INVESTIGATION OF METHODS TO ESTIMATE MORTALITIES OF UNMARKED SALMON IN MARK-SELECTIVE FISHERIES THROUGH THE USE OF DOUBLE INDEX TAG GROUPS

Selective Fishery Evaluation Committee – Analytical Work Group
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ACRONYMS

AABM	Aggregate Abundance Based Management
ASFEC	Ad-hoc Selective Fisheries Evaluation Committee
CTC	Chinook Technical Committee
CV	Coefficient of Variation (used to measure precision)
CWT	Coded Wire Tag
DIT	Double Index Tag
HDS	Hypothetical Direct Sample
EER	Equal Exploitation Rate (method to determine mark-selective fishery mortality)
EMS	Equal marine Survival (method to determine mark-selective fishery mortality)
ESA	Endangered Species Act
ETD	Electronic Tag Detection
ISBM	Individual Stock Based Management
MSE	Mean-squared error (used to measure precision)
PR	Paired Ratio (method to determine mark-selective fishery mortality)
PSC	Pacific Salmon Commission
PST	Pacific Salmon Treaty
SFEC	Selective Fisheries Evaluation Committee
SFEC-AWG	Selective Fisheries Evaluation Committee-Analysis Work Group
SR	Sampling Rate
STT	Salmon Technical Team
TERM	Terminal (method to determine mark-selective fishery mortality)

Executive Summary

Currently, the coded-wire-tag (CWT) system is the only tool available to estimate and monitor coastwide impacts on individual stocks of natural fish. For example, the ability to use CWT data to estimate age and fishery specific exploitation rates is critical to implementing the June 1999 Pacific Salmon Treaty (PST) agreement. The agreement requires the evaluation of impacts on individual stocks on a fishery and age-specific basis for Individual Stock Based Management (ISBM) fisheries. Constraints on ISBM fisheries are defined by indices that reflect exploitation rates in specific combinations of fisheries. Also, the PST agreement requires Aggregate Abundance Based Management (AABM) regimes to be evaluated annually, pursuant to calibration of the PSC Chinook Technical Committee (CTC) Chinook Model. These regimes are based on relationships between abundance indices and target fishery harvest rates for individual or specific combinations of fisheries (1999 PST annex). CWT analyses are also used in other forums (e.g., domestic management and compliance with the Endangered Species Act (ESA)).

The Pacific Salmon Commission's (PSC) technical committees and management agencies have designated certain coded-wire tagged hatchery groups to be CWT indicator stocks for naturally produced stocks. For this association to be valid, the exploitation rates on a natural stock and its hatchery indicator must be the same. Mark-selective fisheries would, however, attempt to concentrate fishing pressure on hatchery stocks. Exploitation rates on hatchery and natural fish would no longer be expected to be the same, requiring a fundamental change to the indicator stock program.

To maintain the viability of the CWT program for coho salmon under mark-selective fisheries, the Ad-Hoc Selective Fishery Evaluation Committee (ASFEC) devised a double index tagging (DIT) system (ASFEC report to the Pacific Salmon Commission, 1995). A DIT pair consists of two groups of coded-wire tagged fish from the same brood stock and year that are reared and released under identical conditions. Adipose fins are removed from one group of fish (***marked***), but not the other (***unmarked***). The unmarked component of the DIT pair is assumed to be exploited in the same manner as the wild fish that the indicator stock is intended to represent. However, under mark-selective fisheries, unmarked fish are not retained but will undergo some mortality due to hook and release, so methods are necessary for estimating those unobservable mortalities of the unmarked fish.

The ASFEC report describes methods for estimating total mark-selective fishery impacts for coho salmon by linking these DIT groups. However, these methods are of limited applicability to chinook salmon because of confounding that arises from over-winter (or natural) mortality and the unobservable mark-selective fishing mortality. Furthermore, these methods are inadequate to estimate fishery specific exploitation rates for unmarked coho or chinook salmon when multiple mark-selective fisheries impact a brood in the presence of substocks (portions of the population that have a distinct migration or distribution patterns).

The Analytical Work Group of the SFEC (SFEC-AWG) investigated the performance of various methods for estimating age and fishery specific exploitation rates on unmarked chinook salmon exposed to mark-selective fisheries. One of the earlier methods was termed the Movement

Model (Appendix Two). When data without error were simulated and tested, the movement model proved to be capable of calculating the correct values of unmarked mortalities. In addition it was capable of calculating correctly other parameters such as harvest, movement and distribution rates. However, this model produced unreliable results when normal levels of error (e.g., due to catch sampling) were introduced into simulated data. The committee concluded that substantial investment in staff time would be required to pursue further development of the movement model and prospects for successful application to real world data were highly uncertain.

Consequently, the SFEC-AWG turned its attention to trying to find more robust ways to generate unbiased estimates of age-fishery specific exploitation rates for chinook salmon in the presence of mark-selective fisheries. Four methods were examined to estimate unmarked mortalities in mark-selective fisheries. Two of these methods, the equal marine survival (EMS) and equal exploitation rate (EER), were first discussed in the ASFEC 1995 report. It was inferred that these methods were primarily applicable for coho salmon and for estimates of total mark-selective fishery mortalities. Although these methods were not designed to estimate fishery specific impacts, the methods are included in this report to show how that they can be adapted to chinook salmon in terminal areas and to serve as a basis for comparison for the two fishery specific methods developed in this report. The first fishery specific method, the terminal method (TERM), can be applied to mark-selective fisheries in a terminal area provided that certain conditions are satisfied. The second fishery specific method, the paired ratio (PR) method, can be used in preterminal and terminal fisheries, if suitable fishery pairs can be found. Depending on the situation, these methods may be used in combination to estimate mortalities of unmarked fish in mark-selective fisheries.

Total Methods (EMS and EER)

The total methods estimate the sum of unmarked mortalities from all mark-selective fisheries combined and will provide fishery specific estimates if there is only one mark-selective fishery. Both methods estimate mortalities of the unmarked DIT group by subtraction. The number of unmarked fish accounted for (in either escapement or in non-selective fisheries) is subtracted from an initial abundance, therefore, all unaccounted for fish are attributed to mark-selective fishing mortality. In both methods, the initial abundance of unmarked fish is estimated by multiplying the ratio of unmarked to marked fish to an initial abundance of marked fish. The two methods differ in their assumptions and how the ratio of unmarked to marked fish is estimated. The EMS method relies upon the assumption that fish from the DIT pair survive at the same rate until subjected to the first mark-selective fishery. Under this assumption, the EMS method uses the ratio of unmarked to marked fish at release. The EER method relies upon a non-selective fishery to estimate the ratio of unmarked to marked fish from the DIT pair. For this method, geographical and temporal characteristics of the non-selective fishery must be considered to justify that the estimated ratio is appropriate for the method. For chinook salmon, either of the total methods are applicable in terminal areas. In some limited cases, the EER, may be applicable in the presence of preterminal mark-selective fisheries. However, in that case, an alternative method is needed to estimate the unmarked mortalities in any preterminal mark-selective fisheries.

Individual Fishery Methods (TERM and PR)

Two methods (TERM and PR) were developed which are capable of providing fishery specific mortalities of multiple mark-selective fisheries but only under certain conditions. Both methods require external estimates or assumed values for the selective fishery mortality rate (*sfm)* on released unmarked fish. Any bias (i.e., error) in the estimate of unmarked mortalities in mark-selective fisheries will be directly proportional to bias in *sfm*. For example, a positive 10% bias in *sfm* will result in a 10% overestimate of unmarked mortalities. Both methods are impacted if there are multiple encounters (where released fish encounter the gear again). If multiple encounters occur, the TERM method will yield underestimates (negatively biased) of the unmarked mortalities and the PR method will be biased but the direction of the bias will depend on the situation.

Under the TERM method, mortalities of unmarked fish in mark-selective fisheries are estimated by multiplying the number of encounters by an assumed *sfm*. The number of encounters of unmarked fish in the mark-selective fishery is estimated from either exploitation rates[1] or harvest rates[2] on the marked DIT component and a post-fishery estimate of the abundance of the unmarked DIT component. The TERM method requires the unmarked to marked ratio of fish vulnerable to the fishery to be constant throughout the fishery. When this ratio is constant, then mortalities of serial individual mark-selective fisheries can be estimated. However, in practice it will be difficult to identify a situation where the unmarked to marked ratio would be expected to be constant for serial mark-selective fisheries.

In the PR method, a non-selective fishery is paired with each mark-selective fishery. The unmarked to marked ratio for a DIT pair in the non-selective fishery is assumed to be the same as in the mark-selective fishery. If the pair is inappropriate, then the ratio will be biased. Potential bias can be minimized or eliminated by selecting the non-selective fishery as one that occurs immediately prior to or concurrent with the mark-selective fishery in time and area. Of the four methods described, the PR method is the only one capable of providing fishery specific estimates of unmarked mortalities in mark-selective fisheries regardless of their location (terminal or preterminal).

Precision and Accuracy of Unmarked Mortality Estimates

Uncertainty of unmarked mortality estimates is defined in terms of *precision* and *accuracy*. *Precision* is the variability of the estimate arising from sampling processes and is determined by the number of fish tagged, the sampling rates in the fisheries, the size of the fishery (number of mortalities), and the estimation method used. The precision of the estimates is evaluated in terms of the sampling variance of the estimates. *Accuracy* is defined as the capacity of the methods to produce estimates that center about the true value. Accuracy is compromised and bias is introduced when assumptions underlying the estimation methods are violated. The objective of the SFEC-AWG was to develop estimation methods that can produce unbiased estimates of mortalities of unmarked fish from a DIT pair in mark-selective fisheries with an

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[1] Exploitation rate is the proportion of fish harvested relative to some abundance at large.

[2] Harvest rate is the proportion of fish harvested relative to the number of fish vulnerable to the fishery.

acceptable level of precision (the degree of precision required is dependent on management requirements and is not addressed in this report).

Factors such as the method used, the size of the fisheries, marine survival rates, unaccounted for mark-induced mortality, sampling rates, and bias in the assumed value of *sfm* impact the precision and accuracy of the different methods. The four estimation methods rely on different sets of assumptions. In general, estimation methods that rely on more assumptions produce more precise estimates, but are more prone to potential biases. While the precision of unmarked mortality estimates can be estimated, bias will be difficult to monitor or evaluate from sample data.

The SFEC-AWG examined the performance of the four estimation methods when certain key assumptions were violated. This assessment did not represent a complete study of all factors that could potentially bias estimates of mortalities of unmarked fish in mark-selective fisheries. However, the results from the factors identified are summarized below.

Assumption Violations	**Methods Impacted by Assumption Violations (effect on estimate of unmarked mortalities in mark-selective fisheries)**
There is mark-induced mortality	EMS (underestimated)
There is unsampled escapement	TERM (underestimated), EMS & EER (overestimated)
sfm is not known with certainty	PR, TERM (directly proportional to bias in *sfm*)
The unmarked:marked ratio of the DIT group is not accurately estimated.	EER, PR (both biased in the same direction as the estimated ratio)
The unmarked:marked ratio of the DIT group is not constant throughout the mark-selective fishery	TERM, PR (direction of bias is situational)
There are multiple encounters of unmarked fish in a mark-selective fishery	TERM (underestimated) PR (direction of bias is situational)

To evaluate the performance of the methods developed by the SFEC-AWG using real data, a series of workshops will be convened in the next few months. Agency staff will be taught the methods and undertake an evaluation of DIT data for coho salmon collected through the end of 2000. Results of these investigations will be discussed by the individuals performing the data analysis and the SFEC-AWG.

General Conclusions

1. *Each mark-selective fishery proposal must be evaluated individually.* The SFEC-AWG has not been able to develop methods that can provide unbiased age-fishery specific estimates of unmarked mortalities for every fishery scenario. The ability of the methods to provide precise, unbiased estimates is situational, depending on several factors, including the species involved, the location, number, and magnitude of the mark-selective fishery(ies), stock-specific migration patterns, the number of CWTs released and the number of tagged fish surviving to enter the fishery, as well as the adequacy of catch and escapement sampling programs. The ability to measure

the impact of a mark-selective fishery will depend on the specific circumstances surrounding each fishery and the particular fishery management objectives.

Proposals for mark-selective fisheries should provide the information required to assess the potential implications of a proposed mark-selective fishery on all impacted fish stocks. The information must be provided in a timely manner to permit full evaluation. Proposals should include information on marking plans as well as potential mark-selective fisheries that may be implemented when marked fish become available for harvest (see sidebar for suggested elements of a proposal for a mark-selective fishery). The Regional Coordination Workgroup of the SFEC will evaluate the proposal to determine if proposed marking and catch sampling plans are adequately designed while the SFEC-AWG will examine the methods proposed to estimate impacts of the proposed mark-selective fishery on unmarked fish.

Suggested Elements of Proposal for Mark-Selective Fisheries (adapted from Appendix C ASFEC 1995).

- Problem statement (what is the management problem to be addressed by the proposal?)
- Management objectives (what are the specific management objectives that the proposal is intended to achieve).
- Proposed mark-selective fishery (location, timing, duration, magnitude).
- Identify the stocks expected to be impacted. For each of these stocks, provide:
    - Total number of fish to be DIT
    - Proportion of total production to be marked
    - Description of catch or sampling programs throughout the migratory range
    - Description of escapement sampling
    - Methods to assess impacts of mark-selective fishery (ies).
- Implementation activities
    - Public education
    - Enforcement
    - Monitoring and evaluation
    - Time schedules
- Costs
    - Marking
    - Sampling
    - Analysis
    - Planning tools

- Benefits
- Alternative to mark-selective fisheries considered.

2. *Implementation of mark-selective fisheries will require significant modifications to the CWT program.* Double Index Tagging (DIT) will be necessary with matched pairs of marked and unmarked fish. This will require at least twice the number of CWT releases as is currently used in single indicator tag groups to maintain precision levels. To detect CWTs in both unmarked and marked fish, effective electronic tag detection (ETD) will be required wherever a DIT group is encountered.

3. *Regardless of the method used to estimate mortalities of unmarked DIT groups in mark-selective fisheries, there will be a general loss of information.* The loss of information is reflected by increased uncertainty in the estimates of unmarked mortalities. This uncertainty is a function of both precision and bias. Direct samples of unmarked mortalities in mark-selective fisheries will not be available. Assumptions about the relationship between the marked and unmarked DIT pair will be required to estimate these incidental mortalities. Estimates of unmarked mortalities will be biased when these additional assumptions are not met. Since many of the assumptions will be difficult to test, the uncertainty surrounding unmarked mortalities will be increased when mark-selective fisheries are implemented.

It is possible to compensate to some degree for a decrease in precision by increasing tagging levels or sampling rates, such methods will not compensate for bias introduced due to assumption violations. It may not be possible to determine the direction or magnitude of biases.

One motivation for implementing mark-selective fisheries is to reduce fishery mortality of wild stocks while harvesting marked fish. If either the EER or the PR are used to estimate mortalities of unmarked fish in mark-selective fisheries, the uncertainty surrounding those estimates depends upon the ability to obtain a reliable estimate of λ in a non-selective fishery. Therefore when using either EER or PR, any stock impacted must be able to sustain harvest from the associated non-selective fishery. Because the precision of λ increases as the number of CWT's increases, the higher the exploitation rate in the non-selective fishery the better the estimate of unmarked mortalities will be.

4. *The importance of uncertainty due to mark-selective fisheries depends on the proportion of total fishing mortality accounted for by these fisheries.* If, for instance, concern is focused on brood exploitation rates, and if the mark-selective fishery represents a small proportion of total mortalities, the impact of imprecision in an individual estimate of unmarked mortalities in a mark-selective fishery may be minimal. On the other hand, if the management concern is focused on the exploitation rate of an individual mark-selective fishery, then the impact of the increased uncertainty may be significant. The significance in this case will depend on how close the predicted exploitation rates are to the management objective.

5. *If management needs are directed at constraining fishery impacts to an acceptable level, increased uncertainty in estimating the fishery impacts will have to be acknowledged.* A buffer between a maximum limit on the allowable exploitation rate and the target exploitation rate can serve to set confidence that the actual exploitation rate was below that maximum limit. As uncertainty in estimated exploitation rate increases, the buffer must be enlarged to maintain the same level of confidence. For instance, the 1999 PST Agreement obligates the Parties to reduce impacts of ISBM fisheries on chinook by specified amounts compared to a 1979-1982 base period and contains provisions to adjust future fisheries to compensate for overages. With increased uncertainty, there would be a greater chance that the estimated value of an ISBM index would exceed the level permitted and trigger an adjustment in future fisheries. To provide the same chance of obtaining a post-season estimate of an ISBM index that complies with the obligations under the 1999 PST Agreement, reductions in target exploitation rates for ISBM fisheries would be required to compensate for increased uncertainty in estimation methods.

1 Introduction

In 1985, the United States and Canada entered into specific commitments to maintain the viability of the CWT system when they signed the Pacific Salmon Treaty:

> *"The Parties agree to maintain a coded-wire tagging and recapture program designed to provide statistically reliable data for stock assessments and fishery evaluations."* Memorandum of Understanding (Section B – Data Sharing).

This agreement reflected the vital importance of the coded-wire tag (CWT) system to preserving the capacity to complete stock status assessments and evaluate fisheries impacts on coho and chinook salmon.

For chinook and coho salmon, the fisheries management efforts of the Pacific Salmon Commission (PSC) have been focused on bilateral coordination to conserve and manage wild fish. The CWT is the only tool currently available to estimate and monitor fishery impacts coastwide on individual stocks of these species, particularly the naturally spawning fish. Two major factors makes this possible: (1) a coastwide agreement and sampling program has been established (since the mid-1970s) to recover fish with CWTs in fisheries, and (2) marked CWT fish (adipose fin clipped) and unmarked fish have both been retained in fisheries. Most marked CWT fish are of hatchery origin, but the retention of marked and unmarked fish allows agencies to infer exploitation rates on unmarked (hatchery or wild stocks) from estimates based on the marked CWT fish. The CWT program provided a feasible conceptual framework for assessing fishery impacts on hatchery and wild stocks by the development of tagged "indicator" stocks.

For many years, the adipose fin clip has been used almost exclusively to indicate that a fish was implanted with a CWT, facilitating the recovery of CWTs. In recent years, various agencies have begun mass marking hatchery coho and chinook salmon with an adipose fin clip so that hatchery fish targeted for harvest can be visually distinguished from naturally produced fish. This has been done in anticipation of implementing ***mark-selective fisheries***, which would retain fish without adipose fins while releasing fish with adipose fins. Since marked and unmarked fish would be subjected to different fishing pressures, recoveries of CWT releases without adipose fin clips could no longer be used to monitor fishery impacts on wild (unmarked) fish.

In the early 1990's, the PSC established an Ad-Hoc Selective Fishery Evaluation Committee (ASFEC) to investigate the implications of implementing mass marking and mark-selective fisheries on the viability of the CWT program. That report recommended changes to the CWT program for coho salmon but did not address the complicated situation for chinook salmon (multiple age-classes). This report extends this earlier work to chinook salmon and methods to maintain the viability of the CWT program.

1.1 Viability of the CWT Program and Fishery Management

In its 1995 report, the ASFEC (pp. 180-181) defined *viability* of the CWT program in terms of three specific characteristics:

- *it must provide the ability to use CWT data for assessment and management of wild stocks of coho and chinook salmon;*

- *it must be maintained such that the uncertainty in stock and fishery assessments and their applications does not unacceptably increase management risk; and*

- *it must provide the ability to estimate stock-specific exploitation rates by fishery and age.*

For purposes of examining the potential impacts of mark-selective fisheries on chinook salmon, the SFEC-AWG focused its efforts on the first and third characteristics. The capacity to utilize CWT data to estimate age and fishery specific exploitation rates for wild stocks is particularly critical for being able to implement the June 1999 Pacific Salmon Treaty agreement because: (a) estimation of total age-specific mortalities in adult-equivalent terms is required to evaluate management regimes; (b) Individual Stock Based Management (ISBM) regimes require the capacity to evaluate impacts on individual stocks for an individual or a combination of fisheries and on an age-specific basis; and (c) Aggregate Abundance Based Management (AABM) regimes are based on relationships between abundance indices and target fishery harvest rates for individual or specific combination of fisheries.

1.2 Double-Index Tagging and the Development of Analytical Methods

The ASFEC devised a double index tagging (DIT) method to try to maintain the viability of the CWT program for coho salmon (ASFEC, 1995). Under double index tagging, CWT releases consist of two groups known as a DIT pair. A DIT pair consists of two groups from the same brood stock and year that are reared and released under identical conditions. Ideally, the only differences between the groups in a DIT pair should be that each group receives a different CWT code and the adipose fins are removed from all the fish with one of the codes, but not the other. The DIT fish released with an adipose fin clip are referred to as ***marked,*** and the DIT fish released with adipose fins intact as ***unmarked***. The unmarked component of the DIT pair would then be encountered and released in mark-selective fisheries in the same manner as wild fish. Therefore, given the assumptions about the indicator group, the unmarked component can be assumed to be subject to the same fishing pressures as the wild fish. Given that the unmarked group of a DIT release will serve to represent associated wild stocks, a method is necessary for estimating incidental (but unobservable) mortalities of the unmarked component of the DIT pair in individual mark-selective fisheries.

Methods for estimating total (summed over all mark-selective fisheries) mortalities of unmarked fish have previously been developed for coho salmon (ASFEC, 1995). If there is more than one mark-selective fishery, these methods cannot maintain the viability of the CWT system defined above because they cannot apportion the mortalities among individual fisheries. Additionally, these methods depend on the fact that exploitation and maturation of coho predominantly occur over a single age class. This is because the primary assumption required by the methods, that natural mortality is negligible during the period of exploitation and maturation, is unlikely to be seriously violated. This same assumption dictates, however, that the methods developed for coho are not applicable to chinook. Chinook are exploited and mature over multiple age classes and consequently, negligible natural mortality cannot be reasonably assumed. Therefore, new methods that can apportion incidental mortality to individual fisheries and that are applicable to the multiple age class structure of chinook salmon are necessary. Individual fishery mortalities are required for annual fishery assessments and are developed through the application of cohort analysis.

1.2.1 Cohort Analysis

The SFEC focused its efforts on cohort analysis since this use of CWTs is central to many stock and fishery assessment procedures. Cohort analysis reconstructs the exploitation history of a group of fish from CWT recovery data by time period and age for fisheries and escapement, based on estimates of incidental mortality, and assumptions for natural mortality rates. A cohort is reconstructed beginning with the oldest age. The oldest members of a cohort (usually age 5 for chinook) can have one of three fates: die of natural causes, be killed in a fishery, or escape to spawn. All younger ages can have the same three possibilities plus the fourth of surviving to the next age class. Thus cohort analysis can account for all fish alive at the beginning of each age. The abundance of the initial (age 2) cohort for Chinook with a maximum age of 5 is computed as:

$$A_2 = \sum_{a=5}^{2} \frac{\sum_{f \in Fisheries} M_a^f + E_a}{\prod_{i=2}^{a} S_i} \tag{1-1}$$

See Appendix 1 for notation definitions. Landed mortality and escapement are estimated from sampling all fisheries, hatchery returns, and spawning grounds for CWTs. Natural mortality is assumed known (from the literature or past studies; CTC 88-2, CTC 01-2). Incidental mortality in a fishery is estimated through the use of landed mortalities for that fishery as well as estimated encounter rates and assumed release mortality rates. Given these data and assumptions, exploitation rate analysis produces estimates of age-and fishery specific exploitation rates, maturation rates, and pre-recruitment survival rates for CWT releases. The exploitation rate (ER_a^f) in fishery *f* for any age *a*, is then estimated by;

$$ER_a^f = \frac{M_a^f}{A_a} \tag{1-2}$$

When all fisheries are non-selective, marked and unmarked fish belonging to the same region and stock are subjected to the same fishing pressures. Therefore, estimates of exploitation rates from marked fish can be used to make inferences regarding the impacts on unmarked fish. Under mark-selective fisheries, however, marked and unmarked fish are subjected to differential harvest rates and therefore a separate cohort analysis must be completed on each group of fish.

In order to complete this task, unbiased estimates of mortalities for all fisheries and escapements are required. The problem to be addressed in this report is the unbiased estimation of unmarked mortalities from a DIT group in mark-selective fisheries.

1.3 Methods Applicable to Chinook Salmon

During the course of the SFEC- AWG's efforts, several methods for estimating unmarked mortalities in mark-selective fisheries were explored and ultimately abandoned. Efforts to combine DIT with forward cohort analysis methods were terminated when the method could not accurately estimate the encounters of unmarked fish in mark-selective fisheries, and thus could not generate the required age-fishery specific estimates of mortalities of unmarked fish. This problem was related to the difficulty of estimating fishery harvest rates (the proportion of a stock-age class available to a fishery that is killed by the fishery), a problem that has long eluded researchers.

Investigations then turned to the use of mathematical optimization techniques to estimate parameters associated with specific biological constructs of migration and harvest (Movement Model, Appendix 2). A simple simulated data set with three regions, five fisheries and simple migration behaviors of chinook stocks was employed to evaluate performance. Initial results were promising and intriguing. With perfect information, the Movement Model proved capable of accurately estimating a variety of important parameters, such as stock-age-fishery harvest rates, stock migration rates, and mark-selective fishery release mortality rates. Mathematically, all the parameters required to estimate age-fishery specific mortalities of unmarked fish in mark-selective fisheries were identifiable (i.e., could be solved for exactly when the data were without error). Initial optimism faded, however, when sampling (catches and escapements) error was introduced. Estimates from the Movement Model were highly sensitive to the normal range of error expected in CWT data. In addition, mathematical optimization methods sometimes failed to find solutions that generated reasonable estimates. The SFEC-AWG was unable to determine whether the difficulty stemmed from the optimization algorithms, the response surface generated by particular data combinations, or some structural flaw in the estimation model itself.

The SFEC-AWG recognized that the real world was much more complex than the simple model used to test the Movement Model, that separate models would have to be developed for individual stock groups due to differences in migration and fishing patterns, and that substantial uncertainty in estimates of mortalities of unmarked fish in mark-selective fisheries would likely result due to the sensitivity of mathematical optimization methods to variability in CWT data. Although no theoretical "red lights" were encountered indicating that the method was incapable of solving for the model parameters, substantial investment in further research over several years would likely be required and prospects for ultimate success appeared remote.

Consequently, despite the initial promise of the Movement Model, the SFEC-AWG decided to change course. In response to the need to address the near-term question of whether or not the viability of the CWT system for chinook could be preserved with mark-selective fisheries, the SFEC-AWG turned its attention to the development of simpler (less assumption-demanding) methods to estimate age-fishery specific mortalities of unmarked fish in mark-selective fisheries. Most of these methods require either assumptions about the unmarked to marked ratio in mark-selective fisheries, λ, or they estimate this ratio. The importance of this ratio is examined in the next section.

1.3.1 Migration and its relationship to lambda (λ)

The λ in a DIT group will change as mark-selective fisheries occur. Those changes will be both temporal and geographical depending on the distribution and migration patterns of the DIT groups. Some temporal/geographical changes in λ will bias mortality estimates of unmarked DIT fish using the methods outlined in this report so it is important to understand how that occurs. If fish are always randomly mixed, then λ can be expected to be constant over all migrational pathways. However if fish do not mix freely, then a prior mark-selective fishery affecting only some of the pathways would change λ for only those pathways. This would result in geographic variation in λ. Such a situation could occur, for example, if the 2-year olds of a Puget Sound stock distributed themselves geographically to coastal or Puget Sound waters. Then, say, a coastal mark-selective fishery is prosecuted and changes λ in coastal waters but not in Puget Sound. Examination of historical CWT data indicates that coho and chinook tag groups can be widely distributed, and may be recovered in several fisheries over a wide area within a time period. Therefore, the impact of mark-selective fisheries is likely to result in geographical and temporal variation in λ.

A simple example is depicted in Table 1. The example includes a DIT group, with marked and unmarked releases of equal size (λ=1) initially distributed over two regions, outside and inside, with a higher percentage in the outside area. In both regions, the initial λ is equal to that at release. There are two time periods (or ages) and mark-selective and non-selective fisheries in each period. Harvest rates are applied to the fish available in the region to calculate encounters. In non-selective fisheries, we presume that all encountered fish are retained, but in mark-selective fisheries we presume that all marked encountered fish are retained while all encountered unmarked fish are released. A 10% selective fishery mortality rate (*sfm*) is applied to the estimated encounters of unmarked fish to calculate unmarked mortalities. The mark-selective fishery is located in the outside region during the first period and in the inside region during the second period. After the first period 50% of the outside survivors migrate inside and after the second period all survivors escape.

