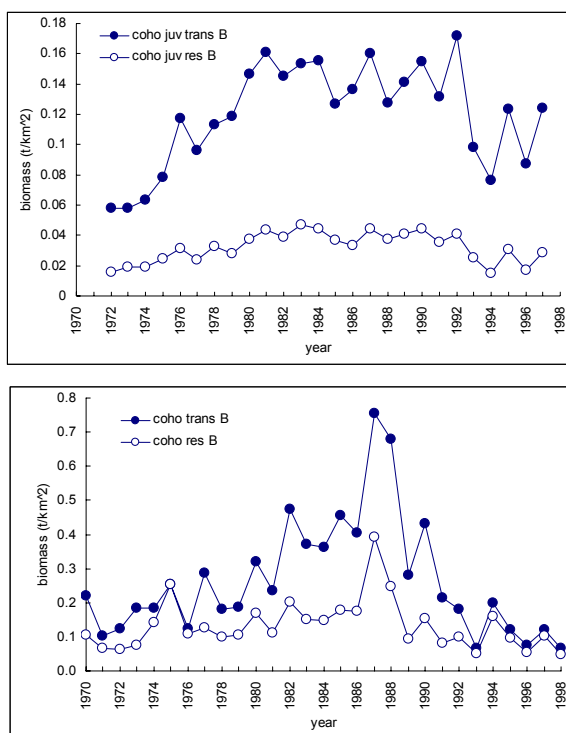
The salmon data for all of these groups was derived from WDFW reports and databases; then summarized for subsequent calculation of model parameters. Jeff Haymes, WDFW 600 Capitol Way N. Olympia, WA, 98501-1091, constructed an Excel spreadsheet with all Puget Sound area hatchery releases from brood years 1970 through 1995, and summarized the SPS releases. Andy Rankis, NWIFC 6730 Martin Way E. Olympia, WA 98516-5540, summarized relevant data from Puget Sound salmon run re-construction reports (commercial catch and escapement estimates), and produced estimates

of potential natural smolt production from SPS areas. Don Noviello, WDFW 600 Capitol Way N. Olympia, WA, 98501-1091, provided monthly summaries of salmon sport catch in the SPS model area for 1976-1998. Note that sport catch of SPS salmon outside of the SPS area was not available. In total these data provided estimates of; hatchery plus natural / normal timed and delayed smolts entering SPS, terminal adult run sizes to SPS of the three dominate salmonid species, and commercial catch numbers of SPS salmon through the Puget Sound system.

The original configuration of the salmonid groups was a source of much debate among the participants during teleconferences and workshops. As many as 14 separate salmonid groups were proposed originally for the SPS EwE model. These groups were derived from a consideration of how SPS is used over time by the three salmon species dominant in SPS: chum, chinook, and coho (pink salmon, having a minor presence in SPS, were included with chum). Chinook and coho were further subdivided into hatchery and wild boxes, which were further subdivided into resident and transient boxes. All boxes were also put in tandem with an adult box. It became apparent, however that the above described groupings were not feasible to construct from either an ecological logic or the manner in which salmonid populations have been monitored. To rectify this situation, wild coho and chinook groups were combined with normal timed hatchery coho and chinook, resulting in the ten groups adopted for the model: adult chum/pink, juvenile chum/pink, adult normal coho, juvenile normal coho, adult delayed coho, juvenile delayed coho, adult normal chinook, juvenile normal chinook, adult delayed chinook, and juvenile delayed chinook.

Figure 7.2a and 7.2b: Changes in chinook juvenile and adult biomasses over time in SPS. note that chinook normal juveniles (solid circles) are measure on the left hand y-axis of Figure 7.2a and extended (or delayed release) juveniles (hollow circles) are measured on the right hand y-axis.
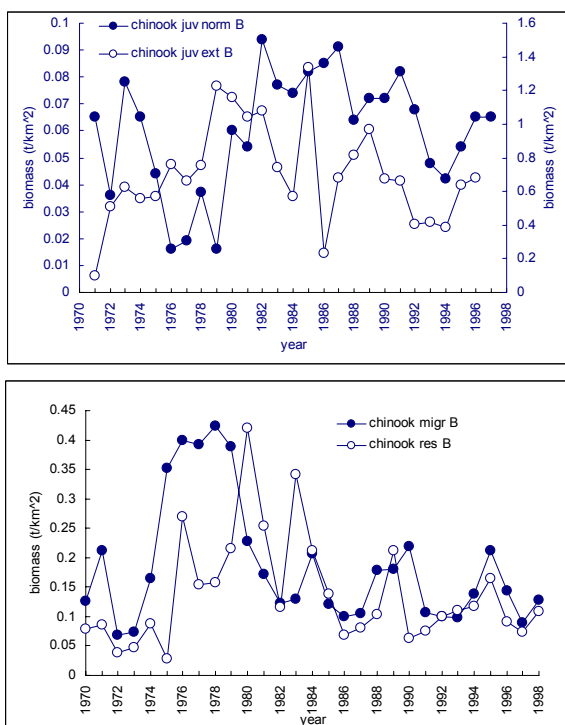
Figure 7.3a and 7.3b: Changes in juvenile and adult chum biomasses over time in SPS.
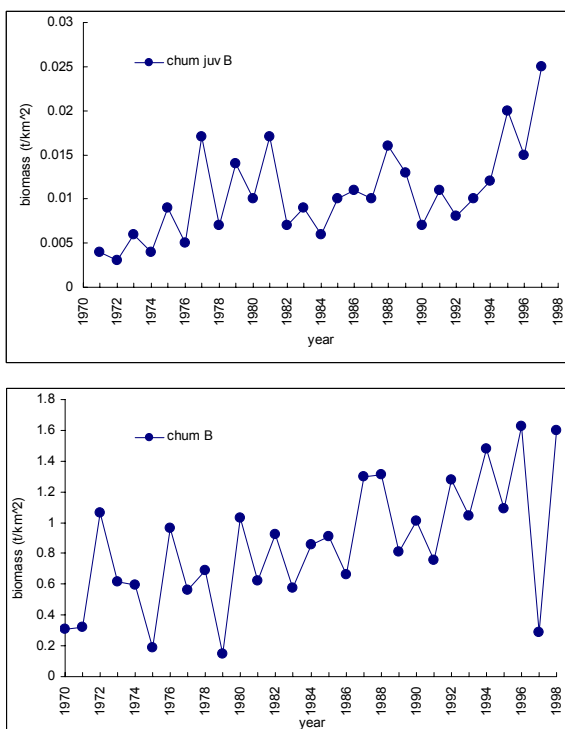
A note on terminology must also be included at this point. Due to the problem of separate definitions of outgoing smolts, i.e., 'normal' and 'delayed / extended' versus resulting adult rearing behavior, i.e., 'transient / migratory' and 'resident, settling on a terminology for the salmonid groups proved to be problematic. In the model we have used the terms transient and migratory interchangeably. In the case of the juvenile chinook all delayed / extended individuals were assumed to become residents, whereas all the normal juveniles became transient / migratory adults. Therefore for the sake of making the defined groups appear rational the names of the juvenile groups are resident and transient chinook juveniles. In the case of juvenile coho the transition is murkier. For the derivation of adult 'transient' and 'resident' coho biomasses, calculations were used which relied on assumed contributions from the 'normal' and 'delayed' juvenile groups. The 'resident' and 'transient' coho juveniles, then are a mathematical consequence of the proportions contributed by the normal and delayed individuals each year. Please refer to the relevant excel spreadsheet for the details.

Fig 7.4a and 7.4b: Sport fishery harvest on coho and chum salmon groups and commercial harvest of chum in SPS. Note that 7.4a begins at 1976 because that was the first year for which sport catch data for the SPS model area was recorded independently from a larger catch reporting area.
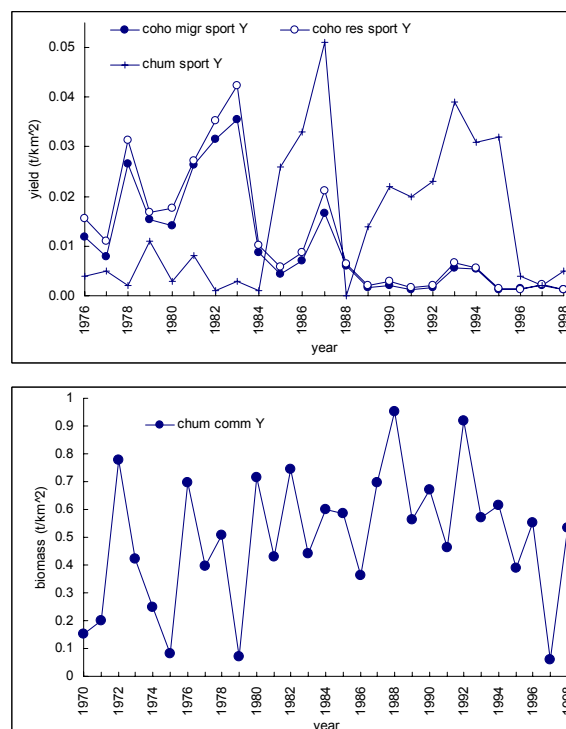
It is important to understand why the modeled salmon groups combined wild and hatchery fish. Historically, SPS was widely productive for wild chum and coho, but wild chinook were probably limited to the Nisqually River. Anthropogenic changes to freshwater habitat have altered conditions to greatly reduce coho and chinook natural production (Weitkamp *et al.* 1995 and Myers *et al.* 1997). Apparently such changes have been less harmful to SPS chum which use freshwater habitat during a smaller portion of their life history (Johnson *et al.* 1997). Wild chum production continues to dominate hatchery production in this region, and for this reason chum were modeled as a wild population. However, chinook were modeled for hatchery production as the present hatchery production levels far surpass seven potential historic SPS wild chinook production levels. One may speculate that historic wild coho production was similar to present day hatchery plus wild production, but during the model period (1970-1999) hatchery production clearly dominates any potential natural coho production from the relatively degraded habitat . Thus, the provided coho data was also to be modeled as hatchery fish. The data available for natural salmon, from PS Run Re-construction, does estimate the number of fish escaping into freshwater stream but for coho and chinook this escapement is very often derived from hatchery strays and not representative of wild production (Weitkamp *et al.* 1995 and Myers et al. 1997). Despite such problems, this information was used to estimate the potential natural smolt production which theoretically could occur for a given year. As natural smolt estimates were largely a function of returning hatchery adults the numbers were combined to be modeled as coho and chinook hatchery groups, as explained above.

