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Thesis

A Comparative Analysis of Fish Stock Assessment methods: Spatial-temporal versus VPA

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Abstract

This thesis presents research on an alternative spatial-temporal method of fish stock assessment. We develop a simulation model of spatial-temporal stock analysis and compare its assessment with the common VPA/SPA method. In recent years, fisheries biologists have depended mainly on age structured aggregated sequential population analysis (SPA)/virtual population analysis (VPA) for stock assessment purposes. The VPA method is an aggregate model that consolidates all spatial and within-season temporal stock dynamics into a single total stock estimate. The proposed spatial-temporal method produces historical estimates of population size and fishing mortality rate by age and year. In this thesis, the abundance states of age-aggregated stock components are tracked in space over the course of each season using computer simulation. Data about fish stock spatial-temporal migration dynamics are used to estimate stock abundance in space and time over the course of a fishing season. The spatial-temporal assessment method is applied to the herring stock of the Scotia Fundy region of Atlantic Canada. The dynamics of the herring spawning groups are described and the simulation model is developed for a given season. The results suggest that disaggregated spatial-temporal estimates provide more information for in-season management of herring spawning groups than the traditional aggregate VPA approach.

Acknowledgement

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1. Introduction

Stock assessment recognizes the dynamic nature of fish population abundance status and uses numerical methods to estimate biological parameters and confidence bounds and to formulate harvest strategies. This work requires data that are best collected with a specific goal in mind. Stock assessment analysis uses these data in population simulation models to provide information necessary for formulating policies for the long-term sustainable management of these resources. From a systems science perspective, fish stock assessment is a complex problem for managing man's intervention in the marine environmental system. Fish populations are highly stochastic and not directly observable. As well, fish stock assessment is a multi-disciplinary activity involving statistics, mathematics, biology, management science and computer technology.

Generally, the size of a fish stock for a given species over a large geographical area is estimated from annual catch statistics and independent research vessel surveys using seasonal aggregation methods. Sequential population analysis (SPA) or virtual population analysis (VPA) is the most commonly used techniques for fish stock assessments worldwide. These methods are applied to catch-at-age data, i.e., data on the number of fish of each age group caught in the fishery in order to estimate historical population size. SPA/VPA are also referred to as cohort analysis because the analysis is done separately for each cohort or year class in the population. The minimum requirements for VPA/SPA are a catch-at-age matrix over time, an assumed or estimated value for the natural mortality rate, and an observed catchability index series, i.e., a series of standardized observations that provide an estimate of the extent to which a stock is susceptible to fishing. VPA/SPA produces historical estimates of population size and fishing mortality rate by age and year. An estimate of the total stock size is then determined by summing the population estimates for all of the ages in for a given year.

The results of VPA stock assessment are used directly to set annual total allowable catch (TAC) limits for commercial marine fisheries. The aggregation and aging of annual catch statistics for VPA/SPA's does not take into account the spatial distribution of catches over all fishing grounds or the temporal dynamics of these catches among seasons. When fishing is concentrated in specific regions, there is always a risk that fishing intensity will affect different areas in different ways. For example, for schooling species, extensive fishing concentrated on a small area and a particular species may cause an individual spawning group to be overexploited locally. It should be more efficient in maintaining the balance of fish species composition to analyze sub-population aggregations during different migration regions and limit the catch for a specific area over a specific time period during the year.

For this thesis, a fish population is considered as a series of discrete spawning groups of adult, harvestable fish - each with its own dynamics defined across smaller areas within the larger whole. Year-over-year catch data can be used to track fish spatial migration patterns of the various spawning groups throughout the year. The migration of the various groups can be simulated and estimation of probability distributions of sub-population abundance in different locations throughout the year can be calculated. In this way the fish stock can be viewed as a set of dynamic subsystems with different abundances throughout the course of the year. Each state is defined by the location and magnitude of the subgroups or spawning groups of the entire population.

In this thesis, a simulation model of standard population generation with spatial-temporal definition is developed using the objected-oriented programming language Visual C++. The results of the model are used to generate catch data, and update population abundance estimates. These results are compared with actual data (e.g. yearly catches) for a specific fishery in Atlantic Canada and the results from the more traditional VPA/SPA approach applied to the same dataset application. The plan of the thesis is presented below.

1.1 Plan of the thesis

We develop an integrated simulation model for herring stock size assessment of the Scotia Fundy region of Atlantic Canada. This thesis includes the following chapters:

2. Literature Review – this chapter presents the published material on: (a) the development of aggregate fish stock assessment methods; (b) spatial-temporal stock assessment methods; and (c) the Scotia-Fundy herring application.
3. Methodology – this chapter presents the specific methodologies used in this thesis to develop the population generation model, background information about the VPA method for estimating fish stock size, and the Spatial-temporal Bayesian updating method to estimate fish stock size.
4. Application – this chapter applies the methodologies described in Chapter 3 to the case of the Scotia-Fundy herring stock including the model data requirements.
5. Results and Analysis – this chapter summarizes the results of the applied methodologies including the comparison of the spatial-temporal model results to the historical VPA results.
6. Conclusion and Extension – this chapter presents the main conclusions of this research and suggests several extensions to improve the analysis and results toward successful implementation of the model to assist in fisheries management systems.

2. Literature Review

2.1 VPA/SPA stock assessment

The concept of virtual populations was first introduced by Derzhavin (1922) who determined that the total catch of fish over time, N_i from a given year-class (year–class: individuals spawned in the same year) of a given stock is equal to the catch of that year, C_1 plus the catch from subsequent years (C_2, C_3...) minus all the fish not of that year-class under assumptions of stable age distribution, constant recruitment and negligible natural mortality.

$$N = C_1 + C_2(1 - x_1) + C_3(1 - x_1 - x_2) + ... + C_r(1 - x_1 - x_2 - .... - x_{r-1}) \qquad (2.1)$$

where, x_a represents the proportion of age a fish in the catch and r is the oldest age in the population.

Fry (1949, 1957) was the first to use the term "virtual population analysis (VPA), which attempts to estimate a single cohort size by summing the catches of fish backwards from the age of the last year. According to to the actual catch data and the estimates of the population by age, he calculated the total exploitable stock of a base year without the assumption of negligible natural mortality as well. A lower bound for the population size and an upper bound on the exploitation rate of the fishery could then be calculated by performing the analysis for all possible ages.

The well-known Canadian fisheries scientist William Ricker (1948) carried out a "sequential population analysis" (SPA) using Baranov's (1918) catch equation (2.2) using estimates for total mortality (Z) and fishing mortality (F) at the maximum age of a cohort. Ricker estimated cohort population size N from Baranov's catch equation as follows:

$$\frac{C_t}{N_t} = (1 - e^{-Z_t}) \cdot \frac{F_t}{F_t + M_t} \qquad (2.2)$$

where, C_t= catch of the oldest year-class in year t, N_t= population size of the oldest cohort in year t, Z_t= F_t+M_t, is the total mortality rate due to natural causes(M) and fish harvest(F) in year t.
Gulland (1965) showed that different fishing mortality on each cohort could be

determined by calculating backwards from the oldest to youngest fish captured in the fishery. Unfortunately, his model can only be used for estimating mortality of cohorts that are no longer part of the population. However, for practical purposes, to calculate the current population estimates, the present values of natural mortality for cohort are essential to be taken into account.

Designed to improve Gulland's approach, Jones (1961, 1968) calculated fishing mortality for cohorts still existing in the population. Catch was estimated from a cohort during a year by using the ratio of catches of that cohort in the two consecutive years to estimate the ratio of the stock size at the end of this year.

Pope (1972) developed cohort analysis, a modification of Fry's VPA approach. Estimates of total cohort mortality are calculated according to the ratio of population estimates in two consecutive years (as in Jones' work). Estimates of fishing mortality are then calculated from the total mortality estimates by subtracting the assumed value for the cohort's natural mortality.

The general population models of Delury (1947), later modified by Allen (1966), provided the basis for the Collie and Sissenwine(1983) model. Their model uses data from the catchability of standardized research vessel surveys to estimate population size. The catchability coefficient q of the survey is assumed equal for all cohorts of fish, i.e.,

$$P_{t,a} = qN_{t,a} \tag{2.3}$$

$$N_{t+1,a} = (N_{t,a} - C_{t,a})e^{-M} \tag{2.4}$$

$$P_{t+1,a+1} = (P_{t,a} - qC_{t,a})e^{-M} + \varepsilon_{t,a} \tag{2.5}$$

where, $P_{t,a}$, $N_{t,a}$ are the survey and true population abundance at year t of fish of age a, M is age-independent natural mortality and $\varepsilon_{t,a}$ is white noise error term. The equations are solved for q by a non-linear least squares estimation procedure. An estimate of population size by age can be calculated by dividing P_a by q according to equation 2.3. In this method, q is assumed constant for all cohorts of fish so that only estimates of population size by age will be biased, instead of the estimate of total population size.

Ray Hilborn and Carl Walters divide the most commonly used catch-at-age methods into two classes of models in their book "Quantitative Fisheries Stock Assessment" published in 1992. The first, commonly called virtual population analysis (VPA) or cohort analysis methods are recursive algorithms that calculate stock size based on catches without underlying statistical assumptions. The second class of catch-at-age methods relies on formal statistical models.

Virtual population analysis calculates the number of fish alive in each cohort for each past year. It is also called cohort analysis because each cohort is analyzed separately. VPA relies on a very simple relationship for each cohort:

Number alive at beginning of next year= (2.6)

Number alive at beginning of this year- catch this year- natural mortality this year

Recruitment does not enter into Equation (2.6) because a single cohort is being dealt with. Unfortunately, we rarely, if ever know the initial number alive; this is in fact one of the things we want cohort analysis to tell us. So we are reasonably safe in assuming that there are essentially no fish older than the oldest fish we ever caught. In general though, especially when stocks are intensively harvested, there will be so few fish older than our oldest catch that we can ignore them. Equation (2.6) can be rewritten as

Number alive at beginning of this year = (2.7)

Number alive at beginning of next year + catch this year + natural mortality this year

If we are willing to assume that at some age there are none alive (or that we know the number alive at some terminal age) and that we assume the rate of natural mortality is constant and age-independent, we can use equation (2.7) to calculate iteratively the number alive each year, starting from the oldest ages and moving backward to the youngest.

Historical stock size and fishing mortality rates can be estimated from catch-at-age data and an assumed natural mortality rate using VPA. There are two major problems with VPA: it can give unreliable estimates for cohorts that have not completely disappeared from the fishery, and it requires an assumption about the natural mortality rate. The first problem is more important; fisheries managers generally want to know the relative strength of cohorts still being fished, and although VPA will provide such estimates, they are obtained by various forms of *ad hoc* manipulation, generally called tuning.

Statistical catch-at-age analysis very elegantly synthesizes many pieces of fisheries theory that have been well known for some time, in particular, catch curve analysis and VPA. Here more details will not be mentioned, but other relevant citations are presented in the bibliography (e.g. collected papers on stock assessment methods by Rivard 1988.)

At the present time, VPA is the most widely used method of fish size (especially groundfish) estimation because of the relative simplicity of the computational approach and because of the widespread validity of its basic underlying assumption of uniform distribution of a stock over its habitat. It is often true, and more often assumed, that even if a species is more heavily fished in some areas than in others, the fish population will eventually return to a uniform population density because of the dispersion of the fish throughout its habitat.

2.2 Spatial-Temporal Analysis

The extension of fisheries modeling to explore the spatial or geographical dimensions of a fishery and its consequence on the resources, were infeasible prior to the development of appropriate spatial-temporal data sources. Recently, with the use of improved computational power and geographic information systems, modeling the spatial dynamics of fisheries is beginning to be developed.

Caddy (1970) performed a survey of ocean scallops and found that they congregated in "patches" or were subject to "contagion". Scallops are basically sedentary, invertebrate animals, so it is possible to assume that there will be little or no stock intermingling or movement by the stock of any significant distance.

Caddy (1975) developed a spatial analysis model where he estimated the scallop population of the Georges Bank by dividing the scalloping grounds into zones of equal size and assumed that effort and population distributions were uniform only over these smaller zones.

GIS (Geographical Information Systems) have been used to do some marine analysis on a spatial basis but most of this work relates to oceanographic issues and little work has focused on analyzing fishery issues and stock assessment. Kulka applied GIS to address the stock status of Northern Cod in NAFO division 2J3KL in 1990, 1995, 1996. Hutchings (1996) examines the spatial dynamics of the 2J3KL Northern Cod stock in defending the hypothesis of overexploitation as the sole explanation for stock collapse.

In an earlier MSc thesis, Storey(1998) developed a spatial-temporal model for assessing the herring stock in 4WX. That work developed the probability transition data for developing the core process and carried out sensitivity analysis of the Bayesian updating model. Aggregate results were compared to standard VPA estimates.

This present thesis is an extension of Storey's Bayesian approach with emphasis on estimating specifically the in-season stock size of known spawning areas. In particular, we use the modeling and computer simulation to generate statistics for estimating local spawning group abundance. These statistics are used to provide an aggregate measure over all spawning groups comparable to the aggregate estimates from VPA. It is argued that over the local spawning group, estimates are more reliable and lead to improved results compared to the VPA. The shift to spawning group estimates from overall aggregate stock size is important for the in-season management of the stock.

2.3 Application

Modern herring fisheries are very difficult to manage. Large scale, efficient purse seines are capable of capturing entire schools of fish in a few hours. Gillnets may become so heavily concentrated on spawning beds that most of the herring in a run are captured before having a chance to reproduce. Over-fishing has in fact combined with poor recruitment of young fish to reduce some Canadian Atlantic herring stocks to low levels.

Overfishing results in the loss of production due to growth and the loss of production of young fish. If the fish were allowed to reproduce more often, they could contribute more to the production of future generations of new recruits. The capture of herring may not take full advantage of the potential growth in weight and reproductive capacity of each fish. However, the maximum possible yield does not occur when all the fish are old and more fish die every year from causes other than fishing (e. g. predator, disease, natural causes). It is important to balance the advantages of growth and reproduction against this continuing natural mortality when deciding what portion of a population should be harvested.

Some of the largest Canadian herring fisheries are carried out when herring from several spawning populations are mixed together for feeding, pre-spawning or migration. Under the present circumstances, it is impossible to predict exactly what portion of the total allowable catch (TAC) will be caught from any one population when that population is mixed. There is a real danger that small populations contributing to a large fishery might accidentally bear much more than their share. The results can induce the virtual elimination of these spawning populations. It may take many years before new stocks repopulate the abandoned spawning sites.

In this thesis, a spatial-temporal methodology is applied to the stock assessment of 4WX herring in the Bay of Fundy off southwestern Nova Scotia. The 4WX management unit is known to contain a number of discrete spawning areas separated in space and time (Stephenson *et al* 1993). According to the known migration patterns of spawning groups, and the dynamics of the 4WX herring stock, its corresponding management control is analyzed by geographical zones and time.

To help deal with the management problems, scientists must estimate the abundance of fish in each subpopulation at a given time. One useful guide for some species of fish is the catch rate of commercial fishing vessels. If they catch more per day this year than they did last year for the same amount of fishing effort, this suggests that fish are more abundant. But the schooling behavior of herring complicates this situation. If a stock is decreasing in size, high catch rates may be distributed over smaller territory, and experienced fisherman using sophisticated electronic equipment can usually find the highly aggregated schools of fish.

Awareness of the complexity of the problem has led scientists to exercise a "precautionary approach" in recent years in their recommendations for annual total allowable catch limits (TACs) (FAO 1995). The spatial-temporal characteristics of stocks like Atlantic herring suggest that a more disaggregated approach to stock management as developed in this thesis is required to protect stock subpopulations. This will have positive results in terms of improving our understanding of fish spatial-temporal dynamics, and improving our management effectiveness toward resource sustainability.

3. Methodology

3.1 Population generation model

The population generation model is the core process of the spatial herring stock assessment process. This model is designed to generate simulated stock data as input for VPA assessment and the spatial-temporal assessment model of herring stock.

The spatial-temporal method is used to describe the dynamic migration behavior of the fish stock. The total fish stock is divided into spawning groups. The state of the dynamic system is defined by its subsystem states, which include the geographical zone of migration pattern and the population of each spawning group during a specific time period. So, with this model we can estimate the population of the stock in a particular spatial zone each period, i.e., weekly. The data are in turn used to determine catch data. These generated catch data can be used in the VPA assessment and in the spatial-temporal assessment of the fish stock size as observations to update stock status. The VPA assessment methodology and the spatial-temporal assessment methods are described in more detail below.

3.2 Using VPA to estimate fish stock size

The VPA method to estimate the fish stock size is popularized in the computational adaptive framework known as ADAPT (Gavaris, 1988) that calibrates the sequential population analysis with index survey results as follows:

$$
\begin{aligned}
&F_{b,t} = F_t pr_a \\
&C_{a,t} = catch \\
&N_{a+1,t+1} = \frac{C_{a,t}(F_{a,t} + M)}{F_{a,t}(e^{(F_{a,t}+M)} - 1)} \\
&N_{a,t} = N_{a+1,t+1} e^{F_{a,t}+M} \\
&N_{a,t} = \frac{C_{a,t}(F_{a,t} + M)}{F_{a,t}(1 - e^{-(F_{a,t}+M)})}
\end{aligned}
\qquad (3.1)
$$

where, $C_{a,t}$ is catch number for age a and for year t, $N_{a,t}$ is the population abundance number at age a and year t, $F_{a,t}$ is the continuous fishing mortality rate (dimensionless) for age a and year t, $0 \leq pr_a \leq 1$ is the partial recruitment (harvestable portion) for age a, M is the continuous natural mortality (dimensionless) assumed constant for all ages and equal to 0.2. Older F's at age are often calculated from F's of younger ages.

Following Gavaris(1993), a model formulation using as parameters the *ln* population abundance at the beginning of the year following the terminal year for which catch at age is available is presented. The model parameters are defined:

$\theta, a, 1998$ = *ln* population abundance for a=5 at the beginning of the year t=1 κ =*ln* calibration constant for the larval abundance index

ADAPT solves for the parameters by minimizing the sum of squared differences between the *ln* observed larval abundance index and the *ln* spawning population biomass. The objective function for minimization is defined as:

$$\psi_t(\theta, k) = \sum_t (\ln I_t - \kappa + \sum_a \ln m_{a,t} w_{a,t} \bar{N}_{a,t}(\theta))^2 \tag{3.2}$$

where, I_t is equal to the larval abundance index for year t (the larval abundance index is a scalar measure of the average density of herring larval at fixed stations in the stock area and is used as an index of abundance of the adult spawning stock), $m_{a,t}$ is the proportion mature and $w_{a,t}$ is the observed weight at age a, in year t.

For convenience, the mid-year population abundance $\bar{N}_{a,t}(\theta)$ is abbreviated to $\bar{N}_{a,t}$.

$$\bar{N}_{a,t} = N_{a,t} e^{-(F_{a,t}+M)0.5} \tag{3.3}$$

3.3 Using the spatial-temporal method to estimate fish stock size

In this thesis, the abundance levels of the spawning group in each geographical zone during each specific time period are estimated by the qualitative levels. The "fuzzy" or qualitative abundance measures are zero, extremely low, very low, low, medium low, medium, medium high, high, very high, extremely high according to the fisherman's observations and categorical descriptions of stock availability.

The state of abundance of each spawning group during the specific time period, which migrates along the specific migration pattern, depends on its state in the previous time period, that is, information of how many fish there were in each zone previously provides useful information about the state of the system in the next time period. A Markov chain is ideally suited for describing the probabilistic population dynamics of this kind of dynamic system behavior.

The following describes the key notation of the partially observable Markov chain problem methodology (Lane 1989). The following model description repeats the definitions provided similarly in Storey's thesis (1998).

Let

$k \in \{1,2,...52\}$ denote the periods of the fishing season-the k^{th} week of the year;

$z \in Z$ represent a zone of the fishery with N_z denoting the the number of discrete zones in the fishery

X_k be a N_Z-dimensional random variable which represents the discrete population levels of the stock for the Z zones at the end of the k^{th} week; and

$\{X_k\}$ denote the dynamics of fish abundance over the year.

The state-to-state dynamics of the process of the system between weeks k-1 and k is assumed to be a finite state Markov chain with nonstationary transition probabilities, $p_{ijk} = \Pr(X_k = j | X_{k-1} = i)$, where p_{ijk} is the probability of moving from $X_{k-1} = i$ in week

k-1, to state $X_k = j$ in week k, and i, j are members of the set of N_z– tuples whose values are from 1 to 10 to represent fuzzy set of stock abundance across all zones. The process of abundance dynamics is described completely by the probability transition matrix for each period k, $P_k = \{p_{ijk}\}$, which describes the transition process of stock -temporal dynamics from zone to zone and week to week over the year.

Let Y_k be a random variable that denotes the signals or observations of the actual state of system at period k in zone z. These signals are the level of total catch by weight. The actual catch zone in each period is determined by the action space described below. The stochastic process $\{Y_k \; k \in K\}$ is known as the observation process of the system.

Information regarding the actual abundance, X_k is obtained when fishermen observe Y_k during fishing. Moreover, the probabilistic relationship between X_k (not observed) and Y_k (observed) is assumed to be known.
Let

$$q_{jlk}(z) = \Pr(Y_k = l | X_k = j), z \in Z, \tag{3.4}$$

define the relationship between X_k and Y_k which describes observations as a function of the population state of the core process, the population level. It is assumed that the observations occur independent of the week. So we define $q_{jlk} = q_{jl}$ for all k.

The observation process is described by signal or observation matrix $Q_k(z) = [q_{jl}(z)]$. They describe the distribution of possible observation probabilities for the given levels of the actual state.

We define the sufficient statistic (Bertsekas 1976) as the conditional probability that the abundance level $X_k = j$ occurs at period k, given the information vector $I_k = \{Y_0, Y_1, Y_2, \ldots Y_k\}$.

$$\pi_j(k) = \Pr(X_k = j | I_k), j \in N, \tag{3.5}$$

where $\pi_j(k)$ is the state variable of the system defining the interaction between the partially observed actual population size and the available information about it. Using

Bayes' formula, $\pi_j(k+1)$ is defined by the transfer function T_k as

$$T_k(\pi|I)_j = \pi_j(k+1) = \frac{q_{jlk} \sum_i p_{ijk} \pi_i(k)}{\sum_{i,j} q_{jlk} p_{ijk} \pi_i(k)} \tag{3.6}$$

for state vector indices *i,j* and weekly periods $k \in \{1,2,...52\}$. Let $\pi(0)$ (= $\pi(52)$ of the previous year) describe the initial probability distribution of the stock at the beginning of the year. The $\pi_j(0)$, the probabilities of initial abundance levels, are assumed to be known through historical estimates or from research survey data.

Equation (3.6) uses Bayes' Theorem to obtain the probability of the state level of abundance by zone and by week through the sufficient statistic (3.5). Since $\pi(k)$ is the probability distribution of the population abundance levels, the population abundance can also be computed in each period by zone as an expectation and then summed over all zones to obtain total aggregate abundance. The estimates of abundance are updated for each period *k* after every fishing period.

Equation (3.6) is used only for zone-week combinations where there are catch data or there is reason to expect that fishing effort took place. However, to update population levels when there is no fishing, the following update equation, involving only the core process and the probability transition matrices, P_k, is used:

$$T_k(\pi)_j = \pi_j(k+1) = \frac{\sum_i \pi_i(k) p_{ijk}}{\sum_j \sum_i \pi_i(k) p_{ijk}} \tag{3.7}$$

The following sections describe the application of these methodologies to the Scotia-Fundy Herring fishery and compare the results between VPA and spatial-temporal methods.

4. Application

The methodology for spatial-temporal stock assessment is applied to the 4WX herring stock assessment in the Bay of Fundy off Nova Scotia. First of all, according to the known migration patterns of spawning groups, we obtain the "standard" population distribution by week and by zone throughout the year. Second, we generate catch data based on the state-to-observation function described in Equation (3.4). Third, we calculate the π matrix as the weekly update of the distribution of the population level using Bayes' formula (3.6).

We then compare the VPA estimates from the herring stock assessment document ("1998 EVALUATION OF 4VWX HERRING", Stephenson et al. 1999) with estimates obtained through the spatial-temporal stock assessment methods described above. The following section (4.1) discusses the entire structure diagram of 4WX herring stock assessment application.