Table 1 shows the initial numbers of fish, fishery mortalities and remaining population for each period. During the first period shown in the top half, λ is equal to one. The mark-selective fishery removes 2,400 marked fish and 240 unmarked fish so λ in the outside region changes from 1.00 to 2.35. In the inside region, λ remains at 1.00, as the inside fishery was non-selective. However, once migration occurs from the outside region to the inside region, the mixing of fish with different λ's results in an inside area λ of 1.72.

Table 1. An example of the change in unmarked to marked ratio due to mark-selective fisheries when stocks are distributed geographically as sub-stocks. Entries in bold can be estimated directly from tag recoveries without further analysis.

	Harvest Rate	**Marked Fish**			**Exploitation Rates**	**Unmarked Fish**			**Exploitation Rates**	**Unmarked to marked ratio**		
		Inside	**Outside**	**Total**		**Inside**	**Outside**	**Total**		**Inside**	**Outside**	**Total**
Period 1												
Initial Abundance		1,000	4,000	**5,000**		1,000	4,000	***5,000***		1.00	1.00	1.00
Percent distribution		20%	80%			20%	80%					
Fisheries												
Non selective	30%	300		**300**	**6.0%**	300		**300**	*6.0%*			
Mark-selective	60%		2,400	**2,400**	**48.0%**		240	240	4.8%			
Remaining		700	1,600	**2,300**		700	3,760	4,460		1.00	2.35	1.94
Period 2												
After Migration		1,500	800	**2,300**		2,580	1,880	4,460		1.72	2.35	1.94
Percent distribution		65%	35%			58%	42%					
Fisheries												
Mark-selective	60%	900		**900**	**39.1%**	155		155	3.5%			
Non selective	30%		240	**240**	**10.4%**		564	**564**	*12.6%*			
Escapement		600	560	**1,160**		2,425	1,316	**3,741**		4.04	2.35	3.23

sfm= selective fishery mortality rate, set at 10% for this example.
Bold entries are tag mortalities or exploitation rates that can be estimated directly from tagged recoveries
Italicized entries can be estimated using the unmarked to marked ratio and marked fish estimates.

The unmarked mortalities in the mark-selective fisheries could be estimated using:

$$U^{SF} = \lambda^{Rel} \cdot M^{SF} \cdot sfm \qquad \textbf{(1-3)}$$

if the λ did not change over time and/or geographic region. However, once the first mark-selective fishery has been prosecuted, the λ changes, and changes to a different degree in each region. This variation in λ between regions and time periods affects the ability to estimate unmarked mortalities in mark-selective fisheries. The remainder of this report discusses methods that could be used to estimate mortalities of unmarked fish in mark-selective fisheries in specific situations.

1.4 Some notes.

When applicable, the methods presented in this report will provide estimates of hook and release mortalities of unmarked DIT fish in mark-selective fisheries. When these generated mortalities are treated as CWT recoveries and are combined with recoveries in non-selective fisheries and escapements, a dataset suitable for completing a cohort analysis on unmarked fish would be available. This completed dataset can then be analyzed by existing methods using CWT recoveries such as PSC CTC chinook exploitation rate analysis and coho cohort analysis. These analyses will include, where appropriate, estimation of drop off mortality, shaker mortality, mark-retention error, and unmarked recognition error which are not discussed in this report.

The SFEC-AWG has made the assumption in this report that electronic tag detection (ETD) will be implemented in all fisheries and escapement areas (hatchery and natural) where DIT groups are present.

2 Total Methods of Estimating Unmarked Mortalities

Two analytical methods for estimating the total number of DIT unmarked mortalities (summed across all mark-selective fisheries) were developed by the ASFEC for their 1995 report. While both of these methods were originally developed to estimate impacts on coho salmon in mark-selective fisheries, they could be applied to chinook salmon in terminal areas (i.e., areas with only mature returning salmon). One should note that these "Total Methods" are not capable of estimating *fishery specific* impacts with multiple mark-selective fisheries, as is required for the viability of the CWT program. Discussion of these methods is included in this report to show they can be adapted for chinook salmon in terminal areas and to provide a context and comparison with new fishery specific methods described in Section 3.

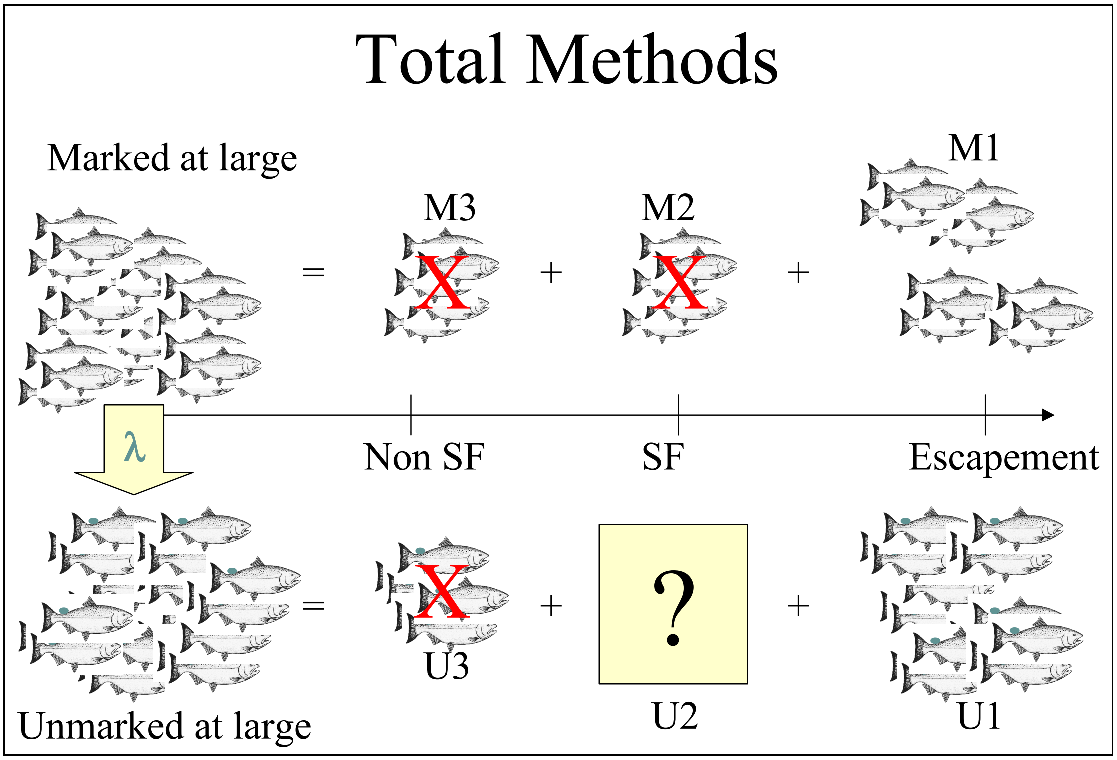

Figure 1. Total methods work by subtracting recoveries in escapement and non-selective fisheries (U1 and U3) from an initial abundance estimate of unmarked fish (labeled "Unmarked at large"). This initial abundance estimate of unmarked fish is obtained by first reconstructing the marked cohort (adding M1, M2, and M3 together to get an estimate of the number of marked fish at large), and then multiplying this estimate of the marked cohort size by an estimate of the ratio of unmarked to marked fish at the time of this initial abundance.

The total methods estimate unmarked mortalities in mark-selective fisheries by subtracting fish that can be accounted for (e.g., non-selective fishery recoveries in landed catch samples or escapement recoveries) from an initial abundance estimate (Figure 1). If a portion of this initial abundance consists of immature fish that are not harvested, the absence of these fish in the harvest or escapement will incorrectly be attributed to mark-selective fishing incidental mortality. Therefore, for the total methods to produce unbiased estimates, one should focus on the mature fish. Because coho salmon largely return in one age class, all fisheries can be considered as terminal and the number at large (left side of Figure 1) can be calculated as the ocean standing stock. On the other hand, chinook salmon return over multiple ages so that the ocean standing stock is comprised of both mature and immature fish. Therefore, for chinook salmon, the total methods are only applicable to the terminal areas. This difference necessitates a separate discussion of method application to the two species.

2.1 Equal Marine Survival (EMS) Method

The Equal Marine Survival (EMS) method (ASFEC 1995, p. 122) relies on an assumption that the marine survival rates of unmarked and marked DIT groups are the same so that the ratio of unmarked to marked fish recruited to the first fisheries is the same as λ^{Rel}. The abundance of unmarked fish at large (left hand side of Figure 1) is then estimated by multiplying an estimate of the number of marked fish at large by λ^{Rel}. The EMS method assumes:

1. there are no differential sources of mortality (between marked and unmarked fish) before the first mark-selective fishery (this assumption will be violated if, for example, there is any post-release mark induced mortality. Under this assumption, λ^{Rel} will serve as an unbiased estimate of the λ at large before the first mark-selective fishery);
2. λ^{Rel} is known with certainty;
3. fisheries and escapement of both unmarked and marked fish are adequately sampled for CWT's;
4. fisheries are the only sources of mortality from the point in time where overall abundance is calculated (left hand side of Figure 1):
    a. for coho salmon, the point in time where overall abundance is calculated is the ocean standing stock of three year olds, assuming that 2 year olds are not vulnerable to fisheries;
    b. for chinook salmon, the point in time where overall abundance is calculated is the beginning of the terminal run;
5. for chinook salmon, there are no preterminal mark-selective fisheries so that λ^{Rel} serves as an unbiased estimate of the λ in the terminal run.

2.1.1 EMS applied to coho salmon

The total number of unmarked mortalities for a DIT tag group pair is estimated using the following steps (see Appendix 1 for notation and Appendix 3 for variance formulas):

1. Estimate the initial cohort abundance of age-3 marked fish:

$$\hat{A}^{M} = \sum_{f \in SF} \hat{M}^{f} + \sum_{f \in NSF} \hat{M}^{f} + \hat{E}^{M} \tag{2-1}$$

2. Estimate the initial abundance of unmarked fish using the λ^{Rel}:

$$\hat{A}^{U} = \hat{\lambda}^{\mathrm{Re}l} \; \hat{A}^{M} \tag{2-2}$$

3. Estimate the total number of unmarked mortalities in mark-selective fisheries as the difference between the abundance estimate in step 2 and the estimated recoveries in non-selective fisheries and escapement:

$$\sum_{f \in SF} \hat{U}^{f} = \hat{A}^{U} - \sum_{f \in NSF} \hat{U}^{f} - \hat{E}^{U} \tag{2-3}$$

2.1.2 EMS applied to chinook salmon

For chinook salmon, the EMS method is applicable if mark-selective fisheries only occur in terminal areas. In this case, the λ in preterminal areas will remain constant for all ages (i.e., terminal mark-selective fisheries will not affect the λ in preterminal areas). Hence, λ^{Rel} can serve as an unbiased estimate of the λ entering terminal areas before any mark-selective fisheries occur.

The total number of unmarked mortalities is estimated using the following steps:

1. Estimate the terminal run size of age-a marked fish (a = 2,3,4,5):

$$\hat{A}_{a}^{TR,M} = \hat{E}_{a}^{M} + \sum_{f \in \text{terminal } SF} \hat{M}_{a}^{f} + \sum_{f \in \text{terminal } NSF} \hat{M}_{a}^{f} \tag{2-4}$$

2. Estimate the terminal run size of unmarked fish using λ^{Rel}:

$$\hat{A}_{a}^{TR,U} = \hat{\lambda}^{\mathrm{Re}l} \; \hat{A}_{a}^{TR,M} \tag{2-5}$$

3. Estimate the total number of unmarked mortalities in mark-selective fisheries from the estimate of the terminal run size in step 2 and estimates of recoveries in non-selective fisheries and escapement:

$$\sum_{f \in \text{terminal } SF} \hat{U}_{a}^{f} = \hat{A}_{a}^{TR,U} - \sum_{f \in \text{terminal } NSF} \hat{U}_{a}^{f} - \hat{E}_{a}^{U} \tag{2-6}$$

2.2 Equal Exploitation Rate (EER) Method

In contrast to the EMS method which uses an estimate of λ from release, the Equal Exploitation Rate (EER) method (ASFEC 1995, p.123) uses an estimate of λ from an appropriate non-selective fishery. For coho salmon, the λ in the non-selective fishery should reflect the λ of the ocean standing stock of three year olds before any mark-selective fisheries have occurred. For chinook salmon, the λ in the non-selective fishery should reflect the λ in the terminal run.

The advantage of the EER method over the EMS method is that it does not require the assumption that there are no differential sources of mortality between marked and unmarked fish. However, the EER method requires an appropriate non-selective fishery to estimate λ. Furthermore, the estimate of λ from this non-selective fishery is likely to be less precise than the estimate of λ at release. The EER method assumes:

1. there is a non-selective fishery that can provide an unbiased estimate of the λ at large;
   a. for coho salmon, the λ at large is the λ of the ocean standing stock of three year olds, assuming that 2 year olds are not vulnerable to fisheries;
   b. for chinook salmon, the λ at large is the λ in the terminal run;

2. fisheries and escapement of both unmarked and marked fish are adequately sampled for CWT's;

3. fisheries are the only sources of mortality from the point in time where overall abundance is calculated:
   a. for coho salmon, the point in time where overall abundance is calculated is the ocean standing stock of three year olds, assuming that 2 year olds are not vulnerable to fisheries;
   b. for chinook salmon, the point in time where overall abundance is calculated is the beginning of the terminal run;

The key requirement of the EER method is an appropriate non-selective fishery (assumption 1). This requirement is most easily met by a fishery or set of fisheries that occur prior (in time) to any mark-selective fishery. However, there are cases where the EER method might utilize a non-selective fishery that occurs after a mark-selective fishery. One such case would be if fish from all geographic regions randomly mix before the non-selective fishery occurs. In this case, the non-selective fishery will provide an unbiased estimate of the λ at large prior to the prosecution of any subsequent mark-selective fisheries. The EER method could then be used to estimate mortalities in all subsequent mark-selective fisheries (although it could not be used to measure impacts in mark-selective fisheries that occur prior to this non-selective fishery). For example, if fish gather and mix at the mouth of a river before entering to spawn, then a non-selective fishery near the river-mouth, late in the season, may provide the needed estimate of λ in the terminal run despite prior preterminal mark-selective fisheries. In this example, the EER method could be used to estimate impacts of all terminal mark-selective fisheries, but not the impact in any of the preterminal mark-selective fisheries.

On the other hand, if there is no mixing between mark-selective fisheries and a non-selective fishery, the non-selective fishery may be used even if it occurs after the mark-selective fishery. Before any mark-selective fisheries occur, λ is expected to be the same everywhere. This "overall" λ is expected to change only in places where the DIT group is affected by one or more mark-selective fisheries. A non-selective fishery that occurs after one or more mark-selective fisheries have begun may still provide a useful estimate of λ if it is far enough away from these mark-selective fisheries so that the λ in the non-selective fishery is not altered by these mark-selective fisheries. In this case, the non-selective fishery will provide an unbiased estimate of the λ at large before there are any mark-selective fisheries for that age class. However, the mark-selective fishery will have created geographical variation in λ making it impossible to obtain an unbiased estimate of the λ at large from a single non-selective fishery for subsequent age classes. Therefore, this application of the EER method (when there is no mixing between the mark-selective fisheries and the non-selective fishery) will typically be limited to coho salmon.

An example of a case where the assumption of no mixing may allow the application of the EER method would be a coho non-selective fishery immediately following a mark-selective fishery in a different region. One could argue that fish that survive the mark-selective fishery are unlikely to migrate between regions before the non-selective fishery begins. In this case, the non-selective fishery may still provide an unbiased estimate of the λ at large even though it occurs after a mark-selective fishery.

2.2.1 EER method for coho salmon

Let F_1 designate all of the non-selective fisheries used to estimate λ. The total number of unmarked mortalities is estimated using the following steps:

1. Estimate the initial cohort abundance of marked fish:

$$\hat{A}^M = \hat{E}^M + \sum_{f \in SF} \hat{M}^f + \sum_{f \in NSF} \hat{M}^f \qquad \textbf{(2-7)}$$

2. Estimate the exploitation rate for marked fish from all non-selective fisheries in F_1:

$$\hat{E}R^{M,NSF} = \frac{\sum_{f \in F_1} \hat{M}^f}{\hat{A}^M} \qquad \textbf{(2-8)}$$

3. Assuming the exploitation rates of marked and unmarked fish in the F_1 fisheries are equal, estimate the initial abundance of unmarked recruits[3]:

$$\hat{A}^U = \frac{\sum_{f \in F_1} \hat{U}^f}{\hat{E}R^{M,NSF}} = \frac{\sum_{f \in F_1} \hat{U}^f}{\sum_{f \in F_1} \hat{M}^f} \hat{A}^M = \hat{\lambda}\hat{A}^M \qquad \textbf{(2-9)}$$

---

[3] The EER method (ASFEC 1995) received its name because the exploitation rates must be equal for marked and unmarked fish in order for the method to work. However, it is more convenient to discuss the method's assumptions in terms of λ.

4. Estimate the total number of unmarked mortalities in mark-selective fisheries using the abundance estimate in step 3 and estimates of recoveries in non-selective fisheries and escapement:

$$\sum_{f \in SF} \hat{U}^f = \hat{A}^U - \sum_{f \in NSF} \hat{U}^f - \hat{E}^U \qquad \textbf{(2-10)}$$

2.2.2 EER method for chinook salmon

For chinook salmon, the EER method can only be used to estimate the impact of terminal mark-selective fisheries. Let F_1 designate all of the non-selective fisheries used to estimate the λ in the terminal run. The total number of unmarked mortalities is estimated using the following steps:

1. Estimate the terminal run size of age-*a* marked fish.

$$\hat{A}_a^{TR,M} = E_a^M + \sum_{f \in \text{terminal } SF} \hat{M}_a^f + \sum_{f \in \text{terminal } NSF} \hat{M}_a^f \qquad \textbf{(2-11)}$$

2. Estimate the λ in the terminal run from all non-selective (terminal and preterminal) fisheries occurring prior to the first mark-selective fishery.

$$\hat{\lambda} = \frac{\sum_{f \in \mathrm{F}_1} \hat{U}_a^f}{\sum_{f \in \mathrm{F}_1} \hat{M}_a^f} \qquad \textbf{(2-12)}$$

3. Estimate the terminal run size of the age-*a* unmarked fish.

$$\hat{A}_a^{TR,U} = \hat{\lambda}\hat{A}_a^{TR,M} \qquad \textbf{(2-13)}$$

4. Estimate the total number of unmarked mortalities in mark-selective fisheries as the difference between the terminal run size estimate in step 3 and estimates of recoveries in the terminal non-selective fisheries and escapement.

$$\sum_{f \in SF} \hat{U}_a^f = \hat{A}_a^{TR,U} - \sum_{f \in \text{terminal } NSF} \hat{U}_a^f - \hat{E}_a^U \qquad \textbf{(2-14)}$$

3 Methods for Estimating Fishery Specific Impacts

The methods developed by the ASFEC (1995) and discussed in Section 2 of this report are not capable of providing fishery specific exploitation rate estimates when there is more than one mark-selective fishery. Of the two methods developed here, the terminal method and the paired-ratio method, the terminal method is only applicable to terminal fisheries (i.e., fisheries that target only mature fish). The paired-ratio method may be used to estimate unmarked mortalities in both preterminal and terminal areas, provided that λ can be estimated for the mark-selective fishery. Both the TERM and PR methods require external estimates or assumed values for the *sfm* on released unmarked fish.

3.1 Terminal (TERM) Method

3.1.1 Assumptions

The terminal (TERM) method is designed to estimate unmarked mortalities in terminal areas and will be appropriate if the following assumptions hold:

1. the λ feeding into the terminal area is constant for the duration of the terminal area fishery and escapement;
2. one can estimate the number of unmarked encounters (this can be accomplished if one can estimate the abundance of marked and unmarked fish after the mark-selective fishery has occurred or one can estimate the number of marked and unmarked fish that were vulnerable to the fishery);
3. *sfm* is known with certainty; and
4. fish do not encounter gear on multiple occasions in the same fishery.

3.1.2 Algorithm

The unmarked mortality in a terminal mark-selective fishery is estimated using the following steps (notation is as outlined in Appendix 1; in this case, SF refers to the terminal mark-selective fishery).

1. Estimate the abundance of the marked fish in the terminal area from the sum of the marked escapement, terminal fishery mortalities, and post-terminal fishery mortalities:

$$\hat{A}_a^{TR,M} = \hat{E}_a^{M} + \hat{M}_a^{SF} + \hat{M}_a^{NSF} \qquad \textbf{(3-1)}$$

If there is a post fishing but pre-spawning mortality (*psm*) and that rate is known, then,

$$\hat{A}_a^{TR,M} = \frac{\hat{E}_a^M}{1 - psm} + \hat{M}_a^{SF} + \hat{M}_a^{NSF} \tag{3-2}$$

2. Estimate the proportion of the terminal run of the marked DIT group that is caught in the terminal mark-selective fishery, which is assumed to be the encounter rate of both the marked and unmarked DIT groups:

$$\text{Encounter rate} = \frac{\hat{M}_a^{SF}}{\hat{A}_a^{TR,M}} \tag{3-3}$$

3. Estimate the abundance of the unmarked fish in the terminal run, adding in post-fishery pre-spawning mortality if it is known:

$$\hat{A}_a^{TR,U} = \frac{\dfrac{\hat{E}_a^U}{(1 - psm)} + \hat{U}^{NSF}}{(1 - HR^{SF} sfm)} \tag{3-4}$$

4. Estimate the unmarked mortalities in the terminal mark-selective fishery by applying the estimated encounter rate from equation (3-3) and the selective fishery mortality rate (*sfm*, assumed known) to the estimated abundance of the unmarked fish given by equation (3-4):

$$\hat{U}_a^{SF} = \hat{A}_a^{TR,U} \hat{HR}_a^{SF} sfm \tag{3-5}$$

In rare cases, the terminal method might be applied to multiple terminal mark-selective fisheries in a "daisy-chain fashion", starting with the last mark-selective fishery prior to escapement. Following estimation of the number of unmarked mortalities in this fishery (using the steps above), one would calculate a new "escapement" equal to escapement plus the estimated number of unmarked mortalities in this last mark-selective fishery. One could then proceed to estimate the number of unmarked mortalities in the next prior mark-selective fishery using this newly calculated "escapement." In order for estimates to be unbiased using this approach, however, the λ for each mark-selective fishery must be constant for the duration of the fishery and all escapement must occur after the last mark-selective fishery. These conditions are unlikely to be met because prior mark-selective fisheries will cause temporal variation in λ. Therefore, the λ feeding into subsequent fisheries is not likely to be constant.

3.1.3 Violation of assumptions

3.1.3.1 The λ of the DIT group entering into the terminal area is not constant

The terminal method will only provide unbiased estimates of unmarked mortalities if the λ feeding into the terminal area is constant. Prior mark-selective fisheries can impact the assumption that the λ feeding into a mark-selective fishery is constant. If there are preterminal mark-selective fisheries, then the λ may vary through time depending on the proportion of the stock impacted by the various preterminal mark-selective fisheries and the migration timing of the different components of the stock. Similarly, if there are multiple terminal mark-selective fisheries, the λ of fish escaping the first terminal mark-selective fishery will not be constant unless fish move in discrete groups following the timing of the fisheries or if the harvest rate is constant over time – an unlikely assumption. An example to illustrate how the assumption violation incurs a bias in the estimate is given in Table 2. The λ of fish feeding into the fishery varies each week due to a prior mark-selective fishery.

Table 2. Example of terminal mark-selective fishery with escapement occurring before and after the terminal mark-selective fishery and with a varying λ feeding into the fishery each week.

Stat Week	# Vulnerable	Mark-selective Fishery	Escapement
30	Unmarked to Marked Ratio Constant	Harvest Rates Vary with Time $sfm = 0.1$	$E^M = 100$ $E^U = 100$
31	$A^M = 500$ → $A^U = 500$ → **λ = 1.0**	$M = 100$ $U = 10$ **HR = 0.2**	$E^M = 400$ $E^U = 490$
32	$A^M = 500$ → $A^U = 750$ → **λ = 1.5**	$M = 200$ $U = 30$ **HR = 0.4**	$E^M = 300$ $E^U = 720$
33	$A^M = 1000$ → $A^U = 2000$ → **λ = 2.0**	$M = 800$ $U = 160$ **HR = 0.8**	$E^M = 200$ $E^U = 1840$
34			$E^M = 400$ $E^U = 400$
		Observed $M = 1100$ Unobserved $U = 200$	Observed $E^M = 1400$ Observed $E^U = 3550$

The estimated encounter rate from the observed marked recoveries is:

$$H\hat{R} = \frac{1100}{1100 + 1400} = 0.44$$

and the estimated number of unmarked mortalities is:

$$\hat{U}^{SF} = \frac{3550}{1-(0.44)(0.1)}(0.44)(0.1) = 164\,.$$

The estimated number of unmarked mortalities ($\hat{U}^{SF}$ = 164) is not equal to the true number of mortalities (U^{SF} = 200 from Table 2). In this example, the λ that feeds into the mark-selective fisheries varies, perhaps due to another downriver mark-selective fishery. It is the change in λ from week to week that causes the bias in the estimate for mark-selective fishery mortalities on unmarked fish.

On the other hand, when the λ feeding into the terminal area is constant, and fish are moving fairly rapidly through the mark-selective fishery so that the λ in the mark-selective fishery is always equal to the λ feeding in, then estimates using the terminal method will be unbiased (Table 3).

Table 3. Example of terminal mark-selective fishery with no assumption violations of a constant λ.

Stat Week	Area A	# Vulnerable	Area B	Hatchery	Estimation
30					
31			*sfm* = 0.1		
32				**Escapement**	
33			**SF 2**		
34		M = 500	HR = 0.2		HRM,SF 2 =
35		U = 500	M = 100	M = 400	2075/ (2075+1175)
36		λ = 1.0	U = 10	U = 490	= 0.638
37		M = 750	HR = 0.5		
38	**NSF**	U = 750	M = 375	M = 375	Estimated U =
39		λ = 1.0	U = 38	U = 712	3043*.638*.1
40		M = 2000	HR = 0.8		(1-.638*0.1)
41	**NSF**	U = 2000	M = 1600	M = 400	= 208
42		λ = 1.0	U = 160	U = 1841	
43					
44			Total M = 2075		
			True U = 208	Total M = 1175	
				Total U = 3043	

The estimated encounter rate from the observed marked recoveries is:

$$H\hat{R} = \frac{2075}{2075+1175} = 0.64$$

and the estimated number of unmarked mortalities is:

$$\hat{U}^{SF} = \frac{3043}{1-(0.64)(0.1)}(0.64)(0.1) = 208.$$

The estimated number of unmarked mortalities ($\hat{U}^{SF}$ = 208) is now equal to the true number of mortalities (U^{SF} = 208 from Table 3).

3.1.3.2 Additional sources of mortality not accounted for

If post-fishery, pre-spawning mortality occurs, but is not accounted for in equations (3-1) – (3-5), then the estimates of unmarked mortalities will be biased. This problem remains even if the mortality rate is the same for both marked and unmarked fish (Table 4). In this case, the assumption that one can estimate the encounter rate is violated since it is not possible to accurately estimate the abundance of marked and unmarked fish after the mark-selective fishery.

Table 4. Terminal mark-selective fishery example with additional mortality occurring after the mark-selective fishery. Shading indicates the unobserved mortalities to be estimated.

	Marked	Unmarked
Abundance in terminal area before terminal fishery	5000	5000
Terminal fishery mortalities (*HR = 0.2, sfm = 0.1*)	1000	100
Abundance in terminal area after terminal fishery	4000	4900
Additional mortality following terminal fishery (mortality rate = 0.1 for both marked and unmarked fish)	400	490
Escapement	3600	4410

If the post-fishery, pre-spawning mortality is accounted for, then the terminal unmarked mortality can be accurately estimated using equations (3-1) – (3-5):

1. $A^{TR,M}$ = 3600 + 400 + 1000 = 5000
2. HR = 1000/5000 = 0.20
3. $A^{TR,U}$ = (4410 + 490)/(1-(0.2)(0.1)) = 5000
4. U^{SF} = (5000)(0.2)(0.1) = 100
= true unmarked mortalities in the terminal area fishery.

The TERM method requires that all mortality losses be accounted for, including pre-spawning mortality. If this mortality is not accounted for, then the estimate of U^{SF} will be biased. Again, using equations (3-1) – (3-5), but ignoring the additional source of mortality:

1. $A^{TR,M}$ = 3600 + 1000 = 4600
2. HR = 1000/4600 = 0.22
3. $A^{TR, U}$ = 4410/(1-(0.217391)(0.1)) = 4508
4. U^{SF} = (4508)(0.217391)(0.1) = 98
≠ true unmarked mortality in the terminal area fishery.

