IEAB Independent Economic Analysis Board

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Cost-Effectiveness of Fish Tagging Technologies and Programs in the Columbia River Basin[1]

Independent Economic Analysis Board
Fish and Wildlife Program
Northwest Power and Conservation Council

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Executive Summary

Fish tagging and marking play important roles for stock assessment, research, management, and recovery efforts for salmonid and other fishes in the Columbia River Basin (CRB). Current fish tagging programs in the CRB include a large set of varied and complex activities, aimed at addressing dozens of management questions involving multiple objectives, multiple species, and differing spatial and temporal scales and geographic domains. Specific tagging programs involve various government agencies and non-governmental entities that overlap and intersect in terms of their interests, responsibilities, and funding. Fish tagging generates information on over one hundred "indicators" used to address a wide range of management questions. The total cost of these programs in 2012 was about $70 million.

This report summarizes the efforts of the Independent Economic Advisory Board (IEAB) to evaluate the cost-effectiveness of CRB fish tagging programs. Those efforts include: a) development and application of a Fish Tagging (FT) mathematical programming model as a tool for evaluating the cost effectiveness of fish tagging, and b) observations and insights gained from the model, as well as from the Fish Tagging Forum and Council staff.

The analyses described in this report reflect findings of an exploratory examination of how a model of this kind can contribute to fish tagging programs. Our observations are both general and specific. One general observation is that fish tagging in the CRB is complex scientifically, technologically, administratively and jurisdictionally. The many sources of overlap, complementarity and spillover represent some of the ways that achieving cost-effectiveness is not straightforward or obvious. The main findings of the study are:

- The marginal (incremental) cost of generating valid indicators needed to answer management questions varies greatly across locations, subbasins, and species. Indeed, the marginal cost of augmenting detections by one fish can be zero in some cases and hundreds or even thousands of dollars in others. Similar results were found for PIT detections for adults and juveniles, as well as for harvest recoveries.

- The FT model was used to evaluate the differences in cost between coded-wire tags and genetic marking for harvest indicators. Despite some cost advantages in tagging and other qualitative advantages, under current conditions, the model suggests that high sampling and lab costs for genetics makes it more expensive than coded-wire tags (CWT) for most stocks. Genetic marking, however, generates data that has qualitative advantages over CWT data, and may have advantages over CWT in some situations. For example, CWT is not cost-effective for monitoring harvests of wild stocks and genetic marking may have cost advantages in basins with few non-target fish in the fishery, such as the Snake River basin.

- To achieve cost-effectiveness, and also to maximize program effectiveness, there is a need for a more centralized and coordinated management program aimed squarely at "rationalizing" (achieving cost-effectiveness and program effectiveness). We see a need for "rationalization" of fish tagging programs basin-wide, where by "rationalization" we mean organizing according to principles of management in order to increase efficiency. Current programs are fairly decentralized, and yet positive spillover effects and coordination benefits exist at many levels. Taking advantage of wide-ranging mutual benefits represents a complex coordination problem. A rationalization program could both improve program efficiency and bring about cost savings at the same time.

- It is generally difficult to answer the "fair share" question (Who should pay for what share of the fish tagging activities?) using objective information alone. This is the case because of: a) the complex spillovers and mutual benefits in tagging and detection actions, b) the strong interdependencies for generating and using data indicators and addressing management questions, c) the complex legal, jurisdictional, and institutional dimensions of responsibility and accountability that characterize relationships between BPA, the Council, the tribes, the states, federal laws, and international agreements, and d) subjective opinions regarding importance, responsibility, and appropriate baselines.

Finally, the initial analyses described in the report give a strong indication that the programming model developed for the study could serve a valuable role in promoting future improvements in fish tagging cost effectiveness and program effectiveness. Indeed, a refined version of the current model could play a key role in the kind of rationalization process being recommended, although the results presented in this report barely scratch the surface of what is possible with the FT model. Many additional issues can be address by examining results from the model, and scenarios can be run to evaluate "what if" questions related to costs, detection probabilities, fish populations, hatchery operations, allocation of budgets and responsibilities, etc.

The kinds of cost metrics that are needed as the basis for making decisions about how to allocate scarce resources for fish tagging cannot be found in project or agency budgets, but rather require a model like the one utilized here, which recognizes and takes account of binding constraints, economies of scale, and spillover effects (sharing data), all of which have sizable effects on questions of cost effectiveness.

I. Introduction

Fish tagging and marking play important roles for stock assessment, research, management, and recovery efforts for salmonid and other fishes in the Columbia River Basin (CRB). Data from tagging are critical for effective decision-making. Fish of various species and stocks are tagged to obtain data on their numbers, harvest rates, behavior, habitat use, mortality rates, as well as the success of hatchery and other enhancement programs. Current fish tagging programs in the CRB include a large set of varied and complex activities aimed at addressing dozens of management questions involving multiple objectives, multiple species, and differing spatial and temporal scales and geographic domains. Specific tagging programs involve various government agencies and non-governmental entities that overlap and intersect in terms of their interests, responsibilities, and funding. Fish tagging generates information on over one hundred "indicators" that are used to address a wide range of management questions. The total cost of these programs in 2012 was about $70 million which makes cost-effectiveness, in addition to program effectiveness, an important goal. Program effectiveness means achieving the science-based objectives of the program; cost effectiveness involves achieving the objectives at the lowest cost. Achieving both cost-effectiveness and program effectiveness for such a complex program is challenging.

This report summarizes our efforts to evaluate the cost-effectiveness of CRB fish tagging programs. Those efforts include: a) development and application of a mathematical model as a tool for evaluating the cost effectiveness of fish tagging, and b) observations and insights gained from the model, as well as from our interactions with the Fish Tagging Forum and Council staff.

The study was timed to take advantage of the parallel effort in the Fish Tagging Forum, an in-depth 18-month process chartered by the Northwest Power and Conservation Council (Council) to evaluate fish tagging activities and their cost-effectiveness and program effectiveness (see www.nwcouncil.org/fw/tag/home/). Having these two activities occur more or less simultaneously has made it possible for the IEAB to benefit from and work cooperatively with the Fish Tagging Forum. The findings of the current study, however, are primarily based on development and use of a mathematical programming model of the CRB system as a tool to evaluate cost-effectiveness.[2]

Although our Fish Tagging (FT) model represents a simplified version of fish tagging in the CRB, it provides insights on a number of questions that would not be possible without such a tool. For each "run" the model optimizes by finding the least-cost way to satisfy a given set of information or "indicator" requirements. The model output includes a wide range of useful information, including economic measures of the tradeoffs and complementarities in the system. The FT model helps to focus attention on the costs and requirements to generate indicators necessary to address a specific management question. For example, to estimate a smolt-to-adult ratio (SAR) at a desired level of precision (e.g., by detecting 100 adults at Lower Granite Dam), the model estimates the number of juveniles that must be tagged, the costs involved, and the incremental cost (marginal cost) of increasing the number of detections.

[2] The FT model is a non-linear mathematical programming model. It uses GAMS optimization software, and was designed to include economic, biological, and engineering components of the CRB system. The model programming was carried out by Greg Latta, a senior faculty research assistant at Oregon State University's School of Forestry.

II. Background

The Council is charged by the Northwest Power Act to develop a fish and wildlife program (FWP) for the Columbia River Basin that effectively achieves its biological objectives with minimum economic cost.

Fish tagging and marking play important roles for stock assessment, research, management, and recovery efforts for salmonid and other fishes in the Basin. Data from tagging are critical for effective decision-making. Fish of various species and stocks are tagged to obtain data on their numbers, harvest rates, behavior, habitat use, mortality rates, as well as the success of hatchery and other enhancement programs. Information obtained from tagging efforts influence decisions on hydrosystem management such as water spill at dams and fish transport; harvest regimes in the ocean and river; hatchery practices; and endangered species risk assessment (ISRP/ISAB 2009). Investigations using tagged fish typically involve collecting, tagging, releasing, and recapturing or detecting fish, and analyzing data to estimate vital statistics. The design of tagging programs requires establishing effective sample sizes for groups to be tagged and developing capture or tag detection methods to recover sufficient numbers of tagged individuals for statistical purposes" (ISRP/ISAB 2009).

During the Council's 2010 and 2011 review of all "Research Monitoring Evaluation and Artificial Production" projects the Fish and Wildlife Committee requested staff develop a charter for a facilitated workgroup to address costs, efficiencies and gaps for all fish tagging efforts that take place under the FWP, including expense, capital and reimbursable programs.

In their 2009 Tagging Report, the ISRP and ISAB stated that cost-effectiveness is "an aspect of tagging that would be best addressed as part of the Fish and Wildlife Program amendment and program-level decision process" and that the "Independent Economic Advisory Board (IEAB) could collaborate with the ISAB or ISRP on evaluating the cost effectiveness of alternative tagging technologies," adding that program effectiveness is "as important as cost effectiveness."

During the Council's 2010/11 review of all Research Monitoring Evaluation and Artificial Production projects, the Fish and Wildlife Committee requested that staff develop a charter for a facilitated workgroup to address costs, efficiencies and gaps for all fish tagging efforts under the FWP, including expense, capital and reimbursable programs. This led in July 2011 to the charter of the Fish Tagging Forum (Forum), to address the cost effectiveness and the program effectiveness of tagging under the FWP as well as other issues discussed in the ISAB/ISRP report.

The Fish Tagging Forum has been meeting regularly since November 2011 with a stated goal "to address costs, efficiencies and gaps for all fish tagging efforts that take place under the FWP, including expense, capital and reimbursable programs." The Forum is compiling information on the following types of tagging technologies: Coded Wire Tags, PIT Tags, Radio Tags, Acoustic Telemetry, Data Storage Tags, Genetic Markers, Otolith Thermal Marks, and Natural Marks and Tags (Otoliths, Scales, and Parasites). The Forum has also developed a framework to identify and organize different management categories, management questions, and relevant indicators. For each of these indicators/questions, relevant forums, responsibilities, and interests have been identified, as well as the relevant tagging technologies.

III. Analytical Framework

The 2009 Tagging Report and other Council and FWP documents include references to "cost-effectiveness" and "program effectiveness." In the Fish Tagging Forum, the topic of "fair share" has been raised. Before describing the FT model and results, we provide here some context and discussion of these concepts.

A. Cost effectiveness

The cost-effectiveness of the CRB fish tagging programs can be approached from several perspectives. Generally speaking, cost-effectiveness analysis is a form of economic analysis that compares alternative ways of achieving a specific outcome, and evaluates the relative cost of the different alternatives. If the outcome for each alternative is identical, but the costs differ, then the most cost-effective approach will be the one with the lowest cost. If the outcomes for each alternative are qualitatively different, or if the approaches have multiple attributes, then it becomes difficult to apply cost-effectiveness analysis in its simplest form, but there are additional ways to account for multiple objectives or multiple types of costs (e.g., a weighted index).[3]

Cost-effectiveness analysis is "built-in" to the FT model given the way it is constructed. Rather than attempting to monetize both benefits and costs (and have the model maximize net benefits), a set of fixed required outcomes (required levels of detection/recovery) are introduced in the model as constraints, and the model searches for the lowest cost way of meeting those requirements.

The model "makes choices" to the extent that there are alternative ways to satisfy the requirements, and that they differ in terms of cost. In this case the model can minimize costs by: a) selecting the lowest cost tag technique to produce a given indicator, b) inserting just the right number of tags necessary to satisfy the required levels of detections/recoveries at a given location (but no more), and c) taking advantage of situations where costs can be shared between multiple activities, or where data sharing or other positive spillover effects are possible. In this way, the information generated to answer management questions effectively will be achieved at the lowest cost.

B. Program effectiveness

Program effectiveness involves achieving the science-based objectives of the program. One way to understand the difference between cost-effectiveness and program effectiveness is to recognize that cost-effectiveness analysis typically takes as given the desired outcome or goal

[3] At the other end of the spectrum is benefit-cost analysis, which requires putting a value on all outcomes in addition to all costs. For activities where the outcomes are not easily quantified monetarily, this framework is problematic and should be avoided.

(such as a desired level of precision in estimating a smolt-to-adult ratio). By contrast, program effectiveness may overlook cost considerations and instead focus exclusively on whether the desired outcomes are achieved. Neither program effectiveness nor cost effectiveness answers the question of whether the benefits of achieving the desired outcome were worth the costs.

If a program's effectiveness involves meeting a threshold level of information, then the kinds of tradeoffs frequently at the center of economic (benefit-cost) analysis do not apply to questions about program effectiveness. If the value of information varies with the quantity of information, then tradeoffs may come into play when evaluating "total program effectiveness." This would be the case if the effectiveness of the total program were determined by allocating scarce resources to a range of activities that generate data on fish. For example, if 100 tagged recoveries produced an estimated indicator with a 10% coefficient of variation (CV), but 150 tagged recoveries would have a 5% CV, the question of whether the improved CV is desirable would appear to involve both cost-effectiveness and program effectiveness components, and with many indicators for which similar questions arise, "total program effectiveness" will require making judgments to raise or lower tagging or sampling so that the best overall set of data is generated within the budget.