4.1 Structure Diagram of 4WX herring stock assessment application

Figure 4.1 presents the map of the Scotia Fundy Fishery Grounds. The following analysis of 4WX herring stock assessment application will be based on this region. The whole analysis procedure is described by the structure diagram below (Figure 4.2), which compares the spatial-temporal assessment analysis proposed in this thesis with the VPA analysis method. For the spatial-temporal method, the analysis procedure is discussed in two ways:

- to update generated population with generated catch data;
- to update generated population with actual catch data;

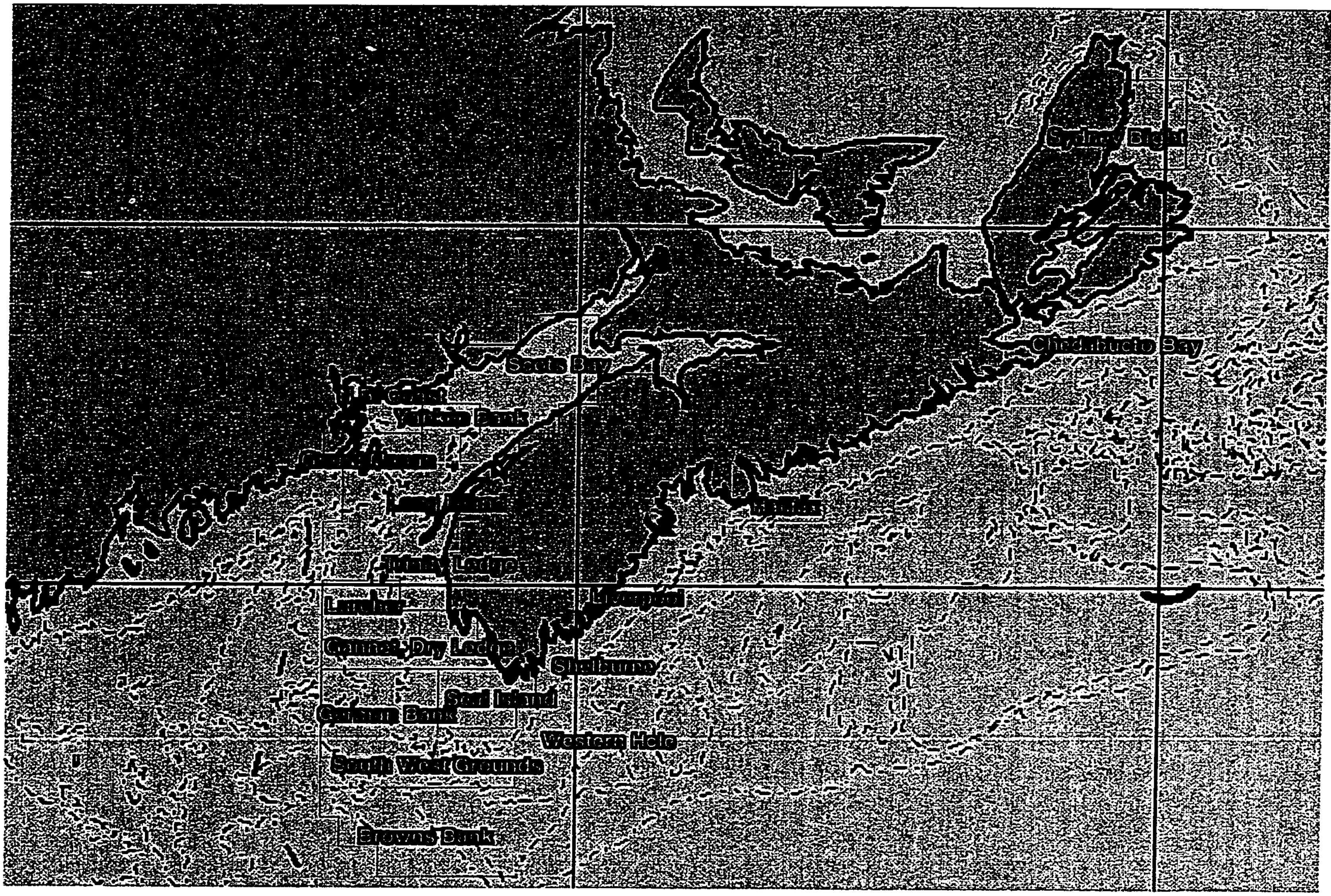

Figure 4.1 Map of the 4WX herring fishing grounds

In addition, the herring population generation model is developed using a graphical user interface (GUI) system to control model input and output.

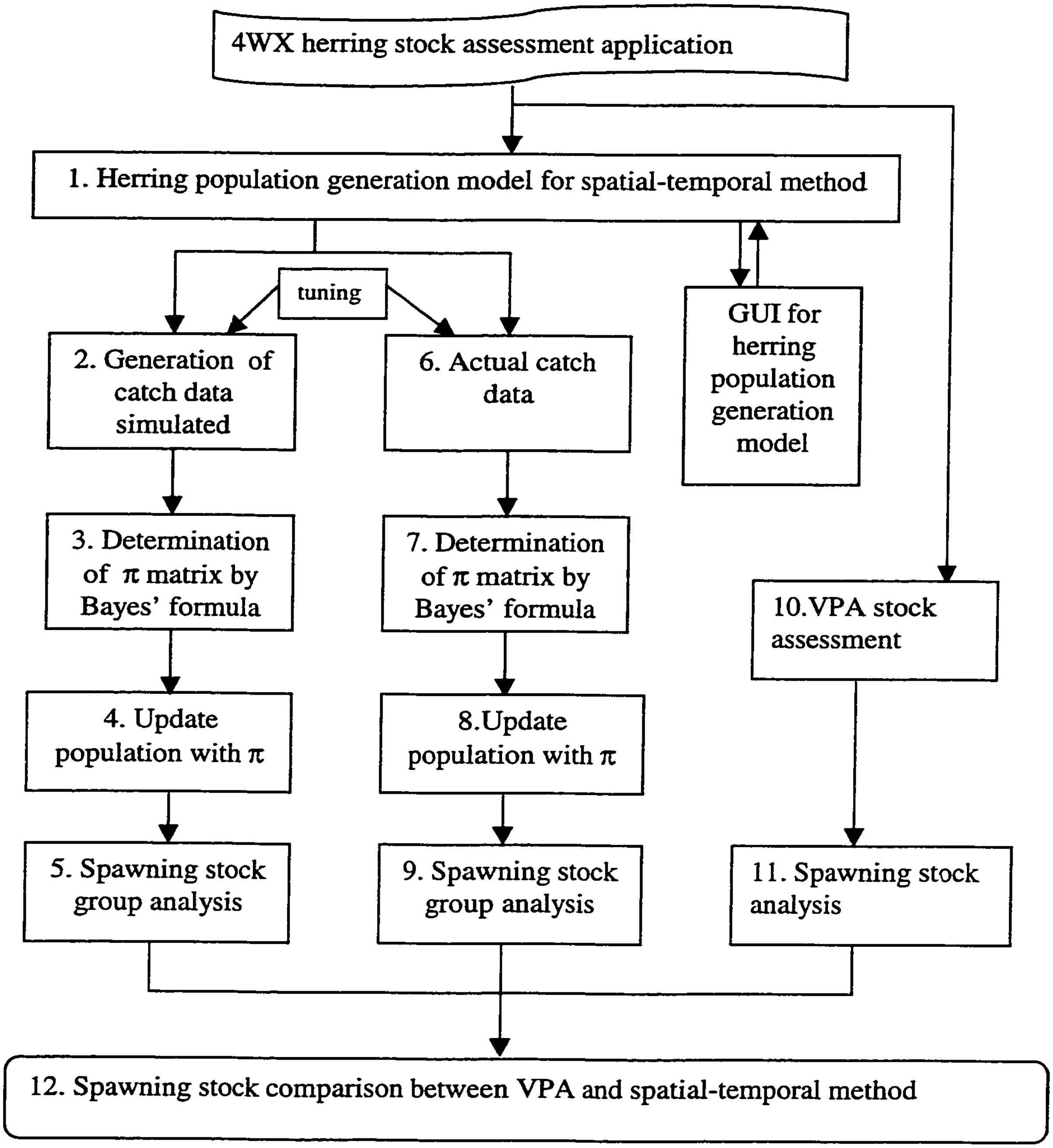

Figure 4.2 Structure diagram of 4WX herring stock assessment analysis

The above structure diagram describes the herring stock assessment comparative analysis process. Details of each analysis are discussed in the following sections. The functions, definitions and implementations of the models are illustrated in the program documentation presented in Appendix E.

4.2 The Herring population simulation model

The herring population generation model is the core process of the entire spatial-temporal analysis in the 4WX herring stock assessment application, which models the actual dynamics of the herring stock. The migration patterns and proportions of the spawning groups of the 4WX herring stock in the Bay of Fundy off southwestern Nova Scotia are relatively well known for the pelagic stock although they are time variant.

We develop the population generation model to analyze the herring stock size week by week during one year, over the geographical zones of the herring migration patterns and changes in abundance levels during the year (Figure 4.1).

In order to describe the population generation model, we need the following required data components:

1) Estimated ranges of the proportions of each spawning group within the herring population
2) Well-defined weekly migration patterns of the "main wave" of each spawning group
3) An initial estimate for the size of the adult population of the whole stock (all spawning groups)
4) The proportions of up to 5 different patterns of waves of migration for each spawning group related to the main wave

As part of the development of the spatial-temporal assessment model, new data requirements arose. For example, fundamental data on stock migration patterns, run timing, and strength of substocks (spawning groups) were determined and derived from several unpublished sources. These included spatial catch data (which in the context of population assessment and VPA were merely described but never used in the analysis), observations from fishermen regarding timing of the fishery (and run timing of herring at various fishing grounds), and unpublished population dynamics hypotheses put forward by the herring scientists (Stephenson, *personal communication*). The following sections describe these data as used in the spatial-temporal model development.

4.2.1 Spawning groups in Scotia Fundy region

In the Bay of Fundy and the Scotian shelf, we define 15 geographical zones (Figure 4.1) for the 4WX stock migration, where we consider 6 distinct spawning subgroups. Table 4.1 illustrates the 6 spawning groups, the estimated annual ranges of the proportion of each subgroup strength within the total population, and the specific spawning zone and peak spawning periods. The 15 Zones are denoted by name in Table 4.2 below. The specific "main wave" migration patterns for each spawning group are described in Appendix A.

Table 4.1 Scotia-Fundy Herring Spawning Group Definition

Spawning Subgroup Index	Spawning Subgroup Name	Minimum Proportion of each subgroup (%)	Maximum Proportion of each subgroup (%)	Expected Proportion of each subgroup (%)	Spawning Zone (No.)	Spawning Period (Dates)
1	Scots Bay, Chedabucto	5.25	18.75	12	8	July 20 -Aug 15
2	Scots Bay, Grand Manan	1.75	6.25	3	8	July 20 - Aug 15
3	Trinity	10	30	20	3	Aug 15 -Sept 15
4	Lurcher	2	10	5	4	Aug 15 -Sept 15
5	Seal Island	10	30	20	6	Sept 1 -Oct 15
6	German Bank	20	60	40	7	Sept 1 - Oct 15

Unlike the other spawning groups, the Scots Bay spawning group has been subdivided for the purposes of this model into 2 components. One part of the spawning group overwinters in Grand Manan and the other spends the winter in Chedabucto Bay. The fish coming from Grand Manan (Zone 1) are assumed start spawning a week earlier than the fish coming from Chedabucto Bay (Zone 9).

In summary, the above Table 4.1 provides information on the herring population subgroups including the following:

- German Bank is currently the largest spawning group in the 4WX herring population.
- Spawning duration occurs in “waves” of herring which typically stay on the spawning grounds for approximately 3 weeks.

- Scots Bay (head of the Bay of Fundy) has 2 sources of spawning from overwintering components in Chedabucto and in Grand Manan.

According to the recent estimates of the herring stock, we know:

- Trinity is subject to seasonal closures to fishing during its spawning period.
- In recent years Seal Island spawning has decreased; its adjacency to German Bank may have increased spawning in that group.

4.2.2 Fishery Zones

The spawning area destinations for the 6 spawning groups represent only a part of the entire area migration of herring through 4WX. Fishing also occurs in other areas where herring are found in aggregations, e.g. for pre-spawning and feeding, and during the overwintering period. Table 4.2 presents the model Zone number and Zone Name description for the fishing zones as part of the herring migration in 4WX. (See also map in Figure 4.1)

Table 4.2 Description of herring fishery zones

Zone Number	Name	Description
1	Grand Manan	Island off N.B. Shore
2	Long Island	Island off Western N.S.
3	Trinity	Fishing Ground South of Long Island, near N.S.Coast
4	Lurcher	Fishing Ground South of Trinity
5	Gannet, Dry Ledge	Fishing Ground South of Lurcher
6	Seal Island	Island off Southern Tip of N.S.
7	German Bank	Fishing Ground Southwest of N.S.
8	Scots Bay	Small Bay at Northern End of Bay of Fundy
9	Chedabucto	Fishing Ground Adjacent to East Coast of N.S. and Cape Breton
10	N.B. Coastal	Fishing Ground Along Coast of N.B.
11	Southwest Grounds	Fishing Ground South of N.S.
12	Diffuse	Fish are Feeding, Diffuse Throughout the Region
13	Yankee Bank	Fishing Ground Between N.S., N.B. (between Scots Bay, Grand Manan)
14	Halifax	Fishing Ground off Halifax Harbour
15	Liverpool	Fishing Ground Between Halifax, Seal Island

Figure 4.3 below summarizes spawning stock dynamics with the overall migration pattern data presented above.

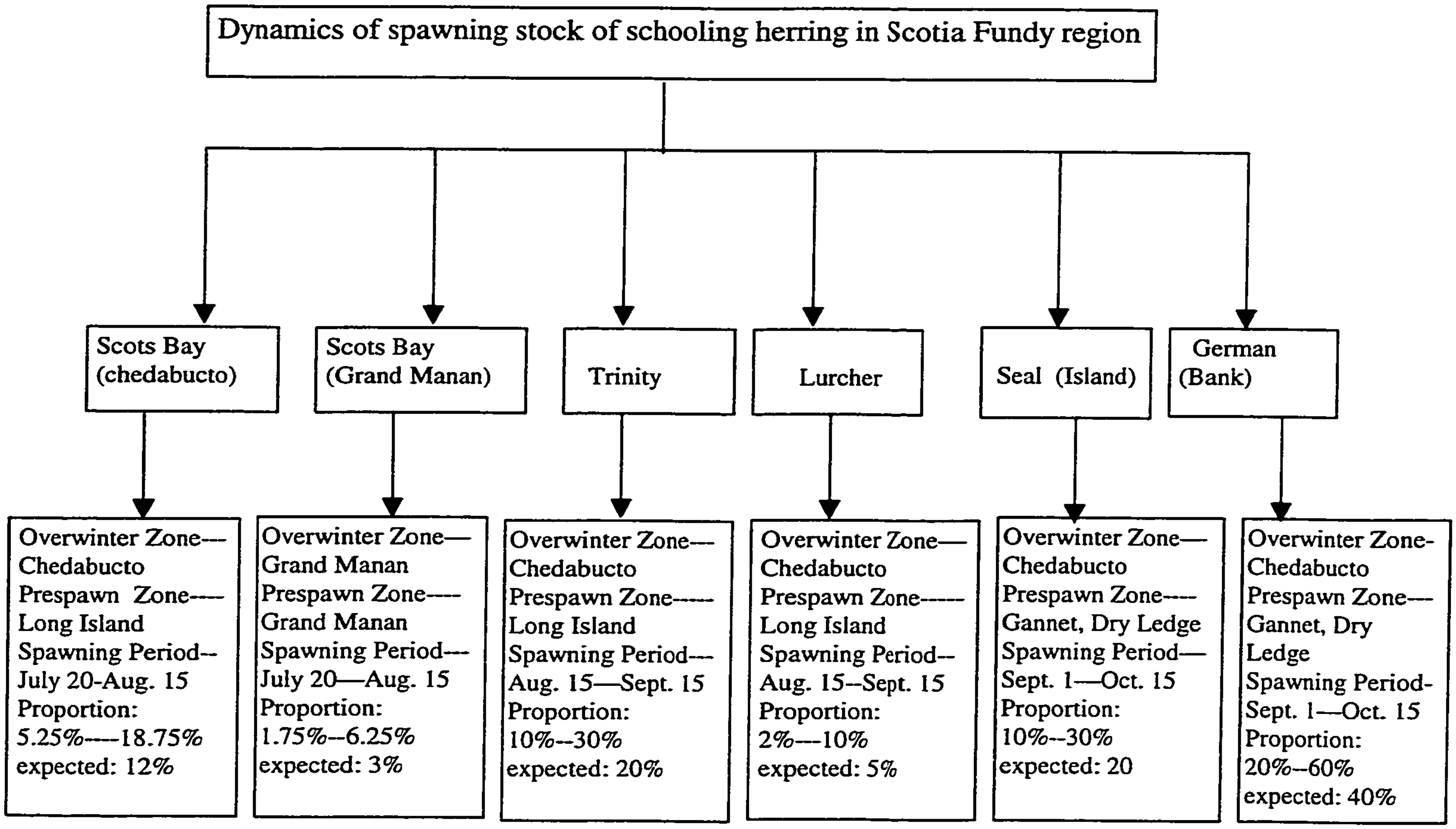

Figure 4.3 Diagram of herring stock dynamics in Scotia Fundy region

4.2.3 Wave patterns

The herring in a spawning group do not all migrate to the spawning grounds at exactly the same time. In this model each herring spawning group has been divided into 5 waves which move at successive weekly intervals. Each wave pattern has a proportional value assigned to two weeks prior to the main wave and two weeks after the main wave. The wave distribution has been modeled as one of five distribution possibilities:

- Flat - the uniform distribution (equal weighting over early, late and main waves)
- Normal - a large main wave with smaller early and late waves
- Truncated uniform (equal weighting over immedate early and immediate late waves
- Skewed left - peaked weight at the left (early) end of the migrating run
- Skewed right - peaked weight at the right (late) end of the migrating run

These five run timing distributions are depicted in Figure 4.4 to Figure 4.8 below.

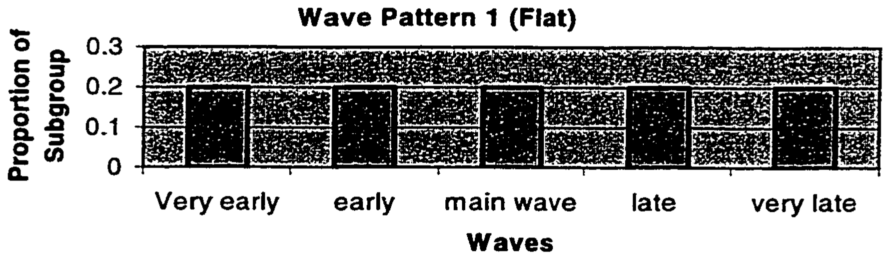

Figure 4.4 Spawning group running time wave pattern 1-flat distribution

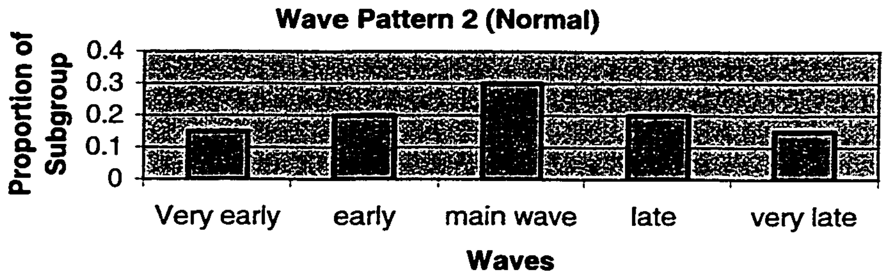

Figure 4.5 Spawning group running time wave pattern 2 – Normal distribution

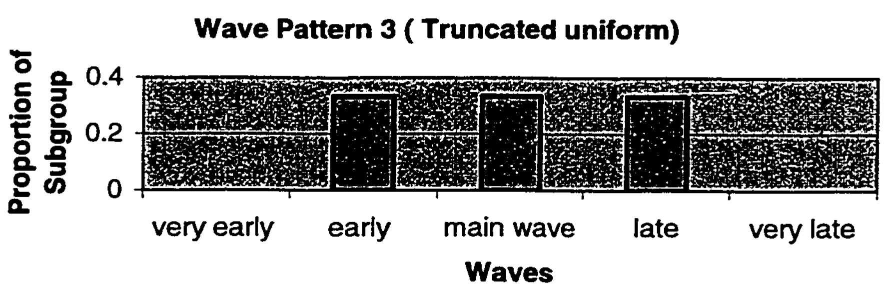

Figure 4.6 Spawning group running time wave pattern 3 – truncated uniform distribution

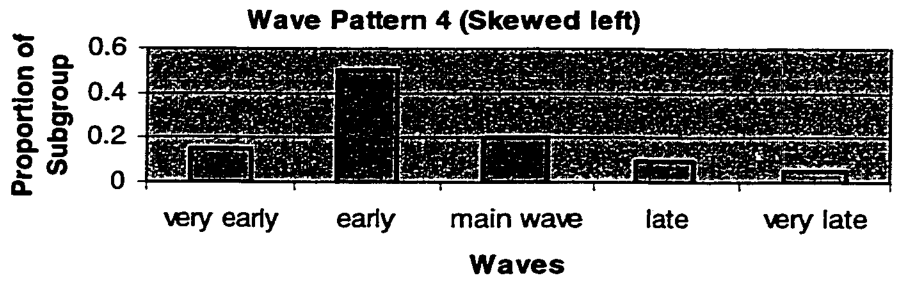

Figure 4.7 Spawning group running time wave pattern 4 – skewed left (early) distribution

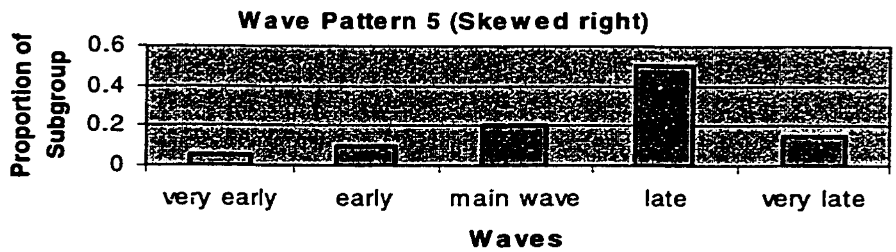

Figure 4.8 Spawning group running time wave pattern 5 - skwed right (late) distribution

A 'main' wave may be accompanied by 'early', 'late', 'very early' and 'very late' runs of migrating herring for each spawning group (Figure 4.4 to Figure 4.8). Each wave of the same spawning group is assumed to follow the same spatial migration pattern as the "main" wave with associated delays and or advances. For example, if spawning group German Bank is migrating with wave pattern 2 in running time, its main wave comes into zone 7 during week 37, however its late and very late wave is enters zone 7 one week and two weeks later respectively. Similarly, its early and very early waves enter zone 7 already one week and two weeks earlier respectively.

Appendix A provides the expected run timing migration patterns for each of the six groups, which describes the location of the main wave of each subgroup during each week of the year. There are two possible migration patterns that the spawning groups follow (since pairs of zone options in some weeks for the spawning groups), one of which is selected randomly by each spawning group for each simulated population generated.

4.2.4 The herring population generation model in Scotia Fundy region

The herring population generation model is described by simulating the spawning group migrations from an initial estimated size of the total herring stock. The initial size of the total herring population is selected randomly from a Normal distribution with mean 300 thousand (metric) tonnes and standard deviation of 100 thousand metric tonnes. The Normal distribution is chosen to characterize the total population as a random variable by virtue of the large number of independent random variates that comprise the total. The 95% range of this distribution size covers the estimated long term historical aggregated stock size from the VPA stock estimates which cover the extended time from 1978 to 1998 (1998 EVALUATION OF 4VWX HERRING by Stephenson et al., 1999). The algorithm for simulating Normal distribution N(300,100) is presented below.

Since z satisfies Normal distribution with mean μ=300, variance σ=100, that is, N(300,100), then x=(z-μ)/σ and x satisfies the standard Normal distribution N(0,1).

Let
$$F(x) + Q(x) = 1 \tag{4.1}$$

$$Q(x) = P(y \geq x) = \frac{1}{\sqrt{2\pi}} \int_x^{\infty} e^{-\frac{x^2}{2}} dx$$

Then
$$Q(x) = 1 - F(x) \tag{4.2}$$

With 95% confidence, x can be approximated as:

$$X(u) = t - \frac{C_0 + C_1 * t + C_2 * t^2}{1 + D_1 * t + D_2 * t^2 + D_3 * t^3}$$
$$t = \sqrt{\ln(\frac{1}{u^2})}$$
$$C_0 = 2.515517; C_1 = 0.802853; C_2 = 0.010328$$
$$D_1 = 1.432788; D_2 = 0.189269; D_3 = 0.001308 \tag{4.3}$$

Where, u is a uniform random number, which is 0<u<0.5, x can be approximated from formula below:

Assume, p is a uniform random number [0,1], so

if $0 < p \leq 0.5$, then $u = p$, and x is a negative number.

if $0.5 < p \leq 1.0$, then $u = p - 0.5$, and x is a positive number.

So we can have a random variable x which satisfies Normal distribution N(0,1).

Then, we can obtain $z = \sigma x + \mu$, which z is distributed as $N(\mu, \sigma)$, σ is the variance, μ is the mean.

Spawning group proportions are randomly determined to fall into estimated historical ranges for each spawning group [Table 4.1]. Randomly estimated sizes for component spawning groups are then simulated as a proportion of the simulated total and described along their respective migration patterns over time. Moreover, the spawning groups of herring migrate relatively independently of each other and their absolute sizes are also independent.

The flow chart for the herring population generation model is described in Figure 4.9. We designate the primary migration pattern vector as migration1[52][15] and the secondary vector as migration2[52][15] for each spawning group. The population generation model is developed through a graphical user interface using the object oriented programming language Visual C++. The procedure and results of population generation model use are described below.