The bias occurs because the harvest rate estimated from the marked fish (and, therefore, the estimate of the encounter rate of the unmarked fish) in the mark-selective fishery does not account for pre-spawning mortality in the analysis.

3.1.3.3 Assumption of no bias in *sfm*.

The Salmon Technical Team (STT) summarized a wide range of hooking mortality studies for the Pacific Fisheries Management Council (STT 2000). The CTC reported on estimates of hook and release incidental fishery mortality rates along the coast (CTC 97-1). Hook and release mortality rates vary widely depending on where the fish was hooked (on the body), fishing methods, and types of fishing gear. The appropriate value for a specific fishery will depend on the area where the fishery is proposed, the gear that is going to be encountered, and the size limit of the encountered fish in question. Given the variability in observed *sfm* rates, the true *sfm* in the fishery is likely to differ from the value used to estimate unmarked mortalities. If the assumed *sfm* is not correct, then the third assumption is violated and there will be a bias incurred in the estimate of unmarked mortalities in the mark-selective fishery. The relative error in the estimate of unmarked mortalities can be derived from equations (3-4) and (3-5).

If *sfm* is biased, say by δ, then $\hat{U}^{SF}$ is also biased. Let $\tilde{U}^{SF}$ be the biased estimate and $\widetilde{sfm} = sfm + \delta$. Assuming there are no terminal non-selective fisheries and $psm = 0$, then $\tilde{U}^{SF}$ is estimated from equations (3-1) – (3-5) as:

$$\begin{aligned}\tilde{A}^{TR,U'} &= \frac{\hat{E}^{U}}{1-H\hat{R}_a^{NSF}(sfm+\delta)} \\ \tilde{U}^{SF'} &= \frac{\hat{E}^{U}}{1-H\hat{R}_a^{NSF}(sfm+\delta)}H\hat{R}_a^{SF}(sfm+\delta)\end{aligned} \qquad \textbf{(3-6)}$$

The relative bias in $\tilde{U}^{SF}$ is expressed as:

$$\begin{aligned}\text{Relative bias in } \tilde{U}^{SF} &= \frac{\left(\tilde{U}^{SF} - U^{SF}\right)}{U^{SF}} \\ &= \frac{\dfrac{\hat{E}^{U}}{1-H\hat{R}^{SF}(sfm+\delta)}H\hat{R}^{SF}(sfm+\delta)-U^{SF}}{U^{SF}}\end{aligned} \qquad \textbf{(3-7)}$$

and, assuming accurate estimates of E^{U} and HR^{SF},

$$= \frac{(\delta)}{sfm(1-H\hat{R}^{SF}(sfm+\delta))} \qquad \textbf{(3-8)}$$

As seen in equation (3-8), the relationship of relative bias in the unmarked mortalities to *sfm* and *HR* is not linear. Figure 2 shows the relationship of relative bias in the estimate of unmarked mortalities to the relative bias of *sfm* for three different harvest rates.

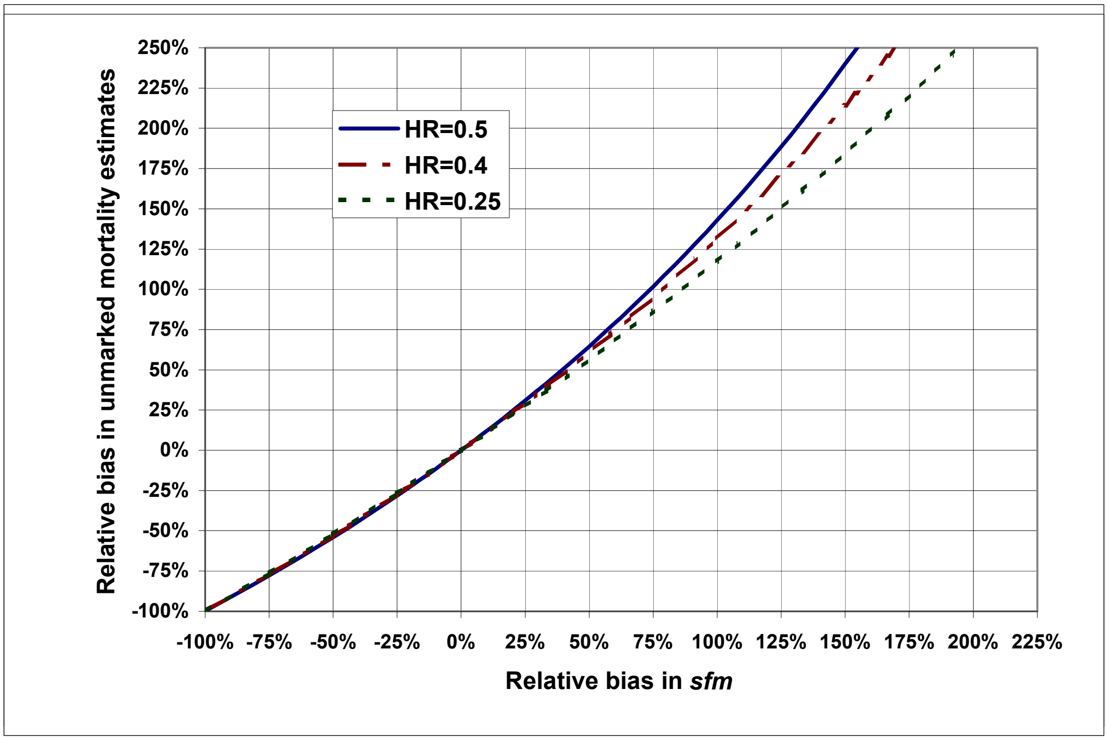

Figure 2. The relationship between the relative bias in the unmarked mortality estimate and both the relative bias in *sfm* and the harvest rate.

3.2 Paired Ratio (PR) Method

3.2.1 Assumptions

In the Paired Ratio (PR) method, estimates of U^{SF} are estimated by the unmarked to marked ratio in a paired non-selective fishery, λ_a^{NSF} [4]. The determination of an adequate pair of fisheries is discussed in Section 3.2.3. The paired ratio method uses the following assumptions:

1. λ_a^{NSF} is an unbiased estimate of the λ in the mark-selective fishery;
2. *sfm* is known with certainty; and,

---

[4] The ratio at release could also be used for the first selective fishery encountered by the DIT group if there is no delayed mark-induced mortality. Similarly, if 2 year olds are not harvested in selective fisheries, then the ratio of unmarked to marked 2 year old fish in escapement may provide an estimate of λ in the first selective fishery encountered by the DIT group.

3. unmarked fish are not encountered on multiple occasions in the mark-selective fishery.

3.2.2 Algorithm

The λ_a^{NSF} estimated for each DIT group in the non-selective fishery is assumed to be equal to the λ in the mark-selective fishery. Under that assumption, the marked recoveries in the mark-selective fishery are multiplied by λ_a^{NSF} to estimate the number of unmarked encounters in the mark-selective fishery:

$$\text{number of unmarked encounters} = \hat{\lambda}_a^{NSF} M_a^{SF} \qquad \textbf{(3-9)}$$

and the number of unmarked mortalities in the mark-selective fishery (U^{SF}) is then the number of encounters multiplied by the mark-selective fishing mortality rate:

$$\hat{U}_a^{SF} = \hat{\lambda}_a^{NSF} \hat{M}_a^{SF} sfm \qquad \textbf{(3-10)}$$

3.2.3 Pairing of fisheries

A critical criterion for the PR model is that the λ in the mark-selective fishery can be estimated outside of the mark-selective fishery in question. The criterion for paired fisheries is met in the following two cases:

1. If there is random mixing of fish within a local area and timeframe, then there is a "local single pool." Under this assumption, all fisheries in that region intercept the same pool of fish and, therefore, the observed λ in the non-selective fishery applies to the mark-selective fisheries (Figure 3).

2. Whenever the mark-selective fishery is downstream in the migration pathway of the non-selective fishery (Figure 4), the information on the λ from upstream fisheries carries to the downstream fisheries. Migration need not be completed before the mark-selective fishery is prosecuted. In fact, migration may occur during and even after the mark-selective fishery without impact in the PR model.

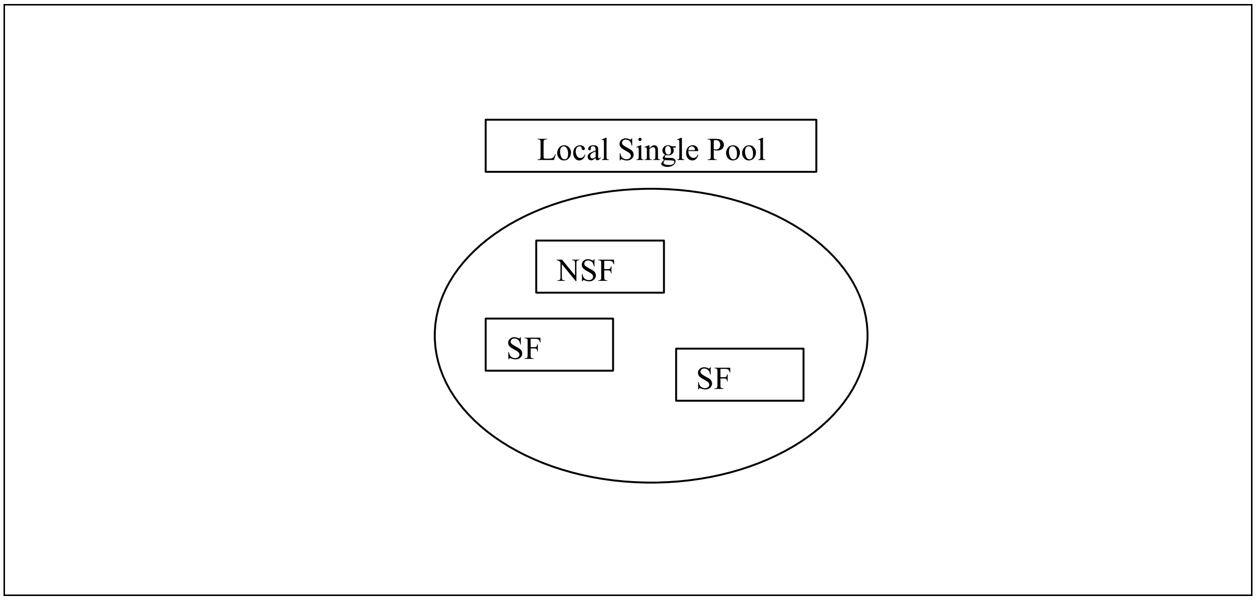

Figure 3. Schematic of any particular region with the single pool assumption.

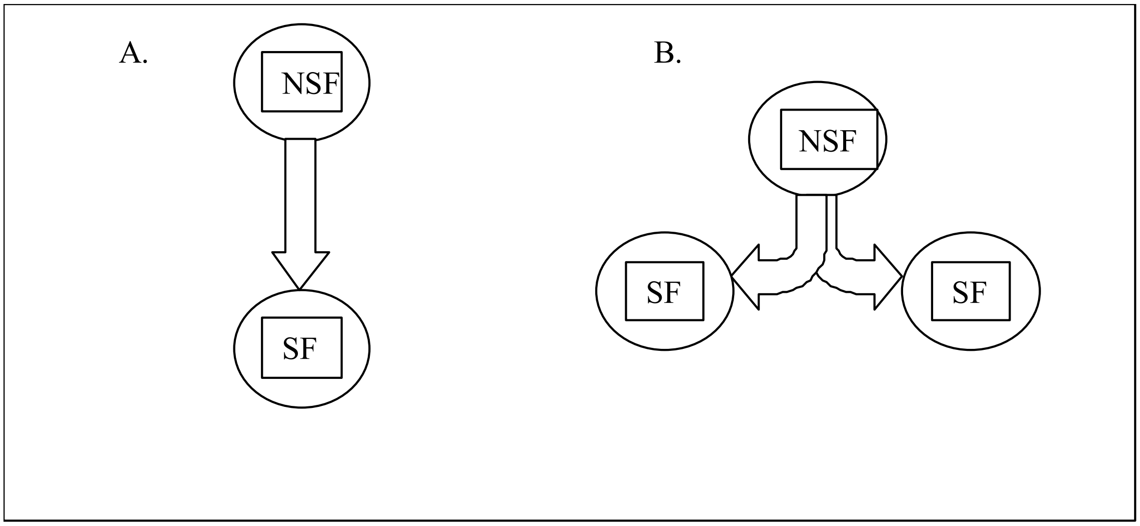

Figure 4. Schematic of migration pathways between non-selective and mark-selective fisheries where the paired ratio method will provide unbiased estimates of U^{SF} . (A) The non-selective fishery feeds directly into the mark-selective fishery. (B) The non-selective fishery feeds into more than one mark-selective fishery. The arrows indicate the direction of the migration stream.

3.2.4 Violation of assumptions

3.2.4.1 Selection of paired fisheries

If another migration stream enters from a source of fish with a different λ (Figure 5), then the λ in the mark-selective fishery cannot be assumed to be the same as that in the non-selective fishery.

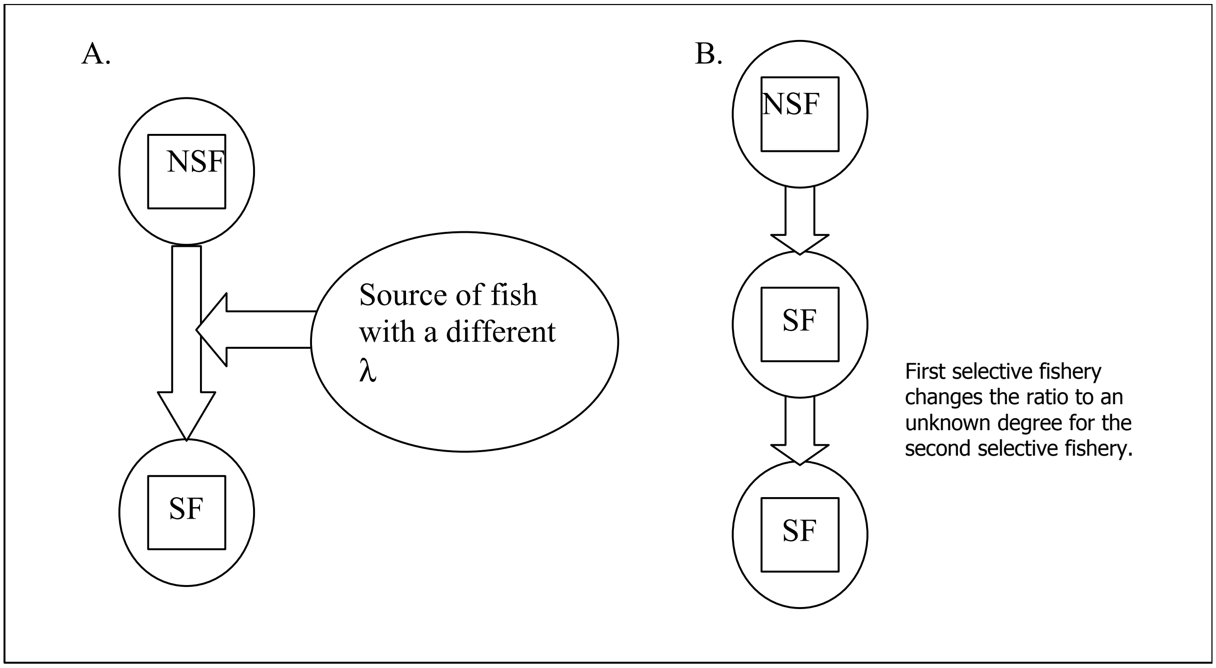

Figure 5. Schematic of migration pathways between non-selective and mark-selective fisheries where the paired ratio method will result in biased estimates of U^{SF}. The direction of the migration stream is indicated by the arrows. (A) The λ in the mark-selective fishery is altered from that in the non-selective fishery by a stream of fish entering the migration pathway before the mark-selective fishery. (B) The λ in the non-selective fishery is altered by the first mark-selective fishery, such that the second mark-selective fishery has a different λ than either of the first two fisheries. Thus, the non-selective fishery can only be paired with the first mark-selective fishery.

Each mark-selective fishery requires at least one appropriate non-selective fishery pair in order for this method to be used. For example, if mark-selective fisheries are executed in the ocean, the Strait of Juan de Fuca and inside Puget Sound, then a non-selective fishery pair that is appropriate for the ocean fishery may not provide correct information for the mark-selective fisheries in the inner two areas, as the λ will most likely change for each successive mark-selective fishery.

3.2.4.2 Bias in *sfm* and λ

As discussed in the section on the TERM method, knowing the true value of catch and release mortalities for a given mark-selective fishery is difficult (see Section 3.1.3.3). When *sfm* rates are known correctly and the non-selective fishery can serve as a "true pair" (i.e., the λ in the non-selective fishery provides an unbiased estimate of the λ of DIT groups in the mark-selective fishery), the PR estimator of unmarked mortalities in the mark-selective fishery is unbiased. However, the model is sensitive to errors in the given *sfm* rates and to errors resulting from selecting an inappropriate non-selective fishery pair for each mark-selective fishery. An error in selecting a pair is equivalent to using biased λ's.

If the λ in the paired non-selective fishery is not representative of the λ in the mark-selective fishery, then there will be a bias in U^{SF}. The bias in λ is linearly related to the bias in U^{SF} (Figure 6). That is, if λ is biased, say by δ, then U^{SF} is biased by B:

$$\begin{aligned} \tilde{U}^{SF} &= (\hat{\lambda}^{NSF} + \delta)\hat{M}^{SF}\, sfm \\ &= \hat{\lambda}^{NSF}\hat{M}^{SF}\, sfm + \delta\hat{M}^{SF}\, sfm \\ &= \hat{U}^{SF} + \delta\hat{M}^{SF}\, sfm \\ &= \hat{U}^{SF} + B \end{aligned} \qquad \textbf{(3-11)}$$

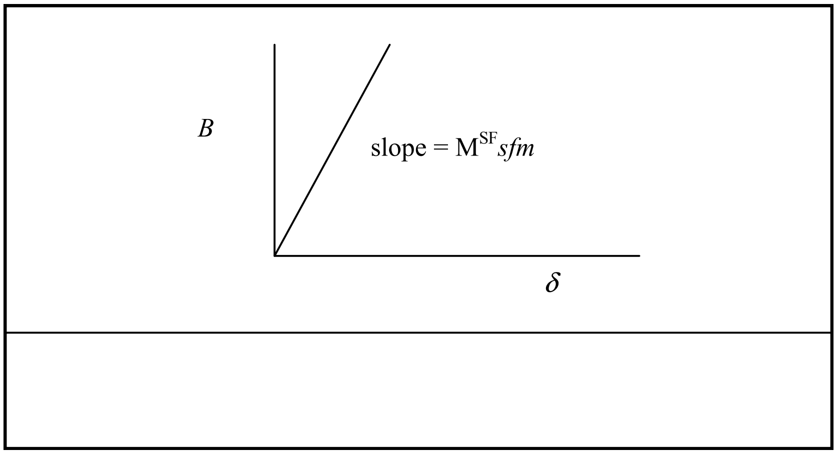

Figure 6. The linear relationship between an absolute bias δ on λ and the consequent absolute bias B on U^{SF}.

If δ is the absolute error in $\hat{\lambda}$, then the relative errors in $\hat{\lambda}$ and $\hat{U}^{SF}$ are identical. Let B' equal the relative bias in $\hat{U}^{SF}$.

$$B' = \frac{\left(\tilde{U}^{SF} - \hat{U}^{SF}\right)}{\hat{U}^{SF}} \qquad \textbf{(3-12)}$$

$$
\begin{aligned}
&= \frac{\left(\hat{\lambda}^{NSF} + \delta\right)\hat{M}^{NSF} sfm - \hat{\lambda}^{NSF}\hat{M}^{NSF} sfm}{\hat{\lambda}^{NSF}\hat{M}^{NSF} sfm} \\
&= \frac{\delta\,\hat{M}^{NSF}\, sfm}{\hat{\lambda}^{NSF}\,\hat{M}^{NSF}\, sfm} \\
&= \frac{\delta}{\hat{\lambda}^{NSF}}\,.
\end{aligned}
$$

Bias in *sfm* has the same effect on the estimates as bias in λ; this can be seen by switching *sfm* and λ in equations (3-11) and (3-12) and substituting *sfm* for λ in Figure 6.

When both the mark-selective fishery mortality (*sfm*) and the unmarked to marked ratio (λ) are biased, then the estimate of unmarked mortality in the mark-selective fishery will be biased by:

$$
\begin{aligned}
\tilde{U}^{SF} &= (\hat{\lambda}^{NSF} + \delta^{\lambda})\hat{M}^{SF}\,(sfm + \delta^{sfm}) \\
&= \hat{\lambda}^{NSF}\,\hat{M}^{SF}\, sfm + \hat{M}^{SF}\,(\delta^{\lambda}\, sfm + \delta^{sfm}\,\hat{\lambda}^{NSF} + \delta^{\lambda}\,\delta^{sfm}) \\
&= \hat{U}^{SF} + \hat{M}^{SF}\,(\delta^{\lambda}\, sfm + \delta^{sfm}\,\hat{\lambda}^{NSF} + \delta^{\lambda}\,\delta^{sfm})
\end{aligned}
\qquad \textbf{(3-13)}
$$

In this case, the relative bias is:

$$
B' = \frac{\delta^{\lambda} sfm + \delta^{sfm}\hat{\lambda}^{NSF} + \delta^{\lambda}\delta^{sfm}}{\hat{\lambda}^{NSF} sfm} \qquad \textbf{(3-14)}
$$

Note that the relationship in equation (3-14) will reduce to equation (3-12) if only one of the parameters is biased. When both parameters are biased, the relative bias in the unmarked mortality estimate is still linearly related to the bias in the parameters, but the slope is not 45^{o}, as it is when only one of the parameters is biased (Figure 7). The effect on the total relative bias will depend on the direction of the bias in the two parameters. If both parameters are biased in the same direction, then the total relative bias will increase (Figure 7). If they are biased in opposite directions, the effect is one of cancellation and the total relative bias is smaller. However, without any knowledge on the size and direction of the parameter bias, it is impossible to know how the estimate of unmarked mortality is affected.

Table 5 and Figure 7 show the effect of bias using equations (3-10) and (3-14). In the mark-selective fishery, the λ is 1.53. The selective fishery mortality rate is 0.2 and the harvest of marked salmon in the mark-selective fishery is 111 fish. Thus, 34 unmarked mortalities occur in the mark-selective fishery (Table 5). If there is bias in the *sfm* or in the λ estimated in the non-selective fishery then there will be bias in the estimate of unmarked mortalities in the mark-selective fishery (Table 5).

Figure 7 shows the relative bias in the λ along the x-axis and the relative bias of the unmarked mortality estimate on the y-axis. The relationship between the parameter bias and the unmarked mortality bias are shown as linear relationships. If both the unmarked to marked ratio ($\hat{\lambda}^{NSF}$) and the selective fishery mortality rate (*sfm*) are unbiased, then the estimated unmarked mortality ($\hat{U}^{SF}$) is unbiased (Figure 7).

Table 5. Relationship between relative bias in *sfm* and/or λ and bias in estimates of U^{SF}.

sfm	Bias in *Sfm*	$\hat{\lambda}^{NSF}$	Bias in $\hat{\lambda}^{NSF}$	M^{SF}	$\hat{U}^{SF}$	Bias in $\hat{U}^{SF}$
0.2	***0%***	***1.53***	***0%***	111	***34***	***0%***
0.1	-50%	1.53	0%	111	17	-50%
0.3	50%	1.53	0%	111	51	50%
0.2	0%	1.80	18%	111	40	18%
0.1	-50%	1.80	18%	111	20	-41%
0.3	50%	1.80	18%	111	60	77%
0.2	0%	1.26	-18%	111	28	-18%
0.1	-50%	1.26	-18%	111	14	-59%
0.3	50%	1.26	-18%	111	42	24%

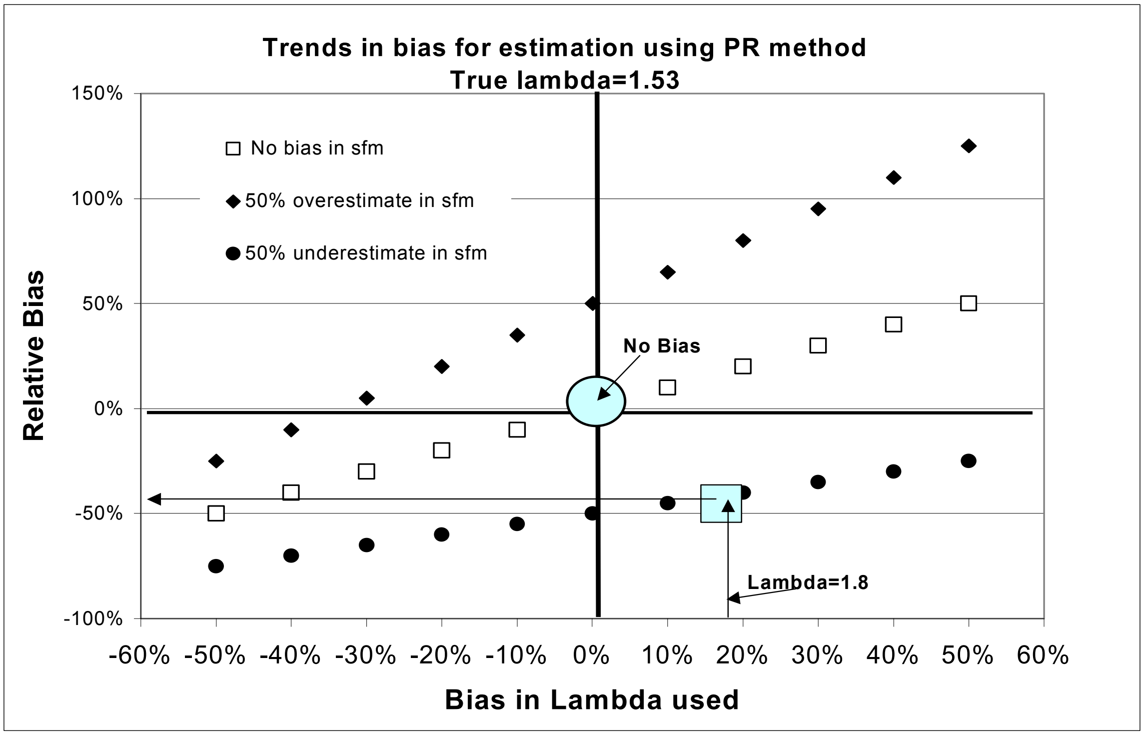

Figure 7. Relative bias in estimates of unmarked mortality (U^{SF}) when there is bias in the selective fishery mortality rate (*sfm*), the unmarked to marked ratio of salmon (λ) or both.

If the selective fishery mortality rate (*sfm*) is unbiased, the relative bias in $\hat{U}^{SF}$ is directly proportional to the bias in the λ (Figure 7). But if both parameters are biased, the resulting relative bias in the unmarked mortalities depends on the size and direction of both biases. For instance, if the λ is 1.8, there is an overestimate of 18%. With an overestimate of 18% for the estimate of λ and a 50% underestimate for the mortality rate, the estimate of unmarked mortality would be underestimated by 14 (34-20) fish or 41% (Figure 7).

3.2.4.3 Conclusions from the above examples

Given unbiased values for the parameters *sfm* and λ^{NSF}, the PR method can provide reasonable estimates of the unmarked DIT mortalities in mark-selective fisheries. The accuracy and precision of the parameters is critical when using the PR method for estimation of unmarked mortalities for a DIT group in a mark-selective fishery. The value of the selective fishery mortality rate (*sfm*) is usually not known and varies with gear, location, and fishing method. In addition, the uncertainty in the ratio of unmarked to marked mortalities in the non-selective fishery will affect the uncertainty of $\hat{U}^{SF}$. In any mark-selective fishery proposal, consideration should be given to the appropriate values for *sfm*. In addition, the choice of a non-selective fishery pair for a proposed mark-selective fishery is critical.

3.2.5 Choosing a non-selective fishery pair for a mark-selective fishery

The accuracy of the PR estimate of unmarked mortality in a mark-selective fishery depends upon a reliable estimate of λ for each affected DIT group. The λ is estimated from CWT recovery data of DIT marked and unmarked fish from a suitable non-selective fishery. Because of differences in exploitation patterns among DIT groups, the value of λ in a non-selective fishery may vary among DIT groups.