Figure 7.5a and 7.5b: Commercial harvest of coho and combined chinook commercial / sports harvest in SPS, note that these values begin in 1976 to facilitate comparison with sport catch data shown in Fig. 7.4a.
Note also that the chinook resident sport harvest for 1980 was off the chart at .274 t/km^2!
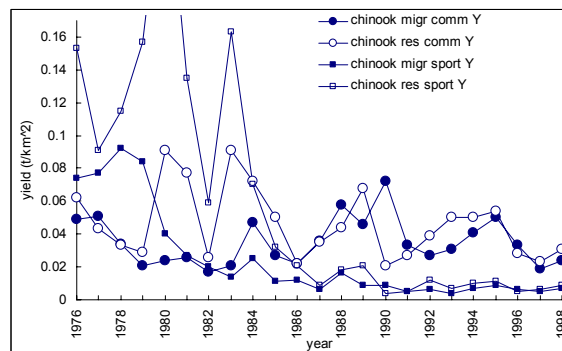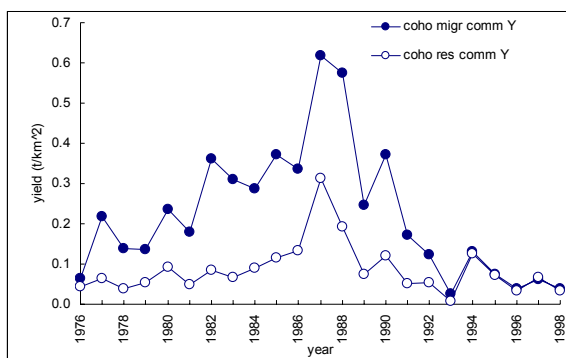
In order to account for the peculiarities of the different residency times of the various juvenile groups in SPS parameters for these groups were generated via a bio-energetics model devised specifically for this project by Kerim Aydin (University of Washington School of Fisheries), see section 7.4. The bioenergetics model provided biomass estimates for each year between 1970 and 1999 for all of the juvenile groups in the model. Dr. Aydin's model also provided estimates for juvenile salmon P/B and Q/B.

7.2. Biomass and Catch Estimations

For adult salmonid groups the chief problem of parameterization lay in the reality that defining the adults as resident or transient was ecologically relevant, but the way the adult coho and chinook have been counted makes no direct distinction as to resident or transient behavior. Similarly, while the outgoing delayed or normal smolts are easy to account for in any given year, there is no accepted way to decide how many of either group become resident or transient adults in any given year. For the purpose of the model we assumed that there were fixed relationships between which outgoing coho and chinook smolts became resident or transient adults. To account for this, an algorithm was devised to take the adult counts and convert them into adult resident and adult migrant numbers. The method for doing this was based on several assumptions and rules;

1) similar survival rates of normal and delayed smolts over time,
2) fixed rates of conversion of normal and delayed smolts into resident or transient adults over time,
3) the amount of time adults spent in SPS during the year,
4) using the above three rules to divide up fisheries yields between resident and transient salmon.

To view the actual calculations, the reader is invited to consult the data files on the CD-ROM distributed with the report. It must be stressed that the large number of assumptions, which were often fixed over time, are likely to produce estimates of biomass for any given year that are inaccurate by up to an order of magnitude. Nevertheless, the general trends of biomass over time correspond with what local experts have seen in terms of decadal changes in abundance over the 30 years between the two Ecopath models. For this reason the numbers provide a useful guide to the modeling since they are accurate in a relative sense and in the absolute direction of their changes over time, see e.g., Figs 7.1. to 7.3. For the purposes of the two Ecopath steady state models, therefore, input B values were the values derived at the beginning, i.e., 1970, and end, i.e., 1998, of the time series values reproduced in Figs 7.1. to 7.3. The reader is advised that this process is not a replacement for a valid stock assessment for the groups described, rather, it provides a 'back of the envelope' estimate of general changes in the populations, necessitated by the time and financial restrictions of the project. The inclusion of a valid salmonid stock assessment in future EwE models of SPS in particular and Puget Sound in general is, thus highly recommended to increase the accuracy of both the Ecopath and Ecosim portions of such studies.

When examining these figures, the reader should bear two important caveats in mind. The first is that because the migrating juvenile and adult salmonids spend only a small portion of any year in SPS, their B values appear to be lower than might be expected. The reason for this is that the models were designed to account for average annual behaviour, so the input B values for transient salmonids was their average biomass in SPS for the whole year. This means that in the case of adult chinook, which spend ~25% of the year in SPS, the effective biomass is 25% of what was actually measured when they returned. This same effect carries through to the fished biomass, i.e., the yield values used to account for fishery effects in the models. The second is that the fixed rates used to convert juvenile to adult biomasses, when combined with the time weighting described above create anomalously high B values for many years, e.g., resident chinook B in 1980. Figs. 7.1. – 7.5. should be interpreted with the understanding that the values represent mathematical artefacts used to create effective averages to allow the models a way to deal with the unique life history of salmonids.

The process of assigning the commercial and sport catch data to the transient or resident chinook and coho groups was similar to that described above for the biomass data. The difficulty in assigning sport and commercial harvest values to the adult salmonid boxes lay in that neither accounts for whether the fish caught were resident or transient. Assumptions on the proportions of these are crucial to understanding the different dynamics that have occurred among salmon species and among resident versus transient populations. Fish entering SPS were taken to all be transients. Thus, as with biomass estimates, assigning transient and resident values to sport and commercial catches within SPS was done by making the resident or transient proportion of the catch a function of the ratio from delayed and normal smolt contributing to that adult return year. These values were also assigned time weights and as with biomass has a strong effect on the values shown in Figs. 7.4. and 7.5. Another consideration is that the effect of commercial fisheries outside of SPS is included in the time series of commercial catch values.

7.3. Diet Composition

Diet compositions for salmonid groups provided another challenge for the SPS model, because of the transitory nature of these fish. Juveniles entering SPS have a significant portion of their diet arising from terrestrial insects, thus an import, yet no quantitative study showed what the timing of shifting to a marine based diet might be. Fresh *et al.* (1979) reported results of limited qualitative diet studies of salmonids and other fish species in Nisqually reach. Inadequate data on diet composition is a common problem when assembling EwE models, because previous work on fish population dynamics has regarded species as isolated from each other (Christensen *et al.* 2000). This problem is critical because "It is easy to overlook a minor diet item in specifying diet composition for some predator. Unfortunately, while that prey type may not be important for the predator, it may represent a very large component of total mortality for the prey type" (Christensen *et al.* 2000). This problem of vulnerability of a prey is manifested in two ways for the salmonid species in the SPS EwE model. In the first case we may under estimate the mortality of juveniles in SPS if they are not represented in diets of predators. Secondly, we might underestimate the true impact of transient adult salmonids, which may represent significant mortality on some prey items.

Based upon the observations of Greg Cloud, WDE, SW Regional Office, P.O. Box 47775, Olympia, WA, 98504-7775, chum salmon adults were assumed to not actively feed when returning through SPS. Juvenile chum were assumed to be in SPS for 3 months. Diet composition (and all parameterization) for this group was based on chum as they have an order of magnitude higher biomass than pink salmon. Salo (1991) states that "in the near-shore waters of Puget Sound and British Columbia, the diet for chum juveniles is dominated by harpacticoid copepods and gamarid amphipods." He also notes that land based dipterans are important to many stocks.

For coho salmon Sandercock (1991) says that invertebrates make up about one fifth of the diet, while forage fish and herring with some demersals make up the rest. Transient coho adults were held to feed a very little amount during an assumed transit of three months through SPS. Juvenile coho diet was based on 3 month residency for those becoming transient adults. Diet composition came from Sandercock (1991) who points out that the juveniles become more piscivorous as they grow so the delayed coho juveniles were assigned more fish in their diet composition as a large proportion of them remain in SPS permanently.

For deriving resident adult chinook diets, Healey (1991) noted that herring is the largest contributor in the Gulf of Alaska (~65%), whereas herring and sandlance dominate in Strait of Georgia, with little predation on other salmon juveniles. Transient adult chinook were assumed to feed on forage fish for one month out of the three they are present (Greg Cloud, pers. communication, Dept of Ecology). Healey (1991) characterized juvenile chinook as feeding mostly on land based insects although some amphipods, copepods, and forage fish appear opportunistically. For the model we assumed the delayed chinook juveniles ate more forage fish as they grew.

7.4. A salmon bioenergetics model

One fundamental assumption of an Ecopath model is that the ecosystem is relatively "closed." That is, the species in the model spend most of the year within the system. Salmon present a specific challenge for such models, as their life cycle takes them through a range of habitats. In SPS, salmon smolts have an intense but brief impact as they pass through the ecosystem. Moreover, while food availability and predators affect the growth and survivorship of smolts,

these effects may be overwhelmed by out-of-system influences such as hatchery stocking or ocean mortality. Thus, changing estuarine conditions may not have a strong feedback in determining the year-to-year variation in smolt biomass.

While salmon have been included in several Ecopath models (e.g. the Strait of Georgia, Dalsgaard et al. 1998), these models have either modeled "area resident" or have downplayed the migratory aspects of the salmon. In SPS the fundamentally migratory dynamic of salmonids can not be ignored. The appropriate parameterization of migratory salmon in SPS models should thus be considered from both a mass-balance (Ecopath) and dynamic (Ecosim) perspective.

From a static (Ecopath) perspective, the total (net) migrations of a species through the system must be explicitly modeled. Furthermore, if the species only spends part of its life cycle in the system in question, B, P/B and Q/B must be scaled for life stage and residency in the system. It is recommended in Ecopoath literature (Christensen et al. 2000) that P/B is equal to mortality (Z), following the derivation in Allen (1971). However, if a species only spends part of its life in a system, this estimation technique may be inaccurate.

From a dynamic (Ecosim) perspective, if a model is used to project year-to-year changes in salmon B, it must take into account both in-system and out-of-system influences, or use smolt B as an input rather than an output of the model. If juvenile and adult groups are linked, they should not be parameterised via "default" growth equations designed for species with a long-period age structure.