4.2.5 Graphical user interface of herring population generation model

The herring population generation model with Visual C++ graphical user interface (GUI) is described below (Figure 4.10). This model includes three parts:

- The input graphical interface which allows the user to input simulation conditions;
- The herring population generation model which has been described in previous section 4.2.4;
- The output analysis graphical interface which can help the user to analyze the spawning stock, consisting of biomass week-zone analysis, spawning group

biomass analysis, and total spawning stock biomass (SSB) analysis.

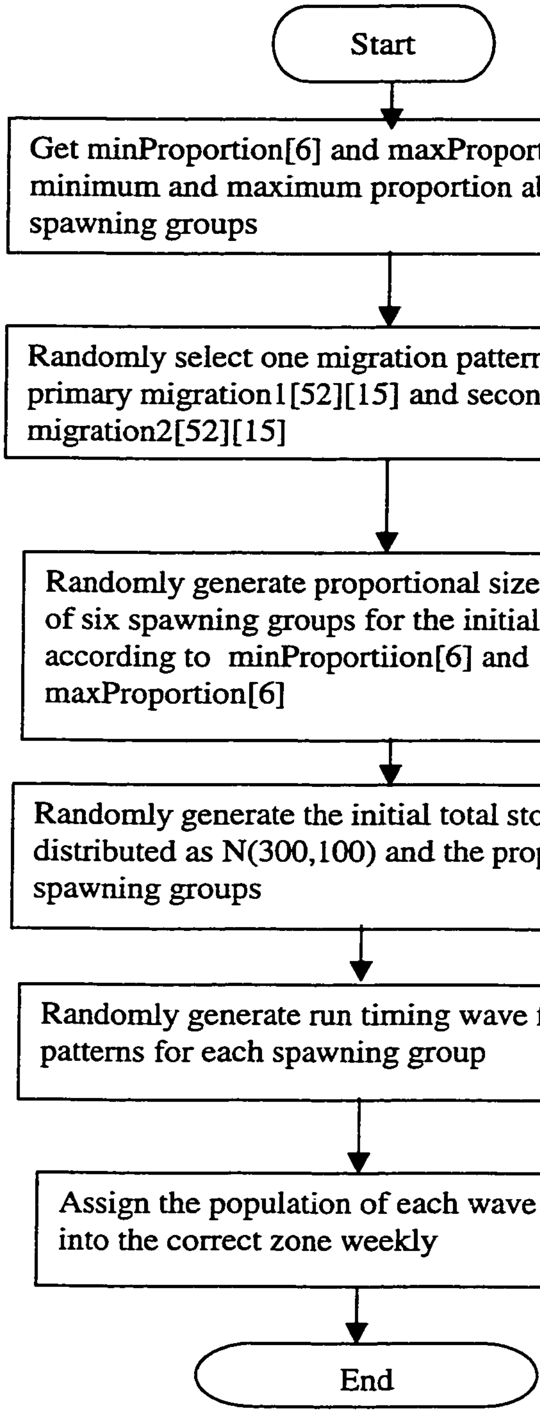

Figure 4.9 Flowchart for the herring population generation model

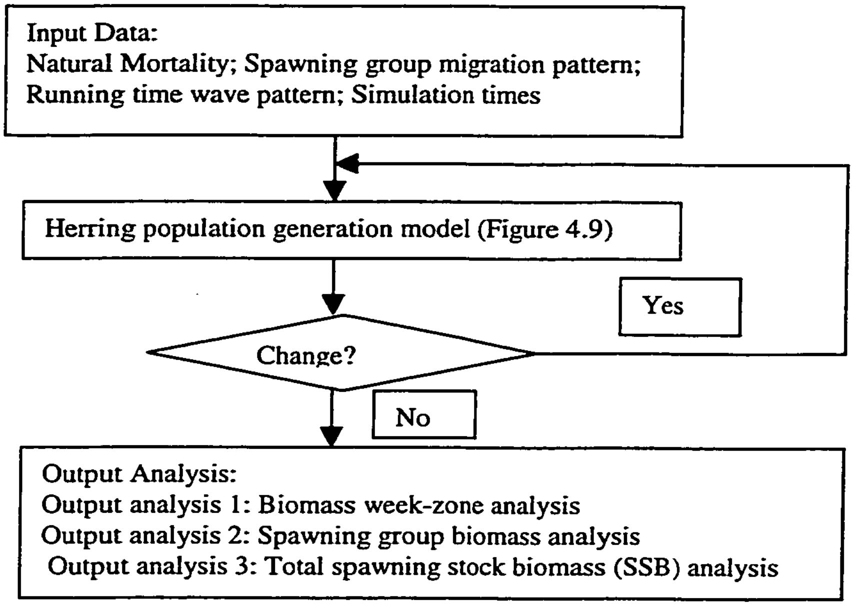

Figure 4.10 Simulation process with graphical user interface (GUI)

4.2.5.1 Input graphical interface:

The input section of the graphical interface includes the welcome screens (Figure 4.11, 4.12), input screens for the herring spawning group natural mortality (Figure 4.13), input section for spawning group migration patterns (Figure 4.14, 4.15), the running time wave patterns (Figure 4.16), and and input screen for the initial population size and parameters for the Normal distribution mean, standard deviation and the number of simulation trials (Figure 4.17).

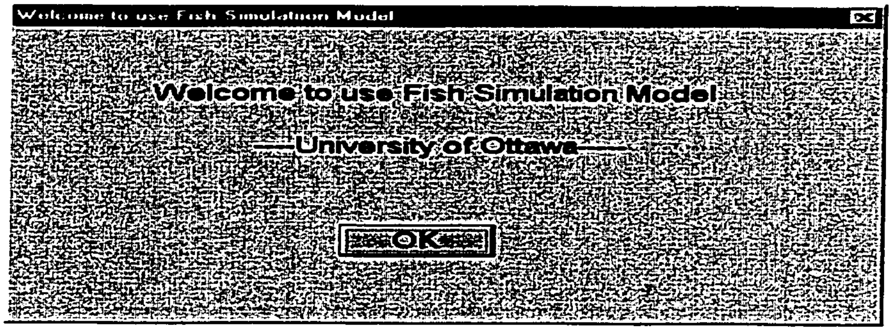

Figure 4.11 Welcome screen

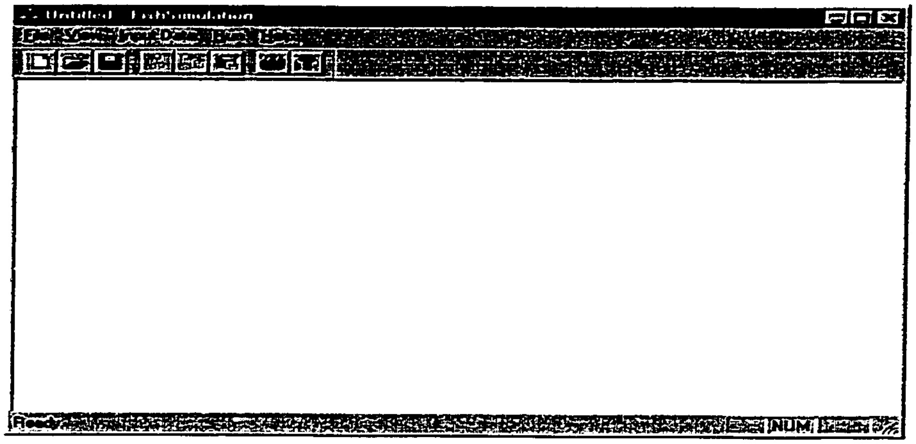

Figure 4.12 Input menu

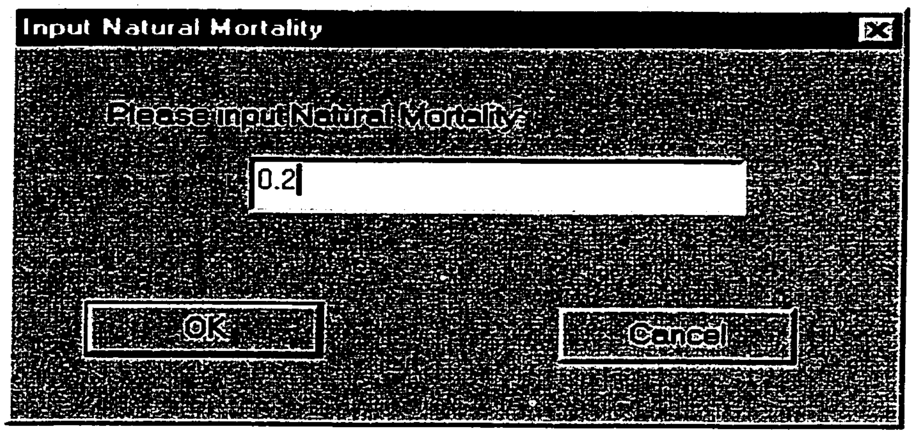

Figure 4.13 Natural Mortality Input Screen interface

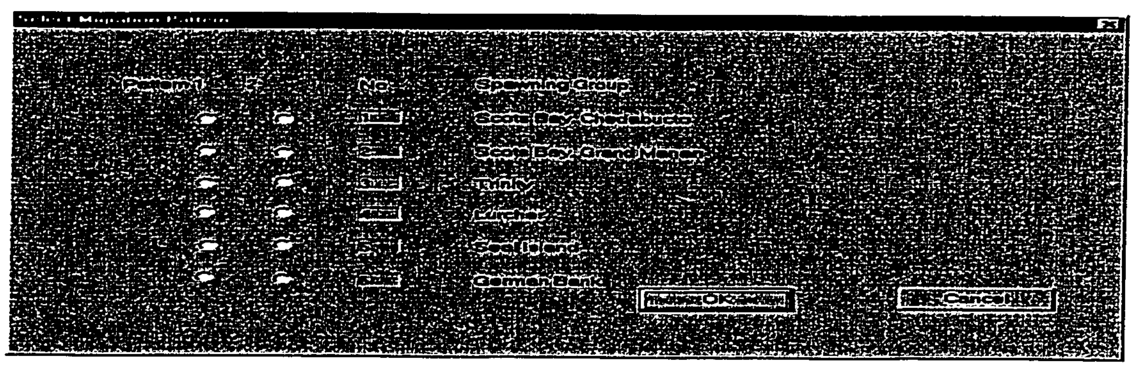

Figure 4.14 Select Migration Pattern Screen interface

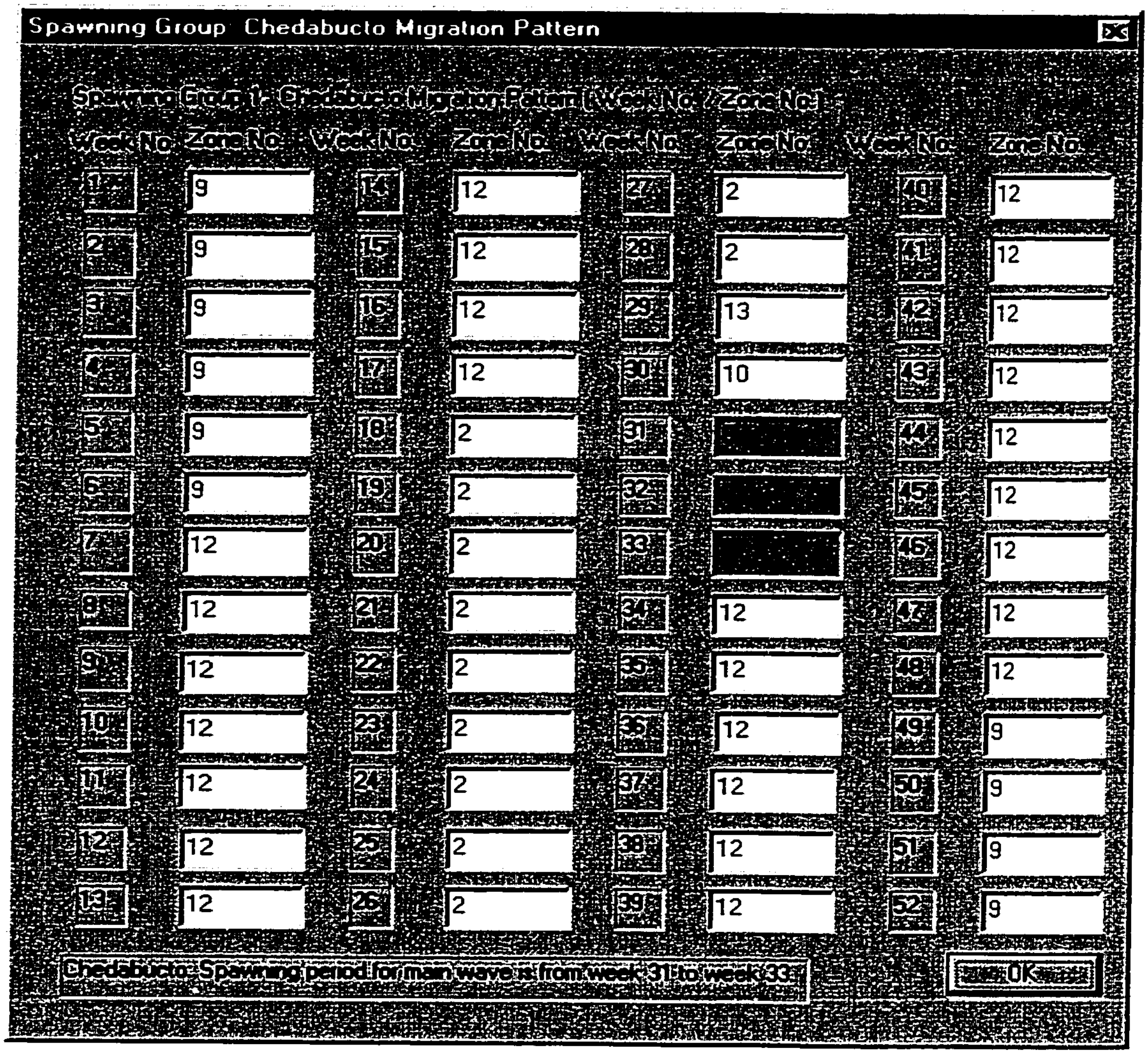

Figure 4.15 Spawning group Chedabucto migration pattern 1 screen

The above Figure 4.14 allows the user to view and change the spawning group migration patterns by selecting one of them. For example, when clicking the radio button for Scots Bay, Chedabucto pattern 1, the window described in Figure 4.15 will pop up.

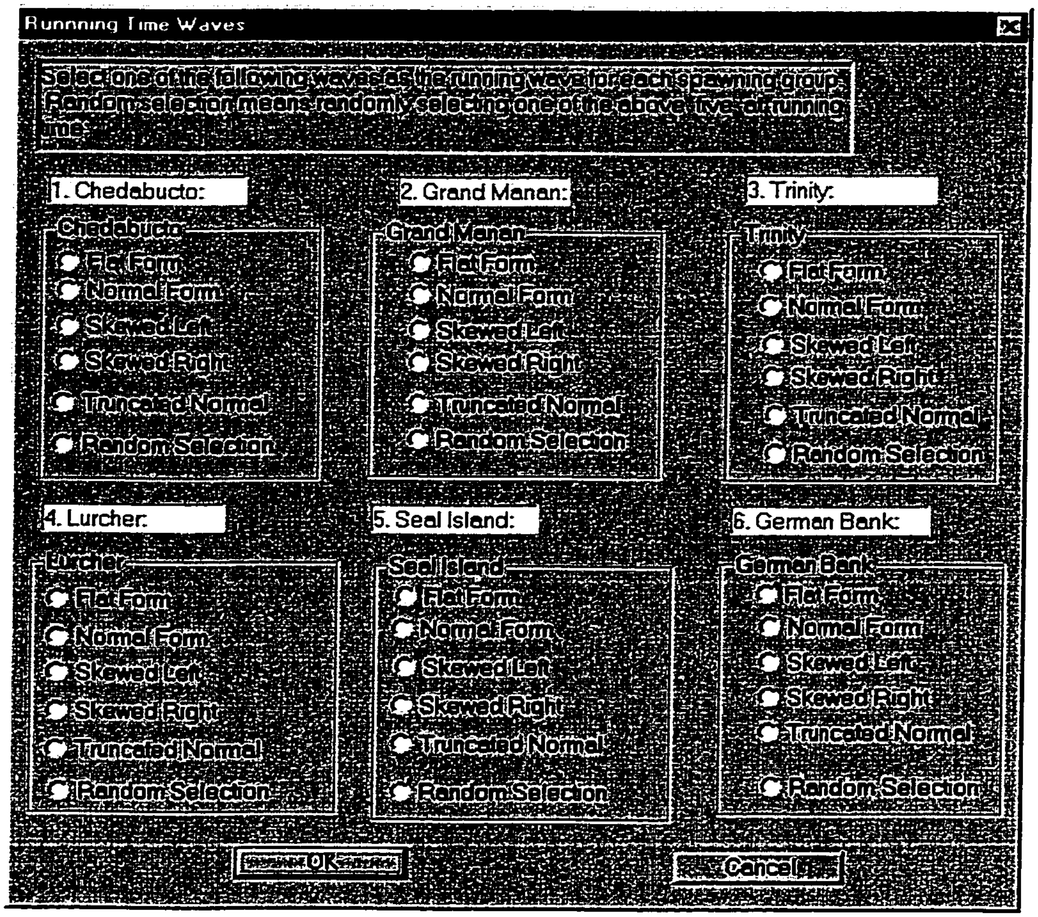

Figure 4.16 Running time wave patterns input

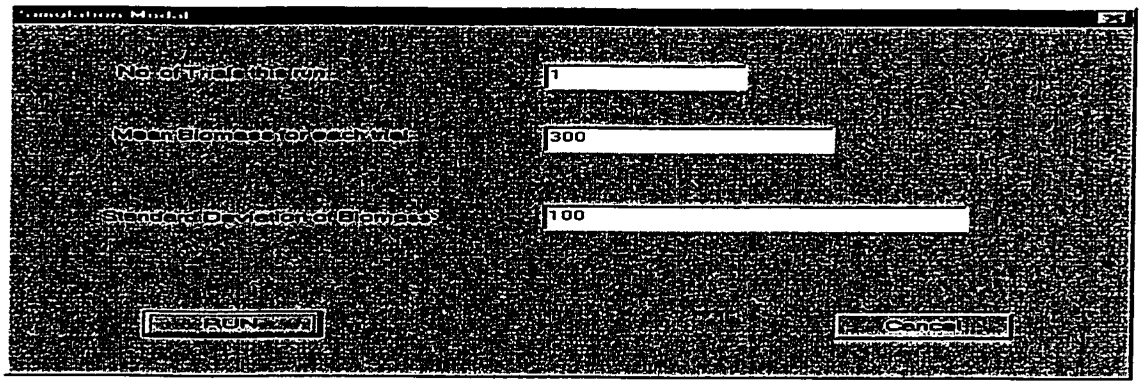

Figure 4.17 mean and deviation input screen

Figure 4.17 allows the user to input the number of simulation trials, normal distribution mean and standard deviation. In the model, we input N(300,100). After that, clicking the run button will execute the population generation model procedures and then the result analysis can be displayed by the GUI output described below.

4.2.5.2 Output analysis graphical interface:

The output analysis graphical interface provides results analysis for the population generation model, which includes biomass week-zone analysis (Figure 4.18, 4.19, 4.20), Spawning group biomass analysis (Figure 4.21, 4.22) and Total spawning stock biomass (SSB) analysis (Figure 4.23, 4.24).

1) Output Analysis 1:

Biomass week-zone analysis illustrates the herring population graphically by zone and by week during one year. In order to use Microsoft Excel chart function to display the result of biomass week-zone analysis graphic, we use the Object Linking and Embedding (OLE) technique to automate Excel chart in Visual C++. OLE is a technology that allows you to take advantage of an existing functionality and incorporate it into your own applications. For example, we utilize Microsoft Excel charting tools into our application. This technology can greatly simplify and speed up software development.
There are three basic ways we can use Automation: MFC, #import, and C/C++. In the implementation for this thesis, with MFC we use the Visual C++ ClassWizard to generate "wrapper classes" from the Microsoft Office type libraries. These classes, as well as other MFC classes, such as COleVariant, COleSafeArray, COleException, simplify the tasks of Automation. Our program is based on Microsoft Excel 97 (or newer versions). Figure 4.18 allows the user to check the population of each zone week by week during one year. Figure 4.19 shows us the example, which displays the population of German Bank week by week during one year.

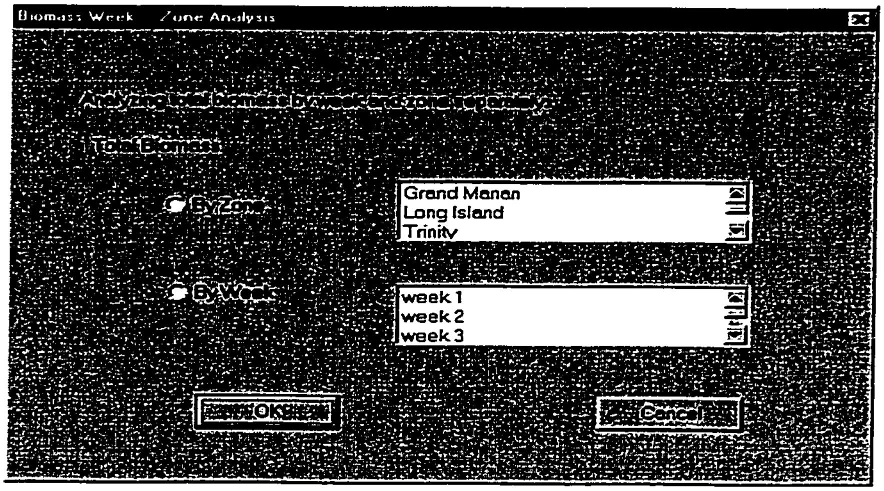

Figure 4.18 population by zone and week selection screen

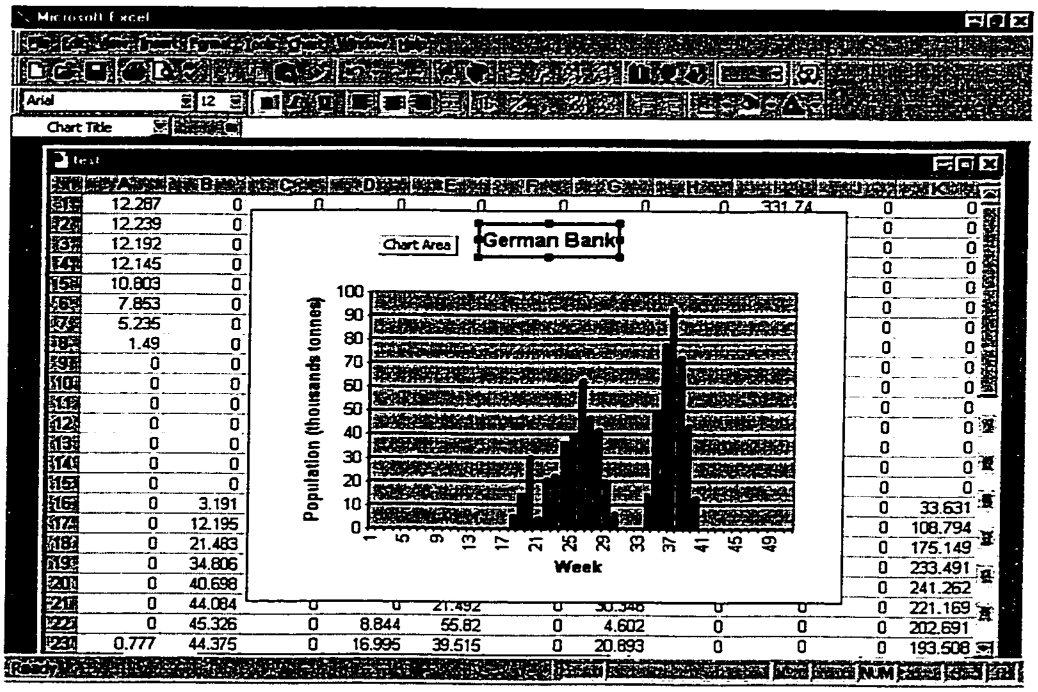

Figure 4.19 Generated population of population generation model for German Bank during one year

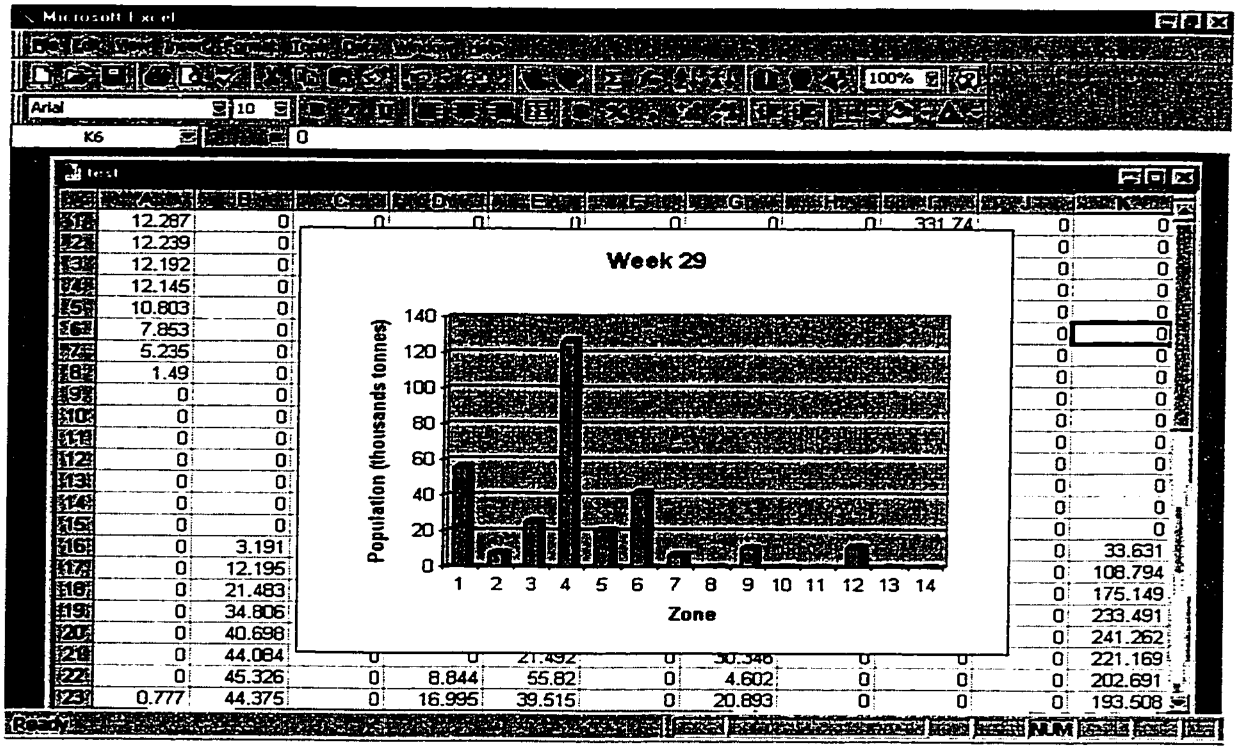

Figure 4.20 Generated population of population generation model of all zones at Week 29

2) Output Analysis 2:

Spawning group biomass analysis displays the mean population and variance of each spawning group.