There are two basic requirements for choosing a suitable non-selective fishery:

1. The λ derived from the non-selective fishery must not change prior to the conduct of the mark-selective fishery. In order of preference, the non-selective fishery should: (1) operate concurrently in the same area as the mark-selective fishery so that both fisheries exploit a single pool of fish; (2) operate immediately before the conduct of the mark-selective fishery and not "upstream" of migration pathways where fish with different λ's can be expected to enter the area where the mark-selective fishery operates (Figure 5).

2. CWT recoveries from sampling the non-selective fishery must be sufficient to provide a reliable estimate of λ. The variation of U^{SF} in relationship to the number of CWTs observed in the non-selective fishery is discussed further in section 4.3.4.

The following steps outline a suggested process for identifying suitable non-selective fishery candidates for pairing with mark-selective fisheries when using the PR method.

1. A set of fisheries and sampling plans is proposed, with the mark-selective fishery and non-selective fisheries identified.

2. From a database of CWT recoveries, identify the CWT groups that had a large proportion of their recoveries in the proposed mark-selective fishery. Estimate the exploitation rates

for the CWT groups that can be associated with CWT indicator stocks that are likely to be affected.

3. From a database of CWT recoveries, identify the non-selective fisheries in the proposed set for which CWT recoveries of the groups identified in Step 2 were reported. Rely upon biologist best judgment to identity which non-selective fisheries are potential candidates for use as a pair (see first characteristic above) for the proposed mark-selective fishery. For this subset, identify the proposed non-selective fisheries that are likely to generate an estimate of λ of acceptable reliability given the anticipated conduct and sampling regime specified in the proposal.

Finally, issues related to bias and precision of the PR estimate should be examined concurrently. One should explore the potential consequences of selecting the wrong pair as well as using the wrong *sfm* rate in order to determine the full range of uncertainty that might be expected.

3.3 Multiple encounters

The ASFEC originally noted that mortalities on unmarked fish can be significantly underestimated due to multiple encounters when harvest rates are high and the recapture interval is small relative to the duration of the fishery (ASFEC 1995; p. 120). This bias occurs because the λ of the fish at risk will continually change during the prosecution of the mark-selective fishery. This change in λ will result in biased estimates of unmarked mortalities in mark-selective fisheries using either the PR or the TERM method.

The ASFEC suggested a possible correction when estimating the encounter rate of unmarked fish (ASFEC 1995; pp. 124-125) which may be useful in those cases where one can estimate the harvest rate of the fishery (ASFEC 1995, pp. 125-131).[5] In order to estimate harvest rates, one must be able to estimate the number of fish at risk to the fishery – a quantity that is rarely available and only for terminal area fisheries. The correction requires converting the harvest rate estimate to an instantaneous rate via:

$$h_a^{SF} = \frac{-\ln(1 - HR_a^{SF})}{t} \qquad \textbf{(3-15)}$$

where h_a^{SF} is the instantaneous rate and t is the duration of the fishery. This equation corrects equation (7-4) in ASFEC (1995) (the "*n*" in equation (7-4) of the ASFEC (1995) report should be replaced by "*t*"). The mortality rate for unmarked fish in the mark-selective fishery is then estimated by:

$$1 - e^{-h_a^{SF} * sfm * n} \qquad \textbf{(3-16)}$$

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[5] Harvest Rate = Catch / Fish at Risk = Catch / (Initial Cohort Size*Proportion of initial cohort at risk to the fishery); In contrast, an exploitation rate is calculated using only the initial cohort size: Exploitation Rate = Catch / Initial Cohort Size.

where n is the number of recapture intervals within the time period when a released fish would be available for recapture, e.g., if the duration of the fishery, t, is 30 days long and released fish are assumed to become available for recapture after one day (recapture interval), $n = 30$.

4 A comparison of methods

4.1 Choosing the appropriate method

Each of the methods described in Chapters 2 and 3 require different inputs and none can be used in all circumstances. Which method(s) are appropriate (if any) will depend on the management objectives, the species and the scenario. For example, if the objective to estimate fishery specific mortalities is required and there are two or more mark-selective fisheries, then neither of the "total" methods are applicable. The tables below (Table 6 for chinook and Table 8 for coho) summarize the conditions under which a particular method is applicable. The first column lists possible mark-selective fishery locations, and their relation to other mark-selective fisheries. For each method, the major assumptions and data requirements needed to implement the method are listed in Table 7 for chinook and Table 9 for coho.

Table 6. Conditions required to give unbiased estimates of fishery and age specific unmarked mortalities from mark-selective fisheries for chinook salmon under several scenarios. See next table for data requirements for each method.

Location of Mark-selective Fishery	Method			
	Total (EMS)[1]	Total (EER)[1]	Terminal	Paired Ratio
Preterminal	No. Cannot separate mark-selective fishery and natural mortalities.	No. Cannot separate mark-selective fishery and natural mortalities.	No. Terminal method is not applicable to preterminal fisheries.	Yes
Terminal Areas (given preterminal mark-selective fishery(ies))	No. λ has changed from release.	Yes, if there is a non-selective fishery from which one can estimate the λ in the terminal run.	Yes, if the λ feeding into the terminal area is constant for the duration of the terminal area fisheries and escapement.	Yes
Terminal Areas (without preterminal mark-selective fisheries)	Yes	Yes	Yes	Yes

[1] For the total methods individual fishery exploitation rates cannot be estimated unless there is only one significant mark-selective fishery.

Table 7. Summary of key assumptions and data requirements for each method of estimating unmarked DIT mortalities in mark-selective fisheries for chinook salmon.

<table>
<tr><th colspan="2">Total Method (EMS) in terminal area</th></tr>
<tr><td>Key Assumptions</td><td>• There are no differential sources of mortality between unmarked and marked fish in preterminal areas. Thus, the method cannot give unbiased estimates if there are preterminal mark-selective fisheries.
• All terminal fisheries and escapement of both unmarked and marked fish are adequately sampled.
• Effects of multiple mark-selective fisheries do not need to be separable by fishery.</td></tr>
<tr><td>Data Requirements</td><td>• Estimate of the terminal or mature run of marked fish ($A_a^{M,TR}$).
• Estimate of escapement of unmarked fish (E_a^U).
• The release ratio in a DIT group (λ^{Rel}).
• Estimated recoveries of tagged, unmarked fish in all terminal non-selective fisheries ($\sum_{f \in \text{terminal NSF}} U_a^f$).</td></tr>
<tr><th colspan="2">Total method (EER) in terminal area</th></tr>
<tr><td>Key Assumptions</td><td>• An appropriate non-selective fishery is available to estimate the λ in the terminal run of fish
• All terminal fisheries and escapement of both unmarked and marked fish are adequately sampled.
• Effects of multiple mark-selective fisheries do not need to be separable by fishery.</td></tr>
<tr><td>Data Requirements</td><td>• Estimate of mature run of marked fish ($A_a^{M,TR}$).
• Estimate of escapement of unmarked fish (E_a^U).
• Estimates of unmarked mortalities in all terminal non-selective fisheries ($\sum_{f \in \text{terminal NSF}} U_a^f$).
• Estimate of λ from an appropriate non-selective fishery.</td></tr>
</table>

Table 7. continued

Terminal Method	
Key Assumptions	• The λ feeding into the terminal area is constant for the duration of the terminal area fisheries and escapement. • One can accurately estimate the abundance of marked and unmarked fish after the mark-selective fishery has occurred or one can estimate the number of marked and unmarked fish that were vulnerable to the fishery. • Fish do not encounter gear on multiple occasions. • The selective fishery mortality rate of unmarked fish released in the mark-selective fishery (*sfm*) is known with certainty.
Data Requirements	• Age specific estimate of the abundance of unmarked and marked fish after the mark-selective fishery occurs or an estimate of the number of marked and unmarked fish that were vulnerable to the fishery. • Estimate of marked mortalities in the terminal mark-selective fishery • Age specific estimate of escapement of unmarked fish (E_a^U) • Selective fishery mortality rate of the unmarked fish release in the mark-selective fishery (*sfm*).
Paired Ratio Method	
Key Assumptions	• The λ in the mark-selective fishery can be estimated accurately by a paired non-selective fishery. • The selective fishery mortality rate of unmarked fish released in the mark-selective fishery (*sfm*) is known with certainty. • Fish do not encounter gear on multiple occasions.
Data Requirements	• Estimate of mortalities of marked fish in the mark-selective fishery (M_a^{SF}) • Estimate of mortalities of marked fish in the non-selective fishery that is paired with the mark-selective fishery (M_a^{NSF}) • Estimate of mortalities of unmarked fish in the non-selective fishery that is paired with the mark-selective fishery (U_a^{NSF}) • Selective fishery mortality rate of the unmarked fish released in the mark-selective fishery (*sfm*).

Table 8. Conditions required to give unbiased estimates of fishery and age specific unmarked mortalities from mark-selective fisheries for coho salmon under several scenarios. See next table for data requirements for each method.

	Method			
Fishery Scenario	Total (EMS)[1]	Total (EER)[1]	Terminal	Paired Ratio
Preterminal	Yes. Total mortalities across all mark-selective fisheries are estimated.	Yes. Total mortalities across all mark-selective fisheries are estimated.	No. Terminal method is not applicable in preterminal fisheries.	Yes
Terminal areas with preterminal mark-selective fisheries	Yes. Total mortalities across all mark-selective fisheries (terminal and preterminal) are estimated.	Yes. Total mortalities across all mark-selective fisheries (terminal and preterminal) are estimated.	Yes, if the λ feeding into the terminal area is constant for the duration of the terminal area fisheries and escapement.	Yes
Terminal without preterminal mark-selective fisheries	Yes. Total mortalities across all terminal fisheries are estimated.	Yes. Total mortalities across all terminal fisheries are estimated.	Yes	Yes

[1] For the total methods, individual fishery exploitation rates cannot be estimated unless there is only one significant mark-selective fishery so that the total effect can be attributed to that one fishery.

Table 9. Summary of key assumptions and data requirements for each method of estimating unmarked DIT mortalities in mark-selective fisheries for coho salmon.

Total Method (EMS)	
Key Assumptions	• There are no differential sources of mortality between unmarked and marked fish before the first mark-selective fishery. • All fisheries and escapement of both unmarked and marked fish are adequately sampled. • Effects of multiple mark-selective fisheries do not need to be separable by fishery.
Data Requirements	• Estimate of the ocean abundance of marked fish (A^M). • Estimate of escapement of unmarked fish (E_a^U). • The release ratio in a DIT group (λ^{Rel}). • Estimated recoveries of tagged, unmarked fish in all non-selective fisheries ($\sum_{f\in NSF} U_a^f$).
Total method (EER)	
Key Assumptions	• An appropriate non-selective fishery is available to estimate the λ at large before any mark-selective fisheries have occurred. • All fisheries and escapement of both unmarked and marked fish are adequately sampled. • Effects of multiple mark-selective fisheries do not need to be separable by fishery.
Data Requirements	• Estimate of ocean abundance of marked fish (A^M). • Estimate of escapement of unmarked fish (E_a^U). • Estimates of unmarked mortalities in all non-selective fisheries ($\sum_{f\in NSF} U_a^f$). • Estimate of λ from an appropriate non-selective fishery.

Table 9. continued.

Terminal Method	
Key Assumptions	• The λ feeding into the terminal area is constant for the duration of the terminal area fisheries and escapement. • One can accurately estimate the abundance of marked and unmarked fish after the mark-selective fishery has occurred or one can estimate the number of marked and unmarked fish that were vulnerable to the fishery. • Fish do not encounter gear on multiple occasions. • The selective fishery mortality rate of unmarked fish released in the mark-selective fishery (*sfm*) is known with certainty..
Data Requirements	• Age specific estimate of the abundance of unmarked and marked fish after the mark-selective fishery occurs or an estimate of the number of marked and unmarked fish that were vulnerable to the fishery. • Estimate of marked mortalities in the terminal mark-selective fishery • Age specific estimate of escapement of unmarked fish (E_a^U) • Selective fishery mortality rate of the unmarked fish release in the mark-selective fishery (*sfm*).
Paired Ratio Method	
Key Assumptions	• The λ in the mark-selective fishery can be estimated accurately by a paired non-selective fishery. • The selective fishery mortality rate of unmarked fish released in the mark-selective fishery (*sfm*) is known with certainty. • Fish do not encounter gear on multiple occasions.
Data Requirements	• Estimate of mortalities of marked fish in the mark-selective fishery (M_a^{SF}) • Estimate of mortalities of marked fish in the non-selective fishery that is paired with the mark-selective fishery (M_a^{NSF}) • Estimate of mortalities of unmarked fish in the non-selective fishery that is paired with the mark-selective fishery (U_a^{NSF}) • Selective fishery mortality rate of the unmarked fish released in the mark-selective fishery (*sfm*).

The tables are meant to be used as guides to determining which method, if any, would be appropriate for estimating the number of unmarked mortalities in mark-selective fisheries. The examples below were created to illustrate the use of these tables.

Example 1: One single stock preterminal mark-selective fishery on coho.
Say that a particular coho DIT group is expected to encounter only one preterminal mark-selective fishery and that the group is not expected to encounter any terminal mark-selective fisheries. There are expected to be multiple preterminal and terminal non-selective fisheries. Under this scenario, three of the four methods can potentially be used (EMS, EER, and PR) (Table 8), but each requires different assumptions and each has different data requirements (Table 9). Say that additionally, one or more of the non-selective fisheries will not be sampled.

In that case, a major assumption of both total methods is violated and it will not be possible to accurately estimate the abundance parameter (A^M), eliminating both methods.

The remaining method (PR) does not require an accurate estimate of abundance but does require three additional elements:

1. The first element is that one must be able to identify an appropriate non-selective fishery pair. The non-selective pair must satisfy two requirements: (a) the expected λ within the DIT group must be the same as that encountered by the mark-selective fishery, and (b) the size of the non-selective fishery must be large enough to ensure a reasonable recovery rate of CWTs to estimate the λ^{NSF}.

2. The second element is that one must be able to sample the proposed mark-selective fishery adequately to recover CWTs from marked fish.

3. An acceptable *sfm* (hook and release mortality) for the mark-selective fishery must be available.

If those three elements can be adequately provided, then the PR method will be applicable.

Example 2: Sequential mixed stock terminal area mark-selective fisheries on chinook.
Let there be a series of terminal mark-selective fisheries on several chinook stocks. Assume that none of the stocks encountered any preterminal mark-selective fisheries. Let there also be a single terminal non-selective fishery that occurs downriver and prior to the first mark-selective fishery. Let all of the terminal fisheries (selective and non-selective) and all escapements be adequately sampled. In this case, the EER and EMS methods could be used to provide an estimate of the total number of mortalities in mark-selective fisheries. However, none of the methods listed can provide unbiased *fishery specific* estimates of U^{SF}. The total methods cannot be used to separately estimate individual fishery mortalities. Furthermore, because there is not a non-selective pair for each mark-selective fishery, the PR method is only applicable for the first mark-selective fishery (the only one with a non-selective pair). Finally, the TERM method will only be applicable if the λ feeding into each successive fishery is constant. This assumption is not likely to be met because each mark-selective fishery will result in temporal variability in the λ feeding into each subsequent mark-selective fishery.

Example 3. One or more mark-selective fisheries on chinook salmon in preterminal areas.
Table 6 shows that only the PR method is a candidate method in this case. Neither of the total methods can be used for chinook salmon in preterminal areas because of the confounding of natural mortality and U^{SF} over multiple ages. The TERM method cannot be used for preterminal fisheries. The only remaining candidate is the PR method. From Table 8 we can see that the overriding requirement for the PR method is having available a well sampled non-selective fishery from which one can estimate the λ in the mark-selective fishery. If an appropriate non-selective fishery cannot be identified, the PR method cannot be used and it will not be possible to estimate the effect of the mark-selective fishery on the unmarked DIT group.

4.2 Uncertainty

Precision and accuracy together define the uncertainty in estimation. These are important when evaluating the performance of alternative methods for estimating the mortalities of unmarked fish in mark-selective fisheries. Specifically, precision is defined as the uncertainty introduced due to sampling the fisheries and is defined by the sampling variance of the estimate. Accuracy is defined as bias that is introduced due to violation of assumptions of the methods. The total level of uncertainty in an estimate is the sum of the uncertainty due to both sampling variance and bias. This uncertainty is often measured by the mean squared-error where:

$$\text{MSE} = \text{Variance} + \text{Bias}^2 \tag{4-1}$$

4.2.1 Uncertainty in current CWT-based estimation of mortalities.

Currently, landed mortalities are estimated for each fishery using the CWTs recovered in a direct sample of that fishery. Assuming, for the purpose of simplicity, that catch (or escapement) is known without error, then the mortalities and their variance are estimated by:

$$\begin{aligned} \hat{X} &= O / p^f \\ Var(\hat{X}) &\approx X(1 - p^f)/p^f \end{aligned} \tag{4-2}$$

where O is the number of tags observed in the sample, $\hat{X}$ is the estimated number (expanded for the sampling rate) of tagged mortalities, and p^f is the sampling rate (Bernard and Clark, 1996). The assumption necessary for this estimator is that total harvest, or escapement, is randomly sampled. Given this assumption, an unbiased estimate of the number of tagged mortalities can be calculated from recovered tags.

The precision of the estimate is described by the variance and the coefficient of variation (CV):

$$CV = \frac{\sqrt{Var(\hat{X})}}{\hat{X}} \tag{4-3}$$

which is equal to:

$$CV(\hat{X}) = \sqrt{\frac{(1 - p^f)}{\hat{X}p^f}} \tag{4-4}$$

The CV of the tagged mortality estimate is proportional to $\sqrt{\frac{1}{\hat{X}p^f}}$. So the precision of mortality estimates using current methods depends on the number of mortalities that occur in the fishery and the sample rate. This relationship is shown in Figure 8 below, where the CV decreases in an exponential fashion with increasing number of tagged fish in the total population sampled.

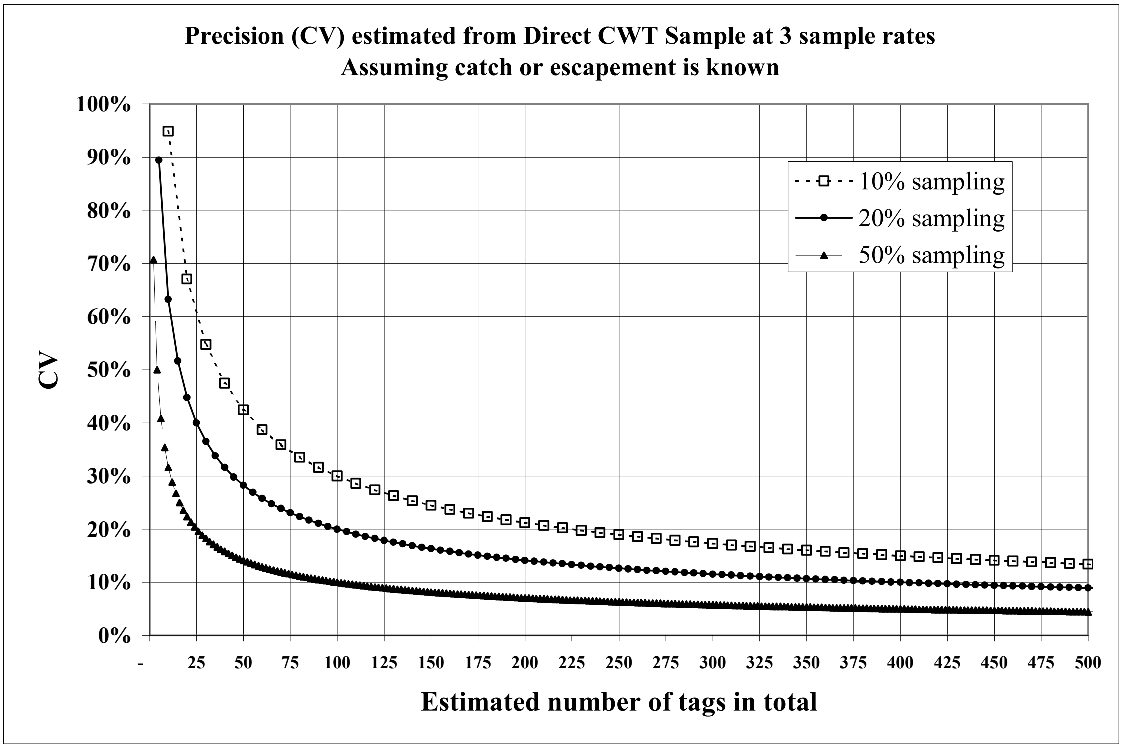

Figure 8. Precision (CV) of CWT-based estimates of tagged mortalities from a direct sample in a fishery or escapement at three sampling rates.

The number of tagged mortalities in a fishery will depend on the harvest rate and the number of tagged fish available to the fishery. The fish available will depend on the number of tagged fish released, the marine survival of the tagged fish, and the prior harvest of the tagged stock.

4.2.2 Uncertainty in estimation of unmarked SF mortalities

For mark-selective fisheries, unmarked mortalities cannot be estimated from CWTs recovered in a direct sample of the landed mortalities. Unmarked tagged fish that die as a result of release in the mark-selective fishery will not be available for sampling.

Estimates of unmarked tagged mortalities in mark-selective fisheries will require a DIT group and depend on recoveries of both the marked and the unmarked components of the DIT pair. Each of the methods discussed in this report have different sampling requirements and assumptions. However, the four methods have the following similarities:

1. For unmarked mortalities in mark-selective fisheries, it is no longer sufficient to sample in the mark-selective fishery itself. Samples are required from a second non-selective fishery for the PR method, or from the fishery and escapement for the TERM method. For estimates of total unmarked mortalities (EMS or EER), sampling from all fisheries and escapement is required.

2. These methods depend on the association between the marked and unmarked DIT groups. The estimates of unmarked mortality in the mark-selective fishery are not independent of the estimated marked recoveries.

3. Additional assumptions (beyond random sampling) which define the relationship between the marked and unmarked fish for each method, are required for the estimation of unmarked mortalities in mark-selective fisheries. With each additional assumption, another potential for bias in the estimate is introduced if the assumption is violated.

4.2.3 Goal of analysis.

An analysis was undertaken to compare the uncertainty of unmarked mortalities in mark-selective fisheries derived using the four methods described above in Chapters 2 and 3. Several simulations were performed to evaluate precision and bias. For each simulation unmarked mortalities in the mark-selective fishery (U^{SF}) were estimated using the PR, the TERM, the EMS and the EER methods. In addition, a reference estimate was generated by simulating a hypothetical direct sample (HDS) of the unmarked SF mortalities. The reference estimate was used to determine what the expected accuracy and precision would be if these mortalities could have been sampled.

The goals of this analysis are to:

1. determine how the precision and accuracy of the different methods compares to HDS estimates; and,

2. illustrate and discuss how various factors impact the level of accuracy and precision of the estimates obtained from the different methods.

The factors that are evaluated in this analysis include harvest rate, uncertainty in escapement, delayed mark-induced mortality, bias in *sfm*, marine survival, and sampling rate. These factors do not comprise a comprehensive list of factors that may influence the precision and accuracy of unmarked mortality estimates in mark-selective fisheries.

4.2.4 Simulations

The sensitivity of the four methods to process error and sampling error was evaluated using a simple simulation model and procedures similar to those employed by Zhou (in press). The model reflects a situation where fish are only harvested by terminal fisheries. In the terminal fishing area, paired DIT groups are first exploited by a non-selective fishery and then by a mark-selective fishery before survivors reach the spawning grounds. Both fisheries are assumed to be managed for a target exploitation rate. The terminal scenario was chosen because it provides a situation where the conditions required for all four methods can reasonably be expected to be met.

First, a baseline scenario was developed from which the factors were varied one at a time to assess their impact (Table 10). The simulations were conducted assuming a release of 200,000 marked fish and 200,000 unmarked fish as a DIT pair. The simulations used the following steps to generate estimates of CWT recoveries:

1. The marked component of the DIT group is subjected to a delayed mark-induced mortality source. The number of mortalities is determined using a binomial random variable with population size equal to the release size of marked fish.

2. The number of fish reaching the terminal area is determined by applying a marine survival rate to the marked and unmarked fish. The number of unmarked fish reaching the terminal area is determined using a binomial random variable with population size equal to the number of unmarked fish at release. The number of marked fish reaching the terminal area is determined using a binomial random variable with population size equal to number of marked fish remaining after the delayed mark-induced mortality source.

3. Mortalities in the non-selective fishery are determined using an assumed encounter rate for this fishery. The number of encounters of marked and unmarked fish are determined using binomial random variables with the population sizes determined in step (2). Encountered fish are assumed to have a 100% mortality rate.

4. Mortalities in the mark-selective fishery are determined using an assumed encounter rate for this fishery. The number of encounters of marked and unmarked fish are determined using binomial random variables with population sizes equal to the number of fish that survive the non-selective fishery. Encountered marked fish are assumed to have a 100% mortality rate. Encountered unmarked fish are subjected to a selective fishery mortality rate with the number of unmarked mortalities determined using a binomial random variable.

5. The landed catch in the two fisheries is sampled. Observed recoveries of marked fish in the non-selective and mark-selective fisheries are simulated using binomial random variables with population sizes equal to the number of marked tagged fish in the catch (as determined in steps (3) and (4) respectively). Observed recoveries of unmarked fish in the non-selective fishery are generated using a binomial random variable with the population size equal to the number of unmarked tagged fish in the non-selective fishery catch. Finally, hypothetical recoveries of unmarked fish in the mark-selective fishery are generated using a binomial random variable with the population size equal to the number of unmarked tagged mortalities in the mark-selective fishery. These recoveries, after expansion for sampling, constitute the HDS estimate of U^{SF}.

6. The fishery survivors escape to the hatchery of release and to the spawning grounds. All fish returning to the hatchery are sampled for tags. Hatchery strays are sampled for tags at a rate < 100%.

7. Estimates of unmarked mortalities are determined using the four methods. A value of *sfm* = 0.2 is assumed when using the PR and TERM methods.

Table 10. Scenarios simulated for comparison of performance of methods of estimating unmarked SF mortalities, both among methods and to hypothetical direct sample estimate.

Case	HR NSF	HR SF	Marine Survival	Mark-induced Mortality	Fishery Sampling Rate	Bias in *sfm*	Sampling of Escapement
Baseline	50%	50%	1%	0%	20%	no bias	No strays (escapement sampled at 100%)
Case II	10%	50%	1%	0%	20%	no bias	No strays (escapement sampled at 100%)
Case III	50%	50%	1%	20%	20%	no bias	No strays (escapement sampled at 100%)
Case IV	50%	50%	1%	0%	20%	no bias	50% of the fish stray to spawning grounds, but are not sampled.
Case V	50%	50%	1%	0%	20%	no bias	50% of the fish stray to spawning grounds. Spawning grounds sampled at 20%.
Case VI	50%	50%	1%	0%	20%	*sfm* under-estimated	All fish escape to hatchery (escapement sampled at 100%)
Case VII	50%	50%	1%	0%	20%	*sfm* over estimated	All fish escape to hatchery (escapement sampled at 100%)
Case VIII	50%	50%	1%	0%	10%	no bias	All fish escape to hatchery (escapement sampled at 100%)
Case IX	50%	50%	0.1%	0%	20%	no bias	All fish escape to hatchery (escapement sampled at 100%)

Data were generated in sets of 1,000 replicates. For each replicate, mortalities for the unmarked DIT component were estimated using each of the four methods and the HDS method.

The performance of the four methods is evaluated by the deviation from the true mortalities calculated by:

$$Deviation = \left[\frac{\hat{U}^{SF} - U^{SF}}{U^{SF}} \right] \quad \textbf{(4-5)}$$

When there is no bias, the distribution of the deviations will be centered at 0, and when there is bias, the distribution of the deviations will not be centered at 0. The spread of the distribution indicates the variability, or precision, of the estimates due to process and sampling error.

Both process error and sampling error were simulated in the data generated for each scenario. The process error encompasses the variability expected between the two DIT groups due to random variability in the marine survival, mark induced mortality, harvest rates, *sfm,* and stray rates. The sampling error is due to the sampling of the fisheries and escapement.

4.2.5 Results

For each case, the four methods presented in this report (i.e., PR, TERM, EMS, and EER) were used to estimate unmarked mortalities in the mark-selective fishery (U^{SF}). In addition, a reference estimate was created by simulating a hypothetical direct sample (HDS) of the unmarked mortalities in the mark-selective fishery. The purpose of the HDS estimate was to provide for a comparison to the accuracy and precision that would be expected if these mortalities could have been sampled.

Results of the analyses are graphically depicted in box plots. Each box plot represents deviations for estimates made for 1,000 replications for the case. The box incorporates the 25-75% quartiles of the data and the whiskers indicate the range to 1.5 times the inter-quartile range (between 25 and 75% quartiles) or the maximum data point whichever is smaller. Outliers are observations that lie outside this range and are indicated by lines outside the range of the whiskers.