Here, bioenergetics models, on the scale of individual salmon smolts, are used to examine the rates of production and consumption of salmon in SPS. Bioenergetics models are an excellent complement for Ecopath, as they also rely on the principle of mass-balance, but on the scale of individuals. Bioenergetics models combine laboratory-measured physiological parameters with field-measured environmental data to determine instantaneous daily rates of somatic growth for a given fish, fed a given ration in a given environment. Parameter sets for many fish have been published (e.g., Hewett and Johnson 1992) and ecosystem-level estimates of growth and consumption for salmon have been quantified using these models (e.g., Stewart and Ibarra 1991; Mason et al. 1998).

To calculate population life-history statistics, bioenergetics models are used in conjunction with simple population and migration models as shown in Fig. 7.1. The bioenergetics model in the center of Figure 1 calculates a daily energy balance which assumes that all energy entering and leaving a fish must be accounted for. The general model formula is:

$$G = C - (R + F + U)$$

where C is a fish's daily consumption (in food calories), G is the expected body growth, R (respiration) and $F+U$ (egestion and excretion) are heat and material losses respectively, arising from the process of metabolism. The benefit of bioenergetics modeling is that R and $F + U$ can been parameterized from laboratory experiments as functions of C, G, water temperature, and fish body size. The formulae, parameters and references for the models used for pink, sockeye, coho, chum and chinook salmon and steelhead trout are given in Hewett and Johnson, 1992.

Figure 7.6. Diagram of modeling method for combining bioenergetics and population parameters to determine Ecopath parameters for salmon smolts (*average includes months with no biomass).
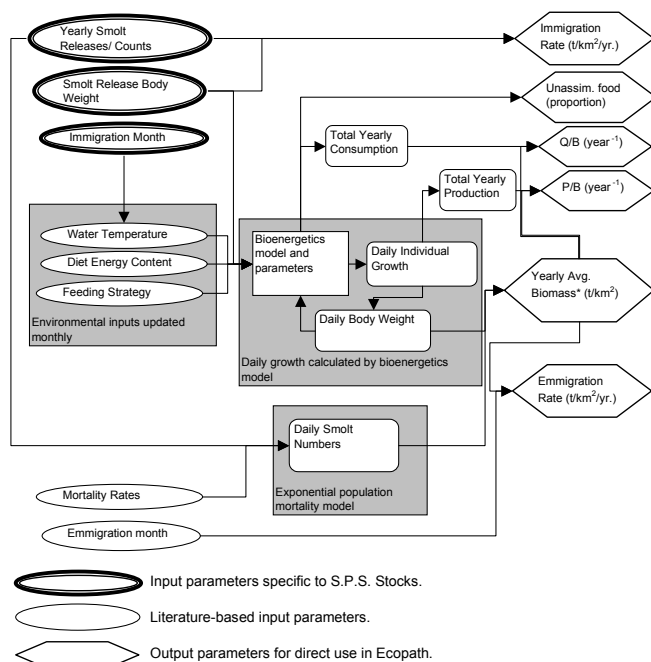
Figure 7.7. (a) Numbers (as a percentage of entering smolts), (b) body weight, and (c) biomass per smolt of two cohorts of coho salmon released into SPS in April at 100g body weight, and emmigrating in July. Biomass and changes in body weight were summed or averaged over whole year to derive Ecopath estimates of B, P/B and Q/B. Arrows show yearly immigration and emmigration. Slight monthly "shifts" in biomass estimates are due to some input values being month-specific.
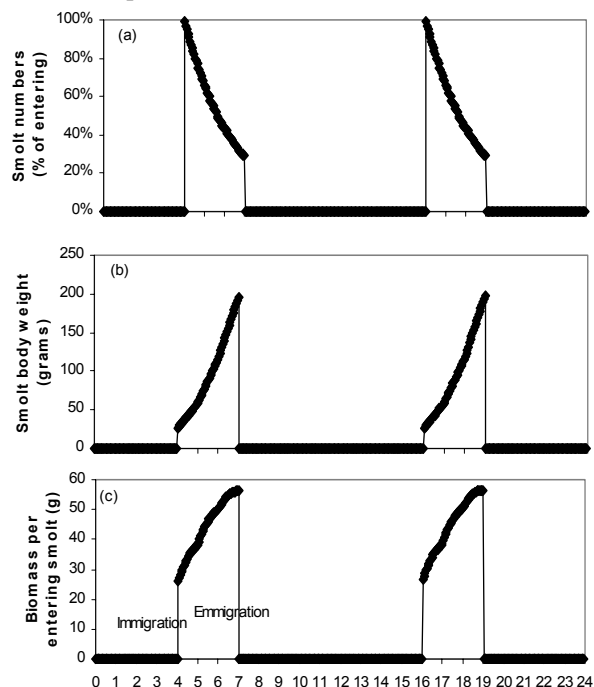
The inputs to the SPS model, as shown in Fig. 7.1., are: smolt release/counts, entry month, and body weights, specific to each stock, SPS water temperature in the late 1990s, averaged by month (WSDOE 2001), mortality rates, diet caloric content, emmigration month, and smolt 'feeding strategy' specific to species. These last four parameters were not available on a stock-specific basis, and were taken from literature. Mortality rates and residence times were taken from species and region-specific values in Groot and Margolis (1991). Diet quality data came from Higgs *et al.* (1995).

Feeding strategy (amount of food consumed per smolt per day as a proportion of the physiological maximum) proved difficult to estimate. Based on high estuarine and nearshore growth rates reported in Groot and Margolis (1991), it was decided that all salmon would be considered to feed at their maximum physiological rate for the given water temperature and prey composition. This decision has the advantage of providing the *maximum* possible impact that a given

population size of salmon might produce in SPS, which is useful in the Ecopath context of determining the carrying capacity of smolts in the modeled system.

This version of the model is parameterized for a daily time increment. The model will predict, in each day, the amount of somatic growth (*G*) experienced by the fish, the unassimilated fraction of food *(F + U) / C*, and the respirative fraction of the food *(R/C)*. These were averaged or summed throughout the residence time for each separately modeled group. Averaging was done on a yearly basis, including months with no biomass or growth for each group (Figure 7.2.). The averaging, combined with population estimates, was used to calculate the following six Ecopath parameters for each defined salmon group: B, P/B, Q/B, unassimilated fraction (proportion), Immigration (t/km²/year), and Emmigration (t/km²/year).

Table 7.1. Comparison of bioenergetic (yearly) PBs and QBs calculated for smolts during their residence in South Puget Sound and Z-based PB and QB values for selected salmon stocks.

SPS Species or Stock	Bioenergetic SPS Smolt PB	Juvenile Z estimate	Bioenergetic SPS Smolt QB	Z-based QB estimate
chum/pink smolt	20.1	2.4	75.6	7.5
coho outmigrating smolt	8.3	1.3	30.2	3.9
coho resident juvenile	4.6	1.3	19.7	3.9
chinook outmigrating smolt	8.2	1.3	47.4	3.9
chinook resident juvenile	1.7	1.3	10.7	3.9

It is interesting to compare estimates of P/B and Q/B obtained by this method with estimates derived directly from estimates of Z (Table 7.1.). The production rate of smolts during their brief residence in SPS may be up to an order of magnitude higher than their natural mortality. While the chosen feeding strategies model the maximum salmon production rate, actual rates would be expected to be 25-50% lower, rather than a full order of magnitude lower as suggested by the Z-based estimates. Clearly, these high growth and consumption rates should be taken into account in computing the mass balance of the ecosystem.

For these bioenergetic calculations, B and migration rates vary yearly as a multiple of entering smolts, but P/B and Q/B values are considered to be independent of population size, a weakness in the bioenergetic model. These consumption and production methods may be an overestimate if differential survival occurs based

on growth, or if feeding opportunities are substantially reduced as the smolt releases approach the system's carrying capacity. At present there is little data to evaluate the relationship between salmon numbers and growth rates in SPS. A systematic survey of smolt growth rates in the region would substantially improve the estimates of growth and consumption presented in this model.

8. BIRDS
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The marine bird data sets used in this EwE exercise were based on seven groupings of marine birds that are the most common species observed in the marine portions of SPS waters at different times of the year. These groups, listed in decreasing order of abundance, include diving ducks, gulls/terns, dabbling ducks, loons/grebes, cormorants, alcids, and herons.

The biomass estimates were based on the average stratified densities (< or > 20 meters) seen for winter and summer aerial surveys conducted by Nysewander and Evenson, WDFW, for the Puget Sound Ambient Monitoring Program (PSAMP) between 1992 and 2000 for the study area. These densities were then extrapolated to the total areas of each stratum. Average body weights (Dunning, 1984) were used to derive subgroup biomasses. Ratios of relative abundance by season (fall, winter, spring, and summer) were used for these species groups (as in Wahl *et al.*, 1981) to come up with weighted annual estimates. Final biomass values were doubled to account for birds missed by the aerial survey, a conversion often used by the principle author (Connant *et al.* 1988). Changes in numbers over time were estimated from changes seen over the eight year PSAMP survey period and from comparisons with Wahl *et al.* (1981).

Previous Ecopath exercises, either Prince William Sound (Okey and Pauly, 1998) or Georgia Strait (Pauly *et al.* 1998), were used for estimates of P/B and Q/B. Diet composition was estimated for the seven species groups from the following sources: Bellrose (1976), Clowater (1993), Hirsch (1980), Johnsgard (1975), Martin *et al.* (1951), Okey and Pauly (1998), Robertson (1974), Sanger (1987), Simenstad *et al.* (1979), Vermeer and Ydenberg (1989), Verbeek and Butler (1989), and Wilson and Manuwal (1986). Diets can vary considerably by site and relatively

few studies have been done in inner marine waters of Washington or nearby Strait of Georgia for these bird species. The data presented represent our assimilation and summary of the above sources.

9. MARINE MAMMALS
DAVE PREIKSHOT, UNIVERSITY OF BRITISH COLUMBIA FISHERIES CENTRE

Three marine mammal groups were included in the SPS EwE model: sea lions, toothed whales, and harbour seals. The sea lion group consists of male California sea lions (*Zalophus californianus*) that move into the Puget Sound during the fall and leave in the late spring (Jeffries *et al.* 2000). The sea lion population appears to be stable without significant changes since about 1970. Biomass for sea lions is based on a consideration of rough counts of individuals at four known haulout sites (Jeffries *et al.* 2000), and the average weight of male California sea lions. Parameterization for P/B and Q/B is based on values for Steller's sea lions (*Eumatopias jubatus*) in Trites and Heise (1996). The sea lion diet composition is also based on values for Steller's sea lions from Dalsgaard *et al.* (1998), and Beattie and Haggan (1999).