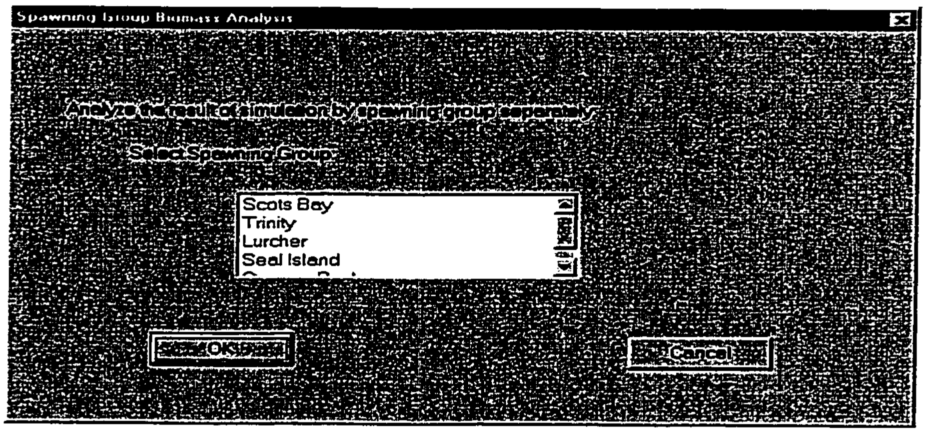

Figure 4.21 Interface of selecting spawning group for spawning stock analysis

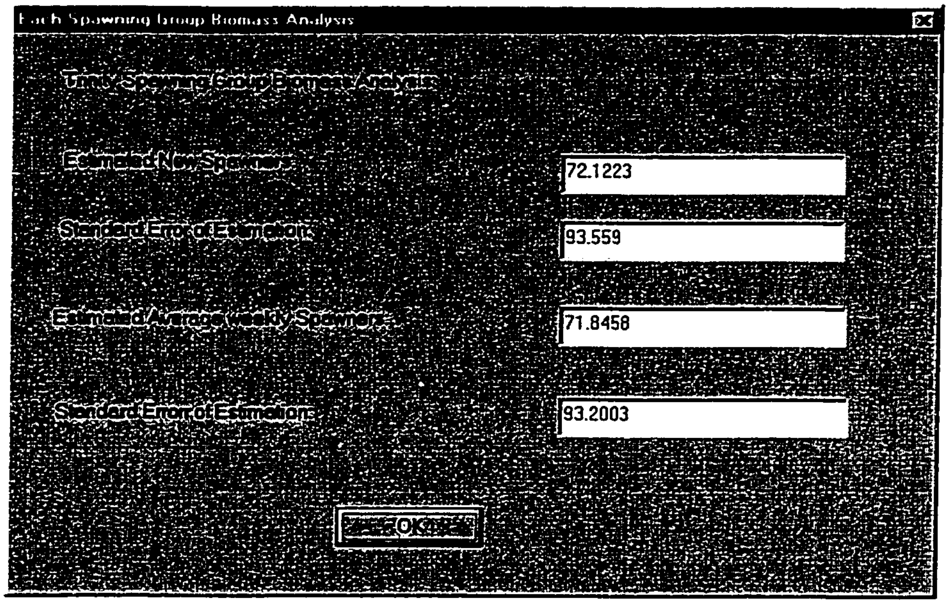

Figure 4.22 Spawning group Trinity mean population and standard error

3) Output Analysis 3:

Total spawning stock biomass analysis displays the total spawning stock biomass (SSB).

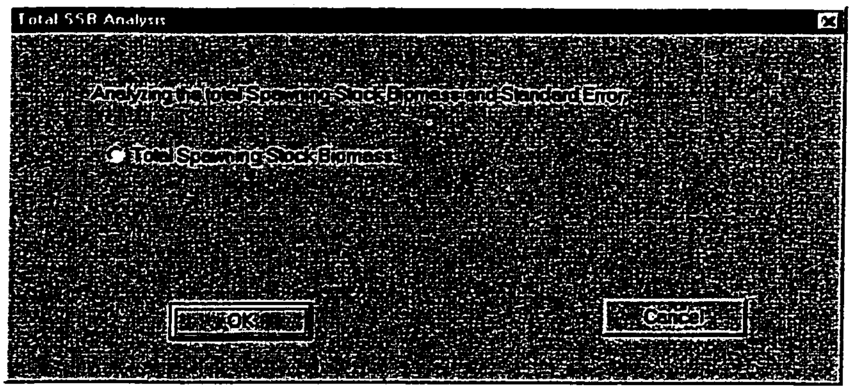

Figure 4.23 Analyzing SSB analysis

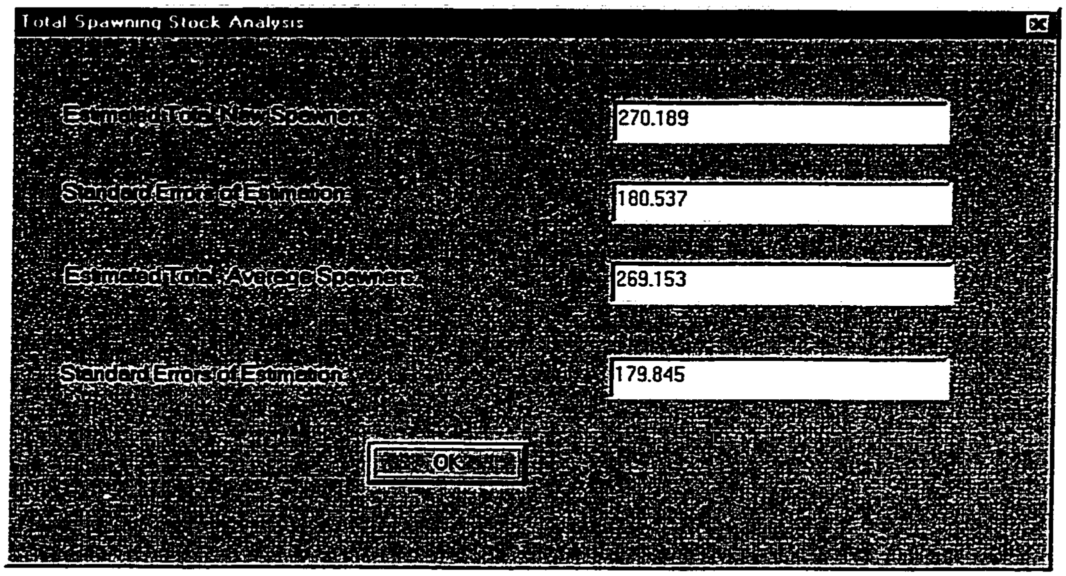

Figure 4.24 The result of SSB analysis

4.3 Determination of Catch Data

4.3.1 Determination of Catch level

An extensive database of catch data for each zone and week is available for this fishery from the logbook data series collected by the federal Department of Fisheries and Oceans (DFO). DFO has required the reporting of herring purse seine set catch data on a daily basis by longitude and latitude location.

Catch data from 1992 to 1998 indicated that the zones fall into several categories or classes with respect to the magnitude of catch. The first class consists of the largest catch zones: Zones 6 and 8 where historical catches have ranged to a maximum of more than 5.5 thousand tonnes. (see Appendix D)

Class 2 is assigned to Zones 1,2,3, and 5 where catches are relatively low all year. Class 3 consists of those zones for which the catches are lowest: Zones 10, 11,13, and 15. Zone 9, the main over-wintering area of Chedabucto Bay, is the only Zone in class 4. Despite the fact that Zone 9 contains almost all of the population during the winter, there are many weeks when there are no catches there since the herring are in Zone 9 for only a limited time period. However, there are also weeks in the winter of actual and potentially high catches.

Class 5 consists of Zone 12 and Zone 14. Zone 12 does not denote a geographical zone as such but that rather denotes a state in which the fish are not available to harvesting gear since they are not schooling in large numbers but are spread out over a wide area. This passage in the seasonal migration pattern is referred to as the "diffuse" state of the stock prior to aggregation in pre-spawning feeding areas or in the spawning aggregations themselves. In some years herring have been found in Zone 14 (Halifax) during the late winter/early spring. The herring may be moving southward through Zone 14 from the main over-wintering area of Chedabucto Bay (Zone 9) towards the spawning areas, however at this time of year there is generally no fishing activity in Zone 14. Fish have been caught in Zone 14 at various times during the year but there is some dispute as to whether large schools found here are actually part of this fishery, or part of a separate inshore herring stock, or part of other offshore banks stocks. There are in-shore herring fisheries all along the southern shore of Nova Scotia and there may also be some fish caught in Zone 14, which belong to fisheries farther off-shore. For these reasons, catch data from Zone 14 has been set to 0 for all weeks of the year from the assumption that Zone 14 herring do not belong to the normal 4WX herring stock.

Finally, Class 6 consists of only Zone 7. We consider Zone 7 separately, because according to the actual catch data of Zone 7, fishing in Zone 7 has been changing significantly in recent years.

4.3.2 Catch data generation model

According to the results of the stock population generation model presented above the population states were discretized (Table 4.3). Table 4.3 defines 10 possible levels of abundance for each of 15 geographical zones. Assuming the state level is known for a given period and zone, then we generate catch data with the tuned Q matrix described in

Equation (3.1) according to actual data from 1992 to 1998. Figure 4.24 illustrates the procedure of generating catch data for each year from 1992 to 1998.

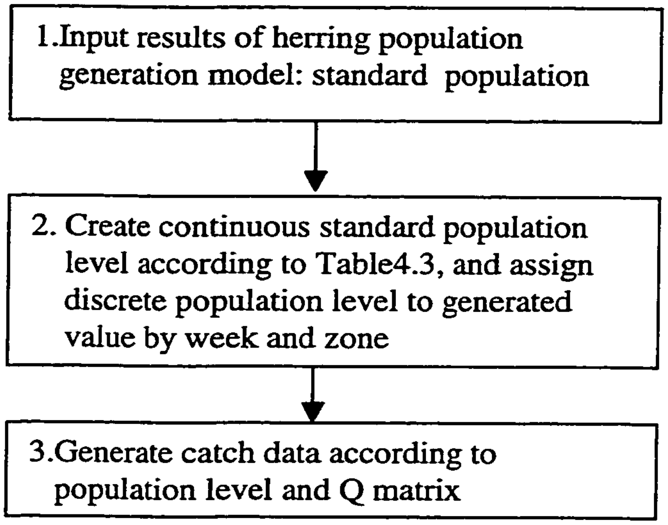

Figure 4.25 Procedure of generating catch data

Table 4.3 Description of population state level (thousands of tonnes)

State Level	1	2	3	4	5
Fuzzy Definition	Zero	Extremely Low	Very Low	Low	Medium Low
Cell Definition	0	1-25000	25001-50000	50001-75000	75001-100000
Cell Midpoint	0	12500	37500	67500	87500
State Level	6	7	8	9	10
Fuzzy Definition	Medium	Medium High	High	Very High	Extremely High
Cell Definition	100001-150000	150001-200000	200001-250000	250001-300000	300000+
Cell Midpoint	125000	175000	225000	275000	325000

Step 2 in the procedure of generating catch data produces a discrete population level in order to generating catch data using the Q matrix. The scaling is carried out in connection with the generation of catch data using the known information from the population generation model. Accordingly, using the known information from the population, generated catches are "refined" through the state-to-observation matrix to yield catches that may approximate more closely the known state of the stock. The state-to-population matrix, being required for Bayesian updating, is thus available to use to provide observation estimated that can in turn be used as input to the population estimated updating process.

From Table 4.3, we note that the level value is very wide, for example, level 0 denotes 0 thousand tonnes population, however, level 1 is between 1 thousand tonnes and 25 thousand tonnes. We recognize that this wide range of values may lead to poor model sensitivity to changes in parameters. Nevertheless, we feel that the analysis of the "optimal" numbers of states goes beyond the primary purpose of presenting the spatial-temporal model. In our model, we produce continuous discrete population levels to improve sensitivity on the state observations from catches by weighting actual population levels to within state values. For example, if the (assumed known) generated population is 10,000 t, then the corresponding population numbered level is 1.8 or state2 min+ state2 max all divided by the cell midpoint, i.e.,1+10/12.5. So we obtain the continuous standard population level according to Table 4.3. Next, we use the ceiling and floor of generated population level to generate catch data respectively. For example, if the continuous population level is 1.8 (as in the above example) the ceiling and floor of generated population level are 2.0 and 1.0 respectively. Further, assuming generated catch data with the ceiling (2.0) of population level are 30.0 thousand tonnes, and generated catch data with the floor (1.0) of population level are 15.0 thousand tonnes, then the whole generated catch data is the weighted average, such as (1.0*15.0+0.8*30.0)/1.8.

4.4 Determination of the π matrix

According to equation (3.3) and (3.4), we next calculate the π matrix, which is a 780×10 matrix and denotes the population probability for 10 population state levels, 15 zones and 52 weeks. The initial π matrix ($\pi(0)$) is 15×10 (15 zones × 10 state levels) is provided below for illustration (Table 4.4). In the first week of each year, herring are in overwintering Zone 1 (relatively small group) and Zone 9 (majority of stock) exclusively and there are no herring in any of the other zone (thus the probability of herring in state level 1 of these zones is 1).

Table 4.4 Initial π matrix(15 zones × 10 state level)

Population state level:

1	2	3	4	5	6	7	8	9	10
0.72	0. 28	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1 .0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1 .0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1 .0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1 .0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1 .0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1 .0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1 .0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0 .0	0.0	0.0	0.0	0.0	0.0	0.2	0.4	0.23	0.17
1 .0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1 .0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1 .0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1 .0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1 .0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1 .0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

4.5 Population Update

This section desribes how the population is updated according to the π matrix with the observed or generated catch, and Table 4.3. Estimation of the population depends on the grid size of the state. The sufficient statistic , π provides a probability distribution over the state levels. The expectation of the state is then naturally defined by equation 4.4. Without question, the issue of a "best" grid size is problematic – and remains an outstanding issue unresolved in this thesis. For example, the updated population for the 1^{th} week, 15 zones is :

$$E[updatepopulation] = \sum_{i=1}^{10} (updateprobabilityofpopulationstate * cellmidpoint) \quad (4.4)$$

where the updated probability of the population state and the corresponding *cellmidpoint* are defined in Table 4.3. For example, for week 1(Table 4.4), the expected population is:

Zone 1:	3.500 (thousands of tonnes);
Zone 2 to Zone 8:	0.000;
Zone 9:	243.500 (thousands of tonnes);
Zone 10 to Zone 15:	0.000(thousands of tonnes);
Total (all zones):	247.00 (thousands of tonnes).

5. Results and Analysis

This section presents the results of the population generation model, the generated catch model and the population estimates updating model. The results are compared to the VPA estimates from "1998 EVALUATION OF 4WX HERRING" (Stephenson et al 1999).

The model results are presented in three parts:

1. *Initial population generation with continuous weekly catch estimation and updating 1992-98*: Run herring population generation model with normal distribution N(300,100) (thousands of tonnes) and then calculate the generated spawning stock biomass. Generate weekly catch data by zone from 1992 to 1998 and compare with the actual catch data. Calculate estimated spawning stock biomass through updating population with successive $\pi(0)$ matrix (Table 4.4) from 1992 to 1998 using (i) generated catch data and (ii) actual catch data. Compare estimated total spawning stock biomass with VPA spawning stock biomass.
2. *Yearly population generation for each year 1992 to 1998 based on total annual SSB from VPA*: Tune the annual mean value of normal distribution for initial population from 1992 to 1998 according to the annual VPA spawning stock biomass estimates and then run herring population generation model with tuned $N(\mu,\sigma)$ to calculate "tuned" generated spawning stock biomass. Generate catch data from 1992 to 1998 and compare the above tuned catch data with actual catch data. Calculate estimated spawning stock biomass with generated catch data tuned by VPA through updating population with successive $\pi(0)$ matrix from 1992 to 1998. Compared tuned total estimated spawning stock biomass with VPA total spawning stock biomass estimates.
3. *Yearly population generation based on total annual SSB from VPA with annual stepwise population adjustment to approximate actual catches*: Tuning to actual annual catches from 1992 to 1998: Tune the annual mean value of normal distribution stepwise from 1992 to 1998 according to actual catch data and then

run herring population generation model with tuned $N(\mu,\sigma)$ to calculate "tuned" generated spawning stock biomass. Generate catch data from 1992 to 1998 and compare the above tuned generated catch data with actual catch data. Calculate estimated spawning stock biomass with generated catch data tuned by actual catch data through updating population with successive $\pi(0)$ matrix from 1992 to 1998. Compare tuned total estimated spawning stock biomass with VPA total spawning stock biomass estimates.

The following section describes the aggregate estimates for Spawning Stock Biomass (SSB) from the VPA analysis. This is followed by the results of the three parts analysis described above.

5.1 SSB analysis of VPA assessment method

We calculate the herring spawning stock biomass (SSB) estimates according to the aggregated population (VPA) by age and year from the research document of "1998 EVALUATION OF 4WX HERRING" (Stephenson et al 1999). It is assumed that herring matures at 4 years old. Table 5.1 describes the number of spawning herring at each age 4 to 11 years from 1992 to 1998 from the VPA. Table 5.2 describes the average weight at age for the 4WX herring fishery from 1992 to 1998. This results in estimates for annual spawning stock biomass (Table 5.3) according to Equation (5.1).

$$SSB = \sum_{age=4}^{11} (number * weight) \qquad (5.1)$$

where, "number" denotes the number of herring at age illustrated in Table 5.1 and "weight" denotes the average weight of each herring at age illustrated in Table 5.2. SSB is the VPA estimate for spawning stock biomass each year. The SSB from 1992 to 1998 is presented in the last column of Table 5.3.

Figure 5.1 below illustrates the percentage of spawning stock biomass that each age holds from 1992 to 1998. The SSB from VPA assessment method will be compared to SSB from the spatial-temporal assessment method to follow.

From Table 5.3, we know that the VPA assessment method can only supply information about the total SSB each year and the herring biomass at each age. It can not supply spatial-temporal details about where and when herring schools exist in-season in order to maintain the balance of herring population into known spawning groups.

Table 5.1 Aggregated population (ages 4+) from VPA assessment method (thousands of pieces)

	Age 4	Age 5	Age 6	Age 7	Age 8	Age 9	Age 10	Age 11
1992	677486	318311	172786	92634	95936	118794	87856	33408
1993	515555	298133	147402	74013	44983	46867	44522	41001
1994	214719	248209	127275	60216	30391	17657	18826	17983
1995	434514	127546	97883	39725	17278	11600	6691	6117
1996	1632734	254915	71407	47540	12837	8349	5720	2836
1997	659162	1106187	159663	43307	30688	7546	5233	3505
1998	901660	469291	787552	113672	30832	21849	5372	3726

Table 5.2 Average weight at age (ages 4+) for the 4WX herring fishery (grams per piece)

	Age 4	Age 5	Age 6	Age 7	Age 8	Age 9	Age 10	Age 11
1992	148	181	216	252	275	295	313	333
1993	153	188	215	251	279	302	324	357
1994	131	175	203	223	253	289	304	326
1995	136	187	223	247	293	300	326	363
1996	136	187	223	247	293	300	326	363
1997	136	187	223	247	293	300	326	363
1998	136	187	223	247	293	300	326	363

Table 5.3 SSB from VPA assessment method (thousands of tonnes)

	Age 4	Age 5	Age 6	Age 7	Age 8	Age 9	Age 10	Age 11	SSB
1992	100.268	57.614	37.322	23.344	26.382	35.044	27.499	11.125	318.598
1993	78.488	56.05	31.69	18.58	12.55	14.15	14.43	14.64	240.97
1994	24.13	43.44	25.84	13.43	8.78	5.07	5.723	5.86	132.903
1995	59.09	23.85	21.83	9.81	5.06	3.48	2.18	2.22	127.52
1996	222.05	47.669	15.92	11.74	3.76	2.5	1.86	1.029	306.528
1997	89.646	206.86	35.605	10.697	8.99	2.26	1.706	1.27	357.034
1998	122.63	87.76	175.624	28.077	9.034	6.55	1.75	1.35	432.775

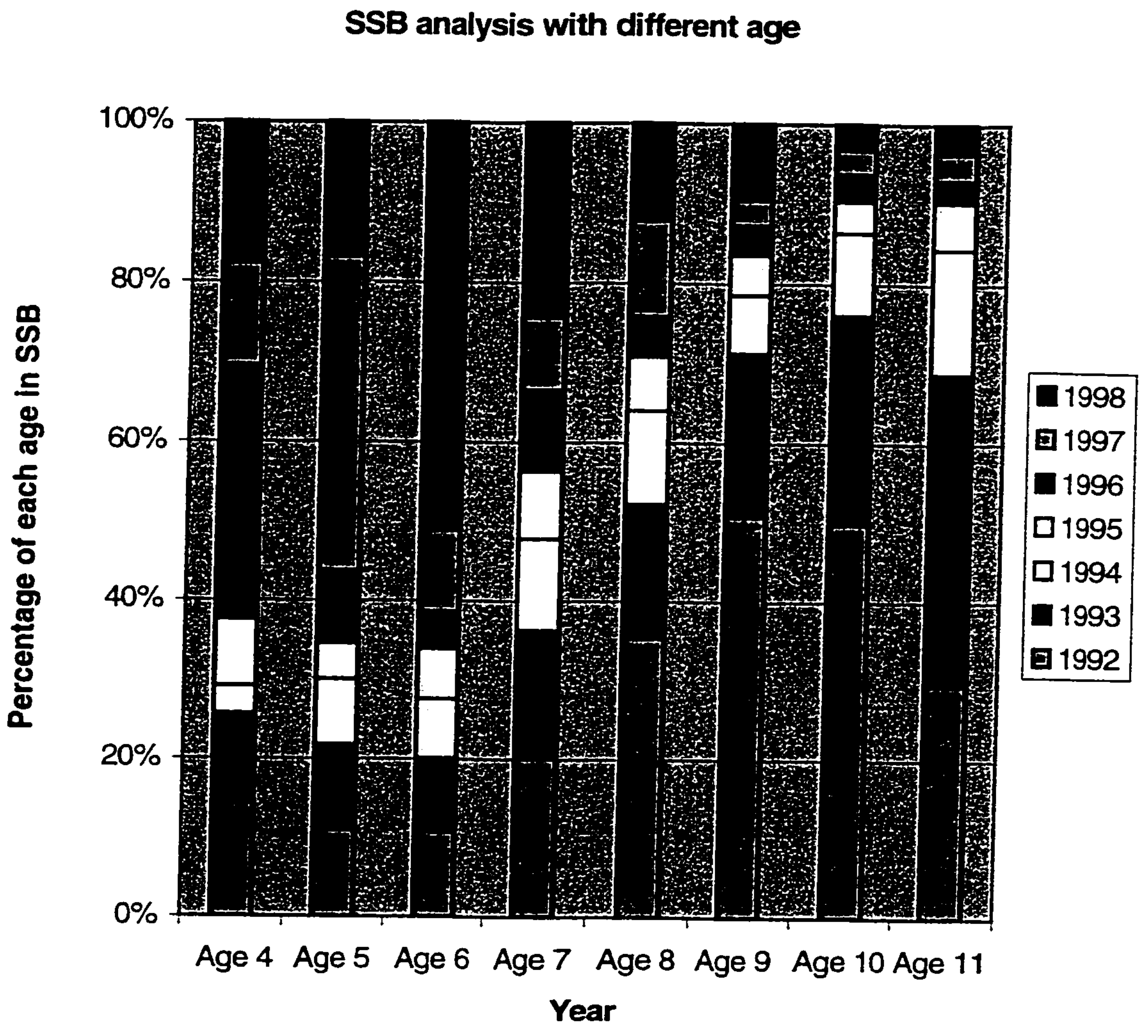

Figure 5.1 SSB percentage at age from 1992 to 1998

5.2 Result of the herring population generation model

The result of a single trial simulation of herring population generation model is described by a 52×15 matrix(52 weeks and 15 zones) (Appendix B). The population of each zone week by week during one year, and the population of all zones during one week was illustrated for a single trial in Figure 4.19 and Figure 4.20. The spawning group stock size was also described in Figure 4.21 and Figure 4.22. The total spawning stock size was presented in Figure 4.23 and Figure 4.24. These results are denoted as the "generated population", "generated spawning group stock size" and "generated total SSB" calculated according to the herring population generation model.