Figure 9 below shows the results for the Baseline Case, comparing the relative deviations of estimated unmarked mortalities in the mark-selective fishery from true mortalities.

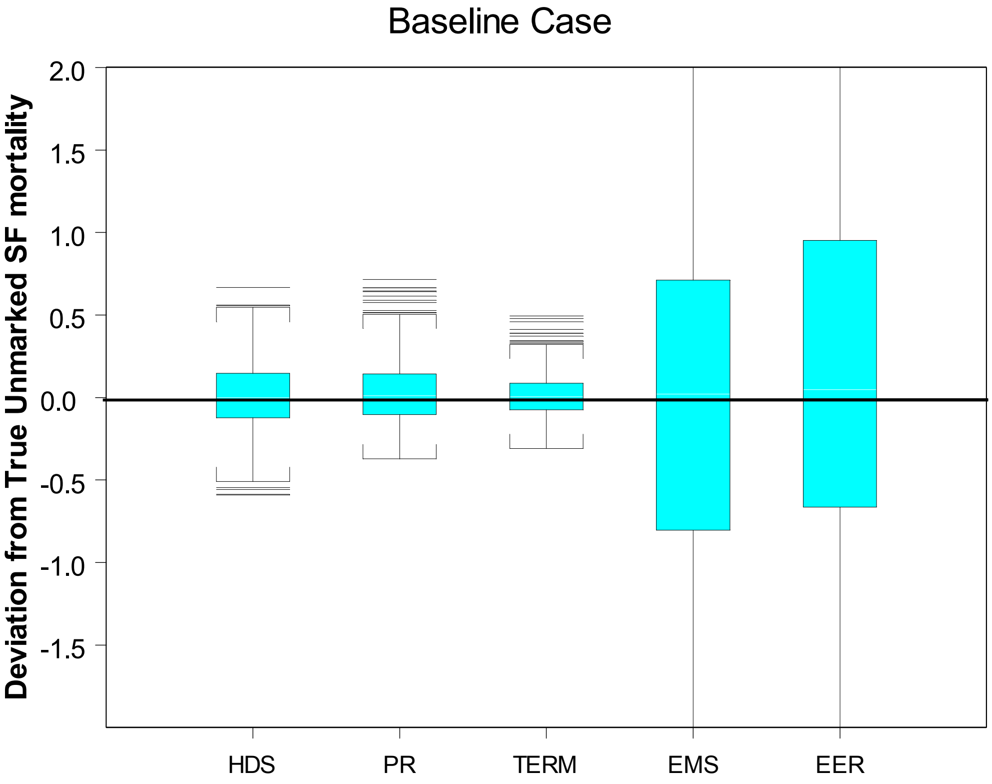

Figure 9. Box plots of relative deviations of estimated from true unmarked mortalities in SFs for Case I (the Baseline Case).

Under the Baseline Case, all of the methods provide unbiased estimates. Therefore, deviations of the center of the boxplots from 0 in the baseline case reflects the random error inherent in the process of running simulations. The precision of each method is described by the length of the inter-quartile box. The PR and the TERM methods provide estimates that are as precise, and even more precise, than the HDS method, but the EMS and EER methods result in significantly less precise estimates of U^{SF}.

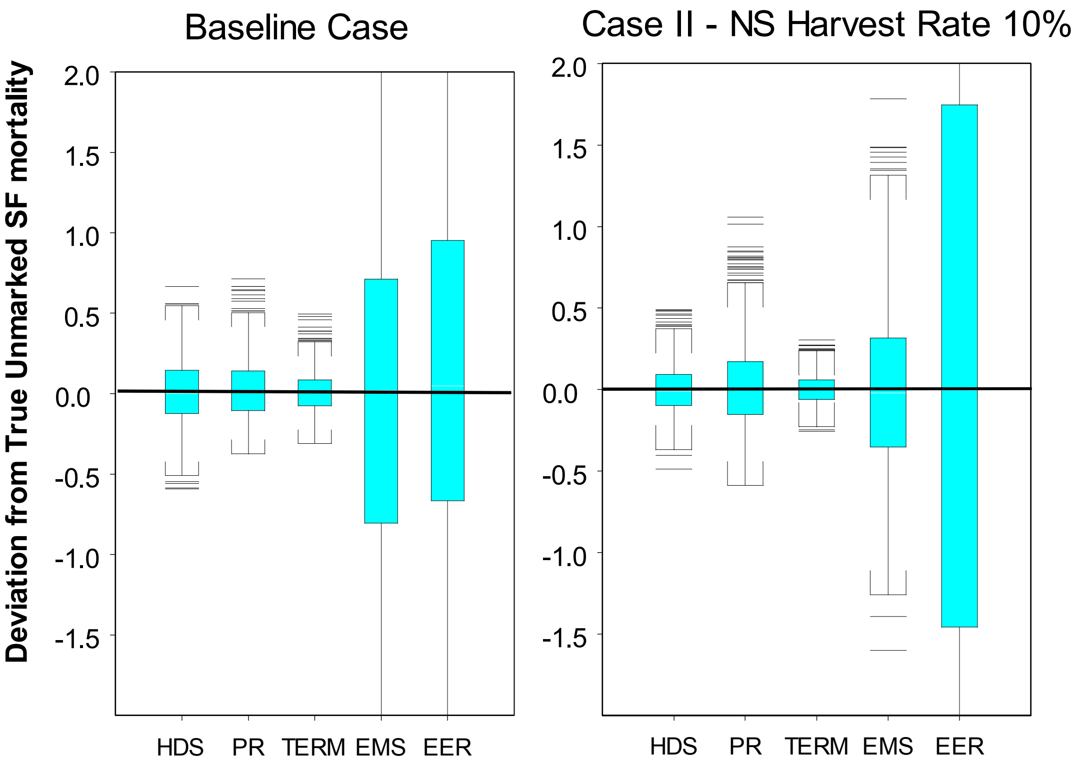

Figure 10. Comparison of box plots for deviations of estimates from Case II (Harvest rate in NS fishery reduced to 10%) to the Baseline Case.

Figure 10 compares Case II to the Baseline Case. In this case, the harvest rate in the first fishery (NSF) is reduced from 50 to 10%. All other parameters are set as in the Baseline Case. The estimators all provide unbiased estimates of the unmarked SF mortality, but precision has been impacted.

- The HDS estimate is more precise than the Baseline Case. Because the number of fish available to the mark-selective fishery increases with decreased harvest rate in the first fishery, a more precise estimate results from the larger number of tags recovered.
- The PR and the EER methods are less precise than the Baseline Case. This result is explained by the dependence of these two methods on estimates of mortalities in the non-selective fishery. With smaller harvest rates in the non-selective fishery, the numbers of tags caught in the fishery and recovered in the sample are also smaller. Less precise estimates of the unmarked to marked ratio (λ^{NSF}) for the PR and of the exploitation rate (ER) for the EER result.
- The TERM method provides more precise estimates. It depends solely on recoveries of marked fish in the mark-selective fishery and escapement of marked and unmarked fish. With a lower harvest rate in the NSF, there are more marked fish available to the SF and consequently more marked tags recovered in the mark-selective fishery and in escapement. This results in improved estimates of the marked U^{SF}.

- The precision of the EMS method is also improved, because of the larger number of fish available to the mark-selective fishery. With larger numbers of encounters and mortalities the number of fish impacted by the mark-selective fishery has increased. The precision of the EMS method improves as the number of mark-selective fishery mortalities increase.

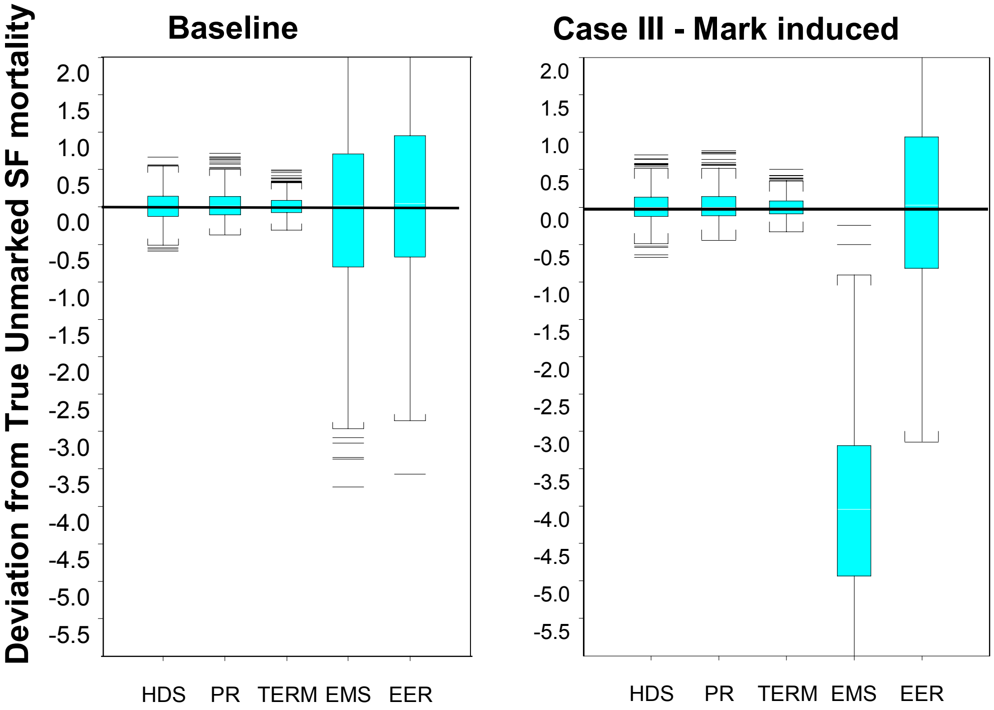

Figure 11. Comparison of box plots for deviations of estimates from Case III (mark induced mortality of 20%) to the Baseline Case.

Figure 11 compares Case III to the Baseline Case. For this Case, the marked group was subject to a 20% mark induced mortality after release. All other parameters are set as in the Baseline Case. The impact in this case is solely due to bias.

- The HDS, PR, TERM and EER estimates are unaffected as they do not require any assumptions about the λ at release for the DIT group.
- The EMS method is dependent on the assumption that λ^{Rel} can be used to estimate the unmarked DIT cohort size from estimated marked cohort size. The mark induced mortality has changed the λ, violating that assumption and resulting in an estimate that is significantly biased (median relative deviation is approximately -400%, Table 11).

Table 11. Median relative deviations for 1,000 replicates for each case.

Case	HDS	PR	TERM	EMS	EER
Baseline	0.0%	1.1%	0.3%	1.9%	4.8%
II	-1.1%	0.3%	-0.1%	-2.1%	-0.3%
III	0.0%	-0.3%	-0.6%	-404.0%	2.7%
IV	0.0%	0.2%	-30.5%	199.0%	197.8%
V	-0.9%	-1.2%	-0.8%	4.6%	-5.7%
VI	-2.2%	101.4%	112.1%	0.9%	4.5%
VII	0.6%	-34.0%	-37.4%	2.2%	3.1%
VIII	-1.1%	0.9%	0.3%	5.8%	6.1%
IX	0.0%	0.0%	-2.4%	-20.0%	-0.2%

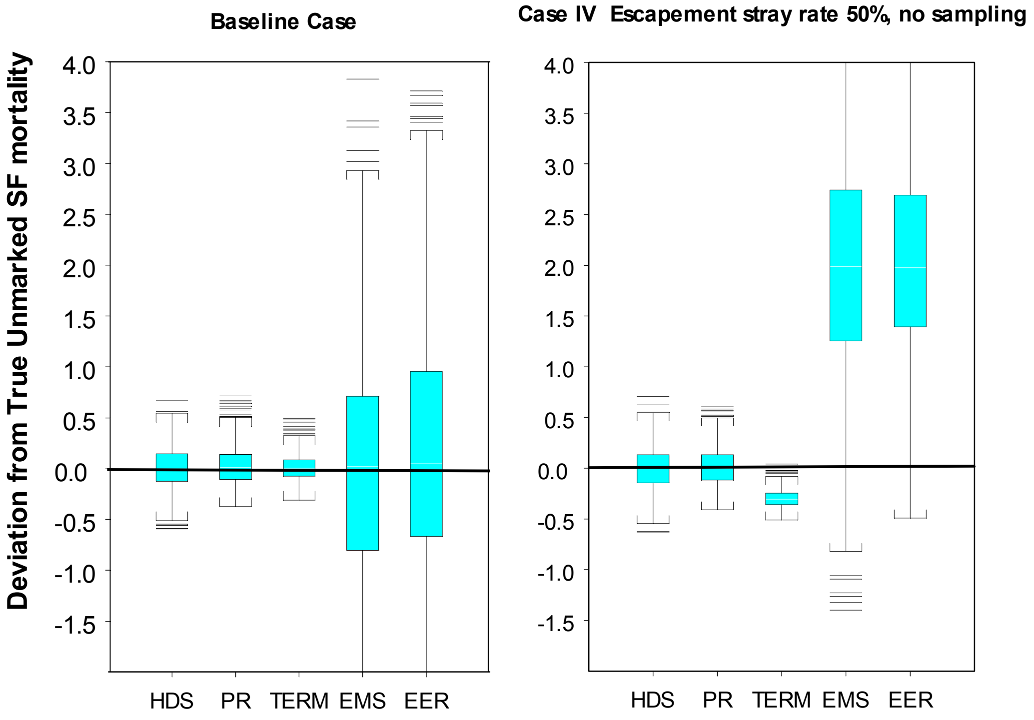

Figure 12. Comparison of box plots for deviations of estimates from Case IV (50% straying to spawning grounds with no sampling) to the Baseline Case.

Figure 12 compares Case IV to the Baseline Case. In this Case, 50% of the escapement strays to spawning grounds, but is not sampled. All other parameters are set as in the Baseline Case. The impact is due to bias resulting from the incomplete accounting of the escapement.

- The HDS and the PR are not affected by this loss of information as they are not dependent on escapement estimates.

- The TERM method relies on the sum of escapement and marked recoveries in the mark-selective fishery to estimate the harvest rate and escapement of unmarked fish. Therefore the estimate is biased in this case, with a median deviation of -30.5% (Table 11).
- The EMS and EER methods also include escapement in the estimation of the marked cohort and total observed mortalities plus escapement of unmarked fish and are therefore biased, with median deviations of 199.0 and 197.8% (Table 11).

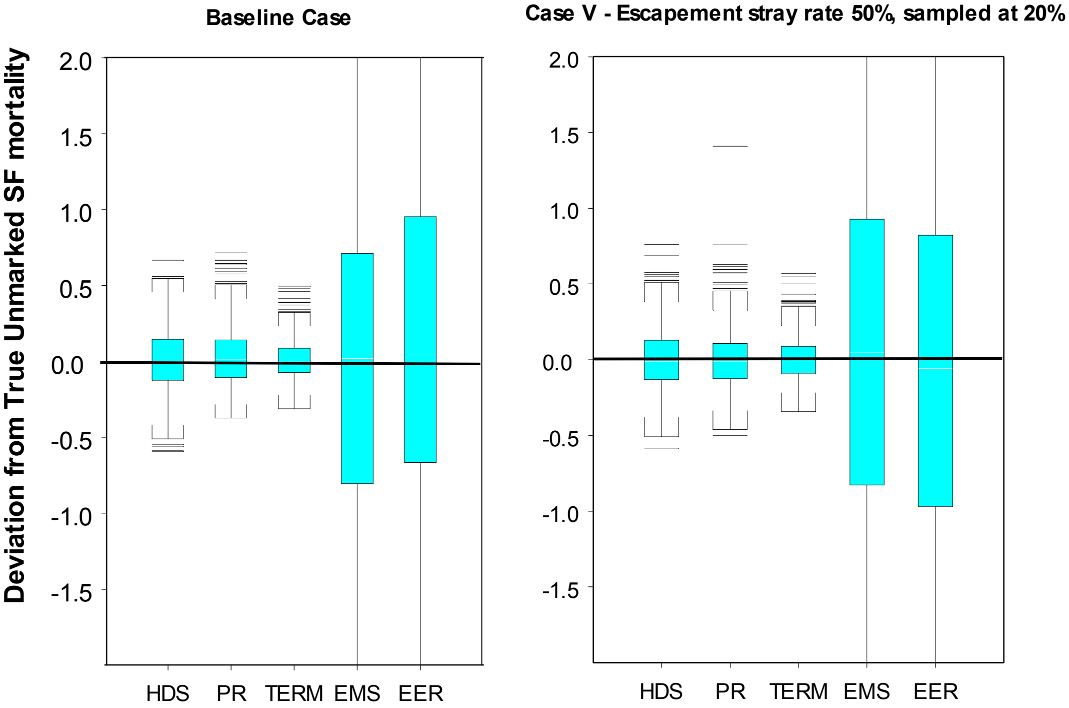

Figure 13. Comparison of box plots for deviations of estimates from Case V (50% straying to spawning grounds sampled at a 20% rate) to the Baseline Case.

Figure 13 compares Case V to the Baseline Case. In this Case, 50% of the escapement strays to spawning grounds, and is sampled at a rate of 20%. All other parameters are set as in the Baseline Case. All estimates are unbiased, but precision is reduced for some methods.

- The HDS and the PR are not affected because they are not dependent on escapement estimates.
- The TERM, EMS and EER methods are unbiased, but are less precise due to the additional variability contributed by sampling spawning ground strays. The impact on precision will be related to the percent strays and the sample rate.

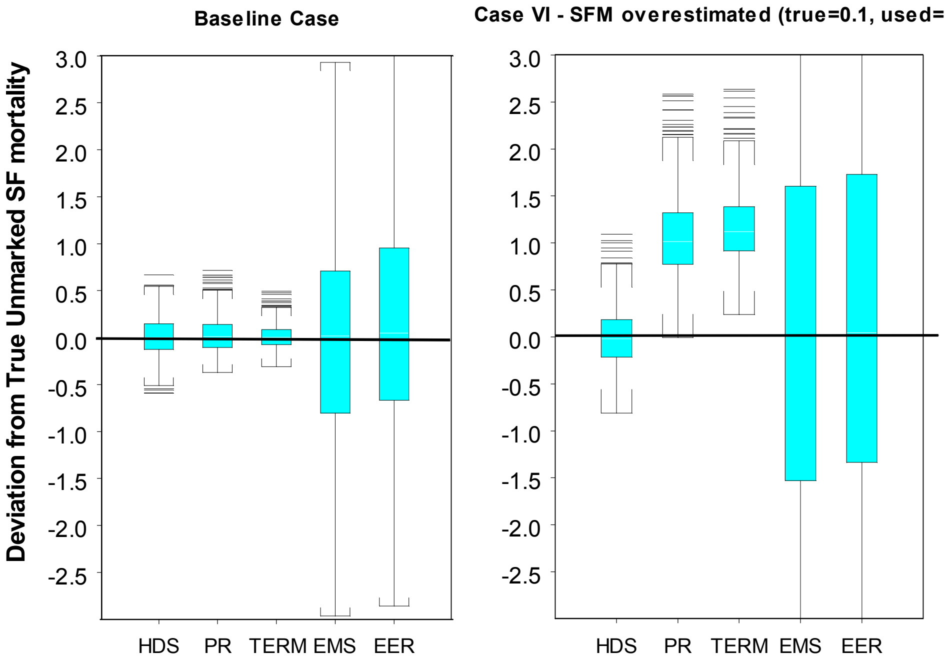

Figure 14. Comparison of box plots for deviations of estimates from Case VI (*sfm* over estimated by 100%, true *sfm* is 0.1, but 0.2 used for estimation) to the Baseline Case.

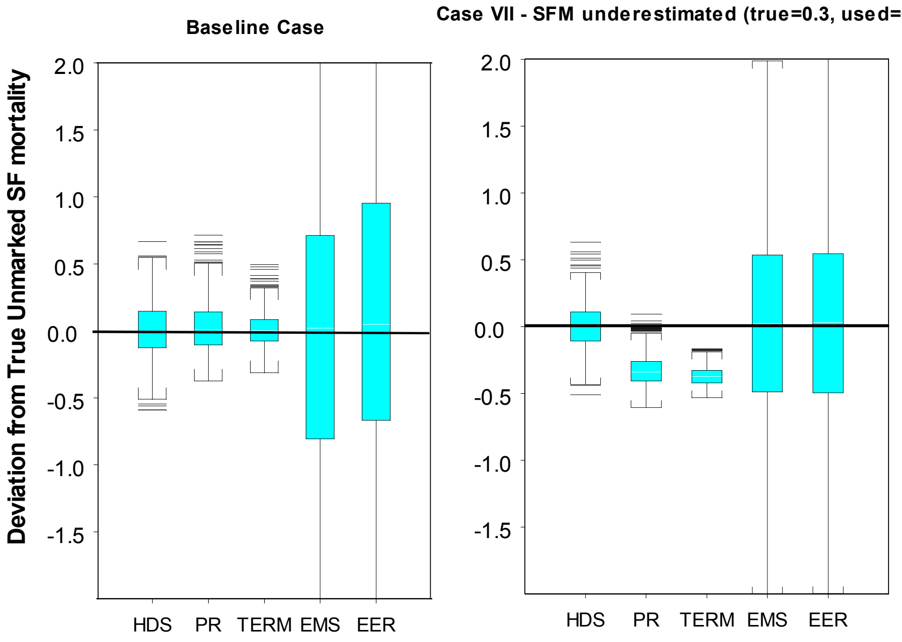

Figure 15. Comparison of box plots for deviations of estimates from Case VII (*sfm* under estimated by 33%, true *sfm* is 0.3, but 0.2 used for estimation) to the Baseline Case.

Figures 14 and 15 compare Cases VI and VII to the Baseline Case. In these two Cases, the *sfm's* used in the simulations were set at 0.1 and 0.3, but 0.2 was used for estimation purposes. All other parameters are set as in the Baseline Case. The impacts in these cases affect both bias and precision.

- The precision of the HDS estimates decreases (true *sfm*=0.1) or increases (true *sfm*=0.3) depending on the direction of the bias.
- The precision of the EMS and EER estimates are affected by changes in true *sfm* because the size of the unmarked SF mortalities impacts the precision. The larger the SF impact, the more precise these total methods become. Consequently, when the true *sfm* is 0.3, the SF impacts are larger and the estimate more precise (Figure 15). The same effect, only in reverse, is seen in Figure 14 for a smaller *sfm* value of 0.1.
- The PR and TERM methods both require an assumed value for *sfm.* If this value is biased, then these estimators produce biased estimates. The bias in the estimate of U^{SF} is directly proportional to the relative bias in the *sfm*. For case VI, the relative bias in *sfm* is 100% and in Case VII the relative bias in *sfm* is 33%. The median relative deviation of $\hat{U}^{SF}$ from its true value using the PR and TERM methods in these two cases approximates these values (Table 11).

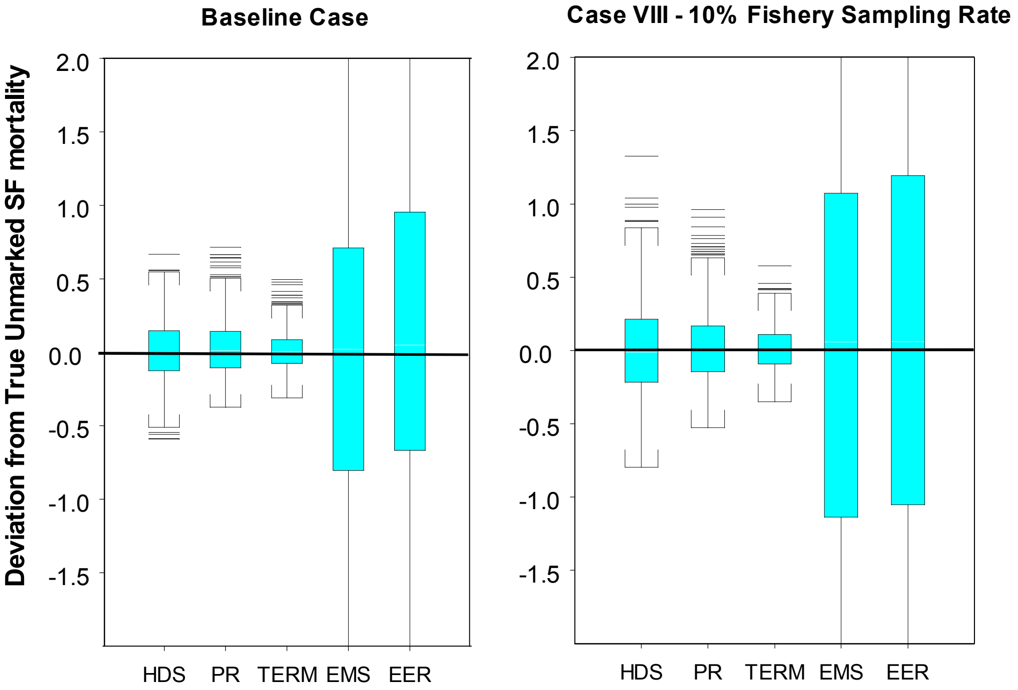

Figure 16. Comparison of box plots for deviations of estimates from Case VIII (fisheries sampled at a rate of 10%) to the Baseline Case.

Figure 16 compares Case VIII to the Baseline Case. In this Case, the fishery sampling rate was set at 10%. All other parameters are set as in the Baseline Case. All of the estimates are less precise as fewer tags are recovered in the sampling.

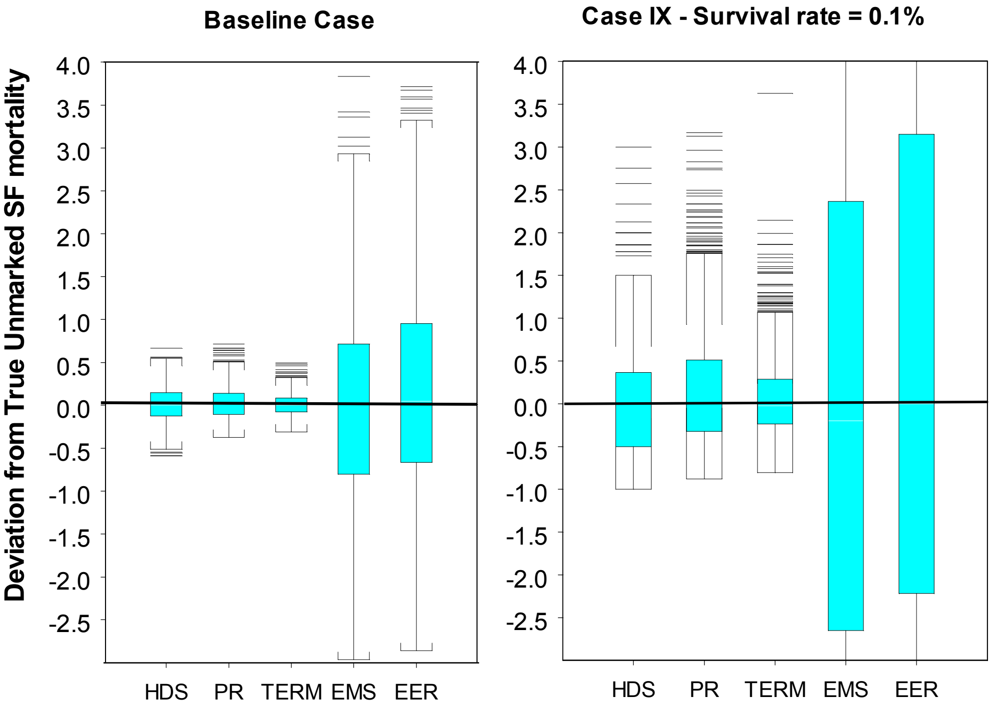

Figure 17. Comparison of box plots for deviations of estimates from Case IX (survival from release to first fishery is 0.1%) to the Baseline Case.

Figure 17 compares Case IX to the Baseline Case. In this Case, the survival from release to the first fishery was set at 0.1%. All other parameters are set as in the Baseline Case. Only precision is affected. As fewer fish return from the release, and fewer are available in the fisheries, mortalities and tag recoveries decrease, resulting in less precise estimates. As few fish are caught and small numbers of tags are recovered, the increase in variability is clearly evident among the estimates generated from the 1,000 replicates.

4.3 Precision and accuracy considerations when choosing among methods

The results of the simulations in section 4.2 illustrate that the uncertainty surrounding estimates of U^{SF} is related to several factors that affect the precision and accuracy of the methods in different ways.