Harbour seals (*Phoca vitulina*) are included in the model and interestingly, unlike many other predators in the model, they appeared to have increased in numbers over the last 30 years. In order to accommodate this increase, they were assigned a biological accumulation rate of 6% per annum (S. Jeffries, pers. comm.). Biomass for the present model was based on the following relationships: 45% of population male, approximately 140 pounds each, and 55% of population female, approximately 110 pounds each. The B of SPS harbour seals for the 1970s model were estimated by deflating the present day biomass by 6% per year back to the first year of the model project period. Harbour seal diet composition is well known due to detailed scats studies done by the WDFW under the supervision of S. Jeffries (pers. comm.).

Toothed whales (e.g., porpoises, dolphins, and orcas) were included in the models as a unified group due to the episodic appearances of one, or a combination of them, in SPS. Parameterization for B, P/B, and Q/B were taken from Wada (1996) based on estimates of a similarly structured group in the Strait of Georgia.

10. BALANCING & ANALYSING THE SOUTH PUGET SOUND ECOPATH MODELS
DAVE PREIKSHOT & ALASDAIR BEATTIE, UNIVERSITY OF BRITISH COLUMBIA FISHERIES

In this section, the process of balancing the Ecopath static models (SPS 1970 and SPS 1999) is discussed, followed by a description of some of the Ecopath program outputs, which indicate several aspects of SPS ecosystem-level changes. All tables containing input values can be found on the CD-ROM attached to this report. They are not included in the text due to the large size of the SPS EwE model data files. The general ecosystem observations for the two static models are then compared to some of the known species changes in particular. The mechanisms for parameter changes discussed in this section can only be suggested from a comparison of the two Ecopath models of SPS. The following section (11) describes the dynamic simulations run with Ecosim (from 1970 to 1999) to examine the mechanisms that best explain differences between the two models. Policy options for future management strategies, using the SPS 1999 model as a starting point, were also explored. Given the Ecopath and Ecosim results, then, interested parties can develop both hypotheses and informative research projects to field-test mechanistic changes to the SPS ecosystem.

10.1. Balancing the models: SPS 1999

The organisms within an ecosystem and their interactions represent the ecological capacity in terms of their biomasses. In any Ecopath model, it is highly unlikely to balance the model with original raw data because of parameter error. For example, as mentioned in the salmonid Section 7, the DC information is often unreliable. In this particular exercise, the DC table contained most of the parameter changes in the process of balancing the model. To see the parameters with which the model was originally conceived refer to the table on the CD-ROM. The actual commands and protocols used in the EwE program are not described here. Rather, the major changes in parameterization and their effects are described. The model is accessible for readers to explore and re-parameterize it with higher quality information as it becomes available. The description below also serves as an heuristic guide to illustrate the exercise of balancing a model. For a guide to Ecopath model balancing procedures, see Christensen *et al.* (2000).

When the model was first prepared it was done with the original 14 salmon groups described at the start of Section 7. Thus for the many of the steps below the balancing was done with regard to those original salmon species. Because the ten new salmon species were formed by an amalgamation subroutine within Ecopath, the changes invoked in the original salmonid groups were implicit in the ten that were ultimately analyzed in the models.

10.1.1. Primary Producers

Originally the model was prepared with EE values for the primary producers. These were removed, and left as unknown, because small changes in EE resulted in wild positive and negative fluctuations in BA for these groups. All biomasses for primary producers were reassessed and adjusted to the upper limit of estimations for SPS made by T. Mumford, WDNR (see Section 4). Shifting herbivore diets to reflect more macroalgae consumption, especially for herbivorous invertebrates, decreased values for grazing on eelgrass, laminaria, and floating kelp.

10.1.2. Invertebrates

The P/B values for all farmed bivalves were set to similar values as for wild bivalves. Also, all farmed bivalve diets were modified to include detritus. Increasing predator selection of predatory invertebrates, grazing invertebrates, and herbivorous zooplankton decreased predation pressure on squids, carnivorous zooplankton, and epibenthic zooplankton. Carnivorous zooplankton DC also shifted to include more phytoplankton and far less epibenthic zooplankton because the mortality for epibenthic zooplankton was too high.

10.1.3. Salmonids

Predation on chum adults and juveniles had to be decreased, especially that arising from marine mammals and other salmonids. This lost predation was replaced by herring, predatory invertebrates, and in the case of chinook and coho juveniles imported prey items (e.g., insects from the land). Ratcheting down their contribution to the DC of marine mammals and dogfish reduced predation upon chinook wild transient juveniles, this lost predation was shifted to chinook resident juveniles. After the assimilation procedure, the adult salmon biomass values were updated for the ten new salmon groups. This resulted in little change to the overall ecological balance of salmonid groups *vis a vis* their predators, competitors, and prey. To allow the model to more realistically use the B, P/B, and Q/B values generated by Aydin's bioenergetics model, BA values were added to the juvenile salmonid groups.

10.1.4. Demersal and Forage Fishes

The biomass of other bottom fish was increased for consistency with W. Palsson's estimate. Decreasing predation from ratfish and chinook resident juveniles reduced predation pressure on herring. Further, herring P/B was increased to 3.6 (calculated from the www.fishbase.org page on *Clupea pallasii*) based on the assumptions that age at first capture (L_c) in the commercial bait fishery is about 12cm, and the average size of herring in the SPS area is 16.1 cm (about halfway between the size of age 2 and 3 fish; lengths from Lemberg *et al*. 1997). Having the SPS herring P/B higher than that observed in Strait of Georgia makes sense because the Lc is small and there are not many old fish in SPS. Herring B was also increased very slightly. Shifting their predators' DCs to include more flatfish, predatory invertebrates, grazing invertebrates, jellies, ratfish, and skates decreased predation on dogfish, hake, rockfish, and miscellaneous demersals.

10.2. Balancing the models: SPS 1970

The 1970s model was derived with the assumption that no group had either become extinct, or been introduced, in SPS over the 30 year model period. Grouping species such that the other creatures with which they share a grouping mask extinctions and introductions has mitigated the effects of changes on this scale for the model. This lack of detail results from the fact that the SPS models were intended to provide detailed information on changes that have occurred mostly in vertebrate groups. As long as the function of species within an Ecopath group is similar, the particulars of which were waxing or waning within that group are important only in so far as the biomass is accounted for in the group's effect on the ecosystem. Again, we encourage those interested to experiment with the model and see if some of the groups can be split to provide new and informative detail about changes that occurred in SPS over the 30-year period.

Bearing the above assumptions in mind, deriving the 1970 Ecopath model was simply a matter of determining which of the groups had changed over the 30-year period and inserting those as different parameter values for the 1970 model. In essence, the SPS main ecosystem dynamics were based upon the best information available from the 1990s. Then, while maintaining trophic linkages, biomasses, fisheries harvests, and diet compositions were modified where we could account for known changes.

10.2.1. Invertebrates

The carnivorous and herbivorous zooplankton B was increased slightly to account for extra predation resulting from higher fish biomasses. Because there was no reason to believe this value has changed, the same adjustment was also applied to the 1990s model.

10.2.2. Salmonids

All salmonid Bs, and fisheries yields were readjusted to reflect the numeric abundance information derived from the WDFW data set provided for the 1970's. However, salmon B estimates specific for the 1970's should also have been utilized to reflect the higher survival rates observed during that decade. This oversight biases our dynamic Ecosim model by underestimating adults at the beginning of the studied period, and needs to be corrected in the next iteration of this model. The bioenergetics model suggests juvenile and resident combined salmon biomass during the 1970's could have been 3 to 4 times greater than what was modeled. Salmonid contributions to the DCs of marine mammals, dogfish and lingcod were redistributed. This resulted in a shuffling of mortality to reflect that juveniles would be a larger portion of those groups diets, while maintaining the trophic linkages established in the 1990s model.

10.2.3. Demersal and Forage Fishes

All fish group Bs and fisheries yields were readjusted to reflect the earliest information derived from the WDFW data provided by W. Palsson. The EE for herring was reset to 0.95, and then Ecopath derived a necessary biomass to satisfy predation needs (1.827 tons/km²). For the most part demersal fish had much higher Bs and Ys, and in the case of lingcod, ten times higher. See Palsson *et al.* (1996) for a discussion of how the populations of many demersal fishes in SPS have experienced sharp declines in the recent past.

10.2.4. Marine Mammals and Birds

Seals B was reduced to 0.14 tons/km² (see Section 9) to accommodate a reasonable starting point for explanation of observed population growth from 1970 to 2000. Sea lion and toothed whale Bs were left unchanged in the absence of any information to the contrary. Based on information from and trends observed by D. Nyeswander (WDFW), bird Bs were adjusted for 1970 values by taking a ratio of numbers present at the start of the 1990s (the earliest available data for this study) versus the end of the 1990s. This ratio was rounded to the nearest whole number to get the following rough changes in bird groups: (start 1990s: end 1990s) herons 1:1, loons/grebes 3:1, cormorants 1:1, alcids 2:1, diving ducks 2:1, dabbling ducks 2:1, gulls/terns 1:1.

10.3. Results from the 1990s and 1970s models

Figure 10.1 is a box diagram output, from an Ecopath subroutine, showing the relative biomasses and trophic positions of species groups in the SPS model for the late 1990s. Trophic levels for the SPS early 1970s model were very similar so a separate box diagram was deemed unnecessary for illustration. However, several of these relationships are different in magnitude due to biomass changes in several groups (see Table 10.1).

Coho resident adults are the only salmonid group to show a reduced biomass in Table 10.1, whereas most other salmonid groups actually increase to varying degrees. Also showing biomass declines are all of the demersal fishes modeled and several bird species. Herring also appears to have declined over the modeled period. Other groups modeled show changes, but the paucity of population studies for these groups suggests that these changes should be regarded with caution. For example, 'other forage fishes' and squid population changes suggest declines but detailed studies were not available to verify suspected changes.