To calculate the spawning stock biomass such as at Trinity, Lurcher, Seal Island, and German Bank, we know, during the first week of spawning period, the spawning zone only contains the very early wave of spawners; during the second week, the early wave of spawners come into that zone and the zone contains the first 2 waves; during the third week, the main wave of spawners may begin to come into the zone and the zone would then contain the first 3 waves of herring spawners; during the fourth week, the very early wave of spawners leave the spawning zone, the late wave of spawners come into the zone and the zone contains early, main and late wave of spawners; during the fifth week, the early wave leaves of spawners leave the spawning zone, the very late wave of spawners come into the zone and the zone contains main, late and very late wave of spawners and so on. During the sixth week, the spawning zone contains the late and very late wave of spawners. During the seventh week, the spawning zone contains the very late wave of spawners. So the average weekly spawning stock for spawning group j on the grounds can be determined as:

$$\bar{SSB} = \sum_{i=1}^{7} SSB_i(j) / 7 \qquad (5.2)$$

where i denotes the week order of the spawning period, (for example, the spawning period of German Bank spawning group is from week 37 to week 39, so i=1 denotes week 35, and i=7 denotes week 41 for this case.) $SSB_i(j)$ is the population for spawning group j during week i of the spawning period from the herring population generation model.

Given the assumed three week spawning period for each herring, then the total spawning stock biomass to have spawned on the grounds is

$$\bar{SSB} = \sum_{i=1}^{7} SSB_i(j) / 3 \qquad (5.3)$$

Multiple trials of the herring population generation model are used to describe spawning group abundance distribution from which statistically valid estimates are determined. The mean spawning stock biomass for each spawning group is the average of 10 trials of generated spawning stock biomass. The standard deviation of the SSB for the spawning group is the sum of square of the difference between mean and each trial, i.e,

$$\sigma = \sqrt{\sum_{i=1}^{10} (mean - ssb)^2} \qquad (5.4)$$

Table 5.4 presents the average results of 10 generated population trials for generated spawning stock biomass from the population generation model with normal distribution N(300,100) thousands of tonnes. Detailed results are found in Appendix B.

Table 5.4 Spawning Stock Biomass with N(300,100)(thousands of tonnes)

	Scots Bay	Trinity	Lurcher	Seal Island	German Bank	Total SSB
Average SSB	43.6417	87.1124	12.3585	61.0972	121.7833	325.9931
Standard error	40.4454	80.6693	11.4434	56.5901	112.7744	155.5469

5.3 The generated catch data of each zone 1992 to 1998

Table 5.5 presents the sum of the actual catch data annually for herring purse seines from 1992 to 1998 from the research document of 1998 EVALUATION OF 4WX HERRING (Stephenson et al 1999) which includes the weekly actual catch data by zone. Table 5.5 illustrates the actual catch data by zone and total actual catch data from 1992 to 1998. From Table 5.5 we note that the actual catch data in Zone 5 (Gannet, Dry Ledge), Zone 6 (Seal Island) and Zone 7 (German Bank) from 1992 to 1998 change significantly. Catching in zone 5 and zone 6 are very high only in 1992 after which they decrease, however, catching in zone 7 increases significantly after 1993.

Table 5.5 Actual catch data from 1992 to 1998 (thousands of tonnes)

	1992	1993	1994	1995	1996	1997	1998
Grand Manan	2.9194	0.703	7.0091	6.55889	5.7948	6.4074	13.4923
Long Island	3.3576	2.8442	7.5712	9.5787	4.288	3.5178	12.5231
Trinity	4.8029	1.3132	2.4355	0.4375	3.531	5.3082	4.2077
Lurcher	2.3336	1.4951	0.5648	0.2955	0.153	0.599	0
Gannet, Dry ledge	19.8752	2.8818	2.332	3.8915	2.0145	4.59	4.9494
Seal Island	11.2179	3.8299	2.9634	0.39666	1.674	0.492	0.5517
German Bank	3.725	4.0574	9.7469	16.9539	15.9415	13.576	20.7283
Scots Bay	8.4101	5.3075	10.7224	1.05025	8.9833	4.894	8.21
Chedabucto	3.4595	1.378	1.407	1.51736	1.7592	1.609	0
N.B. Coastal	1.0005	0.5794	0.0989	1.7525	0.271	1.334	0.8523
Southwest Grounds	0.222	2.7331	3.4316	3.90689	3.073	0.797	1.1451
Diffuse	0	0.396	0	3.223	4.1248	3.5778	0.4094
Yankee Bank	0.127	0	0.175	0.37334	0.009	0.004	0.219
Halifax	0	0.652	1.933	0	0.742	0.5158	0.0393
Liverpool	0	3.8148	4.2492	0	0	0.2729	0.7248
Total	61.4507	31.9854	54.64	49.936	52.3594	47.4949	65.0524
Total(without zone12 and 14)	61.4507	30.9374	53.707	46.713	47.4926	43.4013	64.6037

The following Table 5.6 describes the generated catch data from 1992 to 1998 according to the generated population (Table 5.4) with normal distribution of N(300,100) thousands of tonnes. Catch data are generated according to the ongoing generated population and the Q state-to-observation matrix (3.4) (Appendix C contains the zone specific discrete catch observation levels). Moreover, we generated catch data only according to where and when actual catch data existed except for Zone 12 and Zone 14. We ignore generating catch data in Zone 12 and Zone 14, since herring caught in these two zones weekly comes from separate inshore stocks of herring. For each population generation result, we randomly simulate ten generated catch data trials. The generated catch data are drawn from the Q matrix – the state-to-observation matrix presented in Appendix C. The scaling approach applied to the generated (assumed known) population is noted in Section 4.3.2. The population generation model of ten trials times the catch generation of ten trials per population trial provides a total generated catch data (on which the 'average catch' results are provided) of 100 times per model. Table 5.6 then provides the average generated annual catch data by zone for all 100 trials in each run of the simulation model. The generated catch data by week and by zone are provided in Appendix D.

Table 5.6 and Figure 5.2 display the comparison of total catch data between actual catch and generated catch with N(300,100) (thousands of tonnes) population generation from 1992 to 1998. Figure 5.2A to Figure 5.2F describe the comparison between generated catch and actual catch data for each of the six spawning groups. Moreover, Table 5.7B provides the correlation coefficient of generated catch data and actual catch data. Generated catch data for the N(300,100) population generation are generally below the actual catch data. In the following sections, we tune the mean and variance of the population generation model according to VPA estimated SSB and actual annual catches and then compare them again.

Table 5.6 Generated catch data from 1992 to 1998 (thousands of tonnes)

	1992	1993	1994	1995	1996	1997	1998
Grand Manan	1.032	0.85	1.88	2.119	3.26	2.796	2.193
Long Island	4.502	4.517	4.889	4.366	5.876	4.855	5.984
Trinity	2.831	1.663	1.962	1.144	1.486	2.052	2.308
Lurcher	0.107	0.086	0.07	0.05	0.048	0.047	0
Gannet, Dry ledge	0.249	8.211	4.455	7.432	4.623	7.817	9.512
Seal Island	6.534	6.969	7.464	1.796	4.118	2.749	3.457
German Bank	10.458	8.23	11.718	10.038	14.888	10.869	16.436
Scots Bay	2.605	3.501	3.587	1.009	3.03	3.433	5.592
Chedabucto	4.374	1.741	3.309	1.524	2.585	2.111	0
N.B. Coastal	0.198	0.067	0.034	0.078	0.025	0.059	0.033
Southwest Grounds	0.118	0.318	0.511	0.186	0.078	0.084	0.103
Diffuse	0	0	0	0	0	0	0
Yankee Bank	0.009	0	0.008	0.053	0.006	0.006	0.027
Halifax	0	0	0	0	0	0	0
Liverpool	0	0.021	0.058	0	0	0.012	0.022
Total Generated Catch	43.017	36.174	39.945	29.795	40.023	36.89	45.667
Total Actual Catch	61.4507	30.9374	53.707	46.713	47.4926	43.4013	64.6037

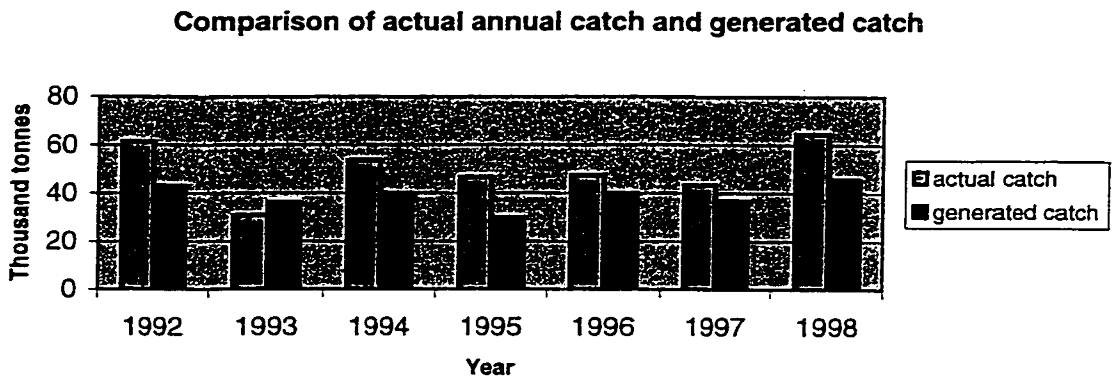

Figure 5.2 Comparison between actual catch and generated catch from 1992 to 1998

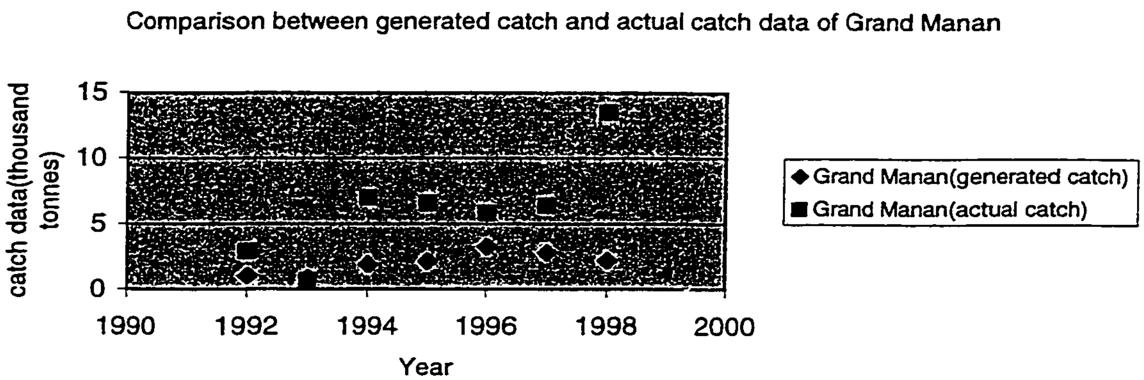

Figure 5.2A Comparison between actual catch and generated catch data of Grand Manan

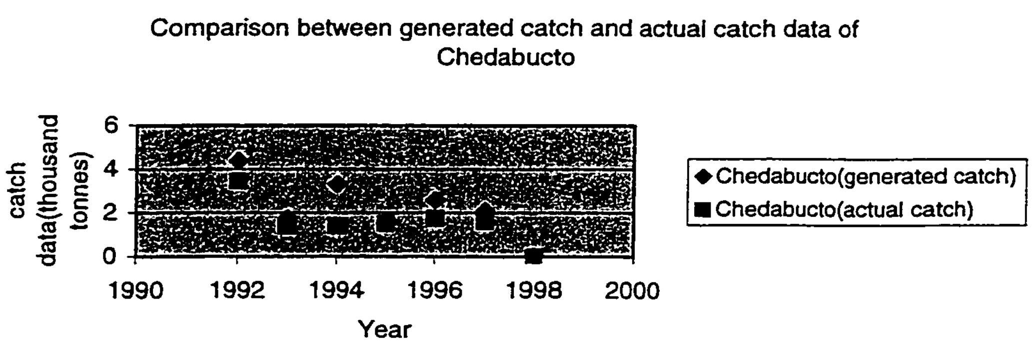

Figure 5.2B Comparison between actual catch and generated catch data of Chedabucto

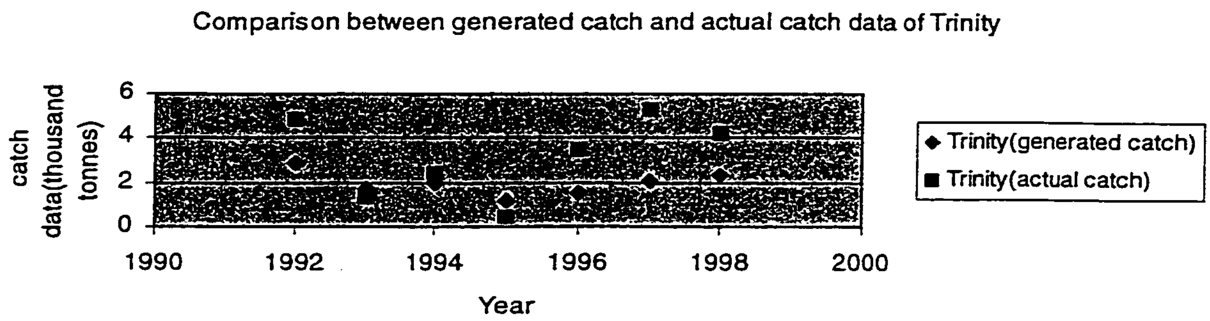

Figure 5.2C Comparison between actual catch and generated catch data of Trinity

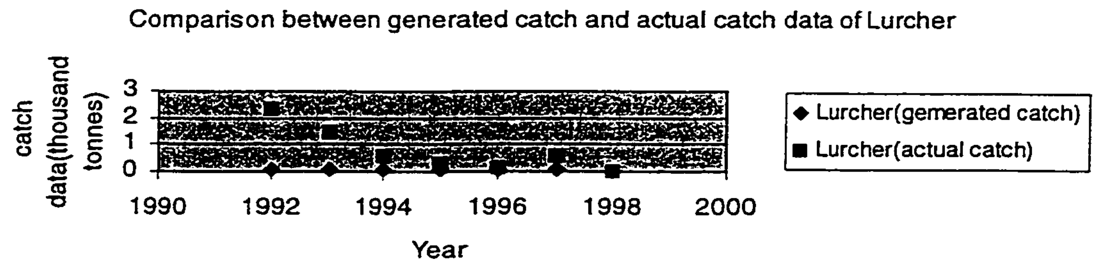

Figure 5.2D Comparison between actual catch and generated catch data of Lurcher

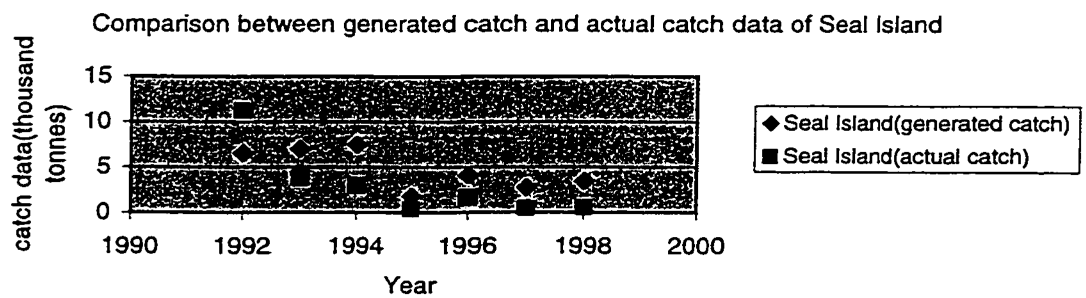

Figure 5.2E Comparison between actual catch and generated catch data of Seal Island

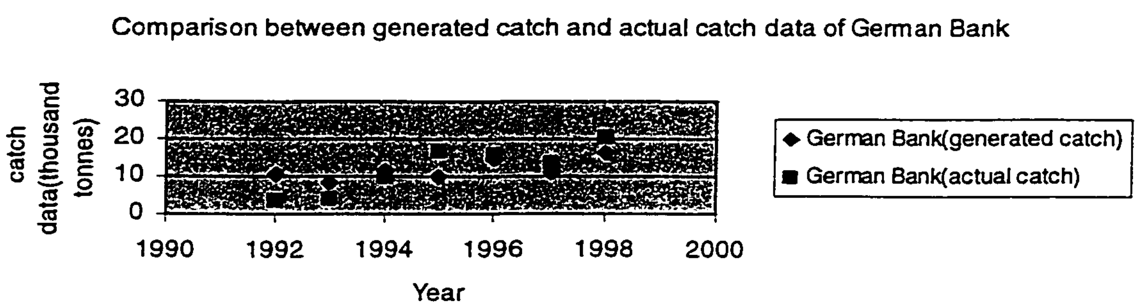

Figure 5.2F Comparison between actual catch and generated catch data of German Bank

The correlation coefficient (r) of actual catch and generated catch from 1992 to 1998 is calculated as follows:

$$SS_x = \sum x^2 - (\sum x)^2/7$$
$$SS_y = \sum y^2 - (\sum y)^2/7$$
$$SS_{xy} = \sum xy - (\sum x \sum y)/7 \qquad (5.4)$$
$$r = SS_{xy} \Big/ \sqrt{SS_x}\sqrt{SS_y}$$

Table 5.7B Correlation coefficient of generated catch and actual catch by zone

Zone No.	Zone Name	Correlation Coefficient
1	Grand Manan	0.49
2	Long Island	0.38
3	Trinity	0.76
4	Lurcher	0.88
5	Gannet, Dry ledge	0.67
6	Seal Island	0.64
7	German Bank	0.73
8	Scots Bay	0.57
9	Chedabucto	0.9
10	N.B. Coastal	0.4
11	Southwest Grounds	0.37
12	Diffuse	(no generated catch)
13	Yankee Bank	0.91
14	Halifax	(no generated catch)
15	Liverpool	0.85
	Total	0.69

5.4 SSB analysis of Spatial temporal assessment model

According to the population generation model, we obtained generated (known) population values by week and by zone. This model can be run multiple trials in order to obtain reliable, variance-reduced estimates. Next we generate catch data according to the generated population from 1992 to 1998 by multiple trials and discretize the generated catch data according to the Q matrix (3.4 and Appendix C). Through the generated catch levels, and the given population state population probability transition matrix (P matrix), we update the π matrix (3.5) using Equation (3.6 and 3.7). The π matrix describes the probability of each population state level by week and by zone during one year. The herring spawning stock biomass by week and zone from the spatial-temporal assessment method is calculated according to the updated population.

The following section describes the π matrix calculation from different aspects:

1) Calculate π matrix with generated catch data and succesive $\pi(0)$
2) Calculate π matrix with actual catch data and successive $\pi(0)$

5.4.1 Calculate π matrix with generated catch data and successive $\pi(0)$

In this analysis procedure, we discretized the previous generated catch data with N(300,100) population generation model according to the Q matrix. Through generated catch levels and the given population state probability transition matrix (P matrix), we calculate the π matrix, whose initial $\pi(0)$ each year is assigned by $\pi(52)$ of the previous year. Next we update the population estimate with the π matrix. The spawning stock biomass (Table 5.8) from the spatial-temporal assessment method is calculated according to the updated population and Equation (5.3). Each spawning group percentage in SSB is described in Figure 5.3 for the period 1992 to 1998.

Table 5.8 SSB estimates by spawning group for the spatial-temporal assessment method with generated catch from 1992 to 1998(thousands of tonnes)

	1992	1993	1994	1995	1996	1997	1998
Scots Bay	54.252	55.928	54.645	52.615	54.782	54.183	56.54
Trinity	81.798	82.452	74.678	75.716	79.421	76.884	77.548
Lurcher	24.555	24.524	24.491	24.545	24.633	24.828	24.458
Seal Island	58.827	59.318	59.848	56.563	54.134	55.331	56.2
German Bank	97.394	104.339	96.632	97.215	97.603	100.568	98.002
Total SSB	316.826	326.562	310.294	306.654	310.573	311.794	312.756

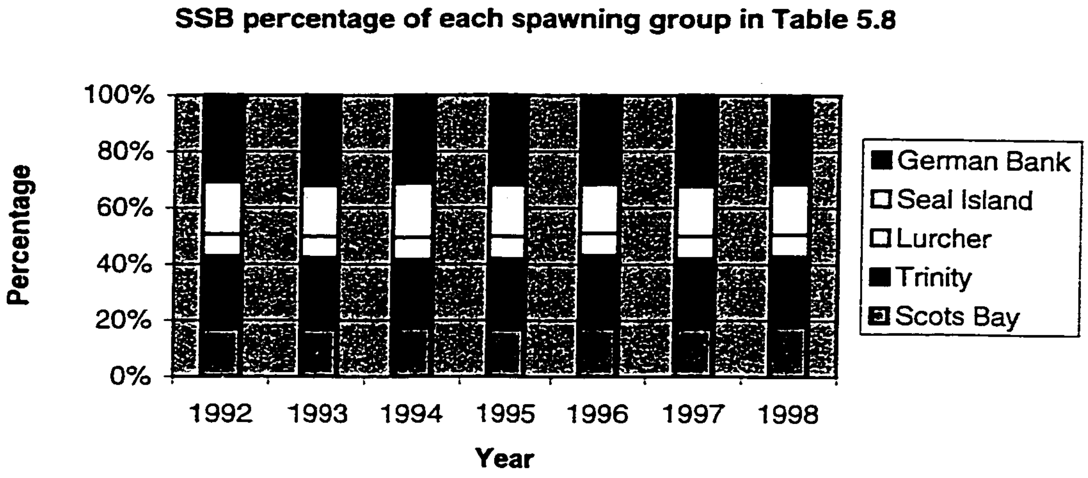

Figure 5.3 Percentage in SSB of each spawning group of spatial-temporal assessment

5.4.2 Calculate π matrix with actual catch data and successive $\pi(0)$

In this analysis section, we did not generate catch data, however, through actual catch data and the population state probability transition matrix (P matrix), we recalculate the π matrix, whose initial $\pi(0)$ of each year is assigned by $\pi(52)$ of the previous year as before, and then update population with π matrix through (3.6) and (3.7). The Spawning Stock Biomass (Table 5.9) from the spatial-temporal assessment method is calculated according to the updated population. Each spawning group percentage in SSB is described in Figure 5.4.