So these two concepts often overlap and frequently there is a need to undertake evaluations that recognize tradeoffs for both cost and program effectiveness. The ISAB/ISRP recognized that their technical review was "not designed to address cost effectiveness" (ISAB/ISRP 2009-1). The ISAB/ISRB report continued by suggesting that if "project budgets appear unreasonable, either too large or too small, concern is often expressed, although this is not a technical review task. This is an aspect of tagging that would be best addressed as part of the Fish and Wildlife Program amendment and program-level decision process… … As important as cost effectiveness is program effectiveness…." The general judgment being made is a sensible one, but the implicit definition of cost-effectiveness is somewhat misleading.

Clarification on this point is worth emphasizing: Judging whether an individual project's budget is too low or too high would appear to involve benefit-cost analysis, where both benefits and costs are quantified using a common metric such as dollars. Since the "value" of a project outcome is not generally monetized, this kind of judgment is unlikely to be possible. Cost-effectiveness analysis can, however, be undertaken as described above, either by comparing alternative means to a specific end, or by expanding the framework somewhat to make comparisons of cost where, at a minimum, different outcomes can be ranked or compared qualitatively. Whether the overall budget for fish tagging programs is too high or too low will have multiple dimensions including judgments about the value or usefulness of the data (for example to promote recovery of fish populations) as well as legal obligations, and regulatory requirements.

IV. The fish tagging model and results

The Fish Tagging (FT) model is a non-linear programming model. The structure is that of a network model (such as transportation or shipping models) that optimizes an objective function (minimize cost) subject to a set of network characteristics, model parameters, unit costs, and constraints. The FT model network reflects the river segments and fish populations of the CRB, characterizing a representative set of wild and hatchery salmon and steelhead life cycles under recent conditions, normalized to a one-year scale for the number of smolts, their juvenile migrations, passage at dams, ocean survival, and adult in-river migrations. Tagging efforts for a variety of other fish species such as resident trout, lamprey and sturgeon are not included in the model.

The model is “required” to fulfill a set of fish tagging goals, which are introduced into the model as constraints that require set levels of fish detections or recoveries for specified species, subbasins of origin, and detection locations. To satisfy these detection requirements, hatchery and wild fish may be tagged at release sites or other locations in sufficient numbers so that they will be detected at another location at the required detection levels. The types of tags included in the model are PIT tags, coded wire tags (CWT), and genetic markers (GEN) of two types, Population Based Tagging (PBT) and Genetic Stock Identification (GSI). Other tag types such as acoustic, radio, and otolith, were not included in the model due to the complexity of doing so, and because they tend to have specialized and unique uses that could not be addressed by alternative tag types. Because of this, additional insight from the model regarding cost effectiveness would be limited.

The model network is a simplified version of the Columbia River system, including 64 distinct river segments within the basin, as well as four ocean zones (Alaska (AK), British Columbia (BC), the coastal and inland waters of Washington State (WA), and the Oregon coast (OR)) where fish migrate and are subject to harvest exploitation before returning to their natal stream or release site. The geographic extent of the model and details of the network of river segments, fish populations and other elements are described in Appendix A, along with documentation of the empirical basis for the model’s parameters and assumptions.

The “reference case” scenario for the FT model is one where detection requirements have been established based on two types of information. First, data were examined on the observed number of detections and recoveries over a ten year period for both PIT and CWT. Second, the relationship between detections, releases, and the estimated coefficient of variation (CV) for a metric such as survival rate was used to establish the desired number of detections at a given location that would achieve the desired level of precision (see Appendix B). In most cases the detection requirements introduced in the model correspond to achieving a 10% CV. The number of detections necessary to achieve this 10% CV is typically 100 detections (see Paulsen 2005). This approach was used to establish detection requirements throughout the basin at all locations (mainly dams where juvenile and adult PIT detections occur) where the average level of observed detections also met or exceeded 100. For harvest recoveries in ocean and in-river fisheries, a similar approach was taken, where between 10 and 200 tag recoveries (of fish from specific subbasins of origin) were required in each of the five harvest zones (AK, BC, WA, OR and in-river). The level of required recoveries was based on a) the observed 10-year average number of recoveries by species and zone, and b) the proportion of fish caught in each zone emanating from each subbasin.

In addition to detection requirements, the model assigns costs to tagging and detection/recovery (see Appendix A for details). In order to meet the detection requirements, the model will tag, detect and recover fish, incurring those established costs. The algorithm in the model makes it possible for the model to find the lowest cost way to satisfy the set of detection requirements, established to represent the indicators needed to answer a range of management questions.

One "run" of the model generates a huge amount of information useful for evaluating CRB fish tagging programs. The model can be expected to achieve lower costs than we observe in the real world for at least five reasons: first, the FT model does not include some tag types (acoustic, radio tags, otolith) and some fish types. Second, the model operates with perfect information and predictability (no uncertainty). Third, it will find the least-cost way to satisfy the detection requirements; this means that not one "extra tag" will be inserted or sampled beyond the number necessary to satisfy the modeled requirements. Fourth, the number of required detections in the model's reference case scenario is lower than the number targeted in many current fisheries. Fifth, the model does not include some types of tagging costs, especially costs that are fixed, or invariant, with respect to the number and types of tags selected by the model. One example is the capital costs for PIT tag detectors. Since a decision to abandon PIT detectors at the major dams is not a plausible alternative for the model to consider, these costs are outside the model's choice set, and so the costs need not be included in the model explicitly. The magnitude of these costs (operating overhead, infrastructure, and maintenance) are considered separately below.

The model generates information on the cost-minimizing levels of tagging, detections, choice of tag type, cost of tagging, cost of detection and recovery, tag mortality, etc. In addition, the model generates "marginal costs" associated with each constraint such as the level of required detections. This metric, in particular, is valuable because it provide insight into the costs of achieving the desired precision or CV for a given indicator. In many cases these marginal costs will be zero, if the constraint is not binding. For example, juvenile detection requirements at Bonneville will sometimes be easily met because a much larger number of tagged fish need to pass Bonneville as juveniles in order for there to be 100 adult fish returning to Bonneville or other adult detection point.

A. <u>Reference case model results</u>

The reference case results are presented in Tables 1-7 below. They describe costs and levels of tagging lower than what is observed basin-wide. The model is able to satisfy all the detection requirements in the reference case by tagging 1.9 million smolts with PIT tags and inserting 7.25 million coded-wire tags. The total cost (for those costs included in the model) is $9.1 million when harvest tagging relies on CWT and $13 million when genetic tagging is used for harvest data.

The distribution of tagging levels among the four Regional Mark Information System (RMIS) regions also varies somewhat differently than the actual tagging numbers observed, as indicated in Table 1 for PIT tags. In the case of coded-wire tags, where the reference case model inserted 7.25 million CWTs, the actual number is about 29 million.[4] This could be due to a

[4] The low tagging and recovery levels in the model's reference case scenario do not appear to affect the cost comparison of CWT versus GEN. When harvest tag recovery requirements were doubled in the model, the resulting

variety of factors. Tagging rates for coded-wire tags are also lower in the model than what is observed; and this is likely due to several factors including: a) the precise efficiencies of an optimization model that has perfect information, b) the introduction of a set of lower (aggregate) recovery requirements in the model rather than those reflected across actual fishery management units or "strata," and c) the identification of opportunities for efficiency gains by eliminating unnecessary tagging. Replicating the exact levels of harvest detection requirements was not possible, in large part due to the unclear and varying way that harvest strata are defined.[5]

For the basins and species where CWTs are utilized, Table 2 suggests that the model's optimal tagging rates vary from 4% to 26%, which is lower than the observed levels. To some extent this reflects the higher recovery levels observed in practice compared to the recovery requirements which had a maximum of 200 even for cases where the observed levels were much higher. Alternative sets of detection or recovery requirements were introduced in the model (e.g., doubling or tripling the requirements) resulting in nearly proportional changes in tagging, sampling and cost.

As indicated above, one reason for the lower tagging and recovery levels in the model compared to what has been observed in the CRB in recent years is the ability of the model to tag just enough fish to satisfy a particular detection requirement, and not one fish more. In the CRB in recent years, however, management practices in most cases are not so well "fine-tuned" or coordinated that they adjust tagging levels to exactly satisfy specific indicators at the desired levels of precision. To some extent it is reasonable that tagging requirements in the model would be exceeded in the real world, given uncertainties and the year-to-year variability in survival rates and populations. But it is unclear to what extent this kind of "margin of error" approach is being carried out explicitly with tagging decisions.

Given the realities of fish tagging technologies and the activities included in the model, the model does not have wide ranging choices where it might choose among many tag technologies across different subbasins, species or metrics. Indeed, to monitor migration and survival in the river system, there is no practical alternative to PIT tags and detections at major dams. Multiple detections without handling or killing the fish represents a large technical advantage of PIT tags over other technologies for generating certain kinds of indicators for addressing a range of management questions (juvenile survival, ocean survival, SAR). When using PIT tags, of particular interest is the level and cost of using these tags across species, regions, etc. In addition, a very useful indicator is the marginal cost for PIT detections (the cost

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CWT tagging and recovery levels rose to levels more similar to those observed in practice, but the relative cost of CWT versus GEN remained largely the same.

[5] Standard approaches to model validation are not possible in this case. The unit costs for tagging, sampling and recovery that are being assumed in the model were estimated based on actual budget and specific cost information as described in the appendix. However, the model minimizes the cost of achieving an explicit set of detection requirements. In practice there are no explicit system-wide detection requirements. The model's costs also represent costs for only a subset of fish tagging activities, excluding some tag technologies, excluding some species, excluding overhead costs and other elements of funded projects for which fish tagging may be only one element. As a result of these differences and limited information, no overall model validation is possible. One approach to model validation is sensitivity analysis; which was performed on several key model assumptions. This included testing the CWT/GEN cost comparisons when detection requirements were doubled. In future analyses it may be possible to perform validation tests on specific elements or subcomponents of the model.

of increasing the number of detections by one fish (e.g., from 100 to 101). Results of these kinds from the FT model reveal a number of important insights relevant to the question of cost-effectiveness:

i. First, many cells in these tables that could have a value are instead zero (blank, or omitted from the table). This means that these constraints are not binding. This is the case for detections at migration points where the number of tagged fish being detected exceeds the number (100) required. In many cases this is because in order to satisfy another detection requirement (e.g., Snake River adult survival at LGR), there are many more than the 100 needed at a location earlier in the life-cycle (e.g., Snake River juvenile fish detected at BON).

ii. The marginal cost of achieving an incremental increase in detections (for example to achieve a desired CV), varies significantly across species, locations, and between juveniles and adults. Juvenile detection costs vary from $30 to $60 per fish (where they are binding). Adult detections, by contrast, vary from $300 to $600 (where they are binding), with a few extreme values above $1,000. (It is likely that these extreme values represent cases where there were not enough hatchery fish (as assumed in the model) to tag, and so the model began tagging wild fish to satisfy the detection requirement.) There are also differences in marginal values for fish that are transported as show in Table 4 (here we required 200 detections for each group, to reflect the need for a transported group and control group comparison).

iii. Given the wide differences in the marginal cost of detection for different species, subbasins, and detection locations, there appear to be opportunities for improving cost effectiveness and program effectiveness. If all indicators have equal value for management purposes, then this evidence of large differences in marginal cost suggests that there are opportunities to increase cost effectiveness by reallocating tagging and recovery effort. If, however, some SAR indicators have a higher priority, are more important, than others, then paying higher marginal costs for those detections may be justified. But have those determinations been made? Have detections or indicators been ranked basin-wide so that costs can be apportioned accordingly? We are unaware of information to suggest that this is systematically done. Are there redundant or excess detections in some locations where changes could be made without jeopardizing the accuracy of important indicators? Information on these kinds of cost-saving decisions was not uncovered during our investigation. Would it be beneficial to evaluate the relative importance or value of different indicators (by species, subbasin, and detection location) by juxtaposing those priorities with these estimates of cost? Might there be substantial cost savings, or increased effectiveness, by undertaking this kind of evaluation? The evidence from the model suggests that a systematic comparison of marginal costs and priorities related to program effectiveness could lead to more effective programs and, at the same time, cost savings.