Ecopath also provides a mechanism to examine the effect of changing input parameters in a sensitivity analysis routine. This routine varies all basic input parameters by increments of ± 10% up to 50% and checks the effect on estimated parameters for other groups. The SPS model sensitivity analysis found that changes to input parameters of marine mammals, dogfish and lingcod had the most effect on unknown values for other groups (see Figure 10.2). Details of the sensitivity analysis are included on the attached CD-ROM.

Figure 10.1: Trophic feeding levels for the species groups in the 1990 model, box area is logarithmically proportional to group biomass.

```
Trophic Level

4   herons          alcids         sea lions   toothed whales                                    chin res. adult  chin migr. adult
    B = 0.004  cormorants  B = 0.004  B = 0.1   B = 0.001        lingcod                          B = 0.1          B = 0.1
               B = 0.01              seals                       B = 0.1    coho res. adult  coho migr. adult
                                     B = 0.3                                B = 0.1          B = 0.1
                                                                                                   chin res. juv
    loons / grebes                                                         dogfish  coho res. juv  coho trans. juv.  B = 0.7
    B = 0.02                 pollock   pacific cod   hake                   B = 0.5  B = 0.0        B = 0.1                  chin trans. juv.
               rockfishes    B = 0.004  B = 0.02     B = 0.1                                                squid          B = 0.1
               P = 0.1                                                   ratfishes               herring   B = 0.01       chum/pink juv
    gulls / terns                                                        B = 10.8    oth for fishes  B = 1.4                B = 0.03
    B = 0.03               skates / rays  oth. bottomfishes  jellies                 B = 3.6
               diving ducks  flatfishes   B = 0.1  B = 4.0    B = 0.2
3              B = 0.1       B = 6.3

                            carn. zoopl.                    pred. inverts
                            B = 6.7                         B = 200.0

    dabbling ducks                                                         oth farm bival  farmed oysters  farm mussels
2   B = 0.02    herb zoopl   epiben zoopl   shellfish   graz inverts       B = 34.0        B = 15.9        B = 17.2
                B = 6.0      B = 0.2        B = 300.0   B = 400.0

    detritus    macroalgae    phytoplankton   eelgrass   laminaria   floating kelp  benthic diatoms  chum/pink adult
1   B = 7.0     B = 1324.9    B = 80.7        B = 2.7    B = 20.3    B = 8.9        B = 14.7         B = 1.6
```

Table10.1: Biomass changes for vertebrate groups. Groups that experience increased biomass are indicated in normal type, whereas those that decreased in biomass are indicated in **bold** type.

Group name	Biomass (tons/km²) 1990s	Biomass (tons/km²) 1970s	Difference
alcids	0.004	0.008	**-0.004**
chin migr. adult	0.128	0.126	0.002
chin res. adult	0.109	0.079	0.03
chin res. juv	0.683	0.098	0.585
chin trans. juv.	0.065	0.065	0
chum/pink adult	1.598	0.311	1.287
chum/pink juv	0.025	0.004	0.021
coho migr. adult	0.067	0.067	0
coho res. adult	0.12	0.221	**-0.101**
coho res. juv	0.03	0.015	0.015
coho trans. juv.	0.122	0.058	0.064
dabbling ducks	0.024	0.048	**-0.024**
diving ducks	0.1	0.2	**-0.1**
dogfish	0.53	9.199	**-8.669**
flatfishes	6.327	15.6	**-9.273**
hake	0.072	0.5	**-0.428**
herring	1.4	3.902	**-2.502**
lingcod	0.05	0.5	**-0.45**
loons / grebes	0.024	0.072	**-0.048**
other bottomfishes	4.0	5.6	**-1.6**
other forage fishes	3.558	5.738	**-2.18**
pacific cod	0.024	0.316	**-0.292**
pollock	0.004	0.22	**-0.216**
rockfishes	0.293	1.497	**-1.204**
seals	0.254	0.14	0.114
skates / rays	0.136	1.04	**-0.904**

Another useful analysis provided by Ecopath is an accounting of the ecological measurements of fishery performance. Organisms at trophic levels 3 and higher in SPS show both biomass and catch were much greater in the 1970s (see Table 10.2). Analysis of the commercial fishery shows the 1970s at a trophic level of 3.03 but by the end of the 1990s, this had declined to a trophic level of 2.49. Similarly, the early 1970s recreational fishery trophic level 3.55 dropped by the end of the 1990s to 3.36.

10.4. SPS 1990s vs. SPS 1970s: Discussion

Comparison of the two SPS Ecopath models shows the only salmonid group with a significant B decline is coho adult resident. The observation fits the general pattern of declining coho populations since the late 1970s, and serious declines in Puget Sound since 1990 (A. Rankis, pers. comm., Northwest Indian Fisheries Commission 6730 Martin Way E. Olympia, WA 98516-5540). Weitkamp *et al.* (1995) state that Puget Sound and Strait of Georgia coho "risk factors include widespread and intensive artificial propagation, high harvest rates, extensive habitat degradation, a recent dramatic decline in adult size, and unfavorable ocean conditions."

Although these concerns are for survival of wild stocks in particular, many are germane to survival of hatchery coho. Also, the aforementioned mechanisms of density dependence are candidate for coho declines in general. During a 1994 WDFW investigation of factors influencing Puget Sound resident chinook and coho numbers, Doty (1994) found a "...significant negative correlation between the survival of yearling chinook and the number released". He speculated that a carrying capacity for resident salmon may exist although other marine conditions could also be influencing survival. Interestingly, delayed release coho showed a different response to increasing release levels and changing marine conditions. Based upon CWT recoveries, delayed coho marine distribution annually fluctuated between SPS and other regions within and outside of Puget Sound.

With respect to the issue of ocean conditions, juvenile coho marine survival has been shown to be strongly correlated to different indices of local climatic conditions (Pinnix, 1999). According to a bottom up hypothesis forwarded by Gargett (1997), phytoplankton blooms provide a wider food base for coho smolts when entering Puget Sound and are more likely during years with median stream flow due to the creation of optimal fjordal mixing. Pinnix (1999) suggests these conditions were met from 1976 to 1990 when the Pacific Decadal Oscillation (PDO) showed neither anomalously high nor low conditions. The PDO is linked to oceanographic conditions within Puget Sound by the precipitation and temperature regime it imparts on the watershed. The PNI has a trajectory similar to that of the PDO (see Figure 10.3; Ebbesmeyer, 1989). The PNI is correlated to salmon production in that cold wet years in the Puget Sound basin lead to high salmon production, whereas warm dry years tend to depress salmon production.

Pinnix (1999) uses a variety of local climatic measurements to demonstrate weak but significant correlations between coho marine survival and phenomena like the PDO and PNI. Beamish *et al.* (2000) states the whole Northeast Pacific region has shown marked declines in marine coho production, especially since 1989 and relates these declines to changes in the ALPI. The biomass trajectory in the present study appears to agree with climatic conditions. The years of highest returning adult coho biomass were observed during the late 1980s (see Figure 7.1b). If it were the case that oceanographic effects were overwhelmingly strong on coho marine survival due to the aforementioned bottom up effects, then the lack of correlation between adult returns and juvenile smolts entering SPS makes sense.

Chum salmon are quite different in that neither the reproductive success nor survival of wild populations in SPS seems to be affected over the period from 1970 to 2000. Johnson *et al.* (1997) note that chum salmon in SPS are near or above historic highs, and that there is a wide variety of breeding characteristics with many rivers and creeks having combinations of summer, fall, and winter runs. Chum salmon appear to be thriving in SPS, and the modeling process suggests they are resilient to whatever factors led to changes in the coho and resident chinook salmon in SPS.

Table 10.2: Changes in the biomass (B) and harvest (Y) at Trophic levels VI through I in SPS over the period from 1970 to the end of the 1990s.

Trophic level	1990s B tons/km²	1970s B tons/km²	1990s Y tons/km²	1970s Y tons/km²
VI	0.013	0.02	0	0
V	0.377	1.019	0.032	0.04
IV	7.448	14.552	0.323	0.464
III	127.197	145.953	3.471	3.967
II	874.202	886.357	22.013	22.063
I	1452.156	1452.156	0	0

Figure 10.2: Results from the sensitivity analysis of the SPS 1990s model. The frequency measured on the y-axis refers to the number of other groups with estimated parameters changed by altering input parameters in the groups noted on the x-axis.
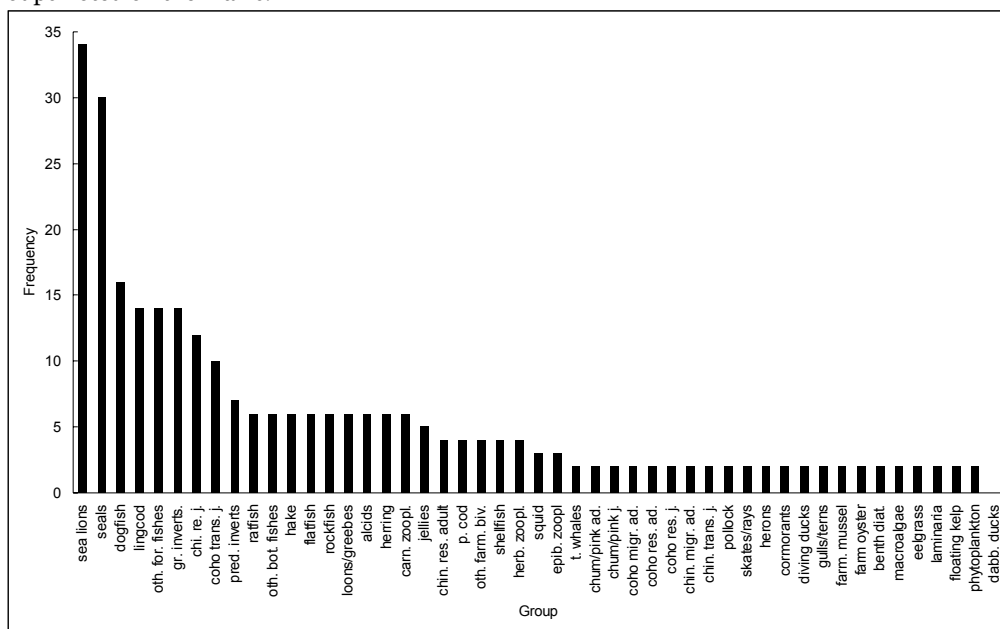