Table 5.9 SSB estimates by spawning group for the spatial-temporal assessment with actual catch data from 1992 to 1998 (thousands of tonnes)

	1992	1993	1994	1995	1996	1997	1998
Scots Bay	64.047	56.459	74.895	53.015	57.652	60.103	53.325
Trinity	80.47	84.706	96.989	81.487	74.827	79.537	88.626
Lurcher	24.487	24.737	24.469	24.472	24.746	24.818	24.458
Seal Island	86.227	56.943	55.832	56.533	52.47	53.37	54.142
German Bank	86.485	98.621	100.795	155.975	140.398	121.528	148.642
Total SSB	341.715	321.466	352.98	371.482	350.093	339.356	369.192

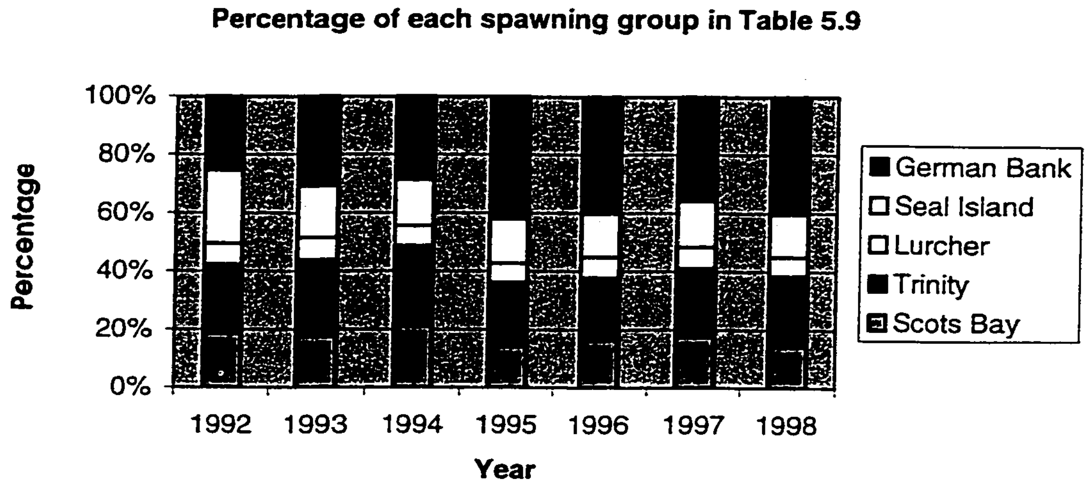

Figure 5.4 Percentage in SSB of each spawning group of VPA assessment

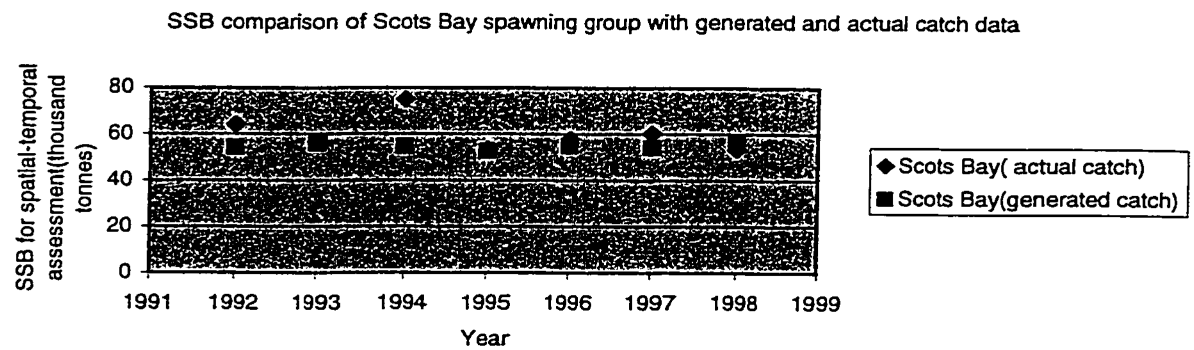

Figure 5.4A SSB comparison of Scots Bay spawning group for spatial-temporal assessment with generated and actual catch data

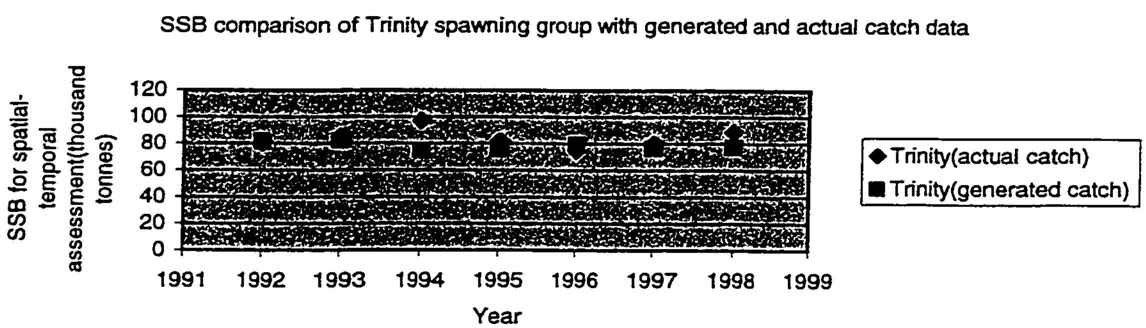

Figure 5.4B SSB comparison of Trinity spawning group for spatial-temporal assessment with generated and actual catch data

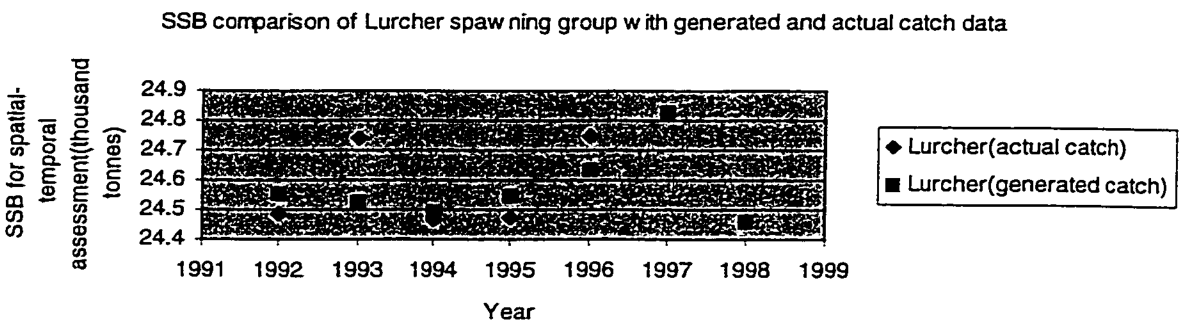

Figure 5.4C SSB comparison of Lurcher spawning group for spatial-temporal assessment with generated and actual catch data

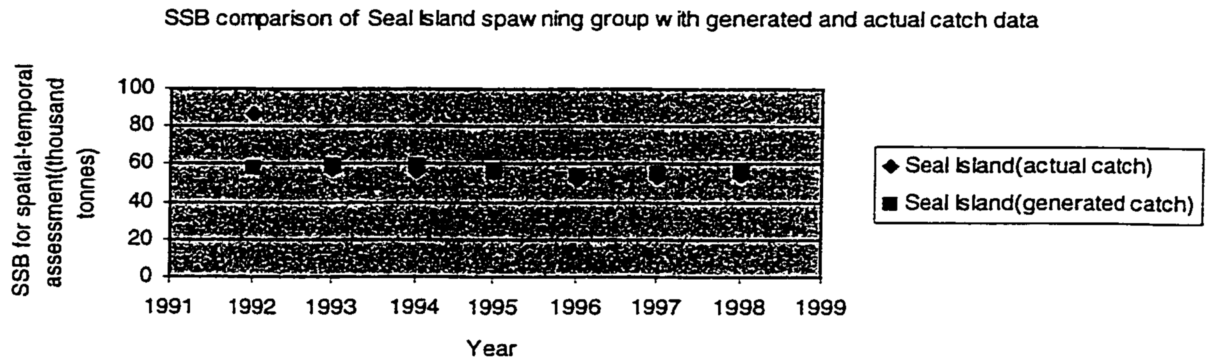

Figure 5.4D SSB comparison of Seal Island spawning group for spatial-temporal assessment with generated and actual catch data

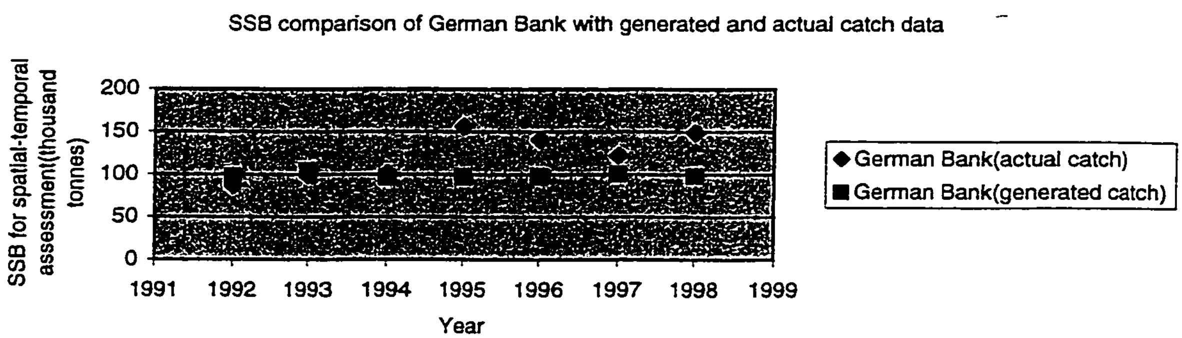

Figure 5.4E SSB comparison of German Bank spawning group for spatial-temporal assessment with generated and actual catch data

5.5 SSB of Spatial-temporal assessment after tuning

Table 5.10 and Figure 5.5 describe the SSB comparison of the VPA and the spatial-temporal assessment method. The spatial-temporal assessment is based on the Normal distribution N(300,100) thousands of tonnes population generation model. We find the SSB of VPA and the spatial-temporal assessment are similar in most years, except that the SSB of VPA assessment are much lower in 1994 and 1995 and much higher in 1998 than the generated population model would indicate.

Table 5.10 SSB comparison of VPA and spatial-temporal assessment method (thousands of tonnes)

	1992	1993	1994	1995	1996	1997	1998
SSB of VPA	318.598	240.97	132.903	127.52	306.528	357.034	432.775
weekly updated SSB with generated catch	316.826	326.562	310.294	306.654	310.573	311.794	312.756
weekly updated SSB with actual catch	341.715	321.466	352.98	371.482	350.093	339.356	369.192

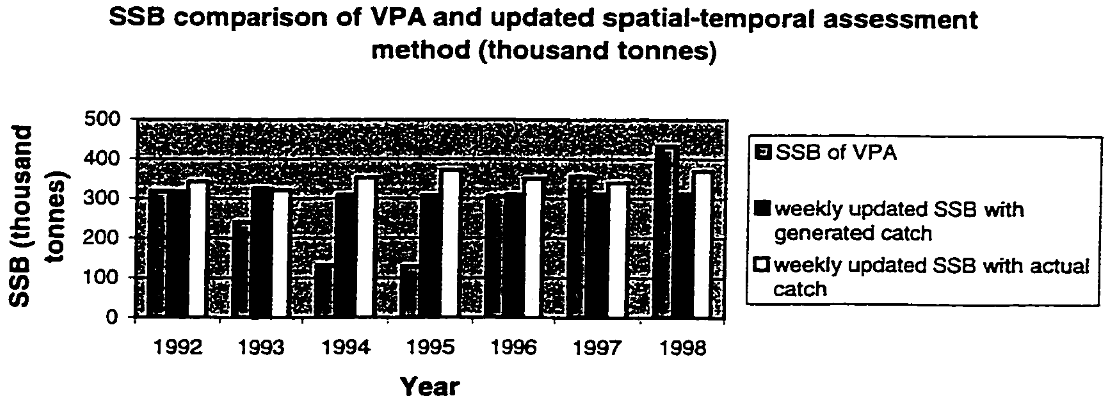

Figure 5.5 SSB comparison of VPA and Spatial-temporal assessment

In order to compare total generated and actual catch data, we do not count actual catch data of Zone 12 and Zone 14, described in Figure 5.2, because we did not generate catch data in these two zones. Comparing Figure 5.2 and Figure 5.4, we find catch data will affect the estimation of SSB. When catch data are higher, SSB of the spatial-temporal assessment is a little higher. We will analyze how catch data affect SSB in the following section.

5.5.1 Tuning with VPA SSB analysis

In order to tune SSB of spatial-temporal assessment to match SSB of VPA, we take the following steps:

1) The Normal distribution mean and variance of the population generation model is tuned annually according to the SSB of the VPA assessment.
2) Generate catch data by week and by zone from 1992 to1998 according only to those weeks and zones where actual catch data occurs.
3) Update the SSB population with successive $\pi(0)$ matrix and generated catch data.
4) Calculate estimated SSB according to updated π matrix of step 3.

Table 5.11 describes the tuned annual mean and variance of the population generation model. Table 5.12 and Figure 5.6 illustrate the estimated SSB of the spatial-temporal assessment method after tuning with the VPA SSB.

Table 5.11 Tuned mean and variance of normal distribution for population generation model (thousands of tonnes)

	1992	1993	1994	1995	1996	1997	1998
SSB of VPA	318.598	240.97	132.903	127.52	306.528	357.034	432.775
tuned mean	325	250	150	150	325	375	425
tuned variance	108	85	50	50	108	125	140

Table 5.12 Estimated SSB of spatial-temporal assessment after tuning for annual SSB of VPA(thousand tones)

	1992	1993	1994	1995	1996	1997	1998
Scots Bay	54.217	54.921	54.706	52.643	55.778	53.616	55.699
Trinity	77.482	77.423	78.177	74.139	77.813	77.747	75.901
Lurcher	24.526	24.515	24.468	24.683	24.554	24.755	24.458
Seal Island	59.926	57.672	58.7	56.663	53.789	56.592	60.595
German Bank	109.917	100.503	74.156	74.002	104.519	111.647	120.611
Total SSB	326.067	315.034	290.207	282.131	316.454	324.358	337.265

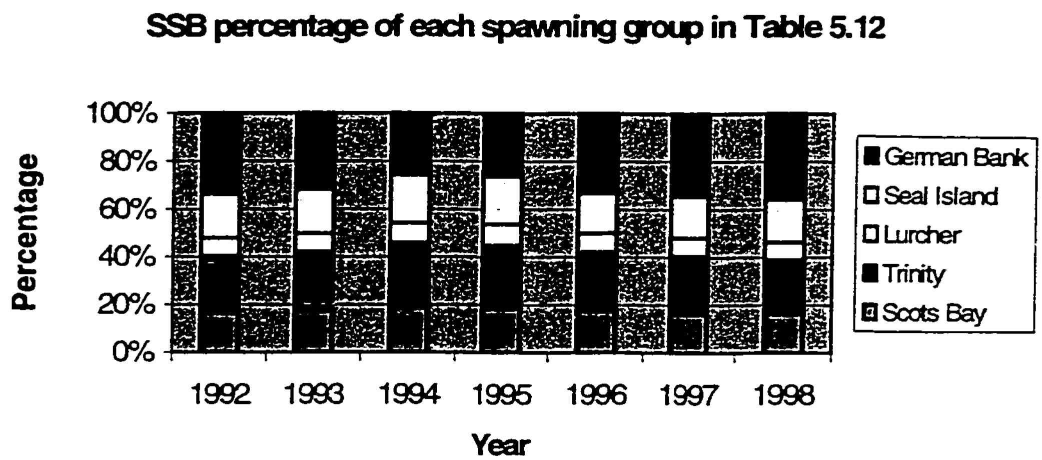

Figure 5.6 Percentage in SSB of each spawning group from 1992 to 1998

Table 5.13 and Figure 5.7 describe the SSB comparison of VPA and spatial-temporal assessment before and after tuning with VPA SSB:

- Generated SSB after VPA SSB tuning is the generated SSB of population generation model result with tuned mean and variance according to the SSB of VPA from 1992 to1998;
- SSB with generated catch denotes the SSB of spatial-temporal assessment method with normal distribution N(300,100) (thousands of tonnes) and generated catch data (Table 5.6) to update population;
- SSB with actual catch denotes the SSB of spatial-temporal assessment method with normal distribution N(300,100) (thousands of tonnes) and actual catch data (Table 5.5) to update population;
- Updated SSB after VPA SSB tuning denotes the SSB of spatial-temporal assessment method with tuned mean and variance of population generation model matching VPA SSB from 1992 to 1998 respectively and generated catch data (Table 5.14) to update population.

Table 5.13 SSB comparison of VPA and spatial-temporal assessment method

	1992	1993	1994	1995	1996	1997	1998
SSB of VPA	318.6	240.97	132.9	127.52	306.528	357.03	432.78
Generated SSB after VPA SSB tuning	323.9	254.42	142.22	135.56	315.247	372.01	443.02
SSB with generated catch	316.83	326.56	310.29	306.65	310.573	311.79	312.76
SSB with actual catch	341.72	321.47	352.98	371.48	350.093	339.36	369.19
Updated SSB after VPA SSB tuning	326.07	315.03	290.21	282.13	316.454	324.36	337.27

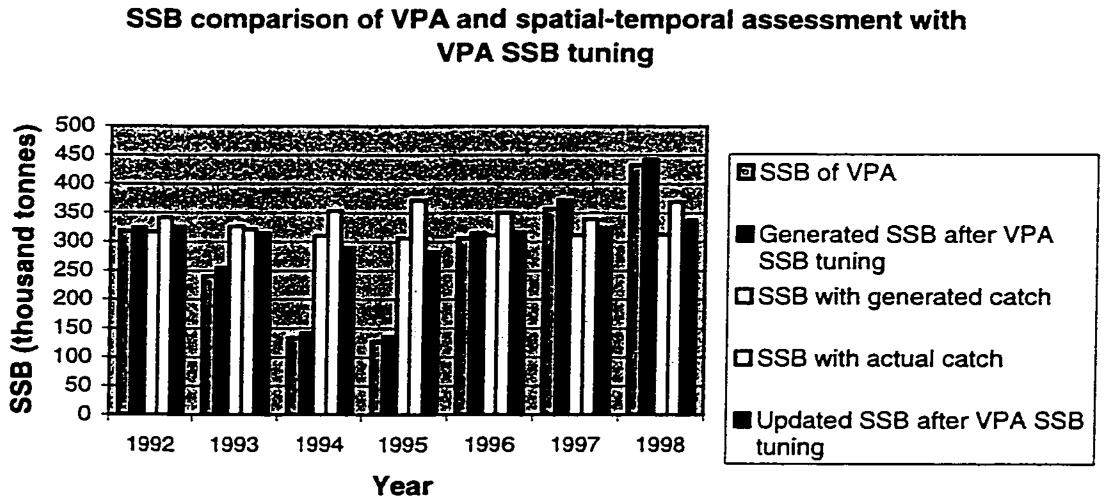

Figure 5.7 Total SSB comparison of VPA and Spatial-temporal assessment method with VPA SSB tuning

Table 5.13 and Figure 5.7 show us that SSB of spatial-temporal assessment indeed comes down slightly after tuning with VPA SSB in 1994 and 1995, but it is still much higher than SSB of the VPA assessment. Moreover, SSB of the spatial-temporal assessment method increase slightly after tuning in 1998. However, when the mean value of the population generation model in 1994 and 1995 is assigned to half of standard population (300 thousand tonnes), the estimation of SSB of the spatial-temporal assessment do not decrease correspondingly. The following Table 5.14 and Figure 5.8 illustrate the change of generated catch data after tuning. Table 5.14 and Figure 5.8 describe the total catch data after and before tuning.

Table 5.14 Generated catch data before and after tuning with VPA SSB (thousands of tonnes)

	1992	1993	1994	1995	1996	1997	1998
Grand Manan	1.313	0.684	1.607	1.567	3.26	2.976	2.648
Long Island	4.634	3.994	3.766	3.215	5.728	5.578	6.424
Trinity	2.44	1.581	1.233	1.025	1.398	2.131	2.718
Lurcher	0.074	0.084	0.023	0.069	0.047	0.028	0
Gannet, Dry ledge	10.677	7.784	3.477	5.973	5.344	8.163	11.064
Seal Island	6.004	6.438	5.823	1.601	3.716	2.71	4.988
German Bank	9.416	6.917	7.132	4.859	15.455	11.885	22.13
Scots Bay	2.777	2.963	3.316	0.829	3.342	3.207	5.382
Chedabucto	4.362	1.407	1.788	0.822	2.679	2.29	0
N.B. Coastal	0.215	0.05	0.036	0.053	0.029	0.049	0.038
Southwest Grounds	0.123	0.213	0.21	0.088	0.073	0.099	0.143
Diffuse	0	0	0	0	0	0	0
Yankee Bank	0.009	0	0.004	0.054	0.006	0.008	0.054
Halifax	0	0	0	0	0	0	0
Liverpool	0	0.021	0.04	0	0	0.005	0.021
total generated catch after tuning	42.044	32.136	28.275	20.155	41.077	39.129	55.612
total generated catch before tunig	43.017	36.174	39.945	29.795	40.023	36.89	45.667
Actual catch data	61.4507	30.9374	53.707	46.713	47.4926	43.4013	64.6037

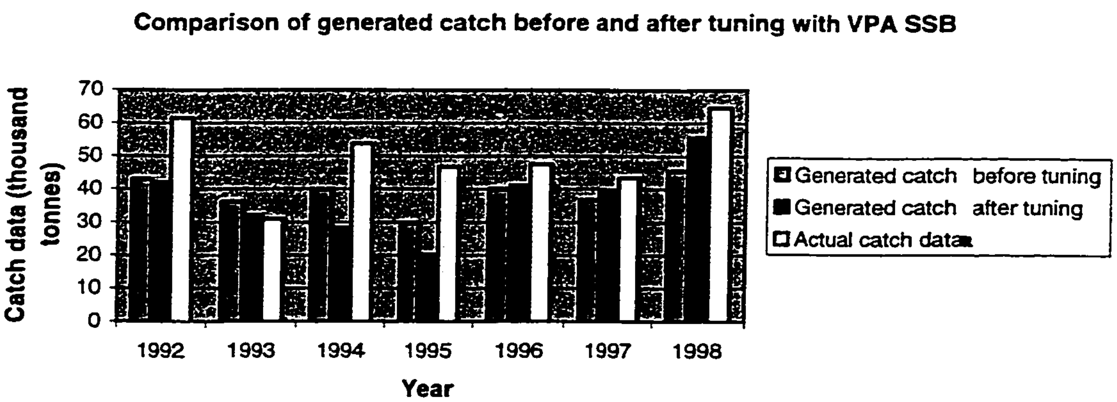

Figure 5.8 Comparison of generated catch data before and after tuning

Table 5.15 SSB of the population generation model with VPA tuned mean and variance (thoutonnes)

	1992	1993	1994	1995	1996	1997	1998
tuned mean	325	250	150	150	325	375	425
generated SSB after tuning	323.9	254.42	142.22	135.56	315.25	372.006	443.02
SSB of VPA	318.598	240.97	132.903	127.52	306.528	357.034	432.775

In Table 5.15, generated SSB denotes the result of the population generation model with VPA tuned mean and variance value. Considering Table 5.15, Table 5.1, Figure 5.7 and Figure 5.8 together, after tuning, the generated SSB of population generation model in 1994 comes down 142.22/ 325.9931=0.436, and generated catch data of the same year accordingly decreases 28.275/39.945=0.7. However, the estimated SSB according to updated population with π matrix just comes down slightly. The main reason for this apparent insensitivity is related to the defined discrete state levels of the population that are not fine enough to register the changes in catch observation. An enlarged set of population state levels (e.g. from 10 states to 20 states) with narrow cell limits could lessen this particular insensitivity.

Table 5.16 and Figure 5.9, Figure 5.10A and Figure 5.10B compare the estimation of SSB and variance with VPA and the spatial-temporal assessment method.