Precision is determined by the number of tags recovered in fishery samples. The number of tags recovered depends on the number of fish available and harvest rates, as well as on tagging rates and sampling rates. Sampling rates are of importance for all of the methods. Unlike the direct sample method, the precision of the estimates of U^{SF} is affected by sampling in more than one fishery, and by recoveries of marked as well as unmarked DIT groups. Each method has different sampling considerations as to how many or which fisheries are of prime importance for sampling. The precision of all of the methods can be improved by increasing tagging rates. For example, doubling tagging rates for a DIT group is equivalent to doubling the sampling rate for that group in all fisheries, as it would result in doubling the number of tags recovered in a sample.

Incorrect input values (*sfm* or λ), incorrect assumptions about the exploitation patterns of fisheries, or missing information due to unsampled fisheries or escapement will cause bias in estimates of U^{SF}. Each method has a separate set of assumptions that, if violated, will lead to biased estimates. In the following sections, the uncertainty of the methods is further explored by considering the fishery regime used in section 4.2 (a single mark-selective fishery following a single non-selective fishery; $\lambda = 1$ in the non-selective fishery). Expected precision levels are calculated using the variance equations in Appendix 3 for a variety of harvest rates, sampling rates, and true and assumed values of *sfm*.

4.3.1 EMS Method

The precision of the EMS method depends on the proportion of the total cohort that die as a result of mark-selective fisheries (referred to as the magnitude of the SF), as well as sampling in all of the fisheries impacting the DIT groups and escapement. This is illustrated in Table 12. The precision of the estimates of unmarked mortalities in mark-selective fisheries improves as the number of unmarked mortalities in these fisheries increases. Estimates of unmarked mortalities in mark-selective fisheries will also improve as the sampling rates increase and larger numbers of marked and unmarked fish are recovered in non-selective fisheries and marked fish in the selective fisheries. The basic rule here, as with the conventional direct sample method, is that the relative precision of the estimate improves as number of tags upon which the estimate is based increases.

Table 12. Relative precision (CV) of estimates of unmarked mortalities in mark-selective fisheries using the EMS method with different levels of sampling and SFM.

Sample Rate in all Fisheries	Marked Fish		Unmarked	
	Observed Tags in NSF	CV	Mortalities in SF	CV
0.20	100	8.9%	100	100.0%
0.40	200	5.5%	100	61.2%
0.50	250	4.5%	100	50.0%
0.20	100	8.9%	250	40.0%
0.40	200	5.5%	250	24.5%
0.50	250	4.5%	250	20.0%

The EMS is most likely to be biased by marking induced mortality (see Case III) and missing information if a fishery or escapement is not sampled (see Case IV). In addition, non-fishery mortalities that cannot be sampled (e.g., predation on returning adults) will cause bias in the EMS estimate.

4.3.2 EER Method

As with the EMS method, the precision of the EER method depends on the number of unmarked mortalities in the mark-selective fisheries, as well as the sample rate in all of the fisheries impacting the DIT groups and escapement. However, for the EER method, λ is estimated from one or more non-selective fisheries, and therefore the number of tags recovered in these fisheries is of prime importance (Table 13). As the number of recoveries in these fisheries increases, the precision of the estimate of λ improves, leading to a more precise estimate of U^{SF}. As with the EMS method, the precision also improves as the magnitude of the mark-selective fishery increases. Bias is introduced in the EER estimates if there is missing information (Case IV).

Table 13. Relative precision (CV) of estimates of unmarked mortalities in mark-selective fisheries using the EMS method with different levels of sampling and SFM.

	Marked in NSF		Marked in SF		Unmarked in SF	
Sample Rates	Observed Tags	CV	Observed Tags	CV	Mortalities	CV
0.20	80	10.0%	160	7.1%	160	106%
0.20	80	10.0%	160	7.1%	400	43%
0.30	120	7.6%	240	5.4%	160	82%
0.30	120	7.6%	240	5.4%	400	33%
0.50	200	5.0%	400	3.5%	160	73%
0.50	200	5.0%	400	3.5%	400	29%

4.3.3 TERM Method

The TERM is dependent on assumptions about the value input for *sfm* as well as assumptions about migration of fish through the fisheries to escapement. The assumption is made that one can accurately estimate the number of encounters of marked and unmarked fish in the terminal mark-selective fishery. Given that all of these assumptions are met the TERM method provides estimates of U^{SF}, which are as precise as those achieved for marked mortalities in the same SF (Table 14).

However, when an assumption is violated, the uncertainty increases as bias becomes larger than zero. With increased sampling, the uncertainty can be decreased, but not below the level of bias (bias is 34% in Table 14).

Table 14. Uncertainty in estimates of unmarked SF mortalities as measured by the CV (CV $= \sqrt{MSE} / U^{SF}$ when the estimate of U^{SF} is biased) for TERM method compared to precision in marked mortalities in mark-selective fisheries (SR=0.2 indicates 20% sampling rate).

Number Tags Observed			Mark-Selective Fishery CV					
				Unmarked				
Marked		Unmarked	Marked	No Bias	Relative Bias = 34%			
NSF	SF	NSF	SR=0.2	SR=0.2	SR=0.2	SR=0.3	SR=0.4	SR=0.5
4	4	4	45%	43%	44%	40%	38%	36%
10	9	10	28%	27%	38%	36%	35%	35%
20	18	20	20%	19%	36%	35%	34%	34%
40	36	40	14%	14%	35%	34%	34%	34%

4.3.4 PR Method

The PR method is dependent on assumptions about the value input for *sfm* as well as assumptions about the non-selective fishery pair. The assumption is made that the λ estimated in the non-selective fishery is equal to the λ of the fish encountered in the mark-selective fishery. If the assumptions of the PR method are met, the estimates of U^{SF} will be less precise than the marked mortalities in the mark-selective fishery (Table 15). Increasing the sampling rate (or tagging rate) improves the precision of the estimates of U^{SF}. If the sample rate in both the fisheries is increased to 40%, the CV has improved to a level similar to that of the marked mortality estimate at a 20% sample rate (Table 15)

Table 15. Uncertainty in estimates of unmarked SF mortalities measured by CV (CV $= \sqrt{MSE} / U^{SF}$ when the estimate of U^{SF} is biased) for PR method compared to precision in marked mortalities in mark-selective fisheries (SR=0.2 indicates 20% sampling rate).

Bias in *sfm* and estimate of U^{SF}	Number Tags Observed			Mark-Selective Fishery CV				
	Marked		Unmarked	Marked	Unmarked			
	NSF	SF	NSF	SR=0.2	SR=0.2	SR=0.3	SR=0.4	SR=0.5
0%	4	4	4	45%	79%	60%	48%	39%
0%	10	9	10	28%	50%	38%	31%	25%
0%	20	18	20	20%	35%	27%	22%	18%
0%	40	36	40	14%	25%	19%	15%	12%
-34%	4	4	4	45%	62%	52%	46%	42%
-34%	10	9	10	28%	47%	41%	39%	37%
-34%	20	18	20	20%	40%	37%	36%	35%
-34%	40	36	40	14%	37%	35%	34%	34%

However, when an assumption is violated, the uncertainty increases as bias becomes larger than zero. The uncertainty can be decreased with increased sampling, but is still affected by the bias (Table 15).

5 How good is good enough?

The development of mark-selective fisheries on mass-marked hatchery fish and associated changes to the CWT program generated concerns for maintaining the viability of the CWT program for management and assessment of chinook and coho salmon. What maintaining viability implies though has generated two common questions: 1) how "good" was the CWT program before the development of mark-selective fisheries; and 2) what determines the utility of this program? Unfortunately, neither of these questions has a simple answer.

How good past programs have been involves several factors and has certainly changed over time. The factors involved include the number of tags released in a stock and brood year, the sampling rate in fisheries and coverage of fisheries, the exploitation rates in fisheries, and the assessment models (i.e., how to incorporate incidental mortality, natural mortality) developed to use these data. In the early years of the CWT program, hundreds to thousands of tags from one stock and brood year were recovered. This high recovery rate was attributed to high exploitation rates, high marine survivals, and intensive sampling programs. Under these conditions, the accuracy and precision of analyses based on CWT data were assumed to be very good. In application, point estimates of important management parameters were used (e.g., total brood exploitation rate, fishery specific exploitation rates, marine survival rates) without consideration of uncertainty in these estimates. Although accuracy could not be verified, confidence in the program's ability to describe exploitation patterns developed because of consistent tag recovery patterns (CTC 01-2) within and between stocks and brood years.

In recent years the situation has changed significantly. The number of tags recovered has declined through reductions in tagging and sampling due to funding constraints, through new management actions (e.g., size limits, non-retention regulations, changes in fishing patterns), and potentially through reduced marine survival and fishery exploitation rates (CTC-01-2) . In addition, the observable recoveries from fisheries now comprise a smaller portion of the estimated production than estimates of incidental mortality and spawning escapements (CTC 01-2). Consequently, the precision about these estimates is lower and concerns for accuracy have increased as the impact of assumed values increases (e.g., application of incidental mortality rates in more fisheries). However, even with the acknowledged loss of information few CWT programs have attempted to compensate for this loss or incorporated uncertainty into stock assessments involving these data.

How good is the CWT program? The answer depends on the basis for comparison. Compared to earlier years, recent CWT-based estimates (prior to mass-marking and mark-selective fisheries) are more uncertain and may not be adequate to meet some management objectives. Consequently, using the past CWT program as a comparative standard to measure the impact of implementing mark-selective fisheries is not likely to be appropriate. The critical issue is how to maintain the utility of the CWT program for management of stocks and fisheries. What are the critical parameters to measure and how should uncertainty be incorporated into management plans and assessments?

The SFEC continues to support the definition of viability of the CWT program as defined in the introduction, but also notes that the impact of mark-selective fisheries can be considered at various levels of resolution required by the management objectives. The increased uncertainty introduced by mark-selective fisheries becomes more significant with higher levels of resolution. Examples of differing levels of resolution include:

1. brood year total exploitation rate over all ages. Incidental mortality due to mark-selective fisheries is part of a stock's total mortality accounted for over the life of a brood.

2. comparison of aggregate exploitation rates over several fisheries within one calendar year (i.e., the ISBM fishery index required in the PST).

3. individual fishery and age specific exploitation rates. This would be the highest level of resolution with the greatest uncertainty.

The effect of mark-selective fisheries on the viability of the CWT program will depend upon the level of precision attained, accuracy of the assumptions (i.e., bias), and the question posed and/or management objective stated. Generally, objectives in salmon fisheries management tend to focus specifically on harvest, allocation and escapement goals and fisheries are subsequently designed to achieve those goals. Given the increased uncertainty of CWT-based estimates, methods to consider and account for uncertainty during preseason planning will be required.

In order to incorporate uncertainty into management decisions, one requires an understanding of the relationship between that uncertainty and the management parameters that can be set. For example, differences in the degree of uncertainty (due to all sources) about an estimated exploitation rate are illustrated in Figure 18a. The thin line represents the variability about an exploitation rate that is estimated with greater precision than the thick line; the vertical solid line is a target value. The flattened shape of the thick line indicates greater uncertainty. In Figure 18b, the shaded area under the curves indicates the estimated probability that an exploitation rate estimate will exceed a given value. In the figure, the shaded areas are an equal portion of the two distributions indicating that given the same target, with greater certainty (thin line) one can set the upper confidence limit at a lower value.

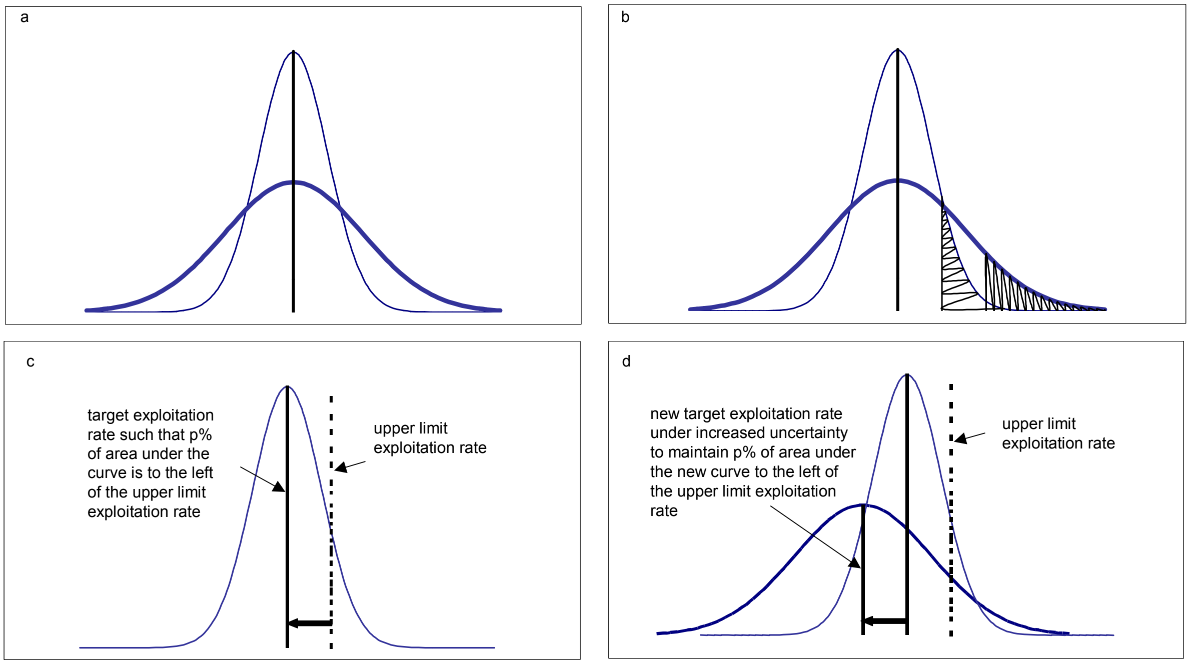

Figure 18. Schematic presentation of two levels of uncertainty in estimates of target exploitation rates.

Figure 18c represents a management objective set to ensure that the exploitation rate achieved is below an established upper limit with an estimated probability of compliance (i.e., p% in figure). In Figure 18c, the estimated probability of non-compliance is the area under the curve to the right of the vertical dashed line. With greater uncertainty, the distance between the target value and the upper limit will increase. Thus, the target exploitation rate must be shifted further to the left to ensure the same estimated probability of compliance (Figure 18d). The difference between the two target values (bold arrow in Figure 18d) represents the cost due to increased uncertainty and a specified level of compliance; for example, reduced fishing mortality and catch.

With the implementation of mark-selective fisheries, estimates of exploitation rates from unmarked-tagged fish, and therefore for natural fish, will be more uncertain. The increased uncertainty is due to loss in precision and introduction of new biases. To some extent, it is possible to compensate for reductions in precision by increasing tagging levels or sampling rates, but these actions will not reduce bias. In addition, it may not be possible to determine the direction and/or magnitude of bias. However, by explicitly considering the analytical methods discussed in this report (EMS, EER, TERM, and PR) and designing mark-selective fisheries to better meet the assumptions necessary for those methods, managers can reduce the risk of bias. For example, a non-selective fishery may be developed for the sole purpose of pairing with a mark-selective fishery for the PR method, provided the impacted stocks could withstand the additional exploitation. In another example, a traditional fishery may be modified slightly in time or space so that it meets the definitions of a terminal fishery to meet the assumptions required for the TERM method.

5.2.1 Conclusions

The utility of the CWT program as an assessment tool is currently threatened by substantial reduction in the numbers of tags recovered. This has resulted from both controllable (e.g., reduced fishing pressures, tagging and sampling rates) and uncontrollable (e.g., poor marine survival) factors. The development of mark-selective fisheries has added additional uncertainty and further impairs our ability to provide inferences about the effect of fishing on natural populations based on CWT data. The additional uncertainty may require reductions in target exploitation rates to maintain assurance that allowable exploitation rates have not been exceeded.

In addition to increasing uncertainty, mark-selective fisheries require additional assumptions to be made. With each additional assumption, the risk of bias increases. Because incidental mortalities are not observable, our ability to assess the impact of mark-selective fisheries is limited and some of the additional assumptions required in these analyses cannot be verified.

Given the current need to meet specified conservation goals (e.g., ESA limited fishery exploitation rates) and/or threshold limits in fisheries (e.g., the PST ISBM obligations), applications of CWT data should begin to incorporate measures of uncertainty into assessments and the development of management plans. Within a context of managing total fishing mortality, mark-selective fisheries are just one source of mortality to be incorporated but all sources of uncertainty must be accounted for. A consequence of increased uncertainty, however, could be trade-offs between fisheries and/or user groups in order to achieve a specified level of confidence in the overall assessments, or substantial increases in assessment programs and costs (e.g., doubling tag allocations for DIT groups).

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6 References

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Appendix one. Notation for description of cohort analysis and other analytical methods and models discussed in this report.[*]

Notation	Description
Indices	
a	Age (not needed for coho, used for chinook)
f	Index for individual fisheries
SF	Index for mark-selective fisheries
NSF	Index for non-selective fisheries
TR	Terminal run or region
M, U	Used as superscript, indicates marked or unmarked DIT group
Rel	At release of DIT group
Variables	
δ	Additive bias factor for λ and *sfm*
λ	The ratio of unmarked to marked fish for a given DIT group at the time of the fisheries.
λ^{NSF}	Ratio of unmarked to marked fish in a non-selective fishery of interest
λ^{Rel}	The ratio of unmarked to marked fish at release of DIT group.
A_a^M	Cohort size of age-*a* marked fish prior to over-wintering natural mortality and fishing
A_a^U	Cohort size of age-*a* unmarked fish prior to over-wintering natural mortality and fishing
$A_a^{TR,M}$	The terminal run size of marked age-*a* fish
$A_a^{TR,U}$	The terminal run size of unmarked age-*a* fish
B	Bias in estimated mortality
B'	Relative bias in estimated mortality
E_a^M	The number of age-*a* marked fish on the spawning ground
E_a^U	The number of age-*a* unmarked fish on the spawning ground
$ER_a^{M,f}$	Exploitation rate for age-*a* marked fish in fishery *f* [*f* may be replaced by *SF* or *NSF* to designate the type of fishery (selective/non-selective)]
$ER_a^{U,f}$	Exploitation rate for age-*a* unmarked fish in fishery *f* [*f* may be replaced by *SF* or *NSF* to designate the type of fishery (selective/non-selective)]
HR_a^f	Harvest rate for fishery *f* on age-*a* fish [*f* may be replaced by *SF* or *NSF* to designate the type of fishery (selective/non-selective)]
h_a^f	Instantaneous harvest rate for fishery *f* on age-*a* fish
M_a^f	The number of mortalities of age-*a* marked fish in fishery *f* [*f* may be replaced by *SF* or *NSF* to designate the type of fishery (selective/non-selective)]

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[*] Throughout, a "^" is used to signify an estimated quantity

Notation	Description
O	Number of observed recoveries in a landed catch sample
p^f	Sampling rate in fishery f
psm	Pre-spawning, post-fishery mortality rate.
S_a	Natural over-winter survival rate of age a fish
sfm	The release mortality rate in mark-selective fishery
U_a^f	The number of mortalities of unmarked age-a fish in fishery f [f may be replaced by SF or NSF to designate the type of fishery (selective/non-selective)]
X	Number of tagged fish landed in a catch

Appendix two.   Movement Model

The Movement Model was an alternative method investigated by the SFEC for its potential to estimate unmarked incidental mortalities using recoveries of DIT groups. The movement model estimates a host of parameters associated with the number and spatial distribution of marked and unmarked fish throughout their life cycle, including harvest rates in each fishery. These parameters are in turn used to estimate age and fishery specific estimates of unmarked mortalities in mark-selective fisheries. Whereas the other methods described in this report involve direct calculations of the incidental unmarked mortalities, the movement model is based on an optimization procedure that solves for the parameter estimates numerically given a set of equations describing expected movement and harvest. Because the solution to the movement model could not be simplified into simple close-formed equations, the properties of the method needed to be evaluated numerically.

Evaluation Approach

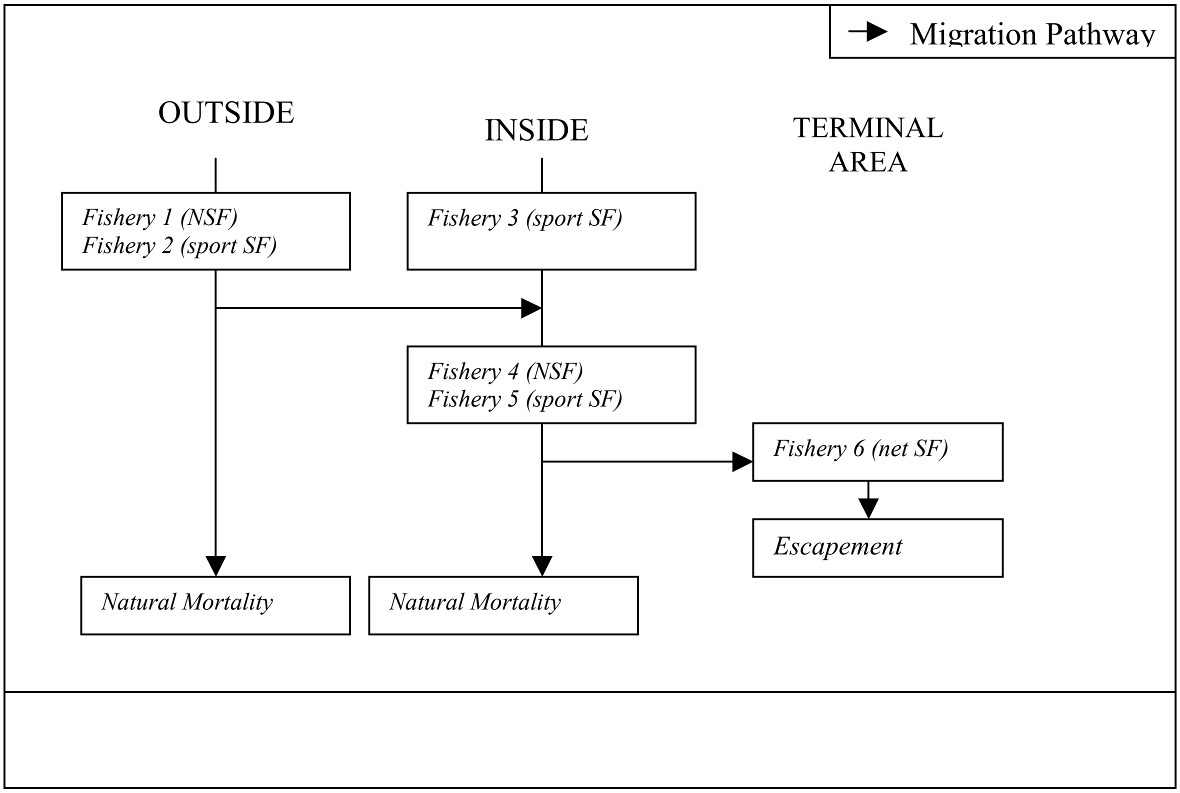
We used the following approach to evaluate the statistical properties of a simplified movement model:

- A simple stock and fishery structure was constructed with an age-specific migration pattern.
- Simulated data were produced from the simple structure for a single DIT group and included fishery and age specific landed catch and escapement. To investigate identifiability (i.e., whether or not the model was over parameterized), the data were generated without error and the resulting estimates were recorded. To investigate accuracy and precision, measurement error was added to catches and escapements to simulate the sampling processes.
- The movement model was then applied to each of the generated datasets and the estimated parameters output from this process were then compared to the "true" parameters used to generate the data.

Stock and Fishery Structure

The single stock and simple fishery structure assumed for this evaluation are shown in Appendix Figure 2-1. The stock was assumed to be 100% CWT tagged and was divided into marked and unmarked categories, thereby effectively comprising a single DIT group. The life history of the stock was divided into 4 ages (2-5 yr. olds), 3 time periods per age, and 3 regions (an outside region, an inside region, and a terminal region). Initially, the stock was distributed as age 2 fish between the outside and inside regions before period 1 (Appendix Table 2-1). Between periods 1 and 2, a unidirectional migration was used to move fish from the outside area to the inside area. Between Period 1 and the terminal period, unidirectional migration was again used to move fish from the inside area to the terminal area. From the terminal area the only migration was to the spawning ground. After the terminal period, an over wintering natural mortality was applied in both the outside and inside areas (same value), remaining fish were aged one year, and the process began again with Period 1 for the next age. For the oldest age class, assumed to be 5 year olds, the migration parameters were assumed to be 100% so that all age 5 fish were either harvested or escaped.

The fishery structure superimposed on this geographic age distribution pattern was simple and designed around when the migrations occurred (see Appendix Figure 2-1). Six fisheries, composed of two on the outside, three on the inside, and one terminal, were distributed amongst the three time periods (Appendix Table 2-1). In each fishing period, a fish could be encountered only once by the gear type used. During the Period 1, two fisheries occurred in the outside region and one in the inside region. The inside fishery and one of the outside fisheries were mark-selective and the remaining outside fishery was non-selective. In Period 2, two fisheries occurred in the inside region, one mark-selective and the other non-selective. In the terminal period, one mark-selective fishery occurred in the terminal area. Fish not harvested in the terminal area escaped to spawning grounds. The outside mark-selective fishery and the two inside mark-selective fisheries were assumed to be sport fisheries, while the terminal mark-selective fishery was assumed to be a net fishery. No other sources of mortality were included (all mortality was assumed to be due to either fishing mortality or over wintering mortality).



Appendix Figure 2-1. Geographic distribution of stock used in simulation model for generating datasets.

Appendix Table 2-1. Structure of fisheries with migration between periods and regions and a fishery occurring in inside area prior to migration.

	Region 1 Outside		Region 2 Inside		Terminal Region	
Period 1	Fishery 1 Non-Selective	Fishery 2 Mark-Selective Sport Fishery		Fishery 3 Mark-Selective Sport Fishery		
Period 2			Fishery 4 Non-Selective	Fishery 5 Mark-Selective Sport Fishery		
Terminal Period					Fishery 6 Mark-Selective Net Fishery	Escapement

Dataset generation

Expected fishery catch and escapement data were generated using the above format according to the equations in Table 2-3. The general notation described in Appendix one was used here**.** However, for this model, additional notation was necessary and is describe in Table 2-2.

Appendix Table 2-2. Additional notation necessary for simplified equation of the movement model.

Notation	**Description**
$A_a^{r,M}$	Abundance of marked fish in region *r* of age *a*.
$A_a^{r,U}$	Abundance of unmarked fish in region *r* of age *a*.
d	Distribution parameter describing the proportion of 2 year olds that distribute to the outside region.
$m_{r1 -> r2, a}$	Movement rate from region *r1* to region *r2* of aged *a* fish.
net	Superscript indicating a net fishery. This superscript is used to distinguish the mark-selective fishing mortality rate between commercial net and recreational sport and fisheries.
sp	Superscript indicating a sport fishery. This superscript is used to distinguish the mark-selective fishing mortality rate between the recreational sport and commercial net fisheries.

Appendix Table 2-3. The equations giving the expected values for marked and unmarked recoveries. The expected value functions are organized by age, then by mark category (marked and unmarked), and finally by area.