Figure 10.3: 1895-1996 Pacific Northwest Index 5 year running average. Years above the x-axis are anomalously warm and dry, whereas years below the x-axis are anomalously cold and wet. This index suggests that since about 1980 conditions in the Puget Sound area have been warmer and dryer than normal
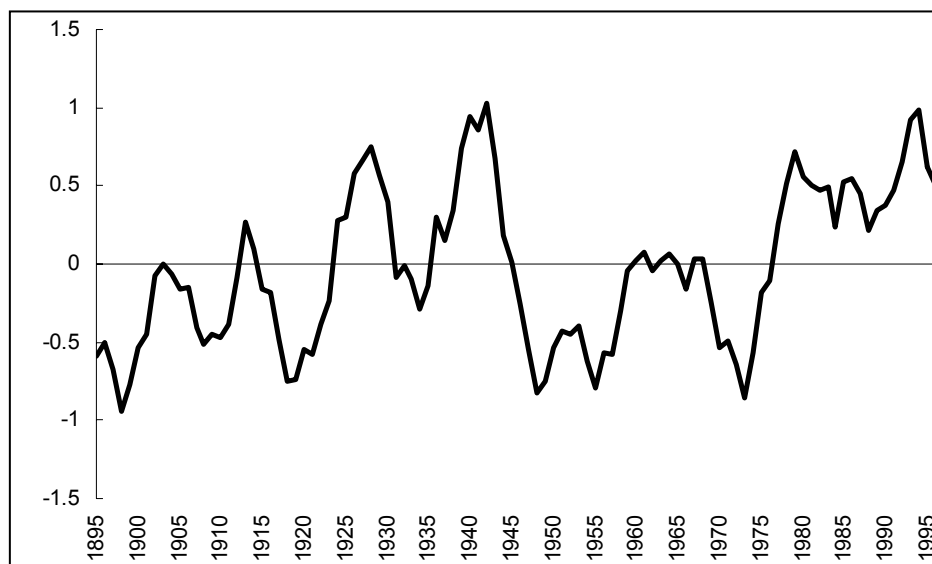
Figure 10.4. Predator / prey overlap indices for the 1970 (left) and 1990 (right) SPS models. Each point represents a pairing of groups from the SPS model. The Y-axis indicates increasing similarity a pairing's predators, whereas the X-axis indicates increasing similarity of their prey. Therefore the higher up and further to the right a pairing is the more similar their niche in the ecosystem modelled. This analysis would indicate that niches in SPS have become increasingly similar.
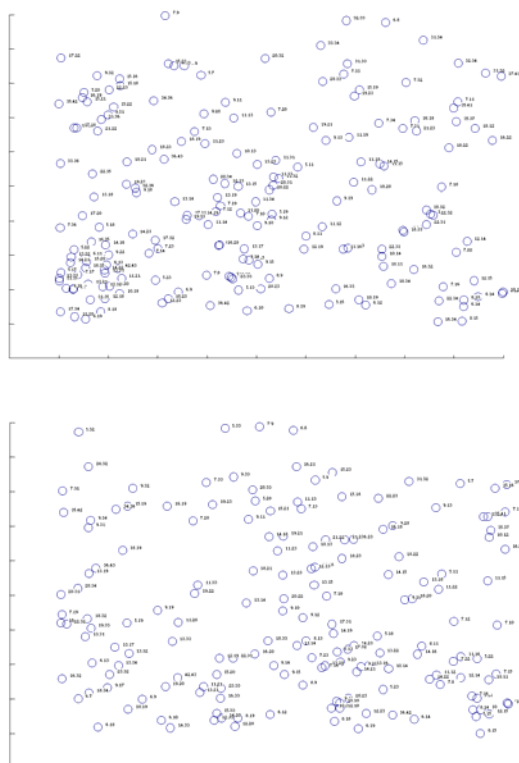
A very obvious phenomenon was the almost universal decline in the Bs of the various groundfishes in SPS. However, the identification of a pathological problem in their population *per se* is difficult because many (e.g., Pacific cod, pollock, and hake) belong to populations that extend beyond the confines of SPS (Gustafson *et al.* 2000). Pacific cod, pollock, and hake have populations that range over large areas, and may provide a local depressed population with the chance for replenishment from outside segments relatively quickly. Such relief is more difficult in the case of species like rockfishes and lingcod, which are notoriously territorial and show very high fidelity to quite localized ranges. Thus the depression of some groundfishes gives much higher cause for concern than others and should be borne in mind when planning management strategies for the SPS ecosystem.

The most troubling observation from a fisheries ecosystem perspective is the 'fishing down the

food web' phenomena in SPS. Fishing down marine food webs was identified by Pauly *et al.* (1998) as the pathology of fishes of the highest trophic levels being reduced in aquatic ecosystems. The fishery often targets new species further down the food web. Although one might suspect that this sort of policy might lead to increases in catch biomass due to targeting lower trophic levels (and, hence, more abundant) species, the evidence suggests this is not achieved (Pauly *et al.* 1998). In SPS, we see a decline in the average trophic level of the fish being caught in the recreational and commercial sectors, see Table 10.2. Declines occur in absolute catch at trophic levels 3 through 6 suggesting that not only are the fish being taken smaller, but there are fewer of them. Figure 10.4. indicates that decreasing diversity can be shown through tendency of species pairs in SPS of the late 1990s to have more similar niches than species pairs of the 1970s.

10.5. Moving to an SPS Ecosim model

Once we had developed the SPS Ecosim model, we recognized a problem at once: The biomasses of salmonid groups were remarkably unstable and given to unrealistic boom and bust cycles that went through absurd shifts of several orders of magnitude. The chief culprit for these fluctuations was determined to be the high P/B and Q/B values for the salmonid groups. A reason for this instability results from the way different scientists define 'production' in an ecosystem. A lengthy discussion about defining production ensued between Dr. Carl Walters (one of the creators of the EwE software) and Dr. Kerim Aydin (the creator of the bioenergetics model used to calculate P/B and Q/B values for the SPS 1970 and 1999 models). At first, we attempted to correct for the high P/B and Q/B values by entering BA terms for the relevant salmonid groups. However this was merely an accounting solution to the problem, which acted to numerically correct the effect of high production in salmonid groups. The increasing abstraction of such exercises, however, was seen as detrimental to the modeling process. After considering the merits of both sides of the production discussion, we decided to use lower P/B and Q/B values. The reasons are presented in the following paragraph, which paraphrases the words of Dr. Walters (UBC Fisheries Centre 2204 Main Mall, Vancouver BC V7R-2L7).

With respect to the issue of setting P/B and Q/B values for Ecosim models, you must not enter correct P/B for juvenile groups when setting up an Ecopath model for which you intend to treat

the juveniles as separate groups in Ecosim. The basic problem is that Ecopath does not have an accounting term for movement of biomass (graduation process) from juvenile to adult biomass pools, and biomass accumulation does not, and cannot, represent that graduation process. Were Ecopath improved to contain the graduation flows, the move to Ecosim would be much simplified. What happens when Esosim is initialized is that we assume the Ecopath user has specified juvenile and adult biomasses and mortality rates, period. Then Ecosim constructs a delay difference model such that these biomasses and rates (and any overall biomass accumulation rates) are matched. This automatically generates the flow process from juvenile to adult. In fact, it is generally true that the juvenile group in EwE has a substantial biomass accumulation (net P/B) internally in the delay-difference time accounting. Until we fix Ecopath to include the graduation flows explicitly, users do not have any choice but to ignore the usual P/B definitions when entering information about groups that are to be represented as split pools. The next section clarifies the Ecosim portion of the SPS EwE exercise.

11. USING THE ECOSIM MODEL TO EVALUATE HISTORIC CHANGES TO THE SOUTH PUGET SOUND ECOSYSTEM
ALASDAIR BEATTIE & DAVE PREIKSHOT, UNIVERSITY OF BRITISH COLUMBIA FISHERIES CENTRE

11.1. Introduction: Ecosim Features

Construction of the SPS model benefited from the use of a new set of features available in Ecosim to fit the model to time series data and comparison with pre-existing Ecosim models from the Strait of Georgia. Contrasting the predicted trends in abundance that Ecosim produces to known trends in abundance (or mortality rates including fishing mortality) allows for greater confidence in describing system dynamics. Ecosim not only incorporates existing traditional stock assessment tools, but also combines them with trophic interactions. The ability to validate a model to many different time series data, for any number of various species or species groups in an ecosystem should increase our confidence in the predictions we make – the hypotheses set – about how an ecosystem will respond to various disturbances.

Table 11.1. Parameters changed in the baseline ECOPATH model. Bold text indicates parameter value was increased or added, normal text indicates that parameter values were decreased.

GROUP	B (t km^-2)	P/B (year^-1)	Q/B (year^-1)	BA (t km^-2)
Seals	0.035	**0.3**	8	
chum/pink adult				
chum/pink juv.		**2.21**	6	
coho trans. juv.		**2.228**		
coho res. Juv.	**0.025**	**2.45**		
chin. res. Juv.		**2.7**		
Dogfish	**10**	0.09		
pacific cod	**0.4**	0.5	**3.53**	**-0.1**
Pollock				**-0.1**
Hake		**0.605**		**-0.31**
Rockfishes	**1**	**0.11**	2	**-0.14**
Squid	**0.25**			
carn. zooplankton	**7.8**			

Here we will describe the process of validating the SPS model, including changes to the Ecopath baseline parameters, establishing a vulnerability table of prey to predators (used by Ecosim to manage predator/prey and top down versus bottom up dynamics), and how other factors such as hatchery production of salmonids and historical primary production anomalies have interacted with the system. We will present a set of possible hypotheses that can be derived from the model We also make suggestions about how the model could be improved in the future. This model represents the second attempt by researchers at the UBC Fisheries Centre to incorporate the new Ecosim features described above. Therefore, we also compared the SPS model to the Strait of Georgia model.