- SSB with generated catch: SSB of updated population based on generated catch before VPA SSB tuning from 1992 to 1998 in Table 5.6 and updated π matrix
- Updated SSB after VPA SSB tuning: estimated SSB of updated population based on generated catch data from 1992 to 1998 in Table 5.14 tuning with the SSB of VPA
- Generated SSB after VPA SSB tuning: generated SSB of population generation model result from 1992 to 1998 whose mean and variance are tuned according the SSB of VPA in Table 5.11

Table 5.16 SSB comparison of VPA and spatial-temporal assessment method

	1992	1993	1994	1995	1996	1997	1998
SSB with generated catch	316.826	326.562	310.294	306.654	310.573	311.794	312.756
low (-2var)	209.678	229.376	156.7	152.714	169.498	162.042	170.752
high(+2var)	423.976	423.744	463.88	460.568	451.642	461.538	454.76
variance	53.574	48.592	76.975	76.957	70.536	74.874	71.002
Generated SSB after VPA SSB tuning	323.9	254.42	142.22	135.56	315.25	372.006	443.016
low(-2var)	53.46	29.22	13.74	44.76	18.07	-42.45	109.796
high(+2var)	594.34	479.62	270.7	226.36	612.43	786.47	776.236
variance	135.22	112.6	64.24	45.4	148.59	207.23	166.61
Updated SSB after tuning	326.067	315.034	290.207	282.131	316.454	324.358	337.265
low (-2var)	177.825	294.526	242.865	269.375	199.754	184.028	198.419
high (+2var)	474.309	335.542	337.549	302.963	433.154	464.688	476.111
variance	74.121	10.254	23.671	10.416	58.35	70.165	69.423

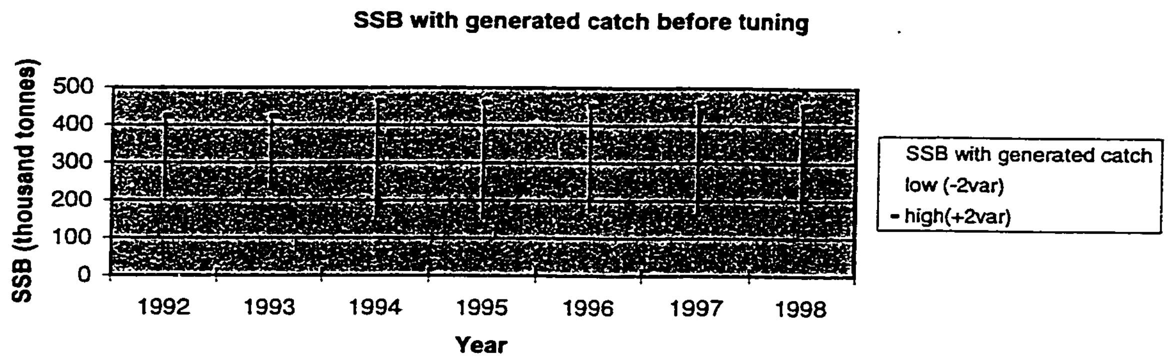

Figure5.9 Low, expected and high SSB with generated catch before VPA SSB tuning

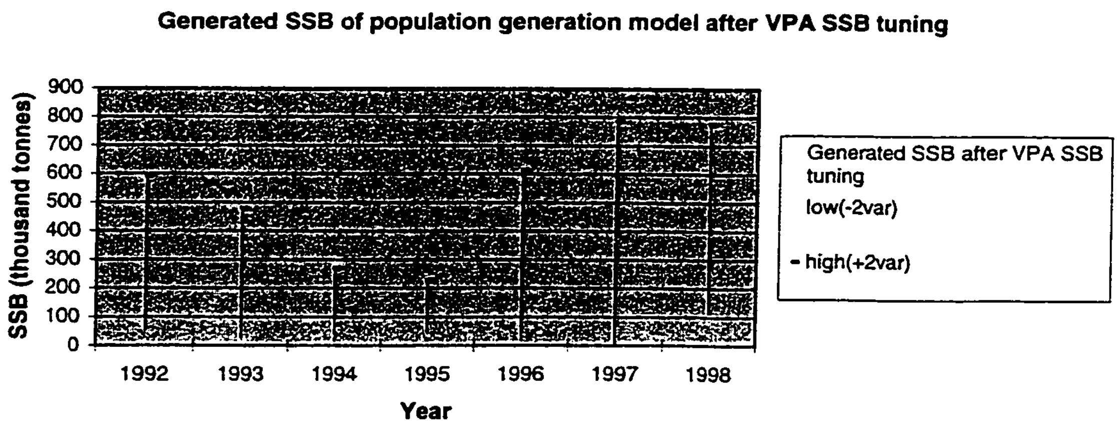

Figure 5.10A Low, expected and high generated SSB after VPA SSB tuning

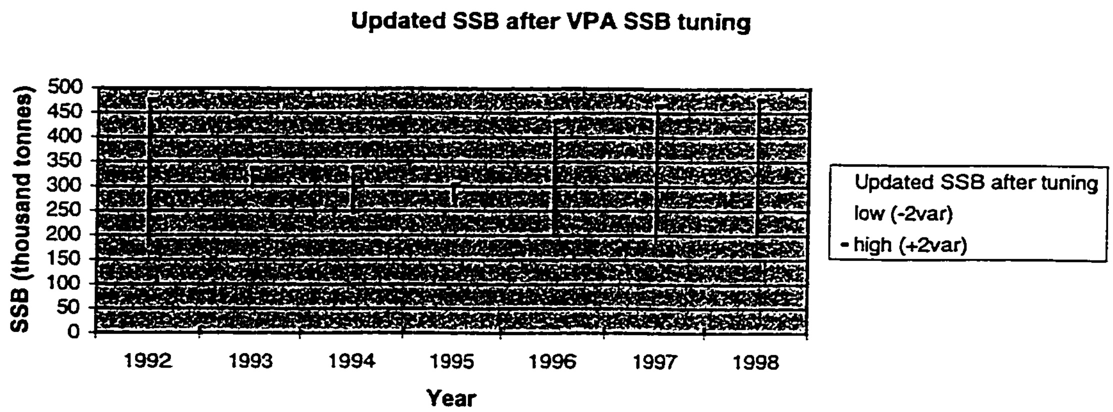

Figure 5.10B Low, close and high updated SSB after VPA SSB tuning in Table 5.11

5.5.2 Tuning with actual catch data from 1992 to 1998

In this analysis, we confirm the mean and variance of the population generation model according to actual catch data (Table 5.2) each year. From multiple trials of the population generation model, we set mean and variance of the initial population size. We take the following steps to tune the mean and variance of the normal distribution from actual catch data from 1992 to 1998:

- Tune mean and the corresponding variance of population generation model so that the generated catch data match as closely as possible the actual catch data from 1992 to 1998 respectively. Table 5.17 describes the tuned mean and variance value from 1992 to 1998.
- Based on the tuned population generation model, generate catch data according to when and where actual catching exists from 1992 to 1998, ignore catches in zone 12 and zone 14. The corresponding results for the generated catch data from 1992 to 1998 are described in Table 5.18.
- Update the population with the generated catch data and successive $\pi(0)$ matrix, and calculate updated SSB of spatial-temporal assessment method with tuned catch data.

Table 5.17 Actual catch tuned mean and variance of population generation model (thousands of tonnes)

	1992	1993	1994	1995	1996	1997	1998
Tuned mean	600	240	540	660	360	390	540
Tuned variance	200	80	180	220	120	130	180
SSB of VPA	318.598	240.97	132.903	127.52	306.528	357.034	432.775

Based on the above tuned mean and variance of population generation model, the following Table 5.18 and Figure 5.11 describe the generated catch data which match closely the VPA actual catch data. Actual catch data in Table 5.18 do not include catch data from zone 12 and zone14.

Table 5.18 Generated catch data based on tuned mean and variance in Table 5.17 and total actual catch data (thousands of tonnes)

	1992	1993	1994	1995	1996	1997	1998
Grand Manan	1.813	0.582	2.325	2.635	3.471	3.072	2.631
Long Island	5.028	3.963	6.012	5.476	6.3	5.491	7.394
Trinity	2.915	1.299	2.222	1.394	1.354	2.619	2.825
Lurcher	0.161	0.083	0.077	0.077	0.055	0.05	0
Gannet, Dry ledge	12.905	7.4	5.026	10.134	5.893	8.578	11.824
Seal Island	10.273	6.229	10.077	1.894	4.246	2.696	6.941
German Bank	17.826	6.909	18.143	19.753	18.072	14.924	24.075
Scots Bay	4.973	2.986	4.752	2.14	3.619	3.221	6.347
Chedabucto	5.123	1.5	4.432	2.799	3.072	2.243	0
N.B. Coastal	0.163	0.063	0.039	0.079	0.038	0.038	0.038
Southwest Grounds	0.214	0.212	0.734	0.365	0.082	0.124	0.205
Diffuse	0	0	0	0	0	0	0
Yankee Bank	0.015	0	0.012	0.066	0.012	0.008	0.031
Halifax	0	0	0	0	0	0	0
Liverpool	0	0.019	0.069	0	0	0.005	0.044
Total	61.409	31.245	53.92	46.812	46.214	43.069	62.355
Total generated catch before tuning	43.017	36.174	39.945	29.795	40.023	36.89	45.667
Actual Total catch	61.4507	30.9374	53.707	46.713	47.4926	43.4013	64.6037

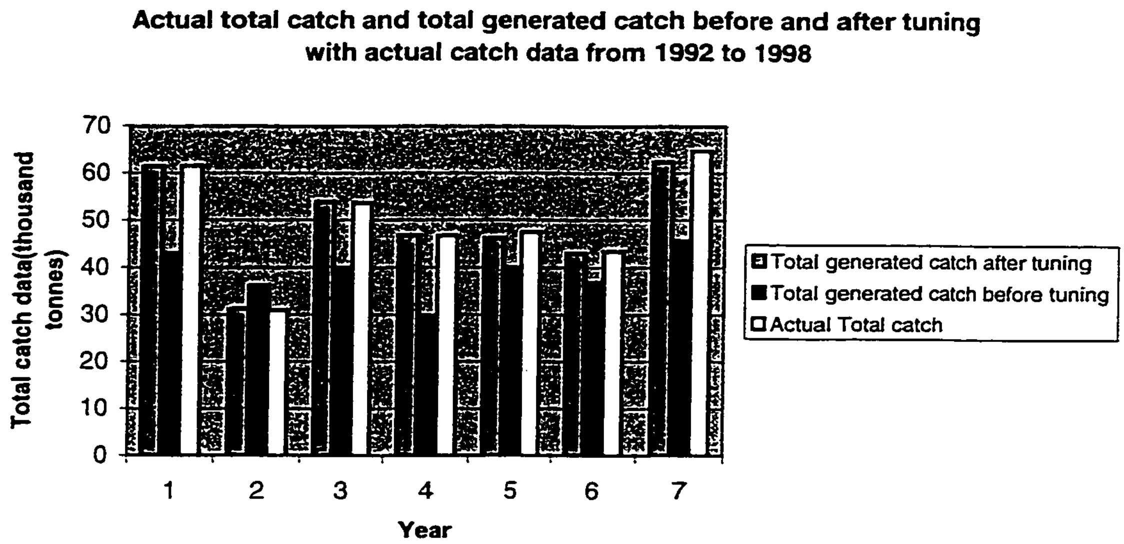

Figure 5.11 Total catch data comparison before and after tuning in Table 5.17

According to generated catch data and the P matrix calculate π matrix using the previous year $\pi(52)$ as next successive $\pi(0)$. After updating the population size estimation through the π matrix, the updated SSB of spatial-temporal assessment method are described in the following Table 5.19.

Table 5.19 and Figure 5.12 compare SSB among:

- Generated SSB after actual catch tuning: generated SSB from results of population generation model with tuned mean and variance of normal distribution according to actual catch data from 1992 to 1998
- SSB of VPA assessment
- Updated SSB after actual catch tuning: updated SSB of spatial-temporal assessment using generated catch and updated π matrix to update population according to actual catch data tuning from 1992 to 1998 (Table 5.17)
- SSB with generated catch: updated SSB of spatial-temporal assessment based on generated catch data (Table 5.6) and updated π matrix to update population without tuning

- SSB with actual catch: updated SSB of spatial-temporal assessment based on actual catch data from 1992 to 1998 (Table 5.5) and updated π matrix to update population without tuning

Table 5.19 SSB comparison of VPA assessment and spatial-temporal assessment method with actual data tuned mean and variance in Table (5.17) (thousands of tonnes)

	1992	1993	1994	1995	1996	1997	1998
SSB of VPA	318.6	240.97	132.9	127.52	306.53	357.03	432.78
Generated SSB after actual catch tuning	669.932	229.301	551.401	739.7853	384.0262	453.4592	570.542
SSB with generated catch	316.83	326.562	310.29	306.65	310.57	311.79	312.76
SSB wth actual catch	341.72	321.466	352.98	371.48	350.09	339.36	369.19
Updated SSB after actual catch tuning	387.73	316.993	365.48	350.6	330.98	341.81	337.27

From Table 5.19 and 5.18, we find there is one conflict between actual catch data and VPA SSB in VPA assessment method. In 1994, SSB of VPA is lower than other years, but actual catch data are very high, so tuned mean and variance of population generation model are higher in order to match actual data from 1992 to 1998 during actual catch tuning, and the corresponding estimates of tuned SSB are higher in 1994. It is also the reason why tuned actual SSB is so high (739.785), because we tune generated catch data to match actual data from 1992 to 1998 and then obtain tuned mean and variance like Table 5.17 and tuned actual SSB of population generation model.

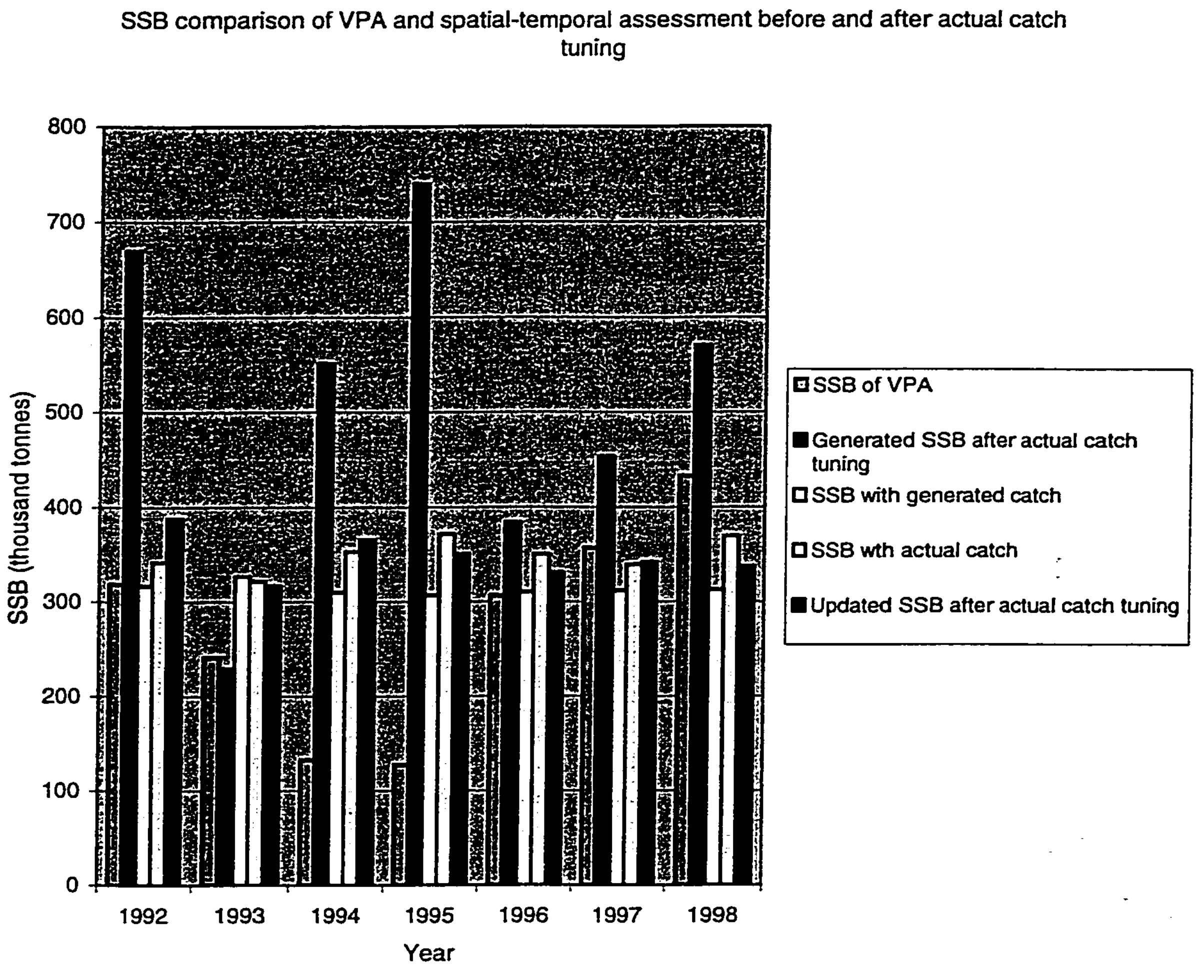

Figure 5.12 SSB comparison of VPA and spatial-temporal assessment before and after actual catch tuning

From Table 5.19 and Figure 5.12, we find that estimates of tuned SSB increase slightly with apparent mean and variance of the population generation model, demonstrating that the discretized population level appears to be too coarse (i.e. too few states) to make much distinction between years. However, in order to make generated catch data match actual catch data from 1992 to 1998, tuned mean and variance of population generation model are much higher than the SSB. This shows us there is conflict between SSB of VPA and actual catch again in 1992, 1994 and 1995, which is lower SSB of VPA assessment but higher actual catch data, especially in 1994 and 1995.

Table 5.20, Figure 5.13 and Figure 5.14 analyse the comparison of estimated SSB and variance with VPA and spatial-temporal assessment method. We note the following:

- SSB with generated catch: updated SSB of spatial-temporal assessment method with population generation model of Normal distribution N(300,100) to generate catch data (Table 5.6) and update population.
- Updated SSB after actual catch tuning: updated SSB of spatial-temporal assessment method with population generation model of actual catch tuning (Table 5.17) to generate catch data (5.18) and update population.
- Generated SSB after actual catch tuning: generated SSB from the results of population generation model with tuned mean and variance according to actual catch data from 1992 to 1998.

Table 5.20 SSB comparison of VPA and spatial-temporal assessment with actual catch tuning

	1992	1993	1994	1995	1996	1997	1998
SSB with generated catch	316.826	326.562	310.294	306.654	310.573	311.794	312.756
low (-2var)	209.678	229.376	156.7	152.714	169.498	162.042	170.752
high(+2var)	423.976	423.744	463.88	460.568	451.642	461.538	454.76
variance	53.574	48.592	76.975	76.957	70.536	74.874	71.002
Updated SSB after actual catch tuning	387.734	316.993	365.48	350.6	330.984	341.812	367.66
low(-2var)	171.26	279.539	176.242	129.104	225.476	221.76	223.066
high(+2var)	604.208	354.447	559.718	572.096	436.492	461.864	512.254
variance	108.237	18.727	97.119	110.748	52.754	61.026	72.297
Generated SSB after actual catch tuning	669.932	229.3008	551.4009	739.7853	384.0262	453.4592	570.5422
low(-2var)	114.5436	79.2188	33.4551	100.9133	110.1606	136.4036	105.7948
high(+2var)	1225.32	379.3828	1069.347	1378.657	657.8918	770.5148	1035.29
variance	277.6942	75.041	258.9729	319.436	136.9328	158.5278	232.3737

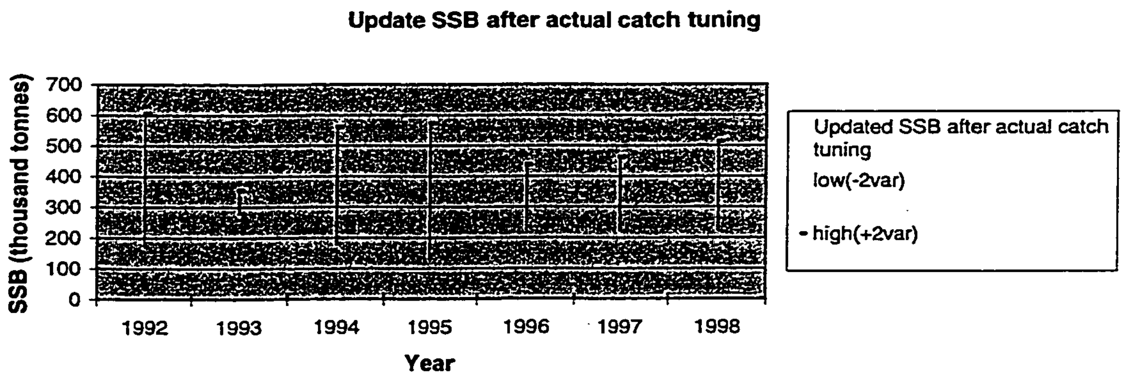

Figure 5.13 Low, expected and high updated SSB after actual catch tuning in Table 5.17

Generated SSB of population generation model after actual catch tuning

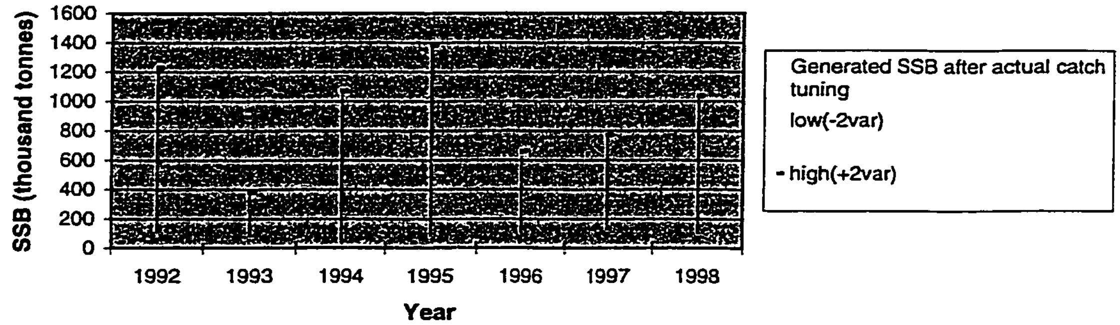

Figure 5.14 Low, expected and high generated SSB after actual catch tuning in Table 5.17

5.5.3 Analysis of tuning with two ways

The above analyses include tuning two ways: one way is to tune the mean and variance of the population generation model according to the SSB of VPA. The other way is to tune the mean and variance of the population generation model so that generated catch data match actual catch. After tuning, they both affect estimated spawning group biomass, but the former changes updated SSB of the spatial-temporal assessment method only slightly. The second approach changes the updated SSB estimates of the spatial-temporal assessment method only by a little more.

Both ways of tuning do not change estimated SSB of the spatial-temporal assessment method very much. The main reason for this is because the updated population is mainly determined by the probability transition matrix P, which is fixed according to the defined discretized levels of population. So how the discretized population level are defined is the major concern.

VPA has low estimates of SSB compared to the anticipated spatial-temporal method from actual catch data. Especially during 1994, 1995, actual catch data might imply a higher population, but spawning stock biomass of VPA assessment method are very low for these years. If tuning the mean and variance of population generation model to match

SSB of VPA in 1994 and 1995, the generated catch data decrease significantly. On the other hand, in 1992, actual catch data are very high, if tuning the mean and variance of the population generation model according to the actual catch data, its tuned mean reached N(600,200) (thousands of tonnes).

6. Conclusions and Extensions

6.1 Conclusions

The data generated by the population generation model to estimate the stock size of 4WX herring spawning group abundance in the Bay of Fundy off southwestern Nova Scotia are used to develop a spatial-temporal assessment estimation procedure. Discretized stock size estimates are used to generate catch data similar to actual catch levels, and stock size estimates are updated by week and by zone through using actual catch data and generated catch data.

Weekly estimates for individual zone populations were produced, which were then aggregated to produce total stock size estimates for the whole fishery. Also, estimates of the size of each spawning group during each year were made by using estimates of the zone populations of spawning areas during the respective spawning seasons. This information gives fishermen and managers to more accurate indication about where and how much fishing effort can be applied in order to maintain stock and spawning group conservation. In contrast, aggregated VPA estimates for stock size cannot provide any indication of stock status among the various spawning groups.

In addition, using spatial-temporal assessment method estimates of the size of each spawning group during each year were made by using estimates of the zone populations of spawning areas during the respective spawning seasons. This information will enable fishermen to more accurately choose where and how much to fish in accordance with the goal of stock and spawning group conservation.

6.2 Extensions

The extensions of this work lie in two areas: application and methodology. Desirable extensions or modifications of the application of this model will involve: (i) more extensive analysis of the model simulation trials, i.e., reevaluation of the probability transition matrix under varying assumption of the total population size, more trials of the population generation simulator together with more trials of the annual generated catch data; (ii) the generalization of signal data and refinement of the state-to-observation matrix, (iii) changing the parameters of the system with respect to the underlying distribution of the size of the fishery, (iv) further experimentation with alternate migration routes of the constituent spawning groups, and (v) refinement of the population state level definitions.

Actual catch data of some zones change sharply for some years. For example, catches in Grand Manan ranged from from 6.4074 thousand tonnes in 1997 to 13.4923 thousand tonnes in 1998: Long Island varied from 3.5178 thousand tonnes in 1997 to 13.4923 thousand tonnes in 1998. Meanwhile, German Bank actual purse seine catch data increased dramatically from 3.75 thousand tonnes 1992 to over 20 thousand tonnes 1998. While these ranges indeed reflect to some degree changes in population, it is incorrect to presume that these aggregate observations are a direct reflection only population changes. The balance of catch changes to reflect population differences remains an open issue.

When updating stock size estimates by week and by zone with probability transition matrices, it was assumed that this fishery has a total size which is normally distribution with a mean of 300 thousand tonnes and a standard deviation of 100 thousand tonnes. In our analysis of results, we find that if the fishery (and the population) has shrunk significantly according to the VPA assessment, we do not change probability matrix, but only change mean population and generated catch data to match SSB of VPA, the spawning stock biomass will come down slightly. The reasons might be considered from two sources:

- Since the discrete population levels are wide, when decreasing initial population and generated catch data, the SSB under updating does not adjust to the same extent. This indicates unsensitivity of the state levels especially in zones where the population level remain low.

- The other reason is the actual estimated parameters of the large P matrix changes in their parameters that reflect apparent population shifts (e.g. from Seal Island to German Bank) may be required.

Spatial-Temporal Analysis is a more accurate approach to produce estimates of stock abundance for a fishery which currently uses estimates produced by the Virtual Population Analysis methodology. The VPA estimates for the years 1992-1998 are not as stable as the Spatial-Temporal estimates, and decrease and increase more sharply over time on the basis of a population index that is age independent (the herring larval abundance index). As well, annual catch by seines may vary due to other than population effects, e.g., change in markets, operating costs, etc. An examination of the degree of fishing effort required to obtain these different catches (through total number of sets, for example) would help clarify the reliability of population estimates.

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Appendix A

Spawning group zonal migration patterns by week. The following table provides the data on the main wave of each spawning group.

Spawning Group	No.	1	2	3	4	5	6
Month	Week	Scots Bay	Scots Bay	Trinity	Lurcher	Seal	German
		(Chedabucto)	(Grand Manan)			Island	Bank
January	1	9	1	9	9	9	9
	2	9	1	9	9	9	9
	3	9	1	9	9	9	9
	4	9	1	9	9	9	9
February	5	9	1	12	12	12	12
	6	9	1	12	12	12	12
	7	12	12	12	12	12	12
	8	12	12	12	12	12	12
March	9	12	12	12	12	12	12
	10	12	12	12	12	12	12
	11	12	12	12	12	12	12
	12	12	12	12	12	12	12
	13	12	12	12	12	12	12
April	14	12	12	12	12	12	12
	15	12	12	12	12	12	12
	16	12	12	12	12	12	12
	17	12	12	12	12	12	12
May	18	2	12	11	11	11	11
	19	2	12	11	11	11	11
	20	2	2	11	11	11	11
	21	2	2	5/7	5/7	11	11
	22	2	2	5/7	5/7	11	11
June	23	2	2	5/7	5/7	11	11
	24	2	2	4/5	4/5	11	11
	25	2	1/2	4/5	4/5	11	11
	26	2	1	4/5	4/5	5	5/7

Spawning Group	No.	1	2	3	4	5	6
Month	Week	Scots Bay	Scots Bay	Trinity	Lurcher	Seal	German
		(Chedabucto)	(Grand Manan)			Island	Bank
July	27	2	1	4	4	5	5/7
	28	2	13	4	4	5/6	5/7
	29	13	10	2	2	5/6	5/7
	30	10	8	2	2	5	5
August	31	8	8	3	2	5	5
	32	8	8	3	3	2/5	5
	33	8	12	3	4	2/5	5
	34	12	12	3	4	5	5
	35	12	12	2	4	5	5
September	36	12	12	2	12	6	5
	37	12	12	2	12	6	7
	38	12	12	12	12	6	7
	39	12	1	12	12	5	7
October	40	12	1/10	12	12	5	5
	41	12	1/10	12	12	5	5
	42	12	1/10	12	12	12	12
	43	12	12	12	12	12	12
	44	12	12	12	12	12	12
November	45	12	12	9	9	12	12
	46	12	12	9	9	12	12
	47	12	12	9	9	12	12
	48	12	12	9	9	9	9
December	49	9	1	9	9	9	9
	50	9	1	9	9	9	9
	51	9	1	9	9	9	9
	52	9	1	9	9	9	9

Appendix B

The following table provides the average results of the population generation model for 10 independent trials with normal distribution N(300,100) (thousands of tonnes) which can be viewed by the Visual C++ GUI model, the columns and the rows are weeks and zones separately.