Age 2: Marked

Area 1 Expected Mortalities

$$M_2^1 = A_2^M (d) HR_2^1$$
$$M_2^2 = A_2^M (d) HR_2^2$$

Area 2 Expected Mortalities

$$M_2^3 = A_2^M (1-d) HR_2^3$$
$$M_2^4 = \left\{ A_2^M (1-d)(1-HR_2^3) + A_2^M (d)(1-HR_2^1)(1-HR_2^2) m_{1->2,2} \right\} HR_2^4$$
$$M_2^5 = \left\{ A_2^M (1-d)(1-HR_2^3) + A_2^M (d)(1-HR_2^1)(1-HR_2^2) m_{1->2,2} \right\} HR_2^5$$

Area 3 Expected Mortalities and Escapement

$$A_2^{M,TR} = \left\{ A_2^M (1-d)(1-HR_2^3) + A_2^M (d)(1-HR_2^1)(1-HR_2^2) m_{1->2,2} \right\} (1-HR_2^4)(1-HR_2^5) m_{2->3,2}$$
$$M_2^6 = A_2^{M,TR} HR_2^6$$
$$E_2^M = A_2^{M,TR} (1-HR_2^6)$$

Age 2: Unmarked

Area 1 Expected Mortalities

$$U_2^1 = A_2^U (d) HR_2^1$$
$$U_2^2 = A_2^U (d) HR_2^2 sfm^{sp}$$

Area 2 Expected Mortalities

$$U_2^3 = A_2^U (1-d) HR_2^3 sfm^{sp}$$
$$U_2^4 = \left\{ A_2^U (1-d)\left(1-HR_2^3 sfm^{sp}\right) + A_2^U (d)\left(1-HR_2^1\right)\left(1-HR_2^2 sfm^{sp}\right) m_{1->2,2} \right\} HR_2^4$$
$$U_2^5 = \left\{ A_2^U (1-d)\left(1-HR_2^3 sfm^{sp}\right) + A_2^U (d)\left(1-HR_2^1\right)\left(1-HR_2^2 sfm^{sp}\right) m_{1->2,2} \right\} HR_2^5 sfm^{sp}$$

Area 3 Expected Mortalities and Escapement

$$A_2^{U,TR} = \left\{ A_2^U (1-d)\left(1-HR_2^3 sfm^{sp}\right) + A_2^U (d)\left(1-HR_2^1\right)\left(1-HR_2^2 sfm^{sp}\right) m_{1->2,2} \right\}\left(1-HR_2^4\right)\left(1-HR_2^5 sfm^{sp}\right) m_{2->3,2}$$
$$U_2^6 = A_2^{U,TR} HR_2^6 sfm^{net}$$
$$E_2^U = A_2^{U,TR}\left(1-HR_2^6 sfm^{net}\right)$$

Age 3: Marked

Area 1 Expected Mortalities

$$A_3^{1,M} = A_2^M (d)\left(1-HR_2^1\right)\left(1-HR_2^2\right)\left(1-m_{1->2,2}\right)$$
$$M_3^1 = A_3^{1,M} S_3 HR_3^1$$
$$M_3^2 = A_3^{1,M} S_3 HR_3^2$$

Area 2 Expected Mortalities

$$A_3^{2,M} = \left\{ A_2^M (1-d)\left(1-HR_2^3\right) + A_2^M (d)\left(1-HR_2^1\right)\left(1-HR_2^2\right) m_{1->2,2} \right\}\left(1-HR_2^4\right)\left(1-HR_2^5\right)\left(1-m_{2->3,2}\right)$$
$$M_3^3 = A_3^{2,M} S_3 HR_3^3$$
$$M_3^4 = \left\{ A_3^{2,M} S_3 \left(1-HR_3^3\right) + A_3^{1,M} S_3 \left(1-HR_3^1\right)\left(1-HR_3^2\right) m_{1->2,3} \right\} HR_3^4$$
$$M_3^5 = \left\{ A_3^{2,M} S_3 \left(1-HR_3^3\right) + A_3^{1,M} S_3 \left(1-HR_3^1\right)\left(1-HR_3^2\right) m_{1->2,3} \right\} HR_3^5$$

Area 3 Expected Mortalities and Escapement

$$A_3^{M,TR} = \left\{A_3^{2,M} S_3 \left(1 - HR_3^3\right) + A_3^{1,M} S_3 \left(1 - HR_3^1\right)\left(1 - HR_3^2\right) m_{1->2,3}\right\}\left(1 - HR_3^4\right)\left(1 - HR_3^5\right) m_{2->3,3}$$

$$M_3^6 = A_3^{M,TR} HR_3^6$$

$$E_3^M = A_3^{M,TR}\left(1 - HR_3^6\right)$$

Age 3: Unmarked

Area 1 Expected Mortalities

$$A_3^{1,U} = A_2^U (d)\left(1 - HR_2^1\right)\left(1 - HR_2^2 sfm^{sp}\right)\left(1 - m_{1->2,2}\right)$$

$$U_3^1 = A_3^{1,U} S_3 HR_3^1$$

$$U_3^2 = A_3^{1,U} S_3 HR_3^2 sfm^{sp}$$

Area 2 Expected Mortalities

$$A_3^{2,U} = \left\{A_2^U (1 - d)\left(1 - HR_2^3 sfm^{sp}\right) + A_2^U (d)\left(1 - HR_2^1\right)\left(1 - HR_2^2 sfm^{sp}\right) m_{1->2,2}\right\}\left(1 - HR_2^4\right)\left(1 - HR_2^5 sfm^{sp}\right)\left(1 - m_{2->3,2}\right)$$

$$U_3^3 = A_3^{2,U} S_3 HR_3^3 sfm^{sp}$$

$$U_3^4 = \left\{A_3^{2,U} S_3 \left(1 - HR_3^3 sfm^{sp}\right) + A_3^{1,U} S_3 \left(1 - HR_3^1\right)\left(1 - HR_3^2 sfm^{sp}\right) m_{1->2,3}\right\} HR_3^4$$

$$U_3^5 = \left\{A_3^{2,U} S_3 \left(1 - HR_3^3 sfm^{sp}\right) + A_3^{1,U} S_3 \left(1 - HR_3^1\right)\left(1 - HR_3^2 sfm^{sp}\right) m_{1->2,3}\right\} HR_3^5 sfm^{sp}$$

Area 3 Expected Mortalities and Escapement

$$A_3^{U,TR} = \left\{A_3^{2,U} S_3 \left(1 - HR_3^3 sfm^{sp}\right) + A_3^{1,U} S_3 \left(1 - HR_3^1\right)\left(1 - HR_3^2 sfm^{sp}\right) m_{1->2,3}\right\}\left(1 - HR_3^4\right)\left(1 - HR_3^5 sfm^{sp}\right) m_{2->3,3}$$

$$U_3^6 = A_3^{U,TR} HR_3^6 sfm^{net}$$

$$E_3^U = A_3^{U,TR}\left(1 - HR_3^6 sfm^{net}\right)$$

Age 4: Marked

Area 1 Expected Mortalities

$$A_4^{1,M} = A_3^{1,M} S_3 \left(1 - HR_3^1\right)\left(1 - HR_3^2\right)\left(1 - m_{1->2,3}\right)$$
$$M_4^1 = A_4^{1,M} S_4 HR_4^1$$
$$M_4^2 = A_4^{1,M} S_4 HR_4^2$$

Area 2 Expected Mortalities

$$A_4^{2,M} = \left\{A_3^{2,M} S_3 \left(1 - HR_3^3\right) + A_3^{1,M} S_3 \left(1 - HR_3^1\right)\left(1 - HR_3^2\right) m_{1->2,3}\right\}\left(1 - HR_3^4\right)\left(1 - HR_3^5\right)\left(1 - m_{2->3,3}\right)$$
$$M_4^3 = A_4^{2,M} S_4 HR_4^3$$
$$M_4^4 = \left\{A_4^{2,M} S_4 \left(1 - HR_4^3\right) + A_4^{1,M} S_4 \left(1 - HR_4^1\right)\left(1 - HR_4^2\right) m_{1->2,4}\right\} HR_4^4$$
$$M_4^5 = \left\{A_4^{2,M} S_4 \left(1 - HR_4^3\right) + A_4^{1,M} S_4 \left(1 - HR_4^1\right)\left(1 - HR_4^2\right) m_{1->2,4}\right\} HR_4^5$$

Area 3 Expected Mortalities and Escapement

$$A_4^{M,TR} = \left\{A_4^{2,M} S_4 \left(1 - HR_4^3\right) + A_4^{1,M} S_4 \left(1 - HR_4^1\right)\left(1 - HR_4^2\right) m_{1->2,4}\right\}\left(1 - HR_4^4\right)\left(1 - HR_4^5\right) m_{2->3,4}$$
$$M_4^6 = A_4^{M,TR} HR_4^6$$
$$E_4^M = A_4^{M,TR} \left(1 - HR_4^6\right)$$

Age 4: Unmarked

Area 1 Expected Mortalities

$$A_4^{1,U} = A_3^{1,U} S_3 \left(1 - HR_3^1\right)\left(1 - HR_3^2 sfm^{sp}\right)\left(1 - m_{1->2,3}\right)$$
$$U_4^1 = A_4^{1,U} S_4 HR_4^1$$
$$U_4^2 = A_4^{1,U} S_4 HR_4^2 sfm^{sp}$$

Area 2 Expected Mortalities

$$A_4^{2,U} = \left\{A_3^{2,U} S_3 \left(1 - HR_3^3 sfm^{sp}\right) + A_3^{1,U} S_3 \left(1 - HR_3^1\right)\left(1 - HR_3^2 sfm^{sp}\right) m_{1->2,3}\right\}\left(1 - HR_3^4\right)\left(1 - HR_3^5 sfm^{sp}\right)\left(1 - m_{2->3,3}\right)$$
$$U_4^3 = A_4^{2,U} S_4 HR_4^3 sfm^{sp}$$
$$U_4^4 = \left\{A_4^{2,U} S_4 \left(1 - HR_4^3 sfm^{sp}\right) + A_4^{1,U} S_4 \left(1 - HR_4^1\right)\left(1 - HR_4^2 sfm^{sp}\right) m_{1->2,4}\right\} HR_4^4$$
$$U_4^5 = \left\{A_4^{2,U} S_4 \left(1 - HR_4^3 sfm^{sp}\right) + A_4^{1,U} S_4 \left(1 - HR_4^1\right)\left(1 - HR_4^2 sfm^{sp}\right) m_{1->2,4}\right\} HR_4^5 sfm^{sp}$$

Area 3 Expected Mortalities and Escapement

$$A_4^{U,TR} = \left\{A_4^{2,U} S_4 \left(1 - HR_4^3 sfm^{sp}\right) + A_4^{1,U} S_4 \left(1 - HR_4^1\right)\left(1 - HR_4^2 sfm^{sp}\right) m_{1->2,4}\right\}\left(1 - HR_4^4\right)\left(1 - HR_4^5 sfm^{sp}\right) m_{2->3,4}$$
$$U_4^6 = A_4^{U,TR} HR_4^6 sfm^{net}$$
$$E_4^U = A_4^{U,TR} \left(1 - HR_4^6 sfm^{net}\right)$$

Age 5: Marked

Area 1 Expected Mortalities

$$A_5^{1,M} = A_4^{1,M} S_4 \left(1 - HR_4^1\right)\left(1 - HR_4^2\right)\left(1 - m_{1->2,4}\right)$$
$$M_5^1 = A_5^{1,M} S_5 HR_5^1$$
$$M_5^2 = A_5^{1,M} S_5 HR_5^2$$

Area 2 Expected Mortalities

$$A_5^{2,M} = \left\{A_4^{2,M} S_4 \left(1 - HR_4^3\right) + A_4^{1,M} S_4 \left(1 - HR_4^1\right)\left(1 - HR_4^2\right) m_{1->2,4}\right\}\left(1 - HR_4^4\right)\left(1 - HR_4^5\right)\left(1 - m_{2->3,4}\right)$$
$$M_5^3 = A_5^{2,M} S_5 HR_5^3$$
$$M_5^4 = \left\{A_5^{2,M} S_5 \left(1 - HR_5^3\right) + A_5^{1,M} S_5 \left(1 - HR_5^1\right)\left(1 - HR_5^2\right)\right\} HR_5^4$$
$$M_5^5 = \left\{A_5^{2,M} S_5 \left(1 - HR_5^3\right) + A_5^{1,M} S_5 \left(1 - HR_5^1\right)\left(1 - HR_5^2\right)\right\} HR_5^5$$

Area 3 Expected Mortalities and Escapement

$$A_5^{M,TR} = \left\{A_5^{2,M} S_5 \left(1 - HR_5^3\right) + A_5^{1,M} S_5 \left(1 - HR_5^1\right)\left(1 - HR_5^2\right)\right\}\left(1 - HR_5^4\right)\left(1 - HR_5^5\right)$$
$$M_5^6 = A_5^{M,TR} HR_5^6$$
$$E_5^M = A_5^{M,TR}\left(1 - HR_5^6\right)$$

Age 5: Unmarked

Area 1 Expected Mortalities

$$A_5^{1,U} = A_4^{1,U} S_4 \left(1 - HR_4^1\right)\left(1 - HR_4^2 sfm^{sp}\right)\left(1 - m_{1->2,4}\right)$$
$$U_5^1 = A_5^{1,U} S_5 HR_5^1$$
$$U_5^2 = A_5^{1,U} S_5 HR_5^2 sfm^{sp}$$

Area 2 Expected Mortalities

$$A_5^{2,U} = \left\{A_4^{2,U} S_4 \left(1 - HR_4^3 sfm^{sp}\right) + A_4^{1,U} S_4 \left(1 - HR_4^1\right)\left(1 - HR_4^2 sfm^{sp}\right) m_{1->2,4}\right\}\left(1 - HR_4^4\right)\left(1 - HR_4^5 sfm^{sp}\right)\left(1 - m_{2->3,4}\right)$$
$$U_5^3 = A_5^{2,U} S_5 HR_5^3 sfm^{sp}$$
$$U_5^4 = \left\{A_5^{2,U} S_5 \left(1 - HR_5^3 sfm^{sp}\right) + A_5^{1,U} S_5 \left(1 - HR_5^1\right)\left(1 - HR_5^2 sfm^{sp}\right)\right\} HR_5^4$$
$$U_5^5 = \left\{A_5^{2,U} S_5 \left(1 - HR_5^3 sfm^{sp}\right) + A_5^{1,U} S_5 \left(1 - HR_5^1\right)\left(1 - HR_5^2 sfm^{sp}\right)\right\} HR_5^5 sfm^{sp}$$

Area 3 Expected Mortalities and Escapement

$$A_5^{U,TR} = \left\{A_5^{2,U} S_5 \left(1 - HR_5^3 sfm^{sp}\right) + A_5^{1,U} S_5 \left(1 - HR_5^1\right)\left(1 - HR_5^2 sfm^{sp}\right)\right\}\left(1 - HR_5^4\right)\left(1 - HR_5^5 sfm^{sp}\right)$$
$$U_5^6 = A_5^{U,TR} HR_5^6 sfm^{net}$$
$$E_5^U = A_5^{U,TR}\left(1 - HR_5^6 sfm^{net}\right)$$

Parameter Values Used for Baseline Data

A base set of parameters were used to test the different methods (Appendix Table 2-4; fisheries are numbered as in Appendix Table 2-1). With these parameters, expected numbers of fishery and age specific mortalities were calculated deterministically (Appendix Table 2-5). In Appendix Table 2-5, the darkened cells are those unobservable mortalities of unmarked fish in mark-selective fisheries.

Appendix Table 2-4. Base parameter values for creation of generated baseline data set. See Appendix 1 for notation description.

Parameter	*Value*
d	0.9
A^{M}_{2}	10,000
A^{U}_{2}	10,000
S_a *(a=2,3,4)*	0.7, 0.8, 0.9
$m_{a,\ 1\text{->}2}$ *(a=2,3,4,5)*	0.1, 0.3, 0.6, 1
$m_{a,\ 2\text{->}3}$ *(a=2,3,4,5)*	0.1, 0.3, 0.6, 1
HR_a^1 *(a=2,3,4,5)*	0.01, 0.2, 0.3, 0.25
HR_a^2 (a=2,3,4,5)	0.02, 0.3, 0.4, 0.2
HR_a^3 (a=2,3,4,5)	0.06, 0.1, 0.2, 0.05
HR_a^4 (a=2,3,4,5)	0.1, 0.3, 0.4, 0.4
HR_a^5 (a=2,3,4,5)	0.1, 0.1, 0.2, .0.1
HR_a^6 (a=2,3,4,5)	0.1, 0.3, 0.4, 0.3
sfm^{sp}	0.2
sfm^{net}	0.4

Appendix Table 2-5. Generated CWT data for baseline marked and unmarked DIT group.*

Fishery	Age 2		Age 3		Age 4		Age 5	
	Marked	Unmarked	Marked	Unmarked	Marked	Unmarked	Marked	Unmarked
1	90	90	1100	1118	462	695	42	129
2	180	36	1650	335	616	185	33	21
3	60	12	91	21	111	34	5	3
4	181	188	494	678	288	675	76	282
5	181	38	165	45	144	68	19	14
6	15	7	89	55	69	91	28	49
Esc	131	158	208	406	104	476	66	359

*Shaded regions represent unobserved mortalities

Adding Measurement Error

In order to evaluate the impacts of measurement error on the parameter estimates, sampling error was added to the baseline data (Appendix Table 2-6). To add measurement error to the data, the target catches were "sampled" for tags by treating the number of tags sampled as a hypergeometric random variable. For example, assume the catch consisted of 1000 fish such that 100 of them were tagged. Then, with a sampling rate of 20%, the number of observed tags would be a hypergeometric random variable with parameters (1000, 100 and 0.2). A random number generator was used to generate "observations" from the appropriate hypergeometric distribution function using either a Poisson or a normal approximation.

Appendix Table 2-6. An example of baseline CWT data with measurement error.*

Fishery	Age 2		Age 3		Age 4		Age 5	
	Marked	Unmarked	Marked	Unmarked	Marked	Unmarked	Marked	Unmarked
1	85	125	1160	1065	500	735	70	100
2	167	40	1590	287	607	180	50	23
3	70	0	70	20	140	10	0	0
4	155	160	460	670	295	740	85	285
5	140	30	170	20	170	60	0	40
6	13	12	92	55	73	70	35	61
Esc	129	159	207	404	105	485	68	354

*Shaded regions represent unobserved mortalities

When the proportion of tags in the catch was small, a Poisson approximation to the hypergeometric was used; otherwise a normal approximation was used. The proportion of tags in the catch was a function of the proportion of the tagged stock vulnerable to a fishery as well as the fraction of the catch that stock was likely to represent. For example, the outside fisheries are expected to be on mixed stocks where the particular tagged stock of interest may only make up 1% of the vulnerable fish. On the other hand, the particular tagged stock of interest may be expected to make up 25% of the stock composition in the terminal fishery and 100% of the escapement. The fractions used are given in Appendix Table 2-7.

Appendix Table 2-7. Assumed fractions of stock composition by fishery.

Fishery	Tagged Stock Composition Fraction	Approximation to Hypergeometric
1 – outside NSF	0.01	Poisson
2 – outside SF	0.01	Poisson
3 – inside SF	0.02	Poisson
4 – inside NSF	0.02	Poisson
5 – inside SF	0.02	Poisson
6 – terminal SF	0.25	Normal
Escapement	1.00	Normal

Along with data exhibiting sampling noise, we also calculated estimates of variance for the data to be incorporated into the estimation models. The variances were calculated using the variance of the approximation distribution and adjusting for the sampling rate. For example, when the Poisson approximation was used, the variance estimated was that of the random Poisson variable divided by the sampling rate. The estimated variances associated with the catch in Appendix Table 2-6 are given in Appendix Table 2-8.

Appendix Table 2-8. Estimated variances for CWT data displayed in Appendix Table 21. *

Fishery	Age 2		Age 3		Age 4		Age 5	
	Marked	Unmarked	Marked	Unmarked	Marked	Unmarked	Marked	Unmarked
1	425	625	5800	5325	2500	3675	350	500
2	556	133	5300	956	2022	600	167	78
3	700	100	700	200	1400	100	100	100
4	775	800	2300	3350	1475	3700	425	1425
5	1400	300	1700	200	1700	600	100	400
6	33	15	200	124	155	204	64	110
Esc	11	13	17	33	9	40	6	30

*Shaded regions represent cells with unobserved mortalities.

The Model

The movement model estimates mortalities of unmarked fish in mark-selective fisheries by assuming a spatial structure that describes how fish are distributed throughout the period during which they are exploited in fisheries. The model requires that regions be defined as well as migration patterns (including the timing of movement) between regions. Both mark-selective and non-selective fisheries are assumed to occur together in local "single pools" defined by a particular spatial location and time period.

Mark-selective fisheries lead to a contrast between marked and unmarked fish in terms of abundance, as marked fish are removed from the population at large faster relative to unmarked fish. The movement model exploits this contrast, using information from observed DIT recoveries to estimate parameters associated with the number and spatial distribution of marked and unmarked fish throughout their life cycle. Observed recoveries include landed catch of marked fish in all fisheries (mark-selective and non-selective), landed catch of unmarked fish in non-selective fisheries, and escapement recoveries of both marked and unmarked fish.

Using the assumptions about stock structure and the simple fishery regime described in the Section above on Stock and Fishery Structure, we tested the movement model concept with simulated data. Model parameters to be estimated include all those listed in Appendix Table 2-4 except for over-winter survival rates and migration rates of age 5 fish, which are assumed to be known without error.

Parameters are estimated using nonlinear regression techniques that minimize the weighted sum of squared differences between observed and expected recoveries, with weights inversely proportional to the variances of the observed recoveries in fisheries and escapement:

$$\sum_{f \in NSF} \sum_{a=2}^{5} \frac{(\hat{U}_a^f - U_a^f)^2}{2V\hat{a}r(\hat{U}_a^f)} + \sum_{f \in SF, NSF} \sum_{a=2}^{5} \frac{(\hat{M}_a^f - M_a^f)^2}{2V\hat{a}r(\hat{M}_a^f)} + \sum_{a=2}^{5} \frac{(\hat{E}_a^M - E_a^M)^2}{2V\hat{a}r(\hat{E}_a^M)} + \sum_{a=2}^{5} \frac{(\hat{E}_a^U - E_a^U)^2}{2V\hat{a}r(\hat{E}_a^U)}$$

In this equation, the “^”indicates that the quantity is estimated from sampling a fishery. The quantities without the “^” are expected values calculated from the parameter values.

A weighted least squares objective function gives more weight to observations with a high degree of precision and is expected to result in more precise parameter estimates than an unweighted least squares objective function. Minimizing the objective function is equivalent to maximizing the likelihood of the data when all recoveries are normally distributed. Therefore, the movement model estimates are maximum likelihood estimates under the assumption that observed recoveries are normally distributed.

The estimated variances in the objective function are determined using observed recoveries and known sampling rates. The expected recoveries of marked and unmarked fish in the objective function are calculated using the population dynamic model discussed above and illustrated in Appendix Table 2-3.

Evaluation of the Movement Model

The first level of evaluation for an analytical method is generally in terms of its theoretical statistical properties (e.g., accuracy and precision of parameter estimates). The second level of evaluation is generally of the ability to implement the method. Although both levels are required to ascertain the capability of maintaining the viability of the CWT program under mark-selective fisheries, in this report we focused only on the first.

The desired statistical properties for successful evaluation of a method include:

- Identifiability: the model should not be overparameterized.
- Accuracy: estimates should be unbiased or asymptotically unbiased (i.e., in the limit estimates should be equal to the true value).

- Precision: the variance of an estimator should be accurately estimated and not be unreasonably large.
- Robustness to model assumptions: the analytical method should continue to provide useful estimates of model parameters even when the assumptions underlying the analytical methods are violated.

Identifiability was assessed with data containing no error (i.e., perfect data). When parameters are confounded, an estimation procedure will not be able to find the correct solution even with perfect data. On the other hand, when parameters are not confounded, the estimation procedure should be able to find the correct solution for all possible parameter combinations.

On the other hand, accuracy and precision were assessed by subjecting the estimation methods to simulated data with sampling error incorporated. Accuracy was assessed simultaneously with imprecision by calculating the mean squared error (MSE) of the estimate. The MSE is the sum of both bias squared and imprecision ($MSE = Bias^2 + Variance$). In order to accurately reflect the level of imprecision expected in the data, two types of variability were included:

- Measurement or sampling error: variability in the number of observed CWTs due to sampling a proportion of the catch. In other words, the deviation between the actual catch and that estimated by the sampling process. For example, say the catch consisted of 1504 tagged fish. With a sampling rate of, say, 20%, one would not expect to estimate the 1504 number exactly.

- Process error: natural variability related to population processes (e.g. stochastic movement, harvest, and survival). More specifically, the deviation between the expected catch based on the true underlying parameters and the actual catch (if it were measured without error). For example, even though the underlying marine natural survival rate were, say, 80%, one would not expect exactly 80% of the fish at risk to survive. Likewise, if a harvest rate were, say, 10%, one would not expect exactly 10% of the fish at risk to be landed.

In this case, process error was not included. Future evaluation of the movement model will need to be evaluated with both sources of variability. The impact of ignoring process error is to underestimate parameter variances.

Results of evaluation of the movement model

The evaluation presented here focuses on two fundamental statistical and mathematical properties necessary to validate the movement model concept. Those properties are (1) identifiability (i.e., are there confounded parameters in the model); and (2) accuracy (i.e., are the parameter estimators unbiased).

Identifiability

The first step in the evaluation of the movement model is to determine if the parameters can be solved for when the assumptions of the model are correct and the data are generated without error. Thus, we first evaluated the model assuming:

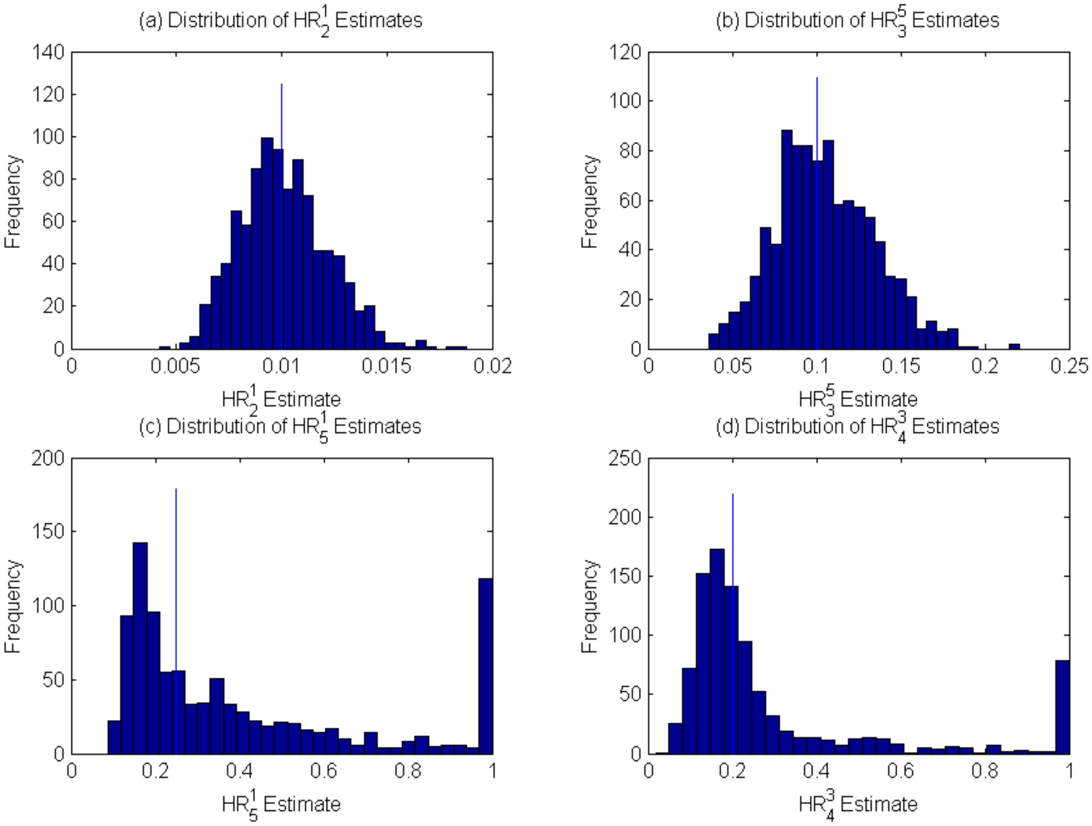
- the stock structure is correctly defined, with 2 regions and movement from outside to inside and to terminal regions occurring at the correct times;
- the over wintering mortality rates are correctly known;
- fish act deterministically (harvest rates, movement rates, mortality rates are all deterministic);
- no process error is present;
- landed catch and escapements are sampled at 100%; no measurement error is present (note: since the data are generated without error, the estimated variances in the objective function are set equal to 1, giving equal weights to each recovery).

When the data were generated without error, the movement model was capable of solving for the exact set of parameters used to generate the data, giving an objective function of 0.0. Furthermore, no other set of parameters resulted in an objective function of 0. Therefore, we concluded that the movement model parameters are identifiable.

Accuracy and Precision

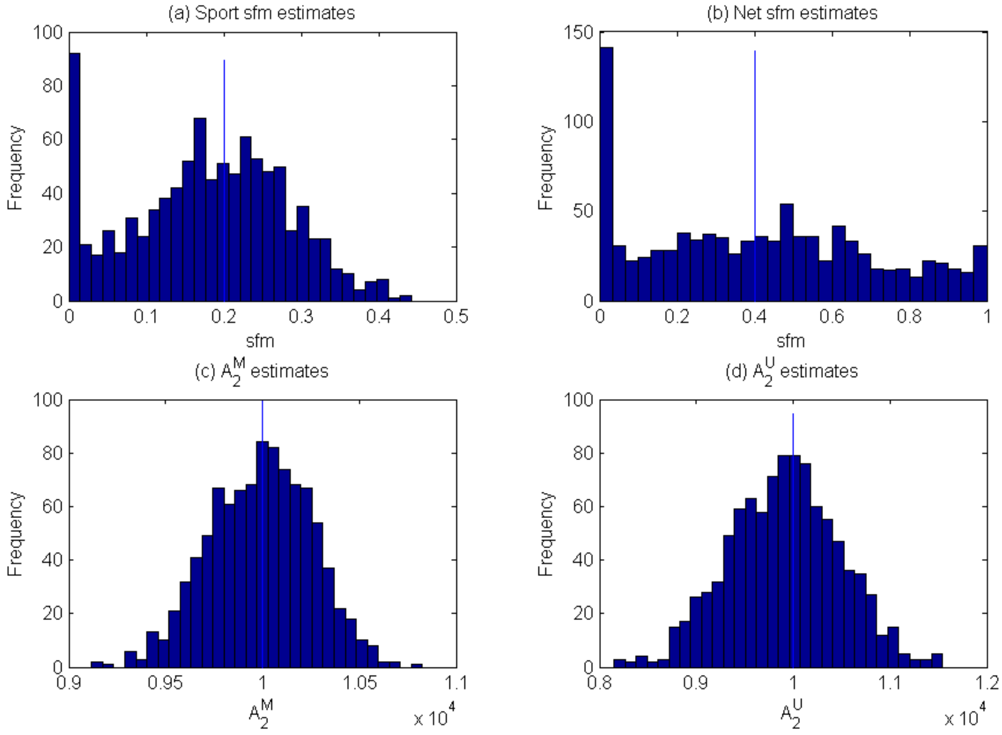
In order to examine the accuracy and precision of parameter estimates, the movement model was fit to 1000 randomly generated data sets (using the same underlying model parameters in Appendix Table 2-4), but adding random sampling error to the data, using the sampling protocol given above.

The non-linear solver failed to converge for 31 out of the 1000 data sets. The distribution of parameter estimates for the 969 data sets for which the non-linear solver did indicate convergence (by reporting all positive eigenvalues for the estimated hessian) was examined further to assess the accuracy and precision of model estimates. Harvest rate parameters associated with fisheries/ages for which substantial mortalities occur (e.g. outside fisheries, ages 3 and 4) were estimated fairly precisely and with a reasonable degree of accuracy. The distributions of these harvest rate estimates were centered around their true values (e.g. see Appendix Figure 2-2a and b) and the spread of these distributions were typically not very large. However, the distributions of harvest rate estimates for age/fishery combinations for which few mortalities occurred (e.g. age 5 fish in the outside fisheries and all ages in fishery 3; see Appendix Figure 2-2c and d) appeared to be quite imprecise with minor modes at extreme values.

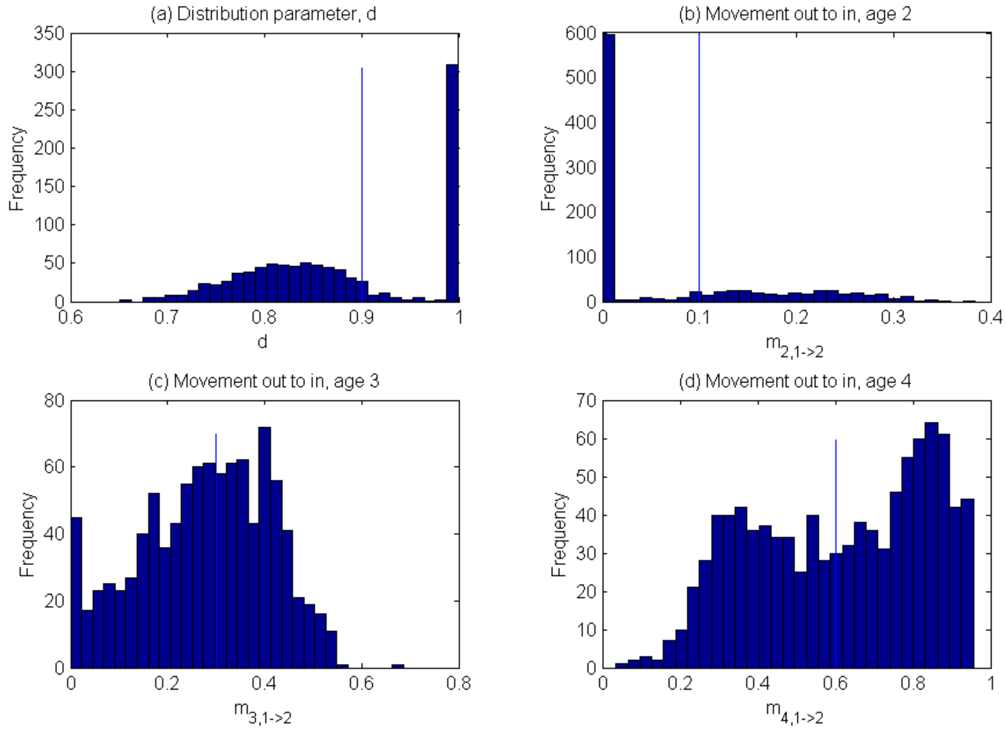


Appendix Figure 2-2. Distributions of estimates of harvest rates: (a) age 2 fish in fishery 1 (outside), (b) age 3 fish in fishery 5 (inside after migration), (c) age 5 fish in fishery 1 (outside) and (d) age 4 fish in fishery 3 (inside before migration). The horizontal line gives the true value for the parameter of interest.

The estimates of $A^M{}_2$ and $A^U{}_2$ were also fairly accurate and precisely estimated (Appendix Figure 2-3 c,d). However, the estimates of the distribution parameter, *d*, migration parameters, and *sfm* rates were not (Appendix Figures 2-3 and 2-4). Furthermore, several of the *sfm* estimates were equal to 0, resulting in an estimated mortality of 0 for unmarked fish in mark-selective fisheries. Although the *sfm* parameters are identifiable, they appear to be highly sensitive to sampling error. Therefore, future modeling efforts could require specification of *sfm* rates, treating these parameters as known without error. In this case, it would be important to determine the sensitivity of the model estimates of unmarked mortalities to mis-specification of these parameters.

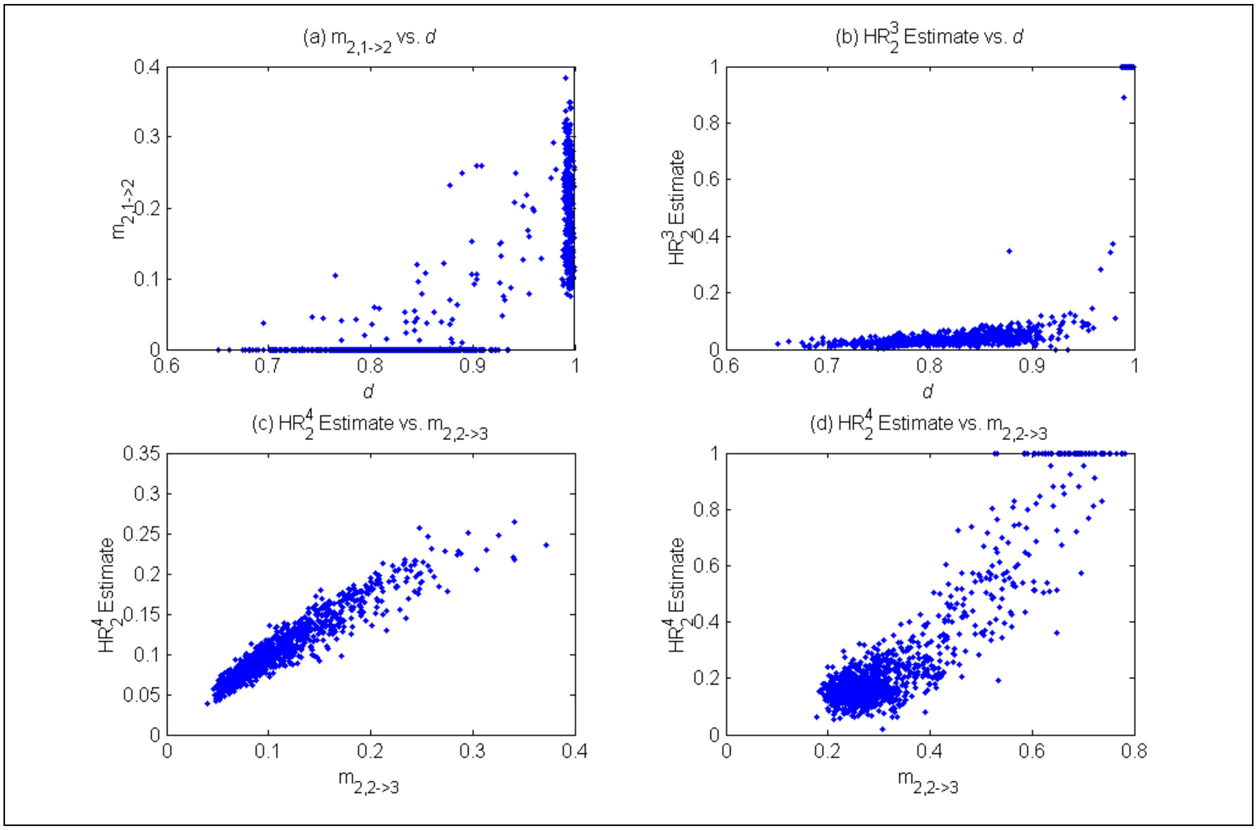


Appendix Figure 2-3. Distribution of estimates of initial abundance and catch and release mortalities. The horizontal line gives the true value for the parameter of interest.



Appendix Figure 2-4. Distribution of estimates of *d* and movement parameters. The horizontal line gives the true value for the parameter of interest.

Frequently, estimates of one or more of the model parameters were found at the extreme ends of the parameter space (e.g., *sfm* = 0 or *d* =1). These estimates could be a result of numerical problems associated with minimizing the objective function. It may be possible to overcome these problems by limiting the number of estimated model parameters (e.g., assuming *sfm* is known), setting tighter bounds on the parameter space (e.g., limiting *sfm* estimates to values between *a* and *b*, with $a,b \in (0,1); a < b$), passing different "initial parameter values" or starting seeds to the numerical optimization routine, or trying other numerical optimizers (e.g., genetic algorithms). In addition, several of the model parameters were highly correlated (Appendix Figure 2-5). For example, overestimates of $m_{a,2\text{->}3}$ were often compensated for by overestimates of the harvest rates in the inside fisheries. These correlations make it difficult to infer what effect future modifications will have on the performance of the model.

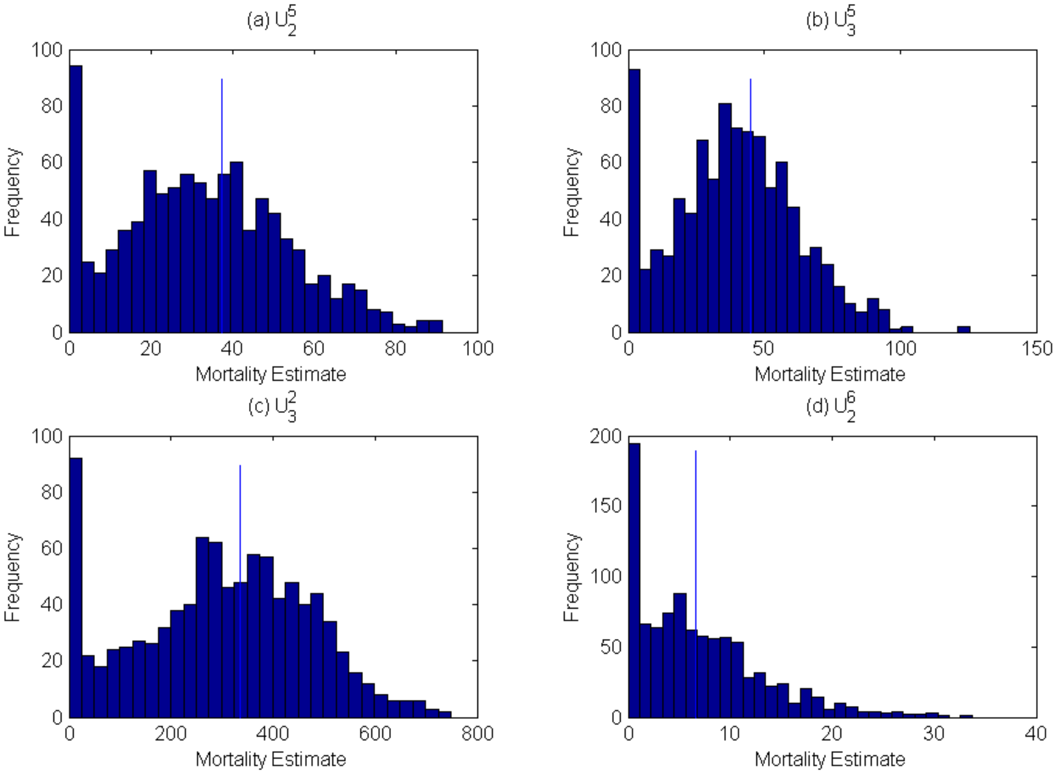


Appendix Figure 2-5. Scatterplots of movement model parameters estimates.

The parameter estimates from these 969 data sets were used to calculate age-specific unmarked mortalities in each of the four modeled mark-selective fisheries. In general, estimates of unmarked mortalities in mark-selective fisheries were centered about their true values (the bias was near 0; Appendix Table 2-9; Appendix Figure 2-6 a and b). However, model-based estimates were typically more variable than they would have been if the mortalities could have been directly sampled (Appendix Table 2-9). Fishery/age combinations for which a large number of mortalities were expected were particularly poor, as were the terminal area fishery estimates of unmarked mortalities (Appendix Figure 2-6 c and d). Additionally, the large number of 0 estimates for *sfm* led to a large number of estimated unmarked mortalities equal to 0 for all of the mark-selective fisheries (Appendix Figure 2-6). These 0 estimates were largely responsible for the large negative bias observed in the outside mark-selective fishery mortality estimates.

Appendix Table 2-9. Statistical Properties of the Movement Model Mortality Estimates

Mortality Estimate	Estimated Bias (# fish)	Estimated Variance (# fish^2)	MSE = B^2+ Variance (# fish^2)	Ratio MSE/Var using Direct Sampling
U_2^2	-3.83	360.85	375.54	2.61
U_3^2	-35.27	29345.30	30589.09	22.80
U_4^2	-17.27	9320.85	9619.26	12.98
U_5^2	1.09	240.37	241.56	2.92
U_2^3	-1.32	58.53	60.27	0.56
U_3^3	-2.35	143.90	149.42	0.80
U_4^3	-3.89	390.53	405.65	1.31
U_5^3	-0.61	22.96	23.33	0.76
U_2^5	-4.71	417.90	440.11	1.30
U_3^5	-6.27	528.89	568.17	1.40
U_4^5	-9.41	1141.24	1229.71	2.02
U_5^5	-3.62	93.94	107.05	0.84
U_2^6	0.35	38.53	38.65	1.95
U_3^6	8.48	2657.25	2729.14	16.44
U_4^6	16.89	8412.58	8697.88	31.95
U_5^6	6.65	2232.06	2276.25	15.48



Appendix Figure 2-6. Distribution of unmarked mortality estimates: (a) age 2 in fishery 5 (inside after migration), (b) age 3 fishery 5 (inside after migration), (c) age 2 fishery 3 (outside) and (d) age 2 fishery 6 (terminal fishery). The vertical line gives the true value.

Conclusions regarding the movement model

The tests conducted on the movement model offer some promise regarding the mathematical viability of the model. The model does appear to be capable of estimating unmarked mortalities in mark-selective fisheries – although the inaccuracy and imprecision of some of the estimates may be too high for management needs. The large number of data sets resulting in one or more parameter estimates at the limits of their biological range (e.g., *sfm* = 0 or *d* =1) is problematic and may suggest a problem with the numerical routine used to minimize the objective function. In addition, the optimizer did not obtain a solution for roughly 3% of the data sets. Further investigation of the numerical properties of the movement model would be required in order to improve the performance of the movement model.

If these problems could be solved, then further tests would still need to be conducted to determine model performance with data sets generated under more realistic assumptions. For example, simulations that allowed certain population processes (e.g., movement rates, harvest rates, and natural mortality rates) to be stochastic would be required. The model would also need to be tested to determine whether or not its performance is robust to various assumption violations. Therefore, data sets would need to be generated under conditions that differ from the population dynamic model assumed by the movement model (e.g., using bi-directional movement or altering the timing of movement between regions in relation to fisheries).

In addition, it should be noted that to be useful in practice, a different movement model would need to be developed for each indicator stock intercepted by any preterminal mark-selective fishery. These models would most likely be substantially more complex than the model described and evaluated in this report. Furthermore, given the paucity of data from which one can infer migration patterns, these stock-specific models are likely to be an over simplistic representation of the real population dynamics. Therefore, analyses that examine the robustness of the model to assumption violations would be extremely important.

The movement model is appealing because of its potential to estimate several important parameters for fisheries management, including harvest and *sfm* rates. Therefore, continued development of the model could warrant consideration. However, the SFEC recognized that a considerable time investment would be required in order to fully develop and test the model. Furthermore, the prospect for success appeared to be fairly limited, given the performance of the model under the relatively simplistic scenarios considered to date.

Appendix Three. Variance formulas for the different DIT estimation methods

The variance formulas contained in this appendix have been determined using the delta method (assuming that covariance terms are negligible). These variance formulas account for uncertainty due to sampling landed catch for tags, but they ignore all sources of process error. The variation associated with realized harvests of fish offers one example of process error. In non-selective fisheries, marked and unmarked fish would be expected to have equal harvest rates. However, realized harvest rates will differ slightly due to the random process of fish encountering gear.

It is important to point out that the different estimators will be affected by process error in different ways. For example, traditional estimates of mortalities obtained from directly sampling landed catch are not affected by the process error described above. For the PR estimator, however, the variation in harvest rates of the marked and unmarked fish will affect the resulting estimate of λ obtained from the non-selective fishery and hence will increase the uncertainty surrounding the unmarked mortality estimate. Similarly, the equal marine survival estimate of unmarked mortalities will be affected by natural variation in survival rates between the DIT groups (note that the PR method will not be affected by this process error).

In general, the uncertainty associated with process error is likely to be smaller in magnitude than the variance associated with sampling the catch for tags. However, ignoring process error will underestimate the uncertainty in the unmarked mortality estimates. Therefore, while the variance formulas presented in this appendix provide estimates of the uncertainty in unmarked mortalities in mark-selective fisheries due to sampling landed catch, in many cases one should also conduct a sensitivity analysis to assess the degree of uncertainty that may result from process error or assumption violations. In addition, simulation approaches (like that of Section 4.2) are extremely useful for examining the properties of various estimators as process error can be included in a straightforward manner.

EMS Method:

Assuming that escapement is sampled at 100%, the variance of the unmarked mortality estimate is give by:

$$Var\left(\sum_{f\in SF}\hat{U}_a^f\right) = \left(\lambda^{Rel}\right)^2\left[\sum_{f\in SF} Var\left(\hat{M}_a^f\right) + \sum_{f\in NSF} Var\left(\hat{M}_a^f\right)\right] + \sum_{f\in NSF} Var\left(\hat{U}_a^f\right) \qquad \textbf{(A-1)}$$

Assuming escapement is sampled at less than 100%:

$$Var\left(\sum_{f\in SF}\hat{U}_a^f\right) = \left(\lambda^{Rel}\right)^2\left[\sum_{f\in SF} Var\left(\hat{M}_a^f\right) + \sum_{f\in NSF} Var\left(\hat{M}_a^f\right) + Var\left(\hat{E}_a^M\right)\right] + \sum_{f\in NSF} Var\left(\hat{U}_a^f\right) + Var\left(\hat{E}_a^U\right) \qquad \textbf{(A-2)}$$

The above variance formulas ignore process error associated with the survival of marked and unmarked fish. Even though, on average, marked and unmarked fish have equal survival rates, the realized survival rates in any given year may differ slightly; this error is due to the binomial sampling process associated with individual survival. In addition, the above formulas ignore that λ^{Rel} is itself an estimate. Ignoring this source of variability will result in an overly-optimistic estimate of the variance of $\sum_{f\in SF} \hat{U}_a^f$. If the variability associated with λ^{Rel} is known, then this variability can be accounted for by adding the term $\left(\sum_{f\in SF} \hat{M}_a^f + \sum_{f\in NSF} \hat{M}_a^f + \hat{E}_a^M\right)^2 Var(\hat{\lambda}^{Rel})$ to equations (A-1) and (A-2).

EER Method:

To simplify the notation in the following section, Appendix Table 4-1 describes which fisheries are included in the collection of fisheries used in the variance equations for the EER method.

Appendix Table 4-1. Definitions of the collections of fisheries used in the sums in the EER variance equations.

Fishery Group	Description
F_1	all non-selective fisheries used to estimate λ
F_2	all fisheries not included in F_1
F_3	all non-selective fisheries not included in F_1

Assuming that escapement is sampled at 100%, and:

$$Var\left(\sum_{f\in SF} \hat{U}^f\right) = \left\{ \frac{E^M + \sum_{f\in F2} \hat{M}^f}{\sum_{f\in F1} \hat{M}^f} \right\}^2 \sum_{f\in F1} Var\left(\hat{U}^f\right) + \left\{ \frac{\sum_{f\in F1} \hat{U}^f \left(E^M + \sum_{f\in F2} \hat{M}^f\right)}{\left(\sum_{f\in F1} \hat{M}^f\right)^2} \right\}^2 \sum_{f\in F1} Var\left(\hat{M}^f\right) + \tag{A-3}$$

$$\left\{ \frac{\sum_{f\in F1} \hat{U}^f}{\sum_{f\in F1} \hat{M}^f} \right\}^2 \sum_{f\in F2} Var\left(\hat{M}^f\right) + \sum_{f\in F3} Var\left(\hat{U}^f\right)$$

where the definitions of F_1, F_2, and F_3 are given in section 2.

Assuming escapement is sampled at a rate less than 100%:

$$Var\Big(\sum_{f\in SF}\hat{U}^f\Big)=\left\{\frac{\hat{E}^M+\sum_{f\in F2}\hat{M}^f}{\sum_{f\in F1}\hat{M}^f}\right\}^2\sum_{f\in F1}Var\left(\hat{U}^f\right)+\left\{\frac{\sum_{f\in F1}\hat{U}^f\,(\hat{E}^M+\sum_{f\in F2}\hat{M}^f)}{\left(\sum_{f\in F1}\hat{M}^f\right)^2}\right\}^2\sum_{f\in F1}Var\left(\hat{M}^f\right)+$$

$$\left\{\frac{\sum_{f\in F1}\hat{U}^f}{\sum_{f\in F1}\hat{M}^f}\right\}^2\sum_{f\in F2}Var\left(\hat{M}^f\right)+\left\{\frac{\sum_{f\in F1}\hat{U}^f}{\sum_{f\in F1}\hat{M}^f}\right\}^2\sum_{f\in F2}Var\left(\hat{E}^M\right)+\sum_{f\in F3}Var\left(\hat{U}^f\right)+Var(\hat{E}^U)$$

(A-4)

The above variance formulas ignore the variance associated with the fishing process. In step 2 of the method, the λ is estimated assuming that the exploitation rates on marked and unmarked fish in all non-selective fisheries before the first mark-selective fishery are equal. However, the estimated exploitation rates for marked and unmarked fish will differ because of two sampling processes: 1) sampling associated with the harvest of fish (a harvest rate of 50% will not likely result in a catch that is composed of half marked and half unmarked fish; therefore, although the exploitation rates for marked and unmarked fish may be equal on average, they are likely to vary slightly in any given year); and 2) sampling landed catch for tags. The variance formulas given by (A-3) and (A-4) only account for the uncertainty associated with sampling the landed catch for tags, ignoring process error associated with the harvest of marked and unmarked fish.

Terminal Method:

Assuming that escapement is sampled at 100% and there is only one terminal fishery:

$$Var(\hat{U}_a^{SF})=\left\{\frac{E_a^U\,E_a^M\,sfm}{\left[E_a^M+\hat{M}_a^{SF}(1-sfm)\right]^2}\right\}^2 Var(\hat{M}_a^{SF}) \qquad \textbf{(A-5)}$$

Assuming that escapement is sampled at less than 100% and there is only one terminal fishery:

$$Var(\hat{U}_a^{SF}) = \left\{ \frac{E_a^U E_a^M sfm}{\left[E_a^M + \hat{M}_a^{SF}(1-sfm)\right]^2} \right\}^2 Var(\hat{M}_a^{SF}) + \left\{ \frac{\hat{M}_a^{SF} sfm}{\hat{E}_a^m + \hat{M}_a^{SF}(1-sfm)} \right\}^2 Var(\hat{E}_a^U) +$$

$$\left\{ \frac{\hat{M}_a^{SF} \hat{E}_a^U sfm}{\left[\hat{E}_a^m + \hat{M}_a^{SF}(1-sfm)\right]^2} \right\}^2 Var(\hat{E}_a^M)$$

(A-6)

If there is both a terminal mark-selective fishery and a terminal non-selective fishery (both simultaneously harvesting from the same pool of fish), the formulas below apply.

Assuming escapement is sampled at 100%:

$$Var(\hat{U}^{SF}) = \left\{ \frac{(E^U + \hat{U}^{NSF})(E^M + \hat{M}^{NSF})sfm}{\left[E^M + \hat{M}^{NSF} + \hat{M}^{SF}(1-sfm)\right]^2} \right\}^2 Var(\hat{M}^{SF}) + \left\{ \frac{(E^U + \hat{U}^{NSF})\hat{M}^{NSF} sfm}{\left[E^M + \hat{M}^{NSF} + \hat{M}^{SF}(1-sfm)\right]^2} \right\}^2 Var(M^{NSF}) +$$

$$\left\{ \frac{\hat{M}^{NSF} sfm}{E^M + \hat{M}^{NSF} + \hat{M}^{SF}(1-sfm)} \right\}^2 Var(\hat{U}^{NSF})$$

(A-7)

Assuming that escapement is sampled at less than 100%:

$$Var(\hat{U}^{SF}) = \left\{ \frac{(E^U + \hat{U}^{NSF})(E^M + \hat{M}^{NSF})sfm}{\left[E^M + \hat{M}^{NSF} + \hat{M}^{SF}(1-sfm)\right]^2} \right\}^2 Var(\hat{M}^{SF}) + \left\{ \frac{(E^U + \hat{U}^{NSF})\hat{M}^{NSF} sfm}{\left[E^M + \hat{M}^{NSF} + \hat{M}^{SF}(1-sfm)\right]^2} \right\}^2 Var(M^{NSF})$$

$$+ \left\{ \frac{\hat{M}^{NSF} sfm}{E^M + \hat{M}^{NSF} + \hat{M}^{SF}(1-sfm)} \right\}^2 Var(\hat{U}^{NSF}) + \left\{ \frac{\hat{M}^{SF} sfm}{\hat{E}^m + \hat{M}^{NSF} + \hat{M}^{SF}(1-sfm)} \right\}^2 Var(\hat{E}^U) +$$

$$\left\{ \frac{\hat{M}^{SF}(\hat{E}_a^U + \hat{U}^{NSF})sfm}{\left[\hat{E}^m + \hat{M}^{NSF} + \hat{M}^{SF}(1-sfm)\right]^2} \right\}^2 Var(\hat{E}^M)$$

(A-8)

The above formulas ignore process error associated with the fishing process (the harvest rate of marked fish is assumed to be exactly equal to the encounter rate for the unmarked fish). In addition, these formulas do not account for the potential bias due to using the wrong *sfm*. Given the variability of *sfm* estimates obtained in various research studies (STT 2000), one can expect that the assumed *sfm* will differ from the true realized *sfm* value in the mark-selective fishery. This difference will cause a bias in the estimate of unmarked mortalities and unfortunately there is no way to determine the magnitude or direction of the bias. Therefore, when using the TERM method one should conduct a sensitivity analysis to determine the effect of using the wrong *sfm*.

Paired-Ratio Estimate:

The approximate variance of the PR estimate is given by:

$$Var(\hat{U}^{SF}) \approx \left(\hat{M}^{SF}\right)^2 sfm^2 \cdot Var(\hat{\lambda}^{NSF}) + (\hat{\lambda}^{NSF})^2 sfm^2 \cdot Var(\hat{M}^{SF}) \qquad \textbf{(A-9)}$$

with

$$Var(\hat{\lambda}^{NSF}) \approx \left(\frac{1}{\hat{M}^{NSF}}\right)^2 Var(\hat{U}_a^{NSF}) + \left(\frac{\hat{\lambda}^{NSF}}{\hat{M}^{NSF}}\right)^2 Var(\hat{M}^{NSF}) \qquad \textbf{(A-10)}$$

The above formulas ignore process error associated with the harvest of marked and unmarked fish (the realized harvest rates of marked and unmarked fish are assumed equal). In addition, the above formulas do not account for the potential bias due to using the wrong *sfm*. As with the TERM method, one should conduct a sensitivity analysis to determine the effect of using the wrong *sfm*.