11.2. Validating the model

11.2.1. Changes to the Ecopath baseline
Fitting the Ecosim model to the time series data required changes to the baseline parameters for 13 groups of the 1970s Ecopath model, Table 11.1. (also see Edited basic parameters worksheet found in "Ecosim tables.xls" on the accompanying CD-ROM). For salmon groups, the majority of changes involved changing the P/B ratios. The P/B ratios were increased to be nearer those used in a Strait of Georgia model developed by researchers at the UBC Fisheries Centre. For other groups, the P/B ratios were increased or decreased relative to the requirements to fit the time series data while being within the range values in peer-reviewed literature. For example, hake has a reported range of natural mortality M = 0.2-0.3 and

exploitation rates are often estimated between 0.3 and 0.5 (Dorn *et al.* 1999). Reported values of total mortality (Z) for dogfish are near 0.1 (Wood *et al.* 1979). An exception suggested by the model is the P/B value for harbour seals, 0.3, nearly double the rate obtained for both the Strait of Georgia model, 0.18, and for seals (*Phoca largha*) in the Liaodong Bay area in China, 0.16 (Dong and Shen, 1991). These populations exhibit similar trends over a similar time period, suggesting the P/B value obtained by the model may be too high.

In four groundfish groups; Pacific cod, hake, rockfish and pollock, a negative biomass accumulation (BA) term was included. This allowed for higher rates of predation by predators such as seals and dogfish. This can also represent emigration from the system, however these species did not have stable population levels (they appear to have been in a state of decline), in the initialization year (1970). For other groups, biomass (B) was increased (e.g., squid), to allow for either lower P/B levels or higher predation mortality at a given P/B level.

11.2.2 Vulnerabilities
The vulnerability table used in fitting the model to time series data is found on the Vulnerability table worksheet of "Ecosim tables.xls" (see CD-ROM). These vulnerability settings resulted in a 34% improvement to the sum of squares (SS) obtained with default settings for all groups (SS default = 185). The SS, in terms of the vulnerability settings, is highly sensitive to herring predation on carnivorous zooplankton, and very sensitive to other forage fish predation on carnivorous zooplankton. The SS was also moderately sensitive to other forage fish predation on herbivorous zooplankton, grazing invertebrate predation on macroalgae, and shellfish predation on detritus.

Carnivorous zooplankton has a very low (0.001) vulnerability setting to both small pelagic fish groups, i.e., small pelagic fish groups see relatively few carnivorous zooplankton in their environment. Note that vulnerability settings have an implicit time and space component – that is, we are hypothesizing with such a low vulnerability setting that herring and other forage fish are rarely in the same place at the same time as carnivorous zooplankton. Such an effect may be either behavioral or random. Changing the setting to the highest vulnerability (0.999) causes the SS to increase by 18%. The most dramatic changes to fits in the time series occurred for hake, and juvenile chum salmon

(see high vulnerability scenario on the attached CD-ROM).

11.2.3. Hatchery effects
The decision to group the salmon pools provides the option of using a forcing function driving the egg production of the linked salmon pools known to have strong hatchery inputs. Total hatchery production for coho was allocated into each linked coho group according to the same standard applied to the biomass of each pool in the Ecopath model. The recruitment power parameter for each pool was then set at 0.001. This is equivalent to assuming the number of returning adults has little impact on the number of juveniles produced.

The scenario 'no hatchery effects' shows the difference to the fits for juvenile coho groups obtained by not including dynamics to mirror the effect of hatcheries (see CD-ROM). Note here that the recruitment power parameter was reset to 1, that is, the groups were modeled as normal wild stocks. The fit appears to be similar for resident coho, but the predicted trend for transient coho does not follow the abundance index. In contrast, the 'Final' scenario predicted biomass follows the declining observed biomass time series for all linked groups closely during the declining period of the last decade. Fits to the Z data series are similar for both scenarios.

The inclusion of hatchery production results in an 11% improvement to the overall SS, however it appears that transient coho were most impacted. This suggests that hatcheries effects do not account for abundance changes to resident coho, but account well for modelled abundance changes in transient coho. The model further predicts that in the absence of hatcheries, the biomass of transient juvenile coho stocks could be higher in SPS, but this is dependent on assuming that spawning habitat could accommodate all spawners.

11.2.4. Estimating historical primary production anomaly
We estimated a time series of primary production anomalies following the adjustments to the vulnerability tables and parameters associated with hatchery effects. Salmon and herring biomass time series were omitted from this procedure, based on low confidence in the data. Continuing analysis of coded wire tag data for coho should address some of these issues for future modeling work. Difficulty in fitting herring time series data in past models, including the Strait of Georgia, suggests problems with historical data. Such problems

may include missed spawning areas or beach spawn surveys failing to take into account spawning below low tide. Either problem may introduce bias to underestimate the spawning stock and subsequent recruitment (C. Walters, pers. Comm., UBC Fisheries Centre, 2204 Main Mall, Vancouver BC, V7R-2L7). The salmon groups were split into resident and transient groups, with no precise data on how much, nor from where, of the juvenile contribution comes from any particular juvenile group (see Chapter 7). For example, it was assumed that 10% of delayed hatchery coho become resident coho. This relationship is further assumed to hold for all years.

The predicted anomaly pattern is shown in Figure 11.1. Note the strong decline over the last two decades. A reduction in the overall SS value of 28% (167 no environment, 121 with) was obtained by including the production anomaly. This supports the hypothesis of a regime shift in the area (Cooney and Brodeur, 1998). For comparison, we have also provided a historical production anomaly predicted in the absence of any transient juvenile salmon species time series (e.g., not including juvenile chum and juvenile transient chinook biomasses, or Z). This exercise was undertaken in order to represent a different hypothesis regarding the behaviour of juvenile salmon not destined to remain resident. The hypothesis in this case is that if they leave the system rapidly, trends in their abundance data would not be reflected on the productivity of SPS. Note the abundance trends for the chum/pink salmon group was contrary to the most other groups in the model, lending support for this hypothesis.

Figure 11.1. Time series production anomolies predicted by Ecosim including all juvenile salmon groups (heavy line) and not including transient juvenile salmon groups (thin line).
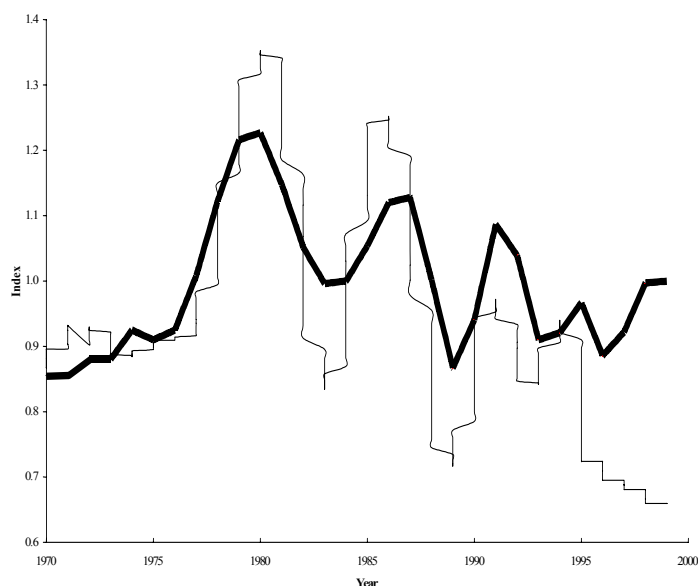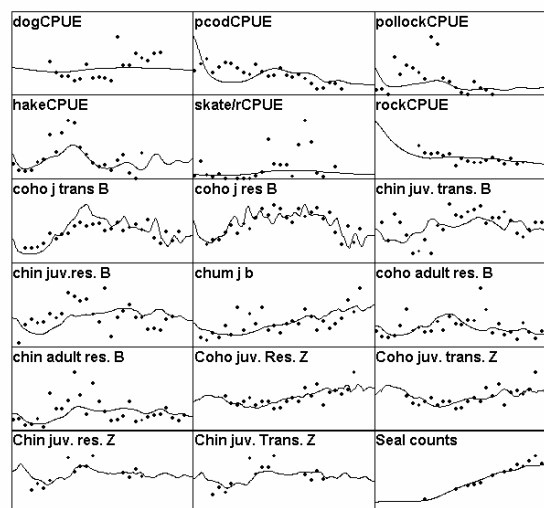
Figure 11.2a. Fits obtained for 18 sets of times series data on abundance and mortality for 13 groups in the South Puget Sound model.


11.2.5 Conclusions

The fits obtained for all groups, all time series data are shown in Figure 11.2a. Note that data series such as harvest are not shown, as they provide little information on the dynamics of the pool. Time series data included in the Ecosim model can be seen in Table 11.2. The data is contained within a comma delineated text file in the EwE data base on the CD-ROM. This file can be accessed by going to the Ecosim model interface, selecting the "run info" tab, selecting the "read time series" button, and selecting the "read from database" button. This will enable a pull-down menu that will show the file for inspection. Please refrer to the EwE manual or help-file for a guide on editing this data. The best fit obtained for all time series was SS=121 (Monte Carlo simulation, 1000 trials, P<0.001), suggesting that more than half of the variation between the observed and predicted data can be explained through either trophic or environmental effects.

Table 11.2. Time series data included in the Ecosim SPS model. Note that seal numbers were based on total counts for all Puget Sound and provided by S. Jeffries (WDFW Wildlife Science Division 600 Capitol Way N., Olympia, WA 98501-1091). Z values for chinook and coho were found in Doty (1994).

| B	CPUE	Y	Z
seals	dogfish	chum/pink	coho
chum/pink	pac. cod	coho	chinook
coho	pollock	chinook	
chinook	hake	lingcod	
herring	skate	dogfish	
	rockfish	ratfish	
		oth. bottomfish	
		pac. cod	
		pollock	
		hake	
		skate	
		rockfish	
		flatfish	

Figure 11.2a shows that the model fails to describe the dynamics for some groups, notably dogfish, pollock and skates. The relative abundance indices used, CPUE data, is well known for misrepresenting true stock dynamics due to factors such as increasing catchability over time. Overall, however, we consider the exercise a success. Note that with Ecosim we have taken traditional stock assessment techniques and overlaid trophic and environmental dynamics upon them. This creates a set of hypotheses for further investigation:
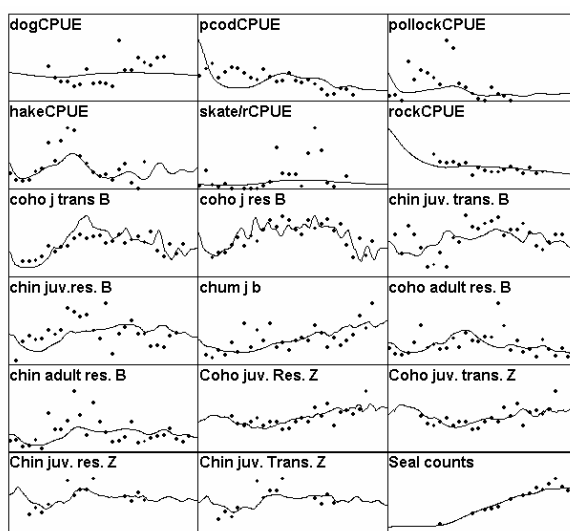
-Trophic dynamics are important to the South Puget Sound ecosystem;
-There is strong bottom up forcing in the South Puget Sound ecosystem;
-Hatchery salmon production has an affect upon wild population survival rates.