Result of N(300,100) population generation model by week and by zone(w/z) (thousands of tonnes):

w\z	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	12.3	0	0	0	0	0	0	0	331.7	0	0	0	0	0	0
2	12.2	0	0	0	0	0	0	0	330.5	0	0	0	0	0	0
3	12.2	0	0	0	0	0	0	0	293.8	0	0	35.36	0	0	0
4	12.1	0	0	0	0	0	0	0	213.5	0	0	114.4	0	0	0
5	10.8	0	0	0	0	0	0	0	139.2	0	0	188.8	0	0	0
6	7.85	0	0	0	0	0	0	0	56.85	0	0	272.8	0	0	0
7	5.24	0	0	0	0	0	0	0	14.89	0	0	316	0	0	0
8	1.49	0	0	0	0	0	0	0	3.732	0	0	329.6	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	333.6	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	332.3	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	331	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	329.7	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	328.5	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0	327.2	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	326	0	0	0
16	0	3.19	0	0	0	0	0	0	0	0	33.63	287.9	0	0	0
17	0	12.2	0	0	0	0	0	0	0	0	108.8	202.5	0	0	0
18	0	21.5	0	0	0	0	0	0	0	0	175.1	125.6	0	0	0
19	0	34.8	0	0	4.135	0	5.711	0	0	0	233.5	42.83	0	0	0
20	0	40.7	0	0	18.06	0	14.74	0	0	0	241.3	4.979	0	0	0
21	0	44.1	0	0	21.49	0	30.35	0	0	0	221.2	1.417	0	0	0
22	0	45.3	0	8.84	55.82	0	4.602	0	0	0	202.7	0	0	0	0
23	0.78	44.4	0	17	39.52	0	20.89	0	0	0	193.5	0	0	0	0
24	3.48	41.5	0	24.8	52.7	0	22.54	0	0	0	169.8	0	0	0	0
25	6.32	38.5	0	58.8	54.83	0	36.52	0	0	0	118.7	0	0	0	0
26	6.79	36.7	0	53.7	98.17	3.862	39.75	0	0	0	72.3	0	1.2	0	0
27	6.52	40.6	0	52.5	108	11.32	62.79	0	0	1.19	22.54	0	5.7	0	0
28	4.83	53.3	0	39.8	117	29.92	47.29	1.186	0	5.719	0	0	11	0	0
29	1.37	56	7.91	25.4	126.6	20.69	41.81	6.878	0	10.987	0	0	11	0	0
30	0	49.2	28.8	8.18	161.5	0	19.5	17.8	0	11.158	0	0	12	0	0
31	0	43.8	45.8	1.55	162.2	2.892	6.447	27.67	0	11.523	0	1.172	3.4	0	0
32	0	25.4	58.5	4.24	173.5	0	0	33.41	0	3.403	0	6.799	0	0	0
33	0	1.83	58.1	6.71	186.2	0	0	25.85	0	0	0	25.38	0	0	0
34	0	14	36.8	9.01	164.1	7.293	0	14.77	0	0	0	56.91	0	0	0
35	0	5.64	19.1	8.12	143.3	21.12	14.73	3.363	0	0	0	86.4	0	0	0
36	0	0	6.18	5.64	98.57	36.25	49.24	0	0	0	0	104.7	0	0	0
37	1.15	0	0	1.81	59.52	45.89	77.94	0	0	0	0	113.2	0	0	0
38	3.34	0	0	0	49.06	40	93.58	0	0	0.369	0	112	0	0	0
39	5.32	0	0	0	84.5	24.82	72.62	0	0	0.662	0	109.2	0	0	0
40	4.57	0	0	0	107.9	7.927	43.78	0	0	4.681	0	127.1	0	0	0
41	5.17	0	0	0	98.15	0	13.46	0	0	4.231	0	173.9	0	0	0
42	3.24	0	0	0	67.98	0	0	0	0	3.592	0	218.9	0	0	0
43	4.56	0	0	0	21.19	0	0	0	8.976	0	0	257.9	0	0	0
44	0.43	0	0	0	0	0	0	0	29.9	0.872	0	260.3	0	0	0
45	0	0	0	0	0	0	0	0	47.26	0	0	243.1	0	0	0
46	0	0	0	0	0	0	0	0	84.23	0	0	205	0	0	0
47	1.1	0	0	0	0	0	0	0	140.8	0	0	146.3	0	0	0
48	3.57	0	0	0	0	0	0	0	190.4	0	0	93.04	0	0	0
49	5.76	0	0	0	0	0	0	0	242.3	0	0	37.83	0	0	0
50	8.91	0	0	0	0	0	0	0	271.5	0	0	4.442	0	0	0
51	10.1	0	0	0	0	0	0	0	273.6	0	0	0	0	0	0
52	10.1	0	0	0	0	0	0	0	272.5	0	0	0	0	0	0

Appendix C

The tables below contain the discretized catch observation levels for the state-to-observation Q matrix for each of 6 classes of observation sets corresponding to subsets of fishing zones.

The zones are grouped into 6 classes with respect to the signal matrix and catch data. For all zones, a catch signal of 1 indicates that no fish were caught. Weeks 51-52 are not included as there are no catches during these weeks.

Class 1 contains Zones 6 and 8 except for the spawning periods in areas 6 when they are classified as class 5 instead. Catch levels for class 1 are as follows:

Catch Level	Catch Values
2	0 < catch < 500 tonnes
3	500 < catch < 1000 tonnes
4	1000 < catch < 1500 tonnes
5	1500 < catch < 2000 tonnes
6	2000 < catch < 2500 tonnes
7	2500 < catch < 3000 tonnes
8	3000 < catch < 3500 tonnes
9	3500 < catch < 4000 tonnes
10	4000 < catch < 4500 tonnes
11	4500 < catch <5000 tonnes
12	5000 < catch < 5500 tonnes
13	catch > 5500 tonnes

Class 2 includes Zones 1, 2, 3, and 5. Catch levels for class 2 are as follows:

Catch Level	Catch Values
2	0 < catch < 250 tonnes
3	250 < catch < 500 tonnes
4	500 < catch < 750 tonnes
5	750 < catch < 1000 tonnes
6	1000 < catch < 1250 tonnes
7	1250 < catch < 1500 tonnes
8	1500 < catch < 1750 tonnes
9	catch > 1750 tonnes

Zones 4, 10, 11, 13, and 15 are contained in class 3. Catch levels for class 3 are as follows:

Catch Level	Catch Values
2	0 < catch < 50 tonnes
3	50 < catch < 100 tonnes
4	100 < catch < 150 tonnes
5	150 < catch < 200 tonnes
6	200 < catch < 250 tonnes
7	catch > 250 tonnes

Class 4 consists of Zone 9 only. Catch levels for class 4 are as follows:

Catch Level	Catch Values
2	500 ≥catch > 0 tonnes
3	1000 ≥catch > 500 tonnes
4	1500 ≥ catch > 1000 tonnes
5	2000 ≥ catch > 1500 tonnes
6	2500 ≥ catch > 2000 tonnes
7	3000 ≥ catch > 2500 tonnes
8	3500 ≥ catch > 3000 tonnes
9	4000 ≥ catch > 3500 tonnes
10	4500 ≥ catch > 4000 tonnes
11	5000 ≥ catch > 5500 tonnes
12	catch > 5000 tonnes

Since class 5 exists only to classify Zone 12 and Zone 14 and no signal from this zone is ever used, class 5 has 1 catch level (0).

Class 6 denoted Zone 7 and has the same catch as class 1.

Appendix D

This appendix contains the average generated catch from the catch generation model using multiple trials from the population generation model, based on a Normal distribution N (300,100) (thousands of tonnes). Averages computed for 10 generated populations and 10 generated catch data for each generated population for 1992.

Generated catch data in 1992 by week\zone (w/z) (thousands of tonnes):

w\z	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	0.21	0	0	0	0	0	0	0	1.205	0.005	0	0	0	0	0
2	0	0	0	0	0	0	0	0	1.216	0.006	0	0	0	0	0
3	0	0	0	0	0	0	0	0	1.042	0.021	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0.911	0.011	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0.009	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0.009	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0.012	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0.012	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0.014	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0.003	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0.009	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0.006	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0.005	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0.007	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0.008	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0.007	0	0	0	0	0
17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22	0	0	0.086	0.02	0	0	0.443	0	0	0	0.074	0	0	0	0
23	0.05	0	0	0	0.36	0	0	0	0	0	0	0	0	0	0
24	0.09	0.599	0	0.01	0.47	0.366	0.745	0	0	0	0.044	0	0	0	0
25	0.2	0.429	0.116	0.02	0.58	0	1.239	0	0	0	0	0	0	0	0
26	0.17	0.472	0.016	0.02	0.73	0.434	0.957	0	0	0.017	0	0	0	0	0
27	0.12	0.578	0.087	0.01	0.57	0	1.337	0	0	0.011	0	0	0	0	0
28	0.11	0.639	0.037	0.02	0.64	0	1.306	0	0	0	0	0	0	0	0
29	0.07	0.456	0.226	0.01	0.65	0	1.107	0	0	0.009	0	0	0	0	0
30	0.01	0.498	0.41	0.01	0.71	0	0	0.437	0	0	0	0	0.01	0	0
31	0	0.556	0.56	0	0.74	0.437	0.357	0.583	0	0.017	0	0	0	0	0
32	0	0	0.597	0	0	0.482	0	0.934	0	0	0	0	0	0	0
33	0	0.106	0.696	0	0.7	0.445	0	0.651	0	0	0	0	0	0	0
34	0	0	0	0	0.71	0.673	0.456	0	0	0	0	0	0	0	0
35	0	0.169	0	0	0.74	0.728	0	0	0	0	0	0	0	0	0
36	0	0	0	0	0.64	0.726	1.149	0	0	0	0	0	0	0	0
37	0	0	0	0	0.47	1.048	1.362	0	0	0	0	0	0	0	0
38	0	0	0	0	0.43	0.642	0	0	0	0	0	0	0	0	0
39	0	0	0	0	0.57	0.553	0	0	0	0	0	0	0	0	0
40	0	0	0	0	0.56	0	0	0	0	0	0	0	0	0	0
41	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
42	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
43	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
44	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
46	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
49	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
51	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
52	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

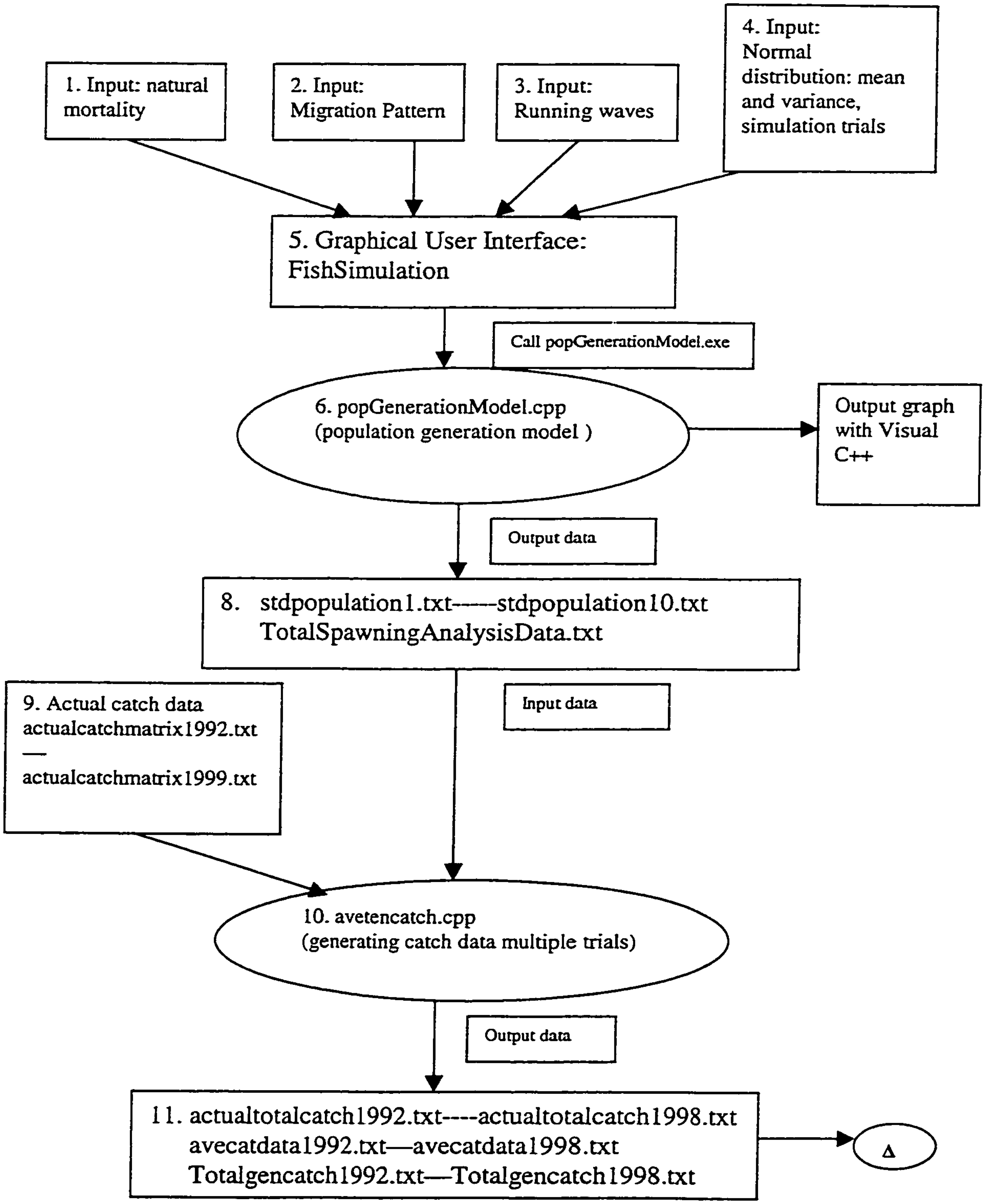
Appendix E

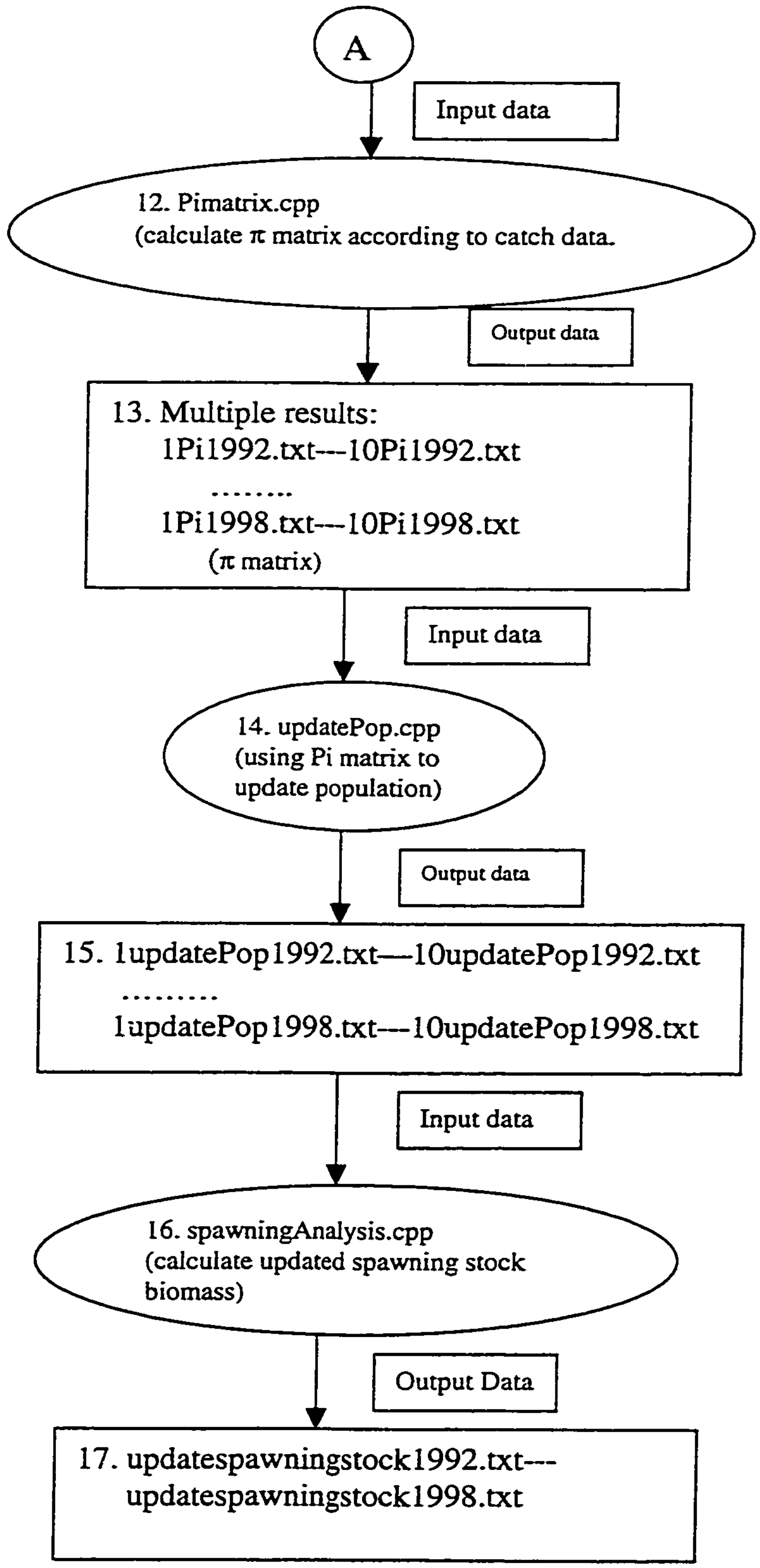
Documentation of the C and Visual C++ routines: model files definition. This appendix presents:

(1) Program flowchart for model use

(2) Program documentation

(1) Program flowchart for model use




A
Input data
12. Pimatrix.cpp
(calculate π matrix according to catch data.
Output data
13. Multiple results:
1Pi1992.txt---10Pi1992.txt
....
1Pi1998.txt---10Pi1998.txt
(π matrix)
Input data
14. updatePop.cpp
(using Pi matrix to
update population)
Output data
15. 1updatePop1992.txt—10updatePop1992.txt
....
1updatePop1998.txt---10updatePop1998.txt
Input data
16. spawningAnalysis.cpp
(calculate updated spawning stock
biomass)
Output Data
17. updatespawningstock1992.txt---
updatespawningstock1998.txt

(2) Program documentation- Documentation for population generation and updating programs. Numbered programs relate to numbers in Appendix flowchart above.

PopGenerationModel.cpp (6): This file is used to simulate the core process of the spatial-temporal assessment method — population generation model, which describes the herring stock dynamics. The initial estimate for the size of the adult population of whole stock (all spawning groups) uses Normal Distribution with given mean and variance.

This program reads the inputs from the following data file:

I. StandardData.dat: It includes three data: the number of simulation trials, the given mean and variance of the normal distribution for spawning stock estimation.

II. MortalityData.dat: It provides natural mortality for the whole year, so weekly natural mortality is 1/52 times of natural mortality.

III. WaveData.dat: It provides a random running wave type for each spawning group.

1 - Flat Form
2 - Normal Form
3 - Skewed Left
4 - Skewed Right
5 - Truncated Form
6 - Random Selection, which means randomly selecting 1,2,3,4, or 5 at running time

IV. migrationPattern.dat: It provides migration pattern for each spawning group at running time

V. spawningProportion.dat: It provides maximum and minimum proportion for each spawning group.

If running ten trials, it produces the main output files as follows.

1. stdpopulation1.txt —— stdpopulation10.txt

   These files describe population by zone and by week for each trial.

1. TotalSpawningAnalysisData.txt

   It supplies

   - Spawning stock biomass of each spawning group and total spawning stock for each trial.
   - The average spawning stock biomass and variance of each spawning group for multiple trials.

Fishsimulation(5): This is Visual C++ single document project file. It provides graphical user interface to get inputs from the user to save theses input data to the above described corresponding files. Next it runs the executable file of popGenerationModel.cpp. Finally it provides graphical user interface to display the output data. It includes the following classes:

1) Two classes for displaying welcome message:
   CDlgWelcome and CDlg4WXSimulation
2) CDlgInputNaturalMortality: Natural mortality input dialog
3) CDlgHerringMap: Displaying 4WX region map dialog
4) CDlgMigrationPattern: Input dialog allowing the user to view and modify the migration patterns for each spawning group.
5) CDlgRunningWave: Input dialog allowing the user to select the running wave for each spawning group.
6) CDlgSimulationModeal: Input dialog allowing the user to input the number of the simulation trials, the mean and variance of initial estimated size for the whole spawning stock
7) Display and allow the user to modify the migration patterns for each spawning group
   CDlgChedabuctoMigration   CDlgGermanBankMigration,
   CDlgGrandmanMigration   CDlgGrandMananMigration
   CDlgSeallslandMigration   CDlgTrinityMigration
8) CDlgOutputAnalysis :output analysis 1 which allows the user to view the population by week and by zone for each zone and each week. It will automatically load Microsoft EXCEL to display the result by chart
9) CDlgOutputAnalysis2 and CDlgEachSpawningAnalysis: output anlysis 2 which allows the user to view the spawning stock biomass and variance for each spawning group
10) CDlgOutputAnalysis3 and CDlgTotalSpawningAnalysis:output analysis3 which allows the user to view the total spawning stock biomass and variance

avetencatch.cpp (10): This file is used to generate catch data from 1992 to 1998. It reads population generation model result: stdpopulation1.txt —stdpopulation10.txt, discretize them and then generate catch data ten trials for each population generation model result according to Q matrix by week and by zone where actual catch data exists.

input data:

1) stdpopulation1.txt—stdpopulation10.txt
2) Q matrix

The main output files include:

1) actualtotalcatch1992.txt----actualtotalcatch1998.txt

   Theses files provide the actual catch data for each zone and whole schooling from

1992 to 1998.

2) avecatchdata1992.txt—avecatdata1998.txt

These files provide the average generated catch data for multiple trials according to generated population by week and by zone

3) Totalgencatch1992.txt---Totalgencatch1998.txt

These data files present the average generated catch data for each zone and the whole schooling from 1992 to 1998

Pimatrix.cpp(12): This file is used to calculate π matrix according to equation 3.6 and 3.7 of the text. It reads initial π matrix for each zone as $\pi(0)$ for 1992, and then takes the $\pi(52)$ of the previous year as $\pi(0)$ of the next year from 1993 to 1998. It calculates π matrix ten trial for each year using the average generated catch data which are discretized first.

Input data:

1) P matrix
2) avecatdata1992.txt----avecatdata1998.txt
3) Q matrix

The main output files are as follows:

1Pi1992.txt---10Pi1992.txt

1Pi1993.txt---10Pi1993.txt

1Pi1994.txt---10Pi1994.txt

1Pi1995.txt---10Pi1995.txt

1Pi1996.txt---10Pi1996.txt

1Pi1997.txt---10Pi1997.txt

1Pi1998.txt---10Pi1998.txt

updatePop.cpp(14): This file is used to calculate updated population according to the above π matrix and equation 4.4 of the text.

Input data:

1Pi1992.txt----10Pi1992.txt

....

1Pi1998.txt----10Pi1998.txt

The main output files include:

1updataPop1992.txt---1updatePop1992.txt

1updataPop1993.txt---1updatePop1993.txt

1updataPop1994.txt---1updatePop1994.txt

1updataPop1995.txt---1updatePop1995.txt

1updataPop1996.txt---1updatePop1996.txt

1updataPop1997.txt---1updatePop1997.txt

1updataPop1998.txt—1updatePop1998.txt

The files present the updated population by week and by zone for each year and each trial.

spawningAnalysis.cpp(16): This file is used to calculated updated spawning stock biomass for each year according to the above updated population.

Input data:

1updatePop1992.txt----10updatePop1992.txt

....

1updatePop1998.txt---10updatePop1998.txt

Output files:

updatespawningstock1992.txt---updatespawningstock1998.txt: these files present the average updated spawning stock biomass and variance for each spawning group and the whole stock from1992 to 1998