B. Harvest results

The growing use of genetic marking has raised questions about whether genetic marking could have cost advantages over coded-wire tagging for ocean harvest. In some ways, there would appear to be some significant advantages and costs savings. To evaluate this we ran our model with CWT as the only option to collect data on harvest recoveries, and then we ran the same model allowing only genetic marking (GEN). The results in terms of costs are shown in Tables 5 and 6 and numbers of fish tagged are shown in Table 7. For those costs that are counted by the model, the costs with GEN are more than double the costs for CWT. The overall result, both from the model findings, and from using a separate analytical approach described in Appendix B, is that genetic marking is not more cost-effective than CWT under current cost conditions, and for the goals that we modeled.[6] Genetic marking, however, can provide additional kinds of information that cannot be provided by CWT or other tag types, such as exact parental identification, and CWT does not appear to be cost-effective for wild fish. Moreover, in fisheries where few non-target fish are present (such as in the Snake River fisheries where returning adults are no longer mixed with fish from multiple other stocks), the cost of using GEN may be lower than the cost of using CWT. This conclusion can be demonstrated numerically using the relationships in Appendix B.

The reasons for this result are somewhat complicated: When tagging, GEN is cheaper than CWT per fish tagged or “marked” ($0.03 versus $0.18). For “sampling” harvested fish (where “sampling” means to handle the fish in order to “wand” in the case of CWT, or to take tissue in the case of GEN), the costs are similar, but likely somewhat lower for GEN because tissue samples can be taken from the first 100 fish encountered, whereas with CWT more fish (perhaps at more dispersed locations) will need to be tested with a wand for CWTs. We estimate average sampling to cost $17/fish encountered for CWT, $12/fish for GEN.[7] So GEN looks cheaper than CWT for tagging and sampling. The comparison changes, however, when we consider the lab costs required to “recover” information about the origin of the fish. There are two differences. First, the lab cost for CWT is much cheaper at $5/fish compared to $40 to genotype the fish. Second, with CWT we have a (partially) effective way to discriminate among fish sampled in the field: fish with no detectable CWT will not be sent to the lab, so no transportation or lab costs will be incurred for fish that do not have a CWT. By contrast, when using GEN, we have no information with which to discriminate, so all fish sampled would be sent to the lab, incurring $40/fish before learning whether or not the fish would help satisfy a detection requirement or not. With CWT, only fish containing a CWT will be sent to the lab. It is the cumulative cost of

[6] It would be impractical to collect harvest data using PIT tags for two reasons. First, harvested fish have generally been “gutted” in the boat so that the PIT tag will no longer be in the fish. Second, to tag the number of fish with PIT tags that are currently tagged with CWT (to achieve the desired level of recoveries) would cost over $100 million.

[7] The difference in sampling cost between CWT and GEN is an estimate based on a number of factors. Sampling costs will increase with the number of fish needing to be sampled, including travel and labor costs to visit and revisit marinas and other sites where harvested fish are landed in both commercial and recreational fisheries. With GEN, a sample from each fish encountered can be sent to the lab; in the case of CWT, fish are tested with a wand and only fish where the presence of a tag is detected will be sent to the lab. As a result, CWT sampling may involve more travel and labor cost to locate enough snouts with CWTs to send to the lab. These added search costs will differ by fishery type (in both commercial and recreational fisheries) and geography and the distances between landing locations. The costs used here are estimated to approximate averages for existing locations and recovery levels.

$40 lab fees to genotype large numbers of non-targeted fish that makes GEN more expensive than CWT, with its lower lab cost and ability to select only fish with CWTs to send to the lab.

Other advantages to collecting genetic information may be important for a variety of reasons including monitoring exploitation rates of wild fish at relatively low cost, or acquiring qualitatively different kinds of information about fish populations. Since the use of genetics for fish tagging is relatively new, costs may decline in the future.

The reference case results overall are based on a level of recovery requirements which were satisfied with tagging and sampling rates significantly lower than the 20% currently targeted in the region. The sampling and tagging levels are determined in the model, but were all below 10%. If we double or triple the levels of detection requirements in all of the fisheries, then we get model results with sampling rates around 20% (some lower, some higher) across the different fisheries. With these higher tagging, sampling and recovery rates, the cost comparisons remain the same: CWT costs are about half the costs of genetic tagging. The differential between the two tag types is smaller for the in-river fisheries.

As with the PIT tag analysis described above, we can evaluate the marginal cost of recovering one additional CWT (or genetic marker) in ocean harvests. To achieve one additional fish recovery, the model may "choose" to increase tagging levels, or sampling levels, which ever minimizes costs. Because there are fish of interest from many subbasins of origin, and there are wild fish and fish that are not from the Columbia Basin, the optimization problem is somewhat complex. Sampling fish will involve collecting fish in proportion to their occurrence in the fishery, which will include many fish that are not of interest (or at some point during the data collection process, sampling fish from subbasins where the detection requirement level has already been met).

The results shown in Table 8 indicate that these marginal costs (to achieve one additional fish recovered from a particular fishery) vary quite a lot across species and stocks. These marginal costs range from several hundreds of dollars per fish to several thousands of dollars per fish. There are a few extreme values (tens of thousands of dollars per fish) that may reflect unrealistic requirements in the model. This could be a situation where the number of fish from a given fishery is very small (as defined in the model), and yet the model is being asked to sample hundreds of (other) fish in the fishery in order to "find" one more tagged fish coming from, say, the Klickitat River (Coho) or the Lower Snake River (Fall Chinook).

Once again, however, these results strongly suggest that the marginal costs vary greatly across stocks and fisheries of interest, which raises the question of whether these differences are justified by the relative value or priority associated with these different indicators. If marginal costs are higher for satisfying certain detection or recovery requirements, then these differences should be based on corresponding differences in the relative importance or priority of those indicators.

If decisions about tagging and sampling are not being made with this kind of information at hand, then there are likely significant opportunities to improve efficiency by adjusting both tagging and sampling efforts to achieve the desired levels of recoveries, at the lowest cost.

Moreover, to the extent that fish from some stocks are tagged at high rates and recovered at levels that exceed those needed to accurately produce the indicators of interest, then these tagging and sampling levels may reflect “wasted resources” (excessive spending) for both the stocks that are excessively tagged, and for the level of effort in the lab that evaluates too many fish from one stock, in order satisfy the level of recoveries from another. There would appear to be significant possibilities for improved cost-effectiveness in this realm, given the widely varying marginal costs shown in Table 8.

It should be noted that the FT model has characterized harvest sampling and recovery in a way that is much simplified from the way it currently occurs. The model does not reflect the shared sampling and lab costs across state and national jurisdictions, nor have we tried to emulate the targets for sampling rates across strata, or tagging level thresholds that depend on hatchery size. Indeed, for the FT model most of these choices are endogenous outcomes that depend on costs.

V. Discussion

Our analysis has focused on salmon and steelhead and on four fish tagging technologies. A number of observations stand out. Fish tagging in the CRB is complex scientifically, technologically, administratively and jurisdictionally. The many sources of overlap, complementarity and spillover represent some of the ways that achieving cost-effectiveness is not straightforward or obvious.

A. Rationalization

The evidence suggests that to achieve cost-effectiveness, and also to maximize program effectiveness, a more concerted and coordinated management program should be aimed squarely at using scarce resources where they contribute toward answering the highest priority management questions. In many kinds of businesses, organizations and governments, a concerted effort to achieve such a goal is referred to as “rationalization.” The term “rationalization” can be defined as organizing an enterprise according to scientific principles of management in order to increase efficiency. The World Bank and IMF, for example, frequently refer to rationalization when promoting reforms that will reduce waste and improve the effectiveness in areas like public enterprises, government agencies, land use, or energy use.

The need for program-wide rationalization with fish tagging reflects, to some degree, the inherently high scope for mutual benefit from shared effort and cooperation with fish tagging. This reality is due to several factors including a) the geographic extent of the life-cycle of salmon and steelhead, b) the range and overlap of management questions, c) the intersecting jurisdictions and interests of the entities wanting to answer various management questions, d) the technical attributes of the different fish tagging technologies themselves, and e) the current confusing and opaque system of funding and financial accountability. As a result of these factors:

- The costs of collecting detection, sampling, and recovery data exhibit strong economies of scale making shared effort and sharing data highly desirable.

- The capital investment cost for PIT detection is very high, but the variable cost to detect an individual fish using this asset is near zero.
- Hatchery fish can be used as surrogates or "indicator stocks" for wild fish (to avoid the tagging mortality and higher cost of capturing and tagging wild fish).
- Fish transportation programs can take advantage of previously-PIT-tagged fish so that they don't have to tag as many fish specifically for transportation studies.
- Indicator quality and answers to management questions can sometimes be augmented by drawing on different types or sources of data.
- Genetic data involves large economies of scale and scope making it essential to establish region-wide databases.
- In many cases consistent, time-series data on indicators is needed, and this requires both coordination and stable funding.

The FT model results discussed above demonstrate that the cost of generating a particular indicator varies substantially from subbasin to subbasin and species to species, and that an outcome with too many or too few detections (compared to the number needed to achieve a desired level of precision) can be wasteful and cost-ineffective. Both of these observations suggest that decisions about fish tagging activities should be coordinated to take account of these costs as well as differences in program priorities.

Equalizing marginal costs across indicators will achieve cost-effectiveness only if the marginal values or priorities for those indicators are the same. Since it cannot be the case that all indicators have equal value toward answering management questions, some process by which priorities are ranked needs to be undertaken in order to at least consider adjustments or shifts in program efforts that may achieve greater success for high-value indicators while reducing excessive spending on low value indicators.

A process of ranking indicators and program effectiveness, and doing so in concert with information about costs and cost-effectiveness, would be a central part of a rationalization program. Although there is some coordination in fish tagging currently (e.g., with a finite budgets and required CV targets, costs and tradeoffs surely enter many decisions), the degree of decentralized decision-making and expenditures is not able to adequately take account of the many spillovers, mutual benefits, or the "big picture" for management questions.

Such an approach would recognize the following:

- Explicit estimates of cost need to be incorporated into tagging decisions, ones that are based on the marginal cost of generating a particular data point (a fish detection or recovery) rather than the cost of marking or sampling one fish, or the relative size of agency or tag-type budgets, or the accounts of funded projects. These dollar amounts rarely tell us anything about the cost-effectiveness of generating valuable data points at the desired level of precision that are needed to address specific management questions.

- A process is needed to evaluate and prioritize or rank, the relative importance of each fish tagging indicator on a species, run, basin of origin, detection/recovery location, and interval (e.g., annual versus bi-annual) basis.

- Ocean harvest tagging activities needs a process to evaluate and rank the importance of information about harvests across ocean locations, species and strata. Decisions about the level of tagging, sampling and recovery need to recognize and reflect the differences in cost for a marginal increase in the number of recovered tags. It cannot be the case that such an analysis would conclude that the most cost-effective program is one in which all fisheries are sampled at a 20% rate and where 17 tags is the cost-effective number to recover from all strata. The heterogeneity of costs, differences in survival, the density of non-target fish, and the spillovers when sampling fish caught in one fishery may recover data from multiple stocks of interest. All these factors suggest that there are significant differences in the cost effectiveness and program effectiveness that work against the use of uniform rules.

- A comprehensive approach to datasets and monitoring is needed. The PIT tag and coded-wire tag databases are not currently fully compatible so that analysis that would involve combining information is difficult. PIT and CWT data use different codes and different geographic areas to indicate fish release locations. There also does not appear to be a comprehensive assessment of the numbers of wild fish by subbasin and species. There are, however, two sources for partial estimates of wild fish populations, Columbia Basin Research, a program at the University of Washington, and the Northwest Fisheries Science Center (Zabel 2012).

B. Program levels and "fair share"

The aspects of an overall evaluation of fish tagging has (at least) three levels, but our analysis has addressed the first and partially explored the second. To be clear on what we have addressed, and what we cannot address, the following distinctions may deserve a recap:

Level 1: If a fixed set of indicators are given, the cost effectiveness analysis can in principle determine the least-cost way to achieve that goal. This would be relatively straightforward if data were available, including detailed cost relationships characterizing the types of economies of scale and spillovers described above. Cost-effectiveness analysis does not question the merits of the types and levels of required indicators.

Level 2: Where budgets are limited, and for an overall program that involves multiple indicators, there will be tradeoffs to make: all indicators cannot be produced at the most desired levels. In this situation, prioritization of indicators would be required to begin to evaluate how best to spend the limited budget to produce the "best" set of indicators. This level of analysis involves recognizing the benefits of indicators, but only in a relative sense, by ranking them.

Level 3: How much should be spent on fish tagging overall? If we know something about the cost of different ways to produce indicators, and we also have some sense of the value or priority of those indicators, but we don't have a way to judge the benefits of those indicators, individually or collectively in terms of their contribution toward restoring wild fish populations in the CRB, then we cannot answer this level 3 question: What is the optimal amount to spend on fish tagging? To answer this question would require benefit-cost analysis, where a value is placed on all benefits and all costs, and only those actions where benefits exceeded costs would pass the benefit-cost test (although, it is important to point out that comparing benefits and costs is typically just one input into decision making, especially when public resources are concerned, and there are considerations of equity, entitlements, and fairness to consider, and these are aspects of decision making that fall outside of benefit-cost analysis).

The approach being taken for cost effectiveness and for program effectiveness, especially when taken together, suggest that the criteria for decisions should be based on the merits of minimizing cost, but achieving the necessary outcome. But to the extent that the debates surrounding fish tagging now include the question of whether the overall level of spending is too high or too low, we are aware of no effort to quantify the dollar value of restoring wild fish populations, or the potential value of fish tagging programs toward achieving that goal, nor would there appear to be a systematic way to evaluate criteria that fall outside of the benefit-cost framework. Indeed, there would appear to be competing arguments and rationales for both higher and lower spending, and legal requirements about what must be done and what must not be done.

VI. Conclusions

Our findings include observations and recommendations that are both general and specific. Fish tagging in the CRB is complex scientifically, technologically, administratively and jurisdictionally. The many sources of overlap, complementarity and spillover represent some of the ways that achieving cost-effectiveness is not straightforward or obvious. The evidence suggests that to achieve cost-effectiveness, and also to maximize program effectiveness, a more concerted and coordinated management program aimed squarely at “rationalizing” (achieving cost-effectiveness and program effectiveness) is needed. We see a need for “rationalization” of fish tagging programs basin-wide, where by “rationalization” we mean organizing according to scientific principles of management in order to increase cost effectiveness and program effectiveness. Current programs are fairly decentralized, and yet positive spillover effects and coordination benefits exist at many levels. Taking advantage of wide-ranging mutual benefits represents a complex coordination problem. A rationalization program could both improve program efficiency and bring about cost savings at the same time.

A second general observation is that answering the “fair share” question (Who should pay for what share of the fish tagging activities?) is nearly impossible to answer in a concrete, quantitative way. This is the case because of: a) the complex spillovers and mutual benefits in tagging and detection actions, b) the strong interdependencies for generating and using data indicators and addressing management questions, and c) the complex legal, jurisdictional, and institutional dimensions of responsibility and accountability that characterize relationships between BPA, the Council, the tribes, the states, federal laws, and international agreements.

In terms of more specific results, the FT model illuminates the high variability in marginal cost for producing indicators that one might expect to have similar costs. This means that the cost of generating valid indicators needed to answer management questions varies greatly across locations, subbasins, and species. Indeed, the marginal cost of augmenting detections by one fish can be zero in some cases and hundreds or even thousands of dollars in others. Similar results were found for PIT detections for adults and juveniles, as well as for harvest recoveries.

The FT model was also used to evaluate the differences in cost between coded-wire tags and genetic marking for harvest indicators. The results indicate that despite some cost advantages in tagging and other qualitative advantages, high sampling and lab costs for genetics makes it more expensive than coded-wire tags by a significant amount in most situations. Although this analysis concludes that CWT has a cost advantage for recovering data on ocean fisheries, genetic marking generates data that has qualitative advantages over CWT data. Indeed, genetic marking may be more cost-effective than CWT for harvest data in specific circumstances, but ones that are different from the main ocean and lower-Columbia River fisheries evaluated in the FT model (see Appendix C). Specifically, in the Snake River basin where few non-target fish from other stocks are present, genetic marking can be more cost-effective than CWT. Genetic marking also has a distinct advantage for monitoring wild fish harvests due to the ability with GSI to genotype an entire fish population while handling a small number of fish.

The results from this version of the FT model deserve further analysis and closer examination. The current analysis was meant to be exploratory: to represent a “proof-of-concept” analysis for the use of the model to evaluate fish tagging, and to provide some evidence of the kinds of results that such a model could produce.

Indeed, these initial analyses give a strong indication of how a programming model of this kind could contribute to future improvements in fish tagging cost effectiveness and program effectiveness. Indeed, a revised and refined version of the current model could play an extremely valuable and useful role in rationalizing fish tagging efforts. Indeed, the results presented in this report barely scratch the surface of what is possible with the FT model. Due to time limits for completing the current report, more refinements to the model and additional analysis and scenarios were not possible. However, there is a large potential to gain further insights, to revise and refine the model, and potentially to use the model as one tool for rationalizing the entire fish tagging program to improve both cost-effectiveness and program effectiveness. Among the most valuable roles a model of this kind might play is to focus attention, going forward, on the strong interconnections and shared benefits that could be utilized more systematically to achieve better outcomes.

In terms of specific analyses, a wide array of additional issues could be addressed by evaluating and examining different scenarios and versions of the model. These kinds of alternative scenarios could be used to evaluate questions like the potential cost savings from increased detection probabilities at specific dams; they could help identify specific opportunities for coordination among projects and programs; they could estimate cost savings, or improved program effectiveness, by reallocating resources among species, subbasins or other program components; and they could provide insights into the costs of improved precision when estimating survival for a species at a particular dam or river reach.

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Table 1. Comparison of PIT tag insertions and observed averages (reference case)

PIT tag releases -- observed levels	Spring/ Summer Chinook	Fall Chinook	Coho	Steelhead	Sockeye
Lower Columbia River	20,000	25,000	4,000	-	6,000
Central Columbia River	46,000	39,000	2,000	-	29,000
Upper Columbia River	279,000	37,000	66,000	11,000	171,000
Snake River Basin	462,000	466,000	8,000	19,000	204,000
Total:	807,000	567,000	80,000	30,000	410,000

PIT tag releases: optimal levels in NLP Model

	Spring/ Summer Chinook	Fall Chinook	Coho	Steelhead	Sockeye
Central Columbia River	108,121	33,109	13,893	112,805	15,512
Upper Columbia River	29,644	15,201	47,699	95,333	5,152
Snake River Basin	207,138	64,922	3,752	189,203	3,834
Total:	344,903	113,232	65,344	397,340	24,498

Model results as % of observed levels:

	Spring/ Summer Chinook	Fall Chinook	Coho	Steelhead	Sockeye
Central Columbia River	235%	85%	695%		53%
Upper Columbia River	11%	41%	72%	867%	3%
Snake River Basin	45%	14%	47%	996%	2%
Total:	43%	20%	82%	1324%	6%

Model results less observed tagging:

	Spring/ Summer Chinook	Fall Chinook	Coho	Steelhead	Sockeye
Central Columbia River	62,121	(5,891)	11,893	112,805	(13,488)
Upper Columbia River	(249,356)	(21,799)	(18,301)	84,333	(165,848)
Snake River Basin	(254,862)	(401,078)	(4,248)	170,203	(200,166)
Total:	(462,097)	(453,768)	(14,656)	367,340	(385,502)

Table 2. Share of hatchery smolts tagged with Coded Wire Tags (reference case)

RMIS Region	Spring / Summer Chinook	Fall Chinook	Coho	Steelhead
Lower Columbia River	14%	8%	12%	0%
Central Columbia River	4%	8%	14%	0%
Upper Columbia River	26%	6%	15%	0%
Snake River Basin	2%	16%	0%	1%

Table 3. Marginal cost to increase detections (from origin to dam) ($/fish) (reference case)

Spring / Summer Chinook	Bonneville Dam	McNary Dam	Rock Island Dam	Rocky Reach Dam	Wells Dam
<u>Spring/summer Chinook, juvenile detections</u>					
Walla Walla	47				
Lower Yakima	49				
Naches	52				
Upper Yakima	19				
Upper Columbia-Entiat	35				
Wenatchee	31				
Okanogan	84				
Methow	46				
Lower Snake	51				
Lower Snake-Tucannon	35				
Clearwater	74				
Lower North Fork Clearwater	45				
Middle Fork Clearwater	46				
South Fork Clearwater	48				
Lochsa	49				
Lower Selway	48				
Lower Grande Ronde	74				
Wallowa	48				
Upper Grande Ronde	51				
Imnaha	46				
Little Salmon	49				
South Fork Salmon	53				
Pahsimeroi	61				
Upper Salmon	67				
<u>Spring/ summer Chinook adult detections</u>					
Middle Columbia-Hood	353				
Klickitat	365				
Lower Deschutes	418				
Umatilla	473				
Upper Yakima		382			
Upper Columbia-Entiat				482	
Wenatchee			443		
Methow					460
Lower Snake-Tucannon	318				
Middle Fork Clearwater		347			
Lochsa		369			
Lower Selway		359			

Table 3. Continued

	Bonneville Dam	McNary Dam	Rock Island Dam	Rocky Reach Dam
Pahsimeroi	389			
Upper Salmon	389			
Lower North Fork Clearwater	345			
South Fork Clearwater	372			
Wallowa	372			
Upper Grande Ronde	391			
Imnaha	355			
Little Salmon	378			
South Fork Salmon	407			

Fall Chinook	Bonneville Dam	McNary Dam	Lower Granite Dam
Fall Chinook juvenile detections			
Umatilla	47		
Lower Yakima	29		
Naches	57		
Upper Columbia-Entiat	81		
Methow	94		
Lower Snake	42		
Lower Snake-Tucannon	39		
Lower Snake-Asotiin	48		
Clearwater	49		
South Fork Clearwater	88		
Lower Selway	88		
Lower Grande Ronde	49		
Lower Salmon	87		
Fall Chinook adult detections			
Middle Columbia-Hood	353		
Lower Yakima		264	
Lower Snake		2,217	
Lower Snake-Tucannon		324	
Lower Snake-Asotiin			337
Clearwater			344
Lower Grande Ronde	329		

Table 3. Continued

Coho	Bonneville Dam	McNary Dam	Rock Island Dam
Coho juvenile detections			
Umatilla	42		
Lower Yakima	49		
Wenatchee	30		
Clearwater	74		
Middle Fork Clearwater	77		
Coho adult detections			
Naches	579		
Upper Yakima		598	
Wenatchee			453
Methow		968	

Steelhead	Bonneville Dam	McNary Dam	Rock Island Dam
Steelhead juvenile detections			
Lower Snake-Tucannon	36		
Lower Snake-Asotiin	45		
Clearwater	46		
Middle Fork Clearwater	47		
South Fork Clearwater	49		
Lower Grande Ronde	46		
Wallowa	50		
Imnaha	47		
Lower Salmon	49		
Little Salmon	50		
Middle Salmon-Panther	56		
Lemhi	98		
Pahsimeroi	60		
Upper Salmon	66		

Table 3. Continued	Bonneville Dam	McNary Dam	Rock Island Dam	Rocky Reach Dam	Little Goose Dam
Steelhead adult detections					
Middle Columbia-Hood	471				
Umatilla	630				
Walla Walla		716			
Upper Columbia-Entiat	1,088				
Wenatchee			1,073		
Methow				1,345	
Lower Snake-Tucannon					441
Lower Snake-Asotiin	429				
Middle Fork Clearwater	453				
Lower Salmon	467				
Clearwater	456				
South Fork Clearwater	496				
Lower Grande Ronde	460				
Wallowa	496				
Imnaha	476				
Little Salmon	504				
Middle Salmon-Panther	586				
Pahsimeroi	586				
Upper Salmon	586				

Sockeye	John Day Dam
Juvenile Sockeye detections	
Wenatchee	79
Upper Salmon	117

Table 4. Marginal cost to increase transportation detections ($/fish)(reference case)

Wild fish		To: McNary Dam	To: Lower Granite Dam
	Fall Chinook detections		
From:	McNary Dam	423	243
From:	Lower Granite Dam	434	929
	Steelhead detections		
From:	Lower Granite Dam	579	905

Hatchery fish		To: McNary Dam	To: Ice Harbor Dam
	Spring/summer Chinook		
From:	Lower Monument Dam	31	543
	Fall Chinook		
From:	McNary Dam	91	234
	Sockeye		
From:	McNary Dam	564	324

Table 5. Harvest-related tagging and recovery costs with coded-wire tags ($) (reference case)

Tagging costs	Spring / Summer Chinook	Fall Chinook	Coho	Steelhead
Lower Columbia River	92,380	183,555	116,875	-
Central Columbia River	29,011	287,353	50,045	-
Upper Columbia River	265,696	11,897	37,156	-
Snake River Basin	28,177	87,337		114,559
Total:	415,263	570,142	204,076	114,559
Ocean sampling and recovery costs				
Sampling				
Alaska	73,888	292,558	-	
British Columbia	81,104	181,199	-	
Washington	72,023	541,944	142,859	
Oregon	125,892	90,695	113,756	
Data recovery				
Alaska	1,823	7,733	-	
British Columbia	2,501	4,989	-	
Washington	1,823	13,407	5,918	
Oregon	1,420	2,449	5,222	
In-river sampling and recovery				
Sampling	81,605	18,227	44,480	116,217
Data recovery	9,850	1,298	5,791	3,500
Total sampling:	434,513	1,124,623	301,096	116,217
Total data recovery	17,419	29,876	16,932	3,500
Totals (tagging, sampling, data recovery)	867,195	1,724,641	522,103	234,275
Grand total:	3,348,214			

Table 6. Harvest-related tagging and recovery costs if genetic tagging replaced CWT ($)(reference case)

Tagging costs	Spring / Summer Chinook	Fall Chinook	Coho	Steelhead
Lower Columbia River	28,832	61,098	30,438	-
Central Columbia River	26,450	75,965	8,341	-
Upper Columbia River	106,490	1,992	8,290	-
Snake River Basin	25,861	15,617	-	128,828
Total:	187,633	154,672	47,069	128,828
Ocean sampling and recovery costs				
Sampling				
Alaska	51,809	184,813	-	
British Columbia	59,884	178,665	-	
Washington	58,219	534,327	141,572	
Oregon	88,240	35,331	70,440	
Data recovery				
Alaska	172,698	616,045	-	
British Columbia	199,612	595,550	-	
Washington	194,063	1,781,090	471,907	
Oregon	294,133	117,769	234,801	
In-river sampling and recovery				
Sampling	14,786	7,102	34,552	21,436
Data recovery	107,534	51,649	251,285	155,896
Total sampling:	272,938	940,238	246,564	21,436
Total data recovery	968,040	3,162,102	957,993	155,896
Totals (tagging, sampling, data recovery)	1,428,611	4,257,013	1,251,626	306,160
Grand total:	7,243,410			

Table 7. Comparison of tagging levels for harvest indicators (CWT versus genetics)

	Spring / Summer Chinook	Fall Chinook	Coho	Steelhead
Coded wire tags				
Hatchery:				
Lower Columbia River	560,864	1,019,749	671,304	
Central Columbia River	171,610	1,596,404	278,028	
Upper Columbia River	1,629,350	72,701	227,062	
Snake River Basin	166,675	485,206		636,436
Total:	2,528,499	3,174,060	1,176,394	636,436
Genetic marking				
Wild:				
Lower Columbia River		51,577		
Central Columbia River	296,217			
Upper Columbia River	897,808			
Snake River Basin	86,368	27,059		401,207
Hatchery:				
Lower Columbia River	961,070	1,985,034	1,014,609	
Central Columbia River	585,464	2,532,176	278,028	
Upper Columbia River	2,651,854	66,401	276,325	
Snake River Basin	775,666	493,494		3,893,067
Total:	6,254,446	5,155,742	1,568,961	4,294,275

Note: Numbers represent optimal tagging levels which, when paired with optimal sampling rates, satisfy identical harvest tag recovery requirements. "Tagging" in the case of genetics refers to the number of fish whose place of origin can be identified by genotyping a sample of tissue.

Table 8. Cost of a marginal ocean tag recovery with CWT ($/detection) (reference case)

	Spring/summer Chinook	Fall Chinook	Coho
<u>Recoveries in Alaska fisheries</u>			
Fish released in:			
Lower Willamette	1,107		
South Santiam	1,200		
Middle Columbia-Hood		2,884	
Klickitat		2,952	
Upper Columbia-Entiat	1,348		
Methow	335		
<u>Recoveries in Canadian fisheries</u>			
Lower Columbia-Clatskanie		530	
Lower Columbia-Sandy		557	
Lower Cowlitz	530		
Lower Willamette		556	
Lower Yakima		621	
Upper Columbia-Entiat	1,029		
Lower Snake		7,127	
Clearwater		652	
Hells Canyon		610	
<u>Recoveries in Oregon coastal fisheries</u>			
Lower Columbia		2,378	
Lower Columbia-Clatskanie	322		
Lower Columbia-Sandy			355
Lower Cowlitz			306
Lower Willamette			354
Clackamas			351
Methow			843
<u>Recoveries in Washington coastal fisheries</u>			
Lower Columbia-Clatskanie	403		
Lower Cowlitz		312	
Middle Columbia-Hood			404
Klickitat			11,715
Methow	3,682		
Lower Snake		21,386	
South Fork Clearwater		187	
Lower Grande Ronde		174	

Appendix A. Description of the Columbia Basin Fish Tagging Mathematical Programming Model

1. General Overview

The fish tagging (FT) model is a non-linear programming model written in GAMS™ (General Algebraic Modeling System), a high-level modeling system for mathematical programming and optimization. The structure is similar to other network models (such as transportation or shipping models) that optimizes an objective function (minimize cost) subject to a set of network characteristics, model parameters, unit costs, and constraints. Some of the model's constraints in the FT model are requirements for detecting or recovering fish at specific locations that were tagged at a different location. The network reflects both the river segments of the Columbia River system and also numbers of fish in each segment based on representative life-cycle information for wild and hatchery salmon and steelhead. The temporal dimension of these life-cycles are handled by normalizing the system to a one-year scale for the number of smolts, their juvenile migrations and survival, passage at dams, ocean survival, and adult in-river migrations. To satisfy the detection requirements (constraints) imposed in the model, fish may be tagged (at a cost) at hatcheries or other locations for later detection and/or recovery. Tagging options in the model include PIT tags, coded wire tags (CWT), and genetic markers of two types, Population Based Tagging (PBT) and Genetic Stock Identification (GSI).

2. Network specification

The model "network" is the set of river segments and dams that represent a simplified version of the Columbia River system. The FT model includes 64 distinct locations or river segments within the CRB, and also includes four ocean zones where fish migrate before returning. The network includes all river segments of the Columbia basin where significant numbers of salmon or steelhead smolts emanate or are released. More than 98% of the hatchery releases and wild populations of salmon and steelhead are represented in the model, based on data described below. Most major dams are also represented.

Transportation of juvenile fish is also represented as part of the network in the model. The numbers of fish transported by location and species are based on multi-year averages of data provided by Doug Marsh (NOAA) on transported fish (Appendix Table A4).

3. Fish populations, migration, survival

The parameters in the model's network replicate the life cycle of fish, their migration, survival rates and harvest pressure. The life-cycles of different fish species are scaled or normalized so that the model incorporates every phase of each species life cycle, but does not include multiple or overlapping brood years. This can be understood to reflect a one-year "slice" of the relevant life cycles in the CRB, the only difference is that all stages of tagged and untagged fish take place within the model. One way to think of this is as a set of equilibrium relationship averages for numbers of smolts, migrating juvenile s, adults in the ocean, and returning adults. The model is intended to represent a typical year under recent conditions in a steady state setting for populations and tagging.

The fish populations begin as hatchery and wild smolts for spring Chinook, fall Chinook, Coho, Steelhead, and Sockeye. The number of smolts occurring/released in each subbasin has been estimated based on ten-year averages of the total estimated releases from CWT data (made available by the Pacific States Marine Fish Commission staff) and from data on PIT tagged fish (made available by PTAGIS database).[8] Wild fish populations were estimated from two sources, estimates of adult escapement assembled by Columbia Basin Research (www.cbr.washington.edu/trends), and also estimates provided by Doug Marsh (NOAA, Northwest Fisheries Science Center). In cases where the only estimates are for adult escapement or number of spawners, an assumption of 200 smolts per adult was assumed to arrive at an estimate of the number of smolts (this would be consistent with a stable population and a 0.5% SAR).

Survival rates are assumed as follow: juvenile survival per 100 km (95%), juvenile survival per major dam (92%), adult survival across each major dam (99%), adult survival other than dam passage (100%). These survival rate estimates are consistent with assumptions made in agency reporting and memos (D. Marsh, personal communication, January 2013).

Ocean survival has been calibrated to realistic values and to ensure return rates similar to those observed: 2.5% for Chinook and Coho, and 4% for sockeye and steelhead, based on data from the Comparative Survival Study (2012 Annual Report). These approximations were inferred from estimates of survival rate estimates for juveniles from Lower Granite to Bonneville, adults from Bonneville to Lower Granite, and SAR estimates Lower Granite to Lower Granite.

The model includes release locations and hatchery releases representing 99% of the average number of fish released based coded-wire tag data (tagged and untagged releases) as well as PIT tag data.

Ocean migration and fishery exploitation is modeled based on CWT recovery data that, when linked to release data made it possible to estimate the migration patterns of fish by species and RMIS basin. The proportional distributions of fish migration to four ocean zones, as well as the numbers of non-Columbia River fish in each fishery, are show in Appendix Table A5.

4. Tagging

Four tag technology choices are included in the model: coded-wire tags (CWT), PIT tags, genetic tagging using PBT, and genetic tagging using GSI. Each technology is represented in the

[8] Coded wire tag data was assembled by and provided to us by Jim Longwill; assistance with PIT tag data was provided by Nicole Tancreto; Van Ware developed a way to translate between the CWT and PIT release location definitions. All are with the Pacific States Marine Fisheries Commission.

model in terms of costs for tagging, detection and recovery (discussed below), tagging mortality, shedding, and detection probabilities (in the case of PIT tags). Estimated detection probabilities by dam and species are shown in Appendix Table A3. Tagging mortality is assumed to be 10% for PIT tags and 1% for CWT. Tagging mortality for genetics are negligible (GSI) or zero (PBT), and so are assumed to be zero.

For transportation the tagging requirements can be satisfied with previously tagged fish (from upstream hatchery releases, for example) if sufficient numbers of previously tagged fish are captured for transport. Capture is assumed to be proportional to the numbers of previously tagged juvenile fish migrating past one of the four dams where transportation occurs (Lower Granite, Little Goose, Lower Monument, and McNary). If sufficient numbers of previously tagged fish are not captured, additional fish must be PIT-tagged at these locations in order to fulfill the transportation tagging requirement.

Fish are also tagged in order to satisfy harvest data requirements for ocean harvests and for in-river harvests in both commercial and sport fisheries. The estimated number of non-CRB fish caught in each fishery in the FT model (see Table A5) is exogenous and based on CWT data and reports from the Pacific Salmon Commission (PSC 2012, 2013). In a given fishery, the proportion of fish caught that is tagged and from the stock of interest is endogenous, and depends on juvenile survival rates (including tagging mortality), as well as the tagging rates.

Recovering tagged fish has two steps. In the first step fish are “sampled.” With CWT this means the fish are “wand tested” for a CWT. If one is detected (no matter the origin or ownership of the tag), the fish is sent to the lab to recover data on the origin of the fish. Both phases involve costs, but only snouts with tags are sent to the lab. In the case of genetic tagging, if it were used in place of CWT to collect harvest data, the two steps are different in one important respect. The first step is the same: fish from a given fishery are sampled. In the case of genetic tagging (GEN), however, there is no way to know if the sampled fish is a “fish of interest” without sending it to the lab. As a result, all sampled fish are sent to the lab to recover data and to learn if the fish was from a stock of interest or not. The higher the proportion of non-target fish in the fishery the larger will be the number of fish sent to the lab that are not from the target stock. This will increase the lab costs spent on fish that have no information from the stock of interest.

As a result of these endogenous tagging rates, harvest sampling and recovery probabilities are endogenous in the model, and they will also vary among fisheries due to the differences in the proportions of the stock of interest in each fishery. In-river fisheries will include only CRB fish, but in many cases the fish sampled may not represent fish of interest if their subbasin of origin is not one with detection requirements, or if the detection requirement has already been satisfied.

Some management questions and related indicators involve fish tagging technologies that are not included in the FT model. Radio tags, acoustic tags, otolith marking, and other techniques were not introduced in the model for several reasons. It was apparent in some cases that for specialized data or indicators (such as temporal monitoring of three-dimensional fish movements), these activities were not amenable to inclusion in the FT model in a way that would allow the model to generate useful insights related to cost-effectiveness.

5. Detection requirements

Detection requirements are what create a “job” for the model to do. In order to satisfy a detection requirement for fish originating at location A and detecting or recovering them at location B, the model must tag fish at A in sufficient numbers so that the required number of fish will be detected at B. The model is able to evaluate the number of fish to tag based on survival rates between A and B, tagging mortality, shedding, and detection probabilities. The model also will seek the least cost way to achieve this result. By requiring, for example, 100 detections of adult Snake River steelhead at Lower Granite dam, but from stocks emanating from the Grand Ronde River, this will force the model to tag perhaps 20,000 smolts that leave from the Grande Ronde as juveniles. Similarly for fish transportation studies, fish will be tagged to monitor survival rates with transportation. In this case, however, fish already tagged at hatcheries can be used as part of the sample needed for the transportation studies. Only one constraint is likely to be binding, with the other “indicator” activity being able to share the information from already-tagged fish.

In-river detection requirements for juvenile and adult were chosen to reflect two factors. First, we examined the average number of PIT tag detections over a ten year period by location of detection and release location. It would be misleading to require the model to achieve these levels of detection, however, since at many locations the majority of the detections are superfluous detections of passers-by but not directly relevant to a specific indicator or management question. These data, however, were used to identify the set of release sites and detection locations where detections of fish appear to be of interests to the programs.

To determine the level of the required detections at a given site, we assume that the indicator of interest is the survival rate from origin to detection with a 10% coefficient of variation (CV). Under reasonable assumptions, we can assume that 100 detections would be sufficient for a 10% CV (Appendix C). Thus the detection constraints require 100 detections for those pairs of release sites and detection locations where the ten year average was 100 or more detections. See Appendix Table A6 for a tabulation of these requirements for hatchery Spring Chinook.

Establishment of a set of realistic harvest recovery requirements was also accomplished in two steps. In the first step, CWT data for a 10-year period were examined to establish both the ocean migration and destinations of CRB fish in fisheries in Alaska, Canada, Washington and Oregon. These data were aggregated for each of these four ocean areas, by fishery type (commercial, sport, high seas, etc.). These aggregations could not be used to identify specific strata or more specific locations. Also, like the PIT-tag data, the average number of recovered tags across these aggregates could not be taken to reflect the number of recoveries needed to generate the desired precision of fishery exploitation. For example, in some cases many more CWT fish than needed would be caught in an ocean fishery, but the high tagging rate was maintained to achieve a desired recovery rate later on in the in-river fishery.

Setting an appropriate harvest recovery requirement is more ambiguous than for PIT detections. The number of recovered tags necessary to achieve a 10% CV for each stratum would require knowing more about the number and size of strata within each ocean region. Doing something like this is beyond the scope of the FT model, and indeed the number of strata can change from year to year. Therefore, the approach taken here was to require between 10 and 200 tags recovered for each ocean (and in-river) fishery based on the average number of recovered tags observed for each. Of course, in some cases the average was much higher than 200 tags, and so for these cases the model may be requiring too low a level of recovered tags. However, the results reported for harvest tagging cost-effectiveness included results for versions of the model in which these harvest detection requirements were doubled or tripled, and the comparative results of interest did not change.

With these harvest requirements in place, the model will adjust tagging levels and sampling rates to satisfy the detection requirements, and where the best combination will be the one that minimizes costs. To address the question of the relative cost of harvest-related tagging, two versions of the FT model were run, rather than allowing the model to choose between CWT and GEN based on cost (the nonlinearities involved in harvest tagging and recovery would make it difficult for the optimizing algorithm to successfully evaluate “switching” between one technology and another in order to minimize costs). The comparison between CWT and GEN, therefore, was undertaken by comparing the costs for two models that are identical except for their reliance on CWT versus GEN for harvest tagging.

The advantage or disadvantage of choosing CWT versus GEN will depend on costs, and on the fact that in the case of GEN all of the fish sampled must be sent to the lab before any information is recovered (as opposed to knowing whether the fish is from a stock of interest by waving a wand over the fish). This difference affects not only the overall cost of satisfying a set of recovery requirements, but also the optimal mix of tagging and sampling. As demonstrated in Appendix B, the optimal tagging rate will differ as a result for the two technologies.

6. Costs for tagging, detection and recovery

The cost relationships in the FT model determine the result because minimizing cost is the goal of the optimization. Cost assumptions enter for a given activity, such as the cost to tag a fish, cost to sample a fish, cost to recover data from a fish in the lab. Most activities have both fixed and variable costs. Fixed costs often reflect the cost of equipment and infrastructure, such as the large arrays of PIT tag detectors at major dams, or the labs build to recover information from CWTs or genetic information. If fixed costs are large relative to variable costs, then the average cost per fish will vary (decline) significantly with the (rising) volume of fish involved. If there are no fixed costs, then the cost per fish may be simply a constant unit cost. If fixed costs are low relative to the total variable costs and volume levels, it may be reasonable to use a constant value per fish.

There are other ways in which the cost relationships are not linear (constant unit cost). Some of these have to do with economies of scale in sampling or recovery. If few fish are tagged in a fishery, then more sampling (and sampling cost) will be incurred for each tag recovered. As tagging increases, the amount of sampling required to recover, say, 100 tags will decline. These relationships play out in the model and therefore give rise to non-linear cost relationships even though the individual cost assumptions (Appendix Table A8) are constant for each activity.

PIT tag detections at major dams represent one extreme where fixed costs are large and variable costs are essentially zero: there is essentially no cost for detecting one additional fish passing by the detector. In cases where there is a non-linear cost function, it can be introduced in the model as a non-linear mathematical function. However, the same result can be achieved simply by including the fixed costs and variable costs for specified activities. With the level of the activity being chosen endogenously, the resulting cost function reflected in the model's choices will be non-linear. This kind of non-linear relationship arises in the current model for harvest where the cost of recovering tags from a specific stock will vary nonlinearly with the level of tagging and sampling.

The cost assumptions in the model are based on many sources, including project budgets, agency budgets, estimates provided by individuals responsible for the tagging, sampling or lab work involved. The cost estimates central to the model are summarized in Appendix Table A8. The remainder of this section will summarize the sources and assumptions for these cost estimates.

<u>Marking costs</u>: Tagging for CWT and PIT are assumed to have low fixed costs so that an average cost per fish is a reasonable approximation ($0.18 for CWT and $4 for PIT). For CWT the $0.18 estimate comes from analysis by Rick Golden (BPA) and other materials presented at the Fish Tagging Forum. The PIT tagging estimate ($4) was estimated from analyses of BPA project budgets. Costs for tagging where in-river capture is required will vary greatly depending on the remoteness of the location and the abundance of fish. An average value for the cost of in-river capture was based on data provided by Brian Leth (Idaho Department of Fish and Game). For both CWT and PIT, the only difference between hatchery marking cost and in-river marking cost is the time/labor required. In the case of PIT tagging at mainstem dams (for transportation) an additional $2/fish reflects the added labor required compared to hatchery conditions (based on information provided by Doug Marsh, NOAA).

Costs of PBT and GSI for both marking and recovery are tied to the $40 cost per fish for genotyping. This cost estimate includes lab supplies as well as labor for technicians and scientists. In the case of PBT for hatchery brood stock parents, the $80 cost per pair results in 3,000 smolts or a negligible cost of about $0.03 per fish (based on information provided by Shawn Narum, Columbia River Inter-Tribal Fish Commission and Matthew Campbell, Idaho Department of Fish and Game). For GSI, used mainly to genetically "tag" wild fish populations, the relationship between the number of fish genotyped and the population identified is less clear cut.

Genetic sampling of this type is somewhat different due to cumulative value of genetic database over many years. The database of genetic information represents an investment with long-term and cumulative value for interpreting future information on recovered fish. A region-wide database for GSI has already been developed and is being expanded. There are large fixed costs involved, but since this work is already ongoing, for our purposes it is assumed to be a fixed or sunk cost, outside the decision process relevant to the FT model, and so they are not explicitly included in the model.

To add a new population to this database (species and subbasin), GSI identification typically involves sampling about 100 fish over a 2-3 year period, with updated samples of 10-20 fish every five years. The population of fish identifiable as a result will vary with the size of the spatially and genetically-identified population. For our purposes, we will assume an average of $0.03 per fish, similar to the cost for PBT (based on information provided by Shawn Narum, Columbia River Inter-Tribal Fish Commission and Matthew Campbell, Idaho Department of Fish and Game).

<u>Detection costs</u>: Non-lethal detection at intermediate points in the life-cycle (to monitor juvenile and adult migration and survival) is relevant mainly for PIT tags. PIT tag detections have an extremely low (nearly zero) marginal cost. Non-lethal detection could be accomplished with genetics in principle by capturing and handling fish to remove a scale for genotyping. The cost of this would be high ($42-$45.50) per fish compared to PIT tag detection which has a negligible marginal cost at large dams and a cost of $10 to $20 per fish at tributaries depending on the equipment used, remoteness and abundance of fish (assumed to have similar costs as for in-river capture discussed above).

The fixed costs associated with PIT tag detections involve large and costly infrastructure, as well as modifications of fish passage to accommodate new technologies and efforts to improve detection probabilities for juvenile passage. These capital and maintenance costs, when annualized or "levelized," can easily range from $100,000 to $500,000 per dam per year (based on cost information reported to the Fish Tagging Forum). But because these costs are not considered realistic "choice variables" in the FT model, they are not included in the model's cost relationships or total costs reported.

<u>Sampling and recovery</u>: Recovery of tagging data from harvested fish, hatchery returns or spawned carcasses is the other main type of setting where tag data is recovered. These cost relationships are non-linear overall, but can be modeled by separating them into sampling tasks and data recovery (lab) costs. The sampling cost is identified here as the cost per fish sampled, whether it contains a tag of interest or not. An average of this sampling cost can be used even though it varies across locations due to distance traveled and the concentration of harvested fish can vary dramatically. For sampling activities that encounter a range of dispersed and concentrated harvested fish (e.g., sport versus commercial docks), the costs in Appendix Table A8 have been estimated from agency budgets for 2011 (Oregon Department of Fish and Wildlife, Washington Department of Fish and Wildlife, Pacific States Marine Fish Commission). Sampling costs for CWT are $17 for ocean sampling and $10.50 for in-river sampling, reflecting the spatial concentration and of harvests in-river. The costs of sampling (only) are estimated to be somewhat lower for genetic sampling since samples can be taken from all fish (rather than retrieving snouts from a small fraction of sampled fish (with a wand) for CWT).

Although the costs of sampling for genetics is, in a sense, lower because all fish sampled would be sent to the lab, this is in fact the most significant drawback to genetic marking for harvest data collection. When sampled, there is no way to know if a fish is from a stock of interest. This contrasts with CWT where passing a wand over the fish reveals the presence of a CWT (it may still not be from a stock of interest, but for a CWT program in another basin or jurisdiction). In the case of genetics, each sample is sent to the lab where the process of determining the usefulness of the genetic information is expensive, $40 to genotype each fish.

Costs for recovery at hatcheries or for spawned carcasses were estimated roughly as indicated in Appendix Table A8, although these types of recoveries were not included in the current version of the FT model. In recent years expenditures on spawning ground recoveries have been about $0.5 million (information from Rick Golden, PBA).

Data management costs: Data management costs are not included in the model because they are assumed to be invariant with respect to the tagging technology used to collect the data.

Figure A1. Map of Columbia River Basin: nearly all rivers and tributaries in colored basins are included in the NLP model

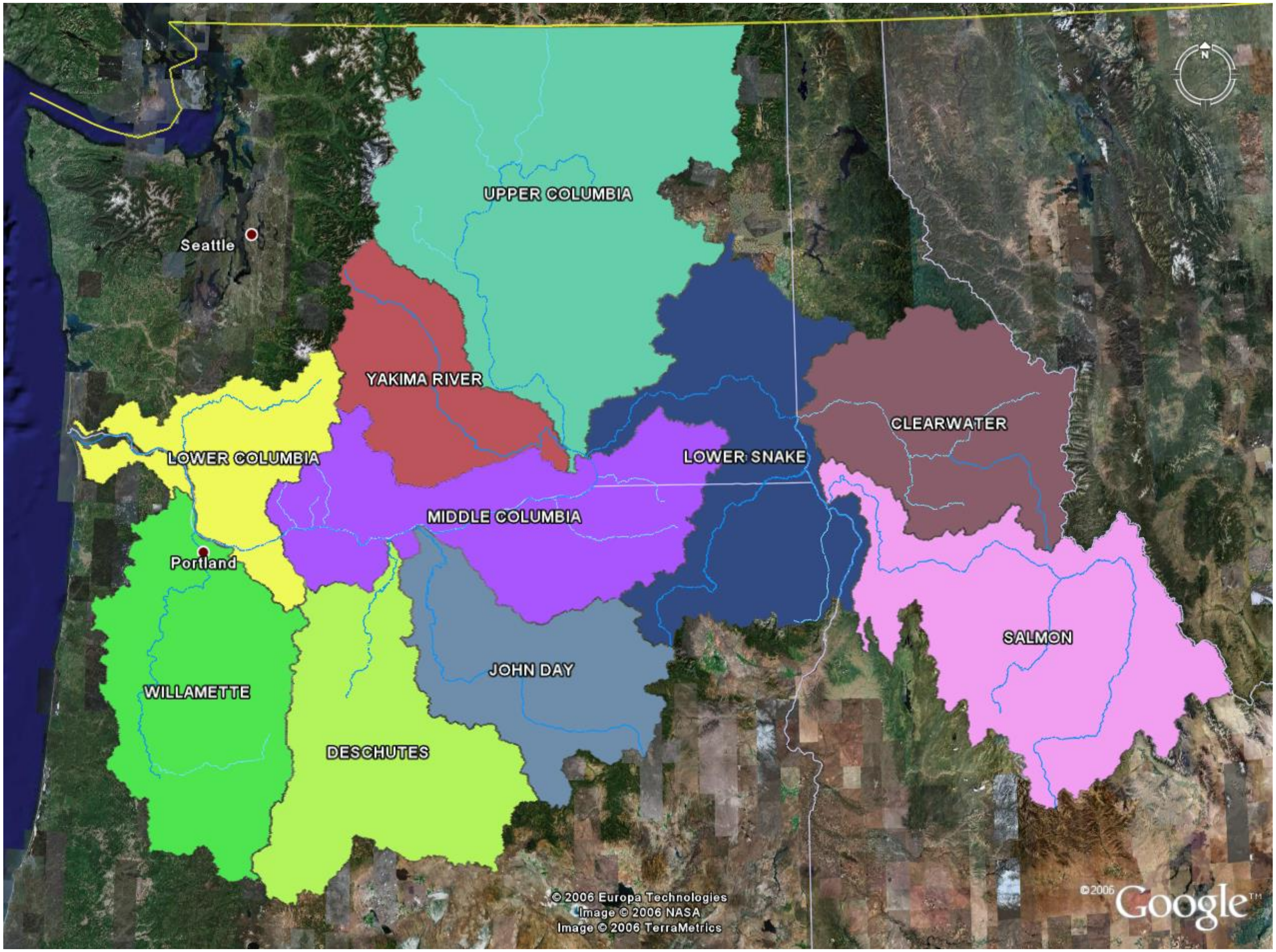

Figure A2. Schematic description of NLP Basin Network

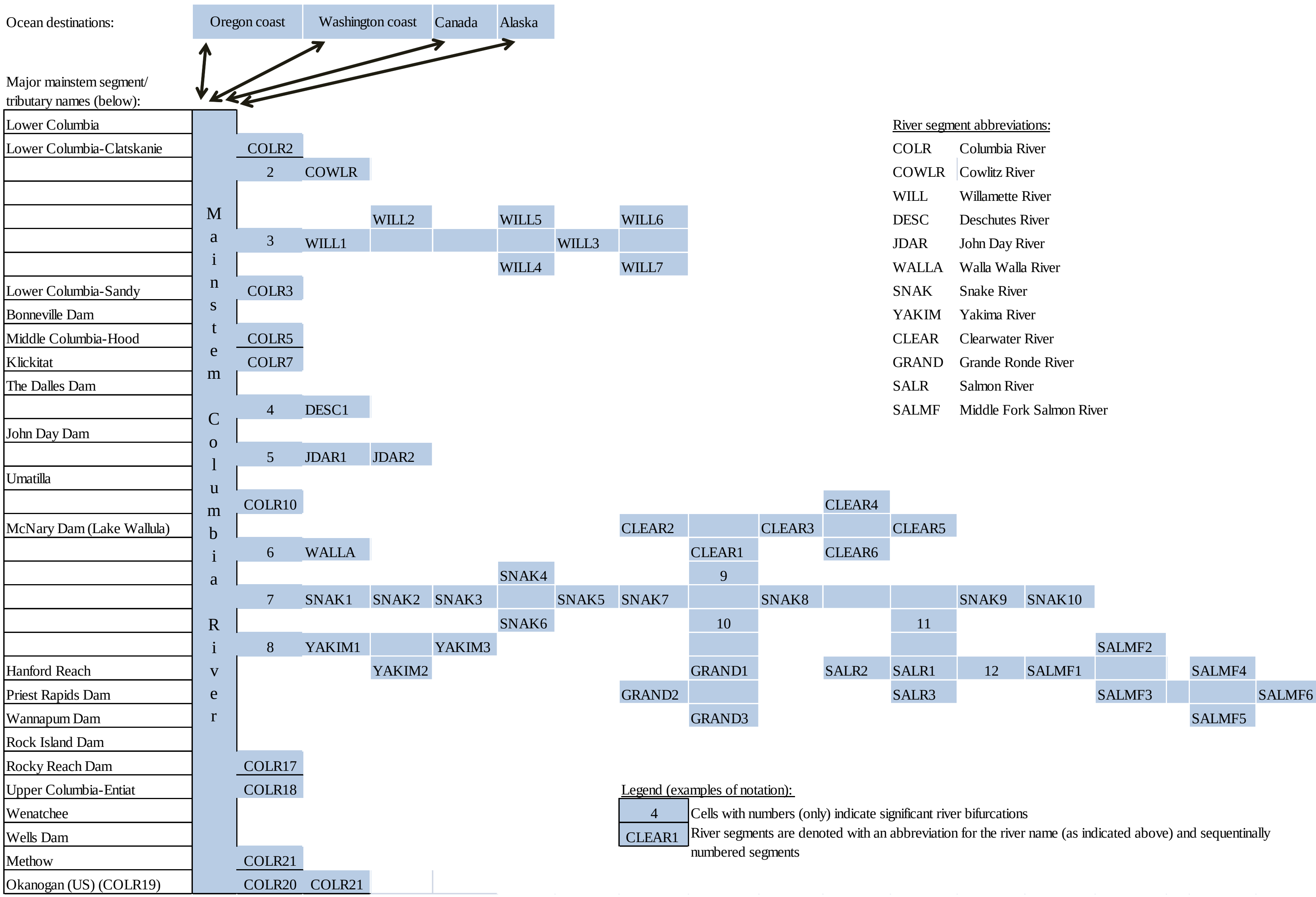

Table A1. Distribution of smolt populations in the Columbia River Basin, as assumed in the NLP Model

Segment/subbasin	Hatchery smolt releases: Spring Chinook	Fall Chinook	Coho	Steelhead	Sockeye
Lower Columbia	910,000	5,657,000	2,482,000	-	-
Lower Columbia-Clatskanie	575,000	2,854,000	354,000	7,000	4,000
Lower Columbia-Sandy	77,000	4,795,000	1,863,000	-	1,000
Lower Cowlitz	33,000	100,000	97,000	-	-
Lower Willamette	306,000	71,000	299,000	-	1,000
Clackamas	-	-	499,000	40,000	-
Middle Willamette	1,000	1,000	-	-	-
North Santiam	755,000	2,000	-	-	-
South Santiam	989,000	1,000	-	-	-
Upper Willamette	2,000	-	-	-	-
Mckenzie	9,000	-	-	-	-
Bonneville Dam	-	-	-	-	-
Middle Columbia-Hood	2,629,000	16,848,000	450,000	6,000	13,000
The Dalles Dam	-	-	-	-	-
Klickitat	127,000	683,000	109,000	-	1,000
Lower Deschutes	629,000	2,000	-	-	-
John Day Dam	-	-	-	-	-
Umatilla	5,000	4,000	2,000	14,000	8,000
McNary Dam	767,000	1,492,000	1,451,000	173,000	2,000
Hanford Reach	-	-	-	-	-
Priest Rapids Dam	-	-	-	-	-
Lower John Day	3,000	-	-	-	1,000
Upper John Day	1,000	-	-	-	4,000
Walla Walla	6,000	-	-	45,000	12,000
Lower Yakima	6,000	1,140,000	4,000	-	2,000
Naches	6,000	4,000	60,000	-	-
Upper Yakima	729,000	1,000	104,000	-	1,000
Wannapum Dam	-	-	-	-	-
Rock Island Dam	-	-	-	-	-
Rocky Reach Dam	-	-	-	-	-
Upper Columbia-Entiat	1,430,000	11,000	10,000	40,000	10,000
Wenatchee	1,877,000	2,000	939,000	34,000	224,000
Wells Dam	-	-	-	-	-
Okanogan	496,000	-	-	-	14,000
Methow	1,178,000	1,000	294,000	32,000	75,000
Similkameen	-	-	-	-	9,000

Table A1. (Continued)

Segment/subbasin	Hatchery smolt releases: Spring Chinook	Fall Chinook	Coho	Steelhead	Sockeye
Ice Harbor Dam	-	-	-	-	-
Lower Snake	6,000	163,000	-	-	4,000
Lower Monument Dam	-	-	-	-	-
Palouse	-	-	-	-	-
Little Goose Dam	-	-	-	-	-
Table 1. (Continued)					
Lower Snake-Tucannon	167,000	120,000	-	54,000	78,000
Lower Granite Dam	-	-	-	-	-
Lower Snake-Asotiin	-	877,000	-	366,000	7,000
Lower Grande Ronde	154,000	191,000	-	36,000	5,000
Wallowa	222,000	-	-	738,000	12,000
Upper Grande Ronde	239,000	-	-	-	4,000
Clearwater	1,073,000	1,230,000	264,000	790,000	13,000
Lower North Fork Clearwater	56,000	-	-	-	-
Middle Fork Clearwater	552,000	-	239,000	79,000	2,000
South Fork Clearwater	650,000	58,000	1,000	429,000	12,000
Lochsa	271,000	-	-	-	10,000
Lower Selway	237,000	9,000	1,000	-	1,000
Imnaha	31,000	-	-	193,000	14,000
Hells Canyon	319,000	369,000	-	-	2,000
Lower Salmon	-	10,000	-	41,000	3,000
Little Salmon	2,493,000	-	-	546,000	7,000
South Fork Salmon	1,240,000	-	-	-	4,000
Lower Middle Fork Salmon	5,000	-	-	-	2,000
Middle Salmon-Panther	-	-	-	22,000	-
Lemhi	4,000	-	-	27,000	3,000
Upper Middle Fork Salmon	10,000	-	-	-	1,000
Pahsimeroi	779,000	-	-	844,000	5,000
Upper Salmon	590,000	-	-	1,154,000	84,000

Table A2. Distribution of smolt populations in the Columbia River Basin, as assumed in the NLP Model

Segment/subbasin	Wild smolts: Spring Chinook	Fall Chinook	Coho	Steelhead	Sockeye
Lower Columbia	-	-	-	-	-
Lower Columbia-Clatskanie	-	-	-	-	-
Lower Columbia-Sandy	-	160,000	-	-	-
Lower Cowlitz	-	-	-	-	-
Lower Willamette	-	-	-	-	-
Clackamas	-	-	-	-	-
Middle Willamette	-	-	-	-	-
North Santiam	-	-	-	-	-
South Santiam	-	-	-	-	-
Upper Willamette	-	-	-	-	-
Mckenzie	-	-	-	-	-
Bonneville Dam	-	-	-	-	-
Middle Columbia-Hood	291,000	-	-	140,000	-
The Dalles Dam	-	-	-	-	-
Klickitat	291,000	-	-	-	-
Lower Deschutes	427,000	1,600,000	-	100,000	-
John Day Dam	-	-	-	-	-
Umatilla	-	-	-	240,000	-
McNary Dam	-	-	-	-	-
Hanford Reach	-	10,000,000	-	-	-
Priest Rapids Dam	-	-	-	-	-
Lower John Day	178,000	-	-	400,000	-
Upper John Day	355,000	-	-	140,000	-
Walla Walla	-	-	-	160,000	-
Lower Yakima	925,000	-	-	240,000	-
Naches	-	-	-	100,000	-
Upper Yakima	925,000	-	-	20,000	-
Wannapum Dam	-	-	-	-	-
Rock Island Dam	-	-	-	-	-
Rocky Reach Dam	-	-	-	-	-
Upper Columbia-Entiat	307,000	-	-	20,000	-
Wenatchee	420,000	-	-	120,000	-
Wells Dam	-	-	-	-	-
Okanogan	-	-	-	-	-
Methow	742,000	-	-	80,000	-
Similkameen	10,000,000	-	-	20,000	-

Table A2. (Continued)

Segment/subbasin	Wild smolts: Spring Chinook	Fall Chinook	Coho	Steelhead	Sockeye
Ice Harbor Dam	-	-	-	-	-
Lower Snake	-	-	-	-	-
Lower Monument Dam	-	-	-	-	-
Palouse	-	-	-	-	-
Little Goose Dam	-	-	-	-	-
Table 2. (Continued)					
Lower Snake-Tucannon	500,000	300,000	-	400,000	-
Lower Granite Dam	-	-	-	-	-
Lower Snake-Asotiin	-	200,000	-	60,000	-
Lower Grande Ronde	80,000	-	-	400,000	-
Wallowa	150,000	-	-	-	-
Upper Grande Ronde	240,000	-	-	200,000	-
Clearwater	18,000	-	-	-	-
Lower North Fork Clearwat	-	-	-	-	-
Middle Fork Clearwater	-	-	-	-	-
South Fork Clearwater	-	-	-	-	-
Lochsa	30,000	-	-	-	-
Lower Selway	-	-	-	-	-
Imnaha	223,000	-	-	-	-
Hells Canyon	-	100,000	-	-	-
Lower Salmon	326,000	200,000	-	-	-
Little Salmon	-	-	-	-	-
South Fork Salmon	300,000	-	-	-	-
Lower Middle Fork Salmon	100,000	-	-	-	-
Middle Salmon-Panther	140,000	-	-	-	-
Lemhi	20,000	-	-	-	-
Upper Middle Fork Salmon	200,000	-	-	-	-
Pahsimeroi	40,000	-	-	-	-
Upper Salmon	50,000	-	-	-	6,000

Table A3. Detection probabilities at major dams for juvenile salmon and steelhead

Dam:	Spring/ summer Chinook	Fall Chinook	Coho	Steelhead	Sockeye
Bonneville Dam	18%	16%	18%	17%	18%
The Dalles Dam	40%	25%	40%	50%	40%
John Day Dam	15%	23%	15%	19%	12%
McNary Dam	36%	19%	36%	21%	19%
Priest Rapids Dam	NA	NA	NA	NA	NA
Rock Island Dam	NA	NA	NA	NA	NA
Rocky Reach Dam	15%	12%	38%	31%	34%
Wells Dam	NA	NA	NA	NA	NA
Ice Harbor Dam	60%	45%	60%	75%	60%
Lower Monument Dam	28%	14%	28%	38%	34%
Little Goose Dam	44%	28%	44%	53%	37%
Lower Granite Dam	38%	19%	38%	43%	28%

Note: Adult detection probabilities are assumed to be 99%
Sources for these estimates include Doug Marsh (NOAA) and Tom Kahler (Douglas PUD)

Table A4. Transportation of juvenile fish to below Bonneville Dam: annual levels assumed in NLP model

From:	Spring / Summer Chinook	Fall Chinook	Coho	Sockeye	Steelhead
McNary Dam	1,060,000	1,870,000	70,000	300,000	330,000
Lower Monument Dam	670,000	330,000	30,000	20,000	570,000
Little Goose Dam	1,440,000	800,000	60,000	20,000	1,760,000
Lower Granite Dam	2,270,000	630,000	50,000	30,000	2,420,000

Source: data provided by Doug Marsh, NOAA Northwest Fisheries Science Center.

Table A5. Ocean Destinations of Columbia River Fish and Fishery Composition

Subbasin of origin	Ocean Fishery Destination	Spring and Summer Chinook	Fall Chinook	Coho
Snake River Basin	Alaska	-	-	-
	Canada	-	39%	-
	Washington Coast	-	50%	-
	Oregon Coast	-	8%	-
Upper Columbia River Basin	Alaska	39%	52%	-
	Canada	45%	39%	-
	Washington Coast	11%	9%	48%
	Oregon Coast	5%	-	52%
Central Columbia River Basin	Alaska	-	3%	-
	Canada	20%	39%	-
	Washington Coast	60%	50%	21%
	Oregon Coast	20%	8%	79%
Lower Columbia River Basin	Alaska	18%	33%	0.00
	Canada	43%	39%	2%
	Washington Coast	32%	26%	55%
	Oregon Coast	7%	3%	43%
Numbers of non-Columbia River fish in fisheries				
	Alaska	78,000	33,000	-
	Canada	51,000	36,000	-
	Washington Coast	17,000	99,000	29,000
	Oregon Coast	3,000	9,000	17,000
Approximate share of fish in fishery coming from Columbia River Basin				
	Alaska	66%	10%	9%
	Canada	59%	36%	9%
	Washington Coast	44%	37%	11%
	Oregon Coast	55%	37%	11%

Sources: Coded Wire Tag data provided by Pacific States Marine Fish Commission; and Pacific Salmon Commission Joint Chinook Technical Report, TCCHINOOK (12)-4

Appendix Table A6. Example of detection requirements: hatchery Spring Chinook

Release location	Detection location, juvenile						Detection location, adult							
	Bonneville dam	John Day Dam	McNary Dam	Lower Monument Dam	Little Goose Dam	Lower Granite Dam	Bonneville Dam	McNary Dam	Priest Rapids Dam	Rock Island Dam	Rocky Reach Dam	Wells Dam	Ice Harbor Dam	Lower Granite Dam
Middle Columbia-Hood	100						100							
Klickitat	100						100							
Lower Deschutes	100						100							
Umatilla	100	100					100							
Walla Walla	100	100	100											
Lower Yakima	100	100	100											
Naches	100	100	100											
Upper Yakima	100	100	100				100	100						
Upper Columbia-Entiat	100	100	100				100	100	100	100	100	100		
Wenatchee	100	100	100				100	100	100	100				
Okanogan (US)	100		100											
Methow	100	100	100				100	100	100	100	100	100		
Lower Snake	100	100	100	100										
Lower Snake-Tucannon	100	100	100	100	100	100	100							
Lower Grande Ronde	100		100	100	100	100								
Wallowa	100		100	100	100	100	100	100						100
Upper Grande Ronde	100		100	100	100	100	100	100						100
Clearwater	100		100	100	100	100								
Lower North Fork Clearwater	100		100	100	100	100	100	100						100
Middle Fork Clearwater	100		100	100	100	100	100	100						
South Fork Clearwater	100		100	100	100	100	100	100						100
Lochsa	100		100	100	100	100	100	100						
Lower Selway	100		100	100	100	100	100	100						
Imnaha	100		100	100	100	100	100	100						100
Little Salmon	100		100	100	100	100	100	100					100	100
South Fork Salmon	100		100	100	100	100	100	100					100	100
Pahsimeroi	100		100	100	100	100	100							
Upper Salmon	100		100	100	100	100	100							

Appendix Table A7. Harvest detection requirements for commercial and sport fisheries

	Ocean and In-river harvests (commercial and recreational)																
	Spring and Summer Chinook					Fall Chinook					Coho					Steelhead
Release location	AK	BC	WA	OR	In-river	AK	BC	WA	OR	In-river	AK	BC	WA	OR	In-river	In-river
Lower Columbia	10	10			100		70	100	50	100			100	100	100	
Lower Columbia-Clatskanie	30	70	80	30	100	20	70	70	10				200	200	100	
Lower Columbia-Sandy						40	50	20					100	100	100	
Lower Cowlitz		10	10				10	20					50	50	100	
Lower Willamette	10	10	10			10	20	10					100	100	100	
Clackamas													10	10		
South Santiam	10	10														
Middle Columbia-Hood					100	110	100	100	50	100			80	30	100	
Klickitat						40	40	10					50	20		
Lower Deschutes					100											
Lower Yakima						30	20									
Upper Columbia-Entiat	200	200	60	30	100											
Wenatchee					100								20	10	100	
Methow	30	30	10		100								10	10		
Lower Snake							30	100	10							
Lower Grande Ronde								10								100
Wallowa																100
Clearwater						10	80	100	20							100
South Fork Clearwater								10								100
Imnaha																100
Hells Canyon							20	60	10							
Little Salmon					100											100
South Fork Salmon					100											
Upper Salmon																100

Appendix Table A8. Estmated cost in FT model for tagging, detecting, sampling, and data recovery ($/fish

Marking fish	CWT	PIT	PBT	GSI
Marking at hatchery	0.18	4.00	0.03	NA
With in-river capture	13.00	15.00	NA	0.03
Tagging at dams	3.00	6.00	NA	NA
Tagging mortality	1%	10%	0%	0%
Nonlethal detection:				
At large dams	NA	-	2.00	2.00
At tributaries	NA	10.00	5.50	5.50
With handheld device	NA	20.00	NA	NA
Lab costs	NA	-	40.00	40.00
Sampling of harvested or returned fish:				
Sampling per fish (ocean)	17.00	NA	12.00	12.00
Sampling per fish (in-river)	10.50	NA	5.50	5.50
Adult return to hatchery	6.00	1.00	41.00	41.00
Spawned carcass recovery	51.00	46.00	86.00	86.00
Recovery of data from sampled or detected fish:				
Lab costs	5.00	0	40.00	40.00

Sources: see Appendix A text

Note: For CWT, only sampled fish where tags are detected (using wands) are sent to the lab to recover ID information; in the case of PBT and GSI, all fish must be sent to the lab for genotyping (there is no information based on examining a sampled fish with which to recognize fish of interest from non-target fish, or fish from stocks where the threshold recovery level has already been satisfied.

Appendix B
Analytical derivation of the optimal levels of tagging and sampling for harvest data using coded-wire tags or genetic marking

The number of recovered tags from a specific stock that is present in a fishery will depend on the number of smolts marked (M), the survival rate to the fishery, the number of other non-target fish in the fishery, and the sampling level for the catch. To increase the number of recovered tags, this can be achieved by either increased sampling or increased tagging. The optimal (cost-minimizing) approach will depend on the cost of tagging, the cost of sampling, and the cost of recovering data (lab costs).

More precisely, the costs of achieving a desired level of harvest tag recoveries for a CR (Columbia River stock) will depend on three costs:

- marking costs (c_m),
- sampling costs (c_s) from a fishery, and
- recovery costs (c_r) including lab work to recover data from the fish.

The optimal level of tagging will depend on these costs, as well as:

- P, the population of smolts in the target stock
- θ, the share of the population of CR smolts present in the fishery
- N, the number of non-CR fish in the fishery and
- T, the number of recovered tags from the CR stock required.

The share of CR fish in the fishery (S_f) is

$$s_F = \left[\frac{\theta P}{\theta P + N}\right] \tag{1}$$

The share of fish in the fishery with CR tags s_T is:

$$s_T = \left[\frac{\theta M}{\theta P + N}\right] \tag{2}$$

Tags recovered (T) will be

$$T = s_T S \tag{3}$$

where S is the number of fish sampled.

The total cost of achieving T recovered tags will tradeoff the costs of marking M fish and the costs of sampling and data recovery. The total cost is:

$$\text{TC} = TC = c_r T + c_m M + c_s S \tag{4}$$

Substituting (2) and (3) into (4) we can write total cost for coded-wire tags as

$$TC_{CWT} = c_r T + c_m M + c_s \left[\frac{T(\theta P + N)}{\theta M}\right] \tag{5}$$

Differentiating with respect to M and rearranging produces M^*_{CWT}, the cost minimizing level of marking with coded-wire tagging:

$$M^*_{CWT} = \left[\frac{c_s T(\theta P + N)}{\theta c_m}\right]^{1/2} \tag{6}$$

In the case of genetic tagging, all fish sampled must undergo the costs of "recovery" of data (lab work) to determine if the fish is part of the CR stock of interest. Thus, (3) becomes

$$\text{TC} = TC = c_r S + c_m M + c_s S \tag{7}$$

This leads to a modified optimality condition. The optimal or cost minimizing level of marking with genetics, M^*_{GEN}, becomes:

$$M^*_{GEN} = \left[\frac{(c_s + c_r) T(\theta P + N)}{\theta c_m}\right]^{1/2} \tag{8}$$

We can see by comparing (6) and (8) that the optimal number of marked fish is higher with genetic tagging. The intuition is that because all fish sampled will incur lab costs, a higher level of marking will reduce the number of "wasted" lab tests.

Appendix C: Framework for linking detection requirements to coefficients of variation

The following text, excerpted below from Paulsen (2005), describes the relationship between the "coefficient of variation" (CV) for survival rate estimates. For our FT model, we can require the number of "survivors detected" to be 100, and the model will endogenously tag sufficient numbers of tagged releases to achieve a 10% CV:

"In looking at ways to standardize the analysis across life stages, population, etc. we use the coefficient of variation (CV) to compare the precision of survival rate estimates. To see why, consider the equations for survival and its variance, in a case where detection rates are 100% (similar but more complex version apply when detection rates are lower):

$$Mean(\hat{S}) = \text{N(survivors detected) / N(tagged animals released)} \quad (1)$$

The variance is a function of the survival rate, the number detected, and the number released:

$$Var(\hat{S}) = \hat{S}^2 * [1/N(\det ected) - 1/N(released)] \quad (2)$$

The standard deviation is just the square root of the variance, of course:

$$Std(\hat{S}) = \hat{S} * \sqrt{1/N(\det ected) - 1/N(released)} \quad (3)$$

And the CV is just the standard deviation, eq. 3, divided by the mean from eq. 1:

$$CV(\hat{S}) = Std(\hat{S}) / \hat{S} = \sqrt{1/N(\det ected) - 1/N(released)} \quad (4)$$

The survival rate, $\hat{S}$, cancels, leaving the number detected and the number released determining the *sampling* variability of the survival estimate. (Note that this is distinct from process variation among populations or over time.) Since in many cases, as with SAR's, the survival rate is quite low, the number of fish detected will dominate the sampling variation, and the variation obviously decreases as the number of survivors detected increases.

Rather arbitrarily, we have used a target CV of about 10% as a target for survival rate estimates. This is probably too low (too imprecise) for mainstem reach survival estimates, and may be too high for SAR's (at the other extreme) but it is a reasonable starting point.
….
In summary, tracking survival from tagging as parr to LGR the following spring requires about 1,000 - 2,000 fish per release group – population, MPG, etc. if the 10% CV rule of thumb holds. Inriver survival estimates (details not shown here), from LGR to McNary or McNary to Bonneville, also require about 1,000 fish per group. In years past, fish have been grouped based on their date of arrival at LGR or McNary, with daily groups used in the Snake and weekly groups used for the Columbia. SAR's with a 10% CV will need about 10,000 smolts per group, assuming a 1% survival rate from smolt at LGR to adult back to LGR. We employ these heuristics in the next section as a first cut at sample size and monitoring design."