The second hypothesis is difficult to test, but finding some historical record of primary production in the system should provide further verification of other assumptions made in the model. The first and third of these hypotheses, however, could easily be tested. For example, seals generate significant mortality on many groups within the system according to the model. A suggested scenario is reducing the number of seals, perhaps through a culling program, combined with monitoring of prey stocks, to examine the effects. Another suggestion is hatchery production could be varied over several years at several levels of output, and combined with monitoring the survival rates of wild salmon stocks may show the third hypothesis above to be true or false. In either case, such adaptive management experiments appear to be the only way to reduce uncertainty in management policies.

Figure 11.2b. Fits obtained for 18 sets of times series data on abundance and mortality for 13 groups in the South Puget Sound model with modification to reflect that transient salmon juveniles and juvenile chum salmon exit the system quickly, and feed little. Note that little difference is obtained in the fits, except for juvenile chum.
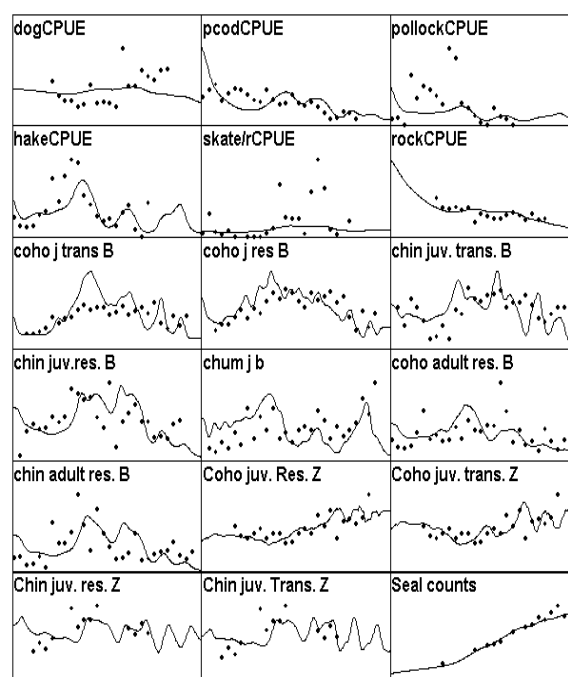
Fits obtained using a production anomaly that does not include the above noted juvenile salmon groups are shown in Figure 11.2b. Some modifications to the juvenile chum DC, vulnerabilities and feeding time rate of change, as well as lowering the seal P/B were required to obtain the fits. The pattern is different only for juvenile and adult chum B, suggesting decadal pattern of changes in abundance rather than a general increase since the 70s. This lends support to the hypothesis that these groups are rearing mainly outside of SPS.

11.3 Improving the model

Several areas could be improved to increase our confidence in the model:

1) Gather data on historical fishing rates. One of the main assumptions underlying this modeling exercise is that the fishing rates remained constant over time. This is unlikely, and must have a strong impact on the predictions made here. Adding such a time series would reduce a major area of uncertainty in the model,
2) Separating the salmon stocks into resident and transient stocks was done using a best guess approach. Improving estimates of actual percent contribution to either stock would reduce uncertainty,
3) Improve the method to identify returning hatchery or wild salmon
4) Improve surveys of all stocks, especially small pelagic fish that play key roles in the diets of many important commercial fish, as well as predators of those same commercial fish. One of the key limitations of this model is that we lack information about forage fish stocks in general. While expensive, independent indices of abundance are far more reliable than catch related indices. If cost is prohibitive, then investigating the feasibility of directly estimating exploitation rates through methods such as tagging is advised. Recent work (Martell and Walters, in press) has shown that such programs need not be expansive and costly to be accurate, especially when done in concert with surveys, which in turn need to be done less often, and
5) Improve the diet information for the species of most concern, and their predators. Diets in this study were often borrowed from studies done in areas remote to SPS (e.g., bird diets). Diet composition often differs dramatically between regions, for instance sea lions in the Bering Sea may eat a lot of pollock but they certainly do not in SPS. While we have tried to take account for this in setting up our diet matrix, even a single good diet study would reduce the uncertainty involved in this process.

It is important to emphasize that models only serve as an aid to pose questions behind which lie an understanding of how a solution set would likely be bounded. It is not intended to replace actual monitoring of the performance of stocks, or replace stock assessments. For instance, the SPS and Strait of Georgia models differ in minor structural ways yet suggest very different management policy development and implementation. As a final note, this model is not *finished* nor complete, rather it is merely the foundation for what should be an ongoing process.

Figure 11.3a. Fits to time series for South Puget Sound (1970-1998)
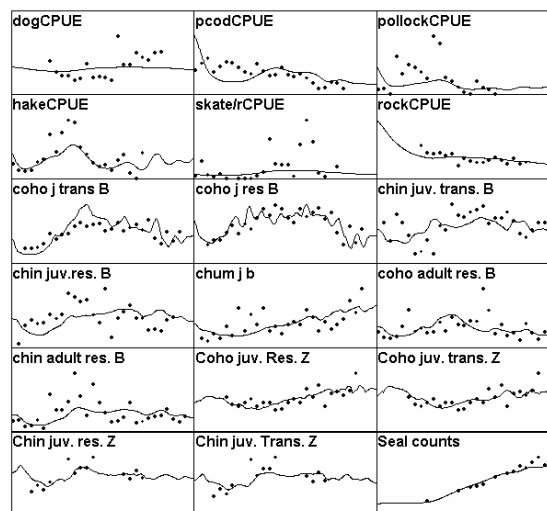
11.4. Comparison with the Strait of Georgia model

11.4.1. Overall fits

A comparison of the fits to time series obtained for SPS and the Strait of Georgia are shown in Figure 11.3a. and 11.3b. respectively. Though we had fewer time series data sets for the Strait of Georgia, many are for the same species/groups and are for a longer time period. The key point here is that, overall, the abundance patterns for groups in both models are similar. In particular, both models show a dramatic decline in abundance of resident salmon groups from the late 1970s and early 1980s to the present. This is concurrent with declines in herring and groundfish groups, as well as a dramatic increase in seal abundance.

Figure 11.3b. Fits to time series for the Strait of Georgia (1950-1998). Note the similarities to the SPS data set, most notably increasing seal abundances and increasing juvenile salmon mortality. As well, the general declines in abundance for coho and hake are similar for the two regions, and occur at approximately the same time.
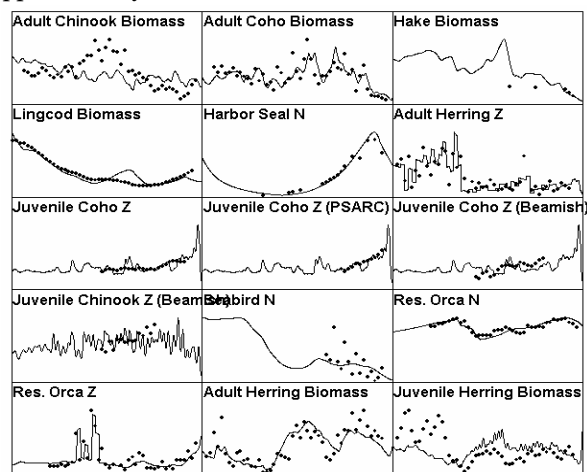
11.4.2. Historical production anomalies
The historical production anomalies predicted by Ecosim for the Strait of Georgia and for SPS are shown in Figure 11.4. Also in the figure is wind speed anomaly data for the Strait of Georgia, collected at Vancouver International Airport in Richmond, BC. Wind data is widely used as an index of primary production. Again, in both areas, the trends are similar, and generally agree with the wind data up until the 1990s. At present, there is no reasonable explanation for this, although we are investigating whether changes in flow rates of the Fraser River, beginning in the 1990s, may have had some impact on wind-driven mixing rates.

Figure 11.4. Comparison of ECOSIM predicted production anomalies for the South Puget Sound and the Strait of Georgia. The pattern is remarkably similar. Also shown for comparison is the wind speed data for the SOG collected at Vancouver International Airport. Again, the correlation appears strong, until the 1990s.
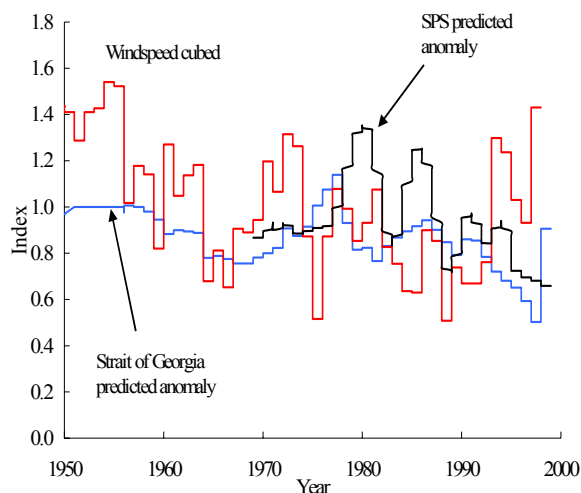
11.5. Conclusions

There are strong similarities in the SPS and Strait of Georgia systems, in similar stock trends and the predicted primary production history. Further, they have both undergone similar histories of human development, not only in terms of fisheries and other industries, but also human settlement. Both systems are a part of the larger Puget Sound / Georgia Basin system. A case can clearly be made that these are not separate systems at all, but sub-regions of the same system. In such a case, activities in one 'system' must have impacts on the other